PUB-5317

Conceptual Design Report

Chemical Dynamics Research Laboratory

February 1992

Project Number 94-LBL

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
Prepared for U.S. Department of Energy under Contract No. DE-AC03-76SF00098

CHEMICAL DYNAMICS RESEARCH LABORATORY

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CONCEPTUAL DESIGN REPORT
REVIEW CHECKLIST

Project Title: CHEMICAL DYNAMICS RESEARCH LABORATORY

Date of CDR: FEBRUARY 1992 Project Location: LAWRENCE BERKELEY LABORATORY

In the space provided below, please indicate where the item is located in the CDR, e.g. page number, section, etc. If not applicable, then indicate N/A and explain in writing.

1)	1-1	Project justification.
2)	2-1	Detailed description of the project scope.
3)	2-56	Performance requirements (facility/building/system/ process).
4)	3-1, 9-2	Project cost estimate.
5)	3-1	Cost estimate assumptions and methodology.
6)	3-6, 9-3, 9-98	Cost estimate date.
7)	3-1	Identification of the originator of the cost estimate.
8)	3-21	Escalation rates used in cost estimate.
9)	N/A	Major areas of cost uncertainties.
10)	3-15, 3-16, 3-17	Financial schedule (annual obligation/cost requirements).
11)	1-3	Discussion on alternatives considered.
12)	7-2	Life cycle cost analysis of proposed project and alternatives.
13)	4-2	Schedule with major milestones and critical path identified (design, procurement, construction, mid-point of construction, environmental compliance and safety analysis).
14)	4-1	Schedule constraints (funding, seasonal, R&D related, etc.).
15)	1-5	Method of performance (acquisition strategy) for design, procurement and construction.
16)	9-4	Work breakdown structure.
17)	N/A	Safeguards and security requirements.
18)	N/A	Safeguards and security features incorporated.
19)	7-1	Energy conservation design/construction features.
20)	7-2	Estimates of energy consumption and types of energy supply.
21)	8-1	Health, safety and fire protection hazards/risks.

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22)	8-1	Health, safety and fire protection features.
23)	8-1	Schedule for safety analysis review/documentation.
24)	8-2	Environmental hazards/risks.
25)	4-1	Discussion on level of required NEPA documentation.
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45)	1-3	Discussion on facility siting, site development plan, site development requirements and real estate issues (easements, permits, etc.).
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47)	3-4, 3-5	List of major standard equipment and special facilities.
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54)	N/A	Strategic Facilities Initiative form.
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CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 1

INTRODUCTION

Summary

IN SUPPORT OF DOE'S NATIONAL ROLE IN COMBUSTION RESEARCH directed towards maintaining U.S. scientific and technological leadership and competitiveness in fuel-related industries and research, the Lawrence Berkeley Laboratory (LBL) and the Sandia National Laboratory (SNL) are proposing the Chemical Dynamics Research Laboratory (CDRL). This new facility is a key part of a major new programmatic thrust known as the Combustion Dynamics Initiative (CDI). The CDI is sponsored by DOE's Division of Chemical Sciences conceived to orchestrate the programmatic efforts of national user facilities to advance DOE's energy sciences mission through enhancing the efficiency of the combustion process while minimizing the undesirable effects, such as the production of pollutants. The CDRL will be located at LBL adjacent to the Advanced Light Source (ALS). The scientific efforts at the CDRL will emphasize fundamental aspects of combustion chemistry, while the efforts at Sandia National Laboratory's Combustion Research Facility will emphasize complementary basic and applied research. This document addresses only the CDRL at LBL.

The CDRL will provide state-of-the-art national user facilities for a laser and synchrotron radiation based program of chemical dynamics research. The proposed laboratory and special research facilities include an Infrared Free Electron Laser (IRFEL); Advanced Light Source (ALS) chemical physics beamlines optimized for chemical sciences research; advanced lasers and molecular beam apparatus; universal particle mass detectors; computer-based modeling systems; and other auxiliary instrumentation.

The facilities will be located in a new three-story 46,600-GSF building directly adjacent to the ALS, which is now under construction. The building, designed to enhance the effectiveness of scientific interactions, will include a high-bay heavy laboratory experimental hall housing the scientific equipment mentioned above, along with eight related support laboratories and offices for 50–60 local and visiting researchers plus 30–40 graduate students. The basement will house the IRFEL, mechanical equipment and electrical substation.

Project Justification

The Combustion Dynamics Initiative is advanced as a national response to major scientific and technological challenges in combustion, chemical reaction dynamics and related science and engineering fields. The facilities will address the following national science and technology problems:

- Inadequate understanding of combustion phenomena, especially the underlying chemical processes, to assist the development of U.S. and global pollution control technologies or for the understanding of emission sources to provide clean and efficient energy conversion systems. An important step to improved cost effective combustion technology is understanding the underlying molecular-level chemical and physical dynamics and mechanisms in great detail.

- Lack of leadership in developing advanced instrumentation for basic and applied research at the frontiers of understanding combustion and chemical reaction processes. Advanced technical resources for experimental research are not being mobilized to meet national and internationally competitive challenges.

- Need for a multidisciplinary approach, with the necessary advanced tools and computational resources to bring major breakthroughs in difficult experimental and theoretical problems underlying combustion science and physical chemistry.

Throughout the past five years, national reports have consistently indicated a need for improvements and new facilities for advanced combustion science and chemical physics research. The Pimentel Report on New Opportunities in Chemistry (1985) identified as a priority frontier "an initiative to apply the full power of modern instrumental techniques and chemical theory to the clarification of factors that control the rates of reaction and to the development of new synthetic pathways for chemical change." The National Research Council Physics Survey (1986) identified a program of research initiatives that included molecular physics, new optical technologies, and advances in spectroscopy. The Basic Energy Sciences Subcommittee Report on Chemical Sciences (1988) identified the need for new combustion research facilities for conducting energy research and "...to provide facilities for training future researchers and assure the transfer of technology through visiting scientist and postdoctoral programs."

Recent national symposia, including the Workshop on Opportunities for Chemistry Related Combustion Science held in July 1986, the Workshop on Chemical Reaction Dynamics held in November 1988, and the Workshop on Combustion Dynamics held at LBL in April 1990, identified the need and the opportunity for advances in spectroscopic techniques, free-electron lasers, synchrotron light sources, conventional lasers, molecular beam methods, and imaging and computational techniques in combustion and chemical reaction dynamics. The workshops stressed that investigations in these areas require integrated research instrumentation.

In response to these broad challenges, DOE's national role in combustion research is being significantly enhanced at the Lawrence Berkeley Laboratory and the Sandia National Laboratories (SNL) through this major initiative. At LBL, the CDRL will be a national user facility to advance DOE's energy mission to enhance the efficiency of combustion processes while minimizing undesirable effects, such as the production of pollutants. The LBL effort will emphasize fundamental aspects of combustion chemistry while the Sandia effort will emphasize complementary research in flow processes and imaging. Both institutions will develop advanced instrumentation to bear on these research topics, and this equipment will be made broadly available to combustion and chemical-physics researchers. The LBL program has been developed in response to:

- The need to gain a molecular-level understanding of unimolecular reactions and energy flow processes necessary to predict and control combustion and control technology performance.

- The need to understand the production, structure, and dynamics of highly excited molecular species and reactive intermediates, many of which lead to formation of pollutants.

- The need to provide technical resources and a multidisciplinary setting to advance basic new knowledge that underlies scientific and technological leadership in internationally competitive combustion systems and control technology industries.

New experimental resources are needed to investigate fundamental chemical physics and combustion chemistry processes. The first user-dedicated Infrared Free Electron Laser, sophisticated molecular beam apparatus, dedicated chemical physics synchrotron-radiation beamlines, and advanced lasers can overcome existing limitations in experimental and diagnostic analytical systems. Such facilities are needed to achieve the simultaneous application of broadly tunable, high intensity infrared radiation with ultra-high brightness XUV radiation from ALS beamlines for pump-probe experiments and with crossed molecular beams. These resources can provide new and powerful tools for combustion science as described in Section 2, Project Description.

LBL is uniquely suited to host this facility. The Advanced Light Source will provide the world's brightest beams of XUV radiation as a major complement to the CDRL. Existing DOE programs support application of advanced molecular beam machines in chemical physics and combustion science. The engineering expertise necessary for IRFEL development and operation are available, together with experience in developing and operating national user facilities. Graduate students and postdoctoral associates provide a strong basis for educational benefits, and LBL's close liaison with the Lawrence Hall of Science provides opportunities to contribute to pre-college science education. Technology transfer programs in place at LBL will promote the direct utilization of potential spin-off technologies by industry, including advanced lasers and ultrafast, highly sensitive detectors.

The CDRL project is proposed as a major national resource to advance the goals of the Office of Basic Energy Sciences and Division of Chemical Sciences. The scientific program, summarized in the following section, will benefit from a focused, multi-investigator approach, broadly available to visiting scientists, with a strong coupling of experimentalists and theorists. The CDRL will develop advanced instrumentation and methodologies, and will educate and train new scientists in chemical dynamics and combustion chemistry to ensure that future U.S. leadership in the field remains internationally unparalleled.

A major consideration in locating the Chemical Dynamics Research Laboratory at Lawrence Berkeley Laboratory was the availability of synchrotron radiation from the 1-2 GeV Synchrotron Radiation Source (ALS). Experimental requirements dictated that the Chemical Dynamics Research Laboratory be constructed adjacent to the ALS facility. Prior to the development of the conceptual design, a Site Selection Study was completed analyzing alternate locations around the perimeter of the ALS building.

The proposed location proved to be the most feasible. It provides the closest possible access to the ALS which results in the shortest optical path from the light source to the experimental apparatus, a user specified requirement. The new facility will allow for better utilization of the site by replacing an inefficient existing wood structure, one of the oldest at LBL. No major changes to existing grades and circulation will be required. The building program and conceptual design were developed with detailed input from users and provides spaces and utilities required for the CDRL research.

Basis of Conceptual Design

The programmatic criteria for the Chemical Dynamics Research Laboratory were established by the LBL Chemical Sciences Division Directorate. The functional requirements were defined by:

- Professor Yuan T. Lee, Nobel Laureate, Chemistry 1986
- Professor C. Bradley Moore, Dean, College of Chemistry, UCB
- Members of the Advanced Light Source (ALS) Chemical Physics Participating Research Team
- SM Scientific and Management Staff
- Members of the Combustion Chemistry and Chemical Physics Community

The conceptual design for the Special Research Facilities was developed by a team of physicists, chemists and engineers at LBL and the University of California at Berkeley (UCB). This effort on the Special Research Facilities was coordinated through the Accelerator and Fusion Research Division at LBL and the Chemistry Department at UCB. Assistance on both the general design approach and key design details was provided by technical consultants, commercial suppliers and workshop participants with expertise in relevant technologies. In particular, we wish to acknowledge Bill Stein, Industrial Radiation Inc., and John Edighoffer, Pulse Sciences, Inc., for their contributions on aspects of the RF system, beam stability and control. Design verifications were conducted by using standard computer simulation techniques.

The conceptual design for the Conventional Facilities was developed by the LBL Plant Engineering Department with the assistance of the following consultants:

Geo/Resource Consultants, Inc.
Geologists/Engineers/Environmental Scientists

The cost estimate was prepared by Lee Saylor, Inc., Construction Consultants, and is based on quantity take-offs from conceptual design drawings and outline specifications developed by LBL and the above consultants.

Method of Performance

- General

  An engineering design team will be organized to develop final design specifications and drawings for the special research facilities and to oversee all aspects of design, procurement/fabrication and installation.

  LBL will assign a Project Manager who will be responsible for coordinating efforts of the project team and for reporting project status relative to scope, schedule and cost for the duration of the project.

- Conventional Facilities Design

  The design program will be prepared by the LBL Plant Engineering Department based upon programmatic requirements developed by LBL's Chemical Sciences Division.

  An Architect/Engineering firm with appropriate laboratory design experience will be selected for Titles I and II design services and for technical oversight during the construction. Independent reviews of the structural design and the cost estimate will be arranged by LBL.

- Conventional Facilities Construction

  Construction will be accomplished by lump-sum Subcontracts awarded after competitive bidding. The cost estimate and schedule is based on two lump-sum bid packages, one for the site preparation work and one for the remainder of construction work. Construction contract administration and inspection will be performed by LBL.

- Procurement

  Standard equipment and certain special facilities will be procured directly by LBL after competitive bidding. Otherwise procurement will be the responsibility of the general contractor.

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 2

PROJECT DESCRIPTION

The proposed research program for the CDRL ranges from basic reaction dynamics studies to experiments aimed at providing initial data that may ultimately help in reducing pollutant output from power plants or automobile engines while improving their efficiency. For a more comprehensive and detailed overview of research opportunities, see the *Combustion Dynamics Facility Scientific Program Summary* (PUB-5284), a joint LBL/SNL publication.

The U.S. is challenged to achieve high efficiency while minimizing environmental damage from combustion devices. Over 90% of all energy utilized in the U.S. today is generated by combustion. The National Energy Strategy, the latest Clean Air Act, and many state and local laws require that combustors be designed and operated with unprecedented fuel efficiency and low levels of emitted pollutants. In order to comply with these requirements, it will be necessary to understand combustion chemistry and its interaction with fluid flow so that decreases in pollutant emission and increases in energy efficiency are optimized.

The oxides of nitrogen (NO_x) and sulfur (SO_x) are major components of pollutants. To reduce these emissions, accurate critical paths for the oxidation of nitrogen and sulfur compounds in fuels and exhausts need to be established. Fundamental information on potential energy surfaces, barrier heights, reaction dynamics, and kinetics will ultimately dictate the effectiveness of NO_x- and SO_x-abatement strategies.

Soot is another important combustion-generated pollutant, and our understanding of the mechanisms of soot formation continues to evolve. Recent basic research investigating the C-H bond strength in acetylene has led to the derivation of a new model for soot formation from acetylene fuel. Significantly more research is required to fully understand and control the generation of soot.

All combustion-related phenomena, engine knock, and CO emission are linked to fuel-consuming processes that begin with free-radical reactions. Different reaction products initiate different sets of chemical processes. An understanding of the fuel cycle cannot be complete without a thorough fundamental study of the chemistry of combustion.

2.1 Scientific Opportunities

At the CDRL, the scientific research program will focus on gaining a rigorous molecular-level understanding of combustion and other energetic molecular processes. These studies will build foundations of basic knowledge to underlie scientific and technological leadership in the combustion-systems and control-technology industries. In addition, the time structure and synchronization of the CDRL special facilities at the ALS and the IRFEL will allow picosecond time-resolved studies of various phenomena.

Researchers at the CDRL will explore these topics by

- Determining the structure and chemical behavior of highly reactive polyatomic radicals and unusual transient species.
- Providing microscopic details of mechanism and dynamics for elementary chemical reactions and primary photodissociation processes.
- Probing the nature of intra- and intermolecular energy relaxation.
- Searching for bond-selective or mode-selective means to modify and manipulate chemical reactivity.
- Establishing a sound theoretical foundation to understand chemical reactivity and to guide experimental efforts.
- Developing novel methodologies and tools to investigate important but currently unsolvable problems in chemical and combustion dynamics.

Input from the user community has been the key to preparing the scientific program for the CDRL. Particularly important roles were played by recent national workshops and symposia, including the Workshop on Opportunities for Chemistry Related Combustion Science (July 1986), the Workshop on Chemical Reaction Dynamics (November 1988), and a chemistry user community review (October 1989). These workshops and reviews identified research in combustion and reaction dynamics as critically dependent upon advanced technologies and techniques, including spectroscopy, free-electron lasers, synchrotron light sources, conventional lasers, molecular-beam methods, and imaging and computational methods.

Two of the more prominent emerging technologies required for this research are the IRFEL initiative at LBL, which is part of the CDRL proposal, and the ALS, now under construction at LBL, which can supply beams of synchrotron radiation for the CDRL program. These facilities (and especially the unique opportunity to integrate them) will be the primary focus of this subsection. Figure 2-1 indicates how the various technologies will be used together in the research efforts.

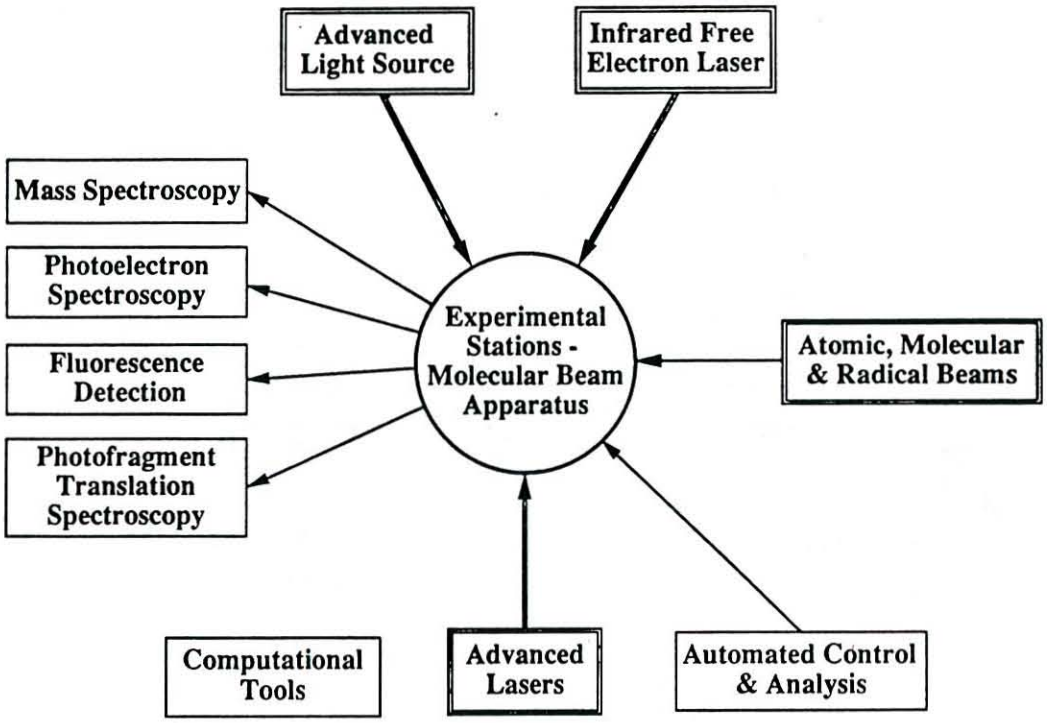


Figure 2-1. A key to the scientific potential of the CDRL will be the opportunity to integrate various research technologies, including synchrotron radiation sources, an infrared free-electron laser, conventional lasers, and molecular beam apparatus.

The CDRL will allow, for the first time ever, the integrated and simultaneous use of dedicated IRFEL and synchrotron-radiation beamlines for pump-probe experiments, as shown conceptually in Figure 2-2. One mode will use the ALS photon beam as the pump and the IRFEL photon beam as the probe; in this mode, researchers will be able to study the vibrational structure of highly excited and superexcited molecules. The other mode—IRFEL pump and ALS probe—will yield IR spectra of transient species (combustion diagnostics); new information on ionization potential and bond energies (reactivity) of transient species; new vibrational spectra of ions; and insight into regioselective photochemistry.

Experiments involving new-generation crossed molecular beams can also be integrated with these studies at the new facility. Powerful conventional laser sources can be synchronized to the ALS and IRFEL pulses; these lasers and the molecular-beam apparatus will work together, forming an integral part of the research described here.

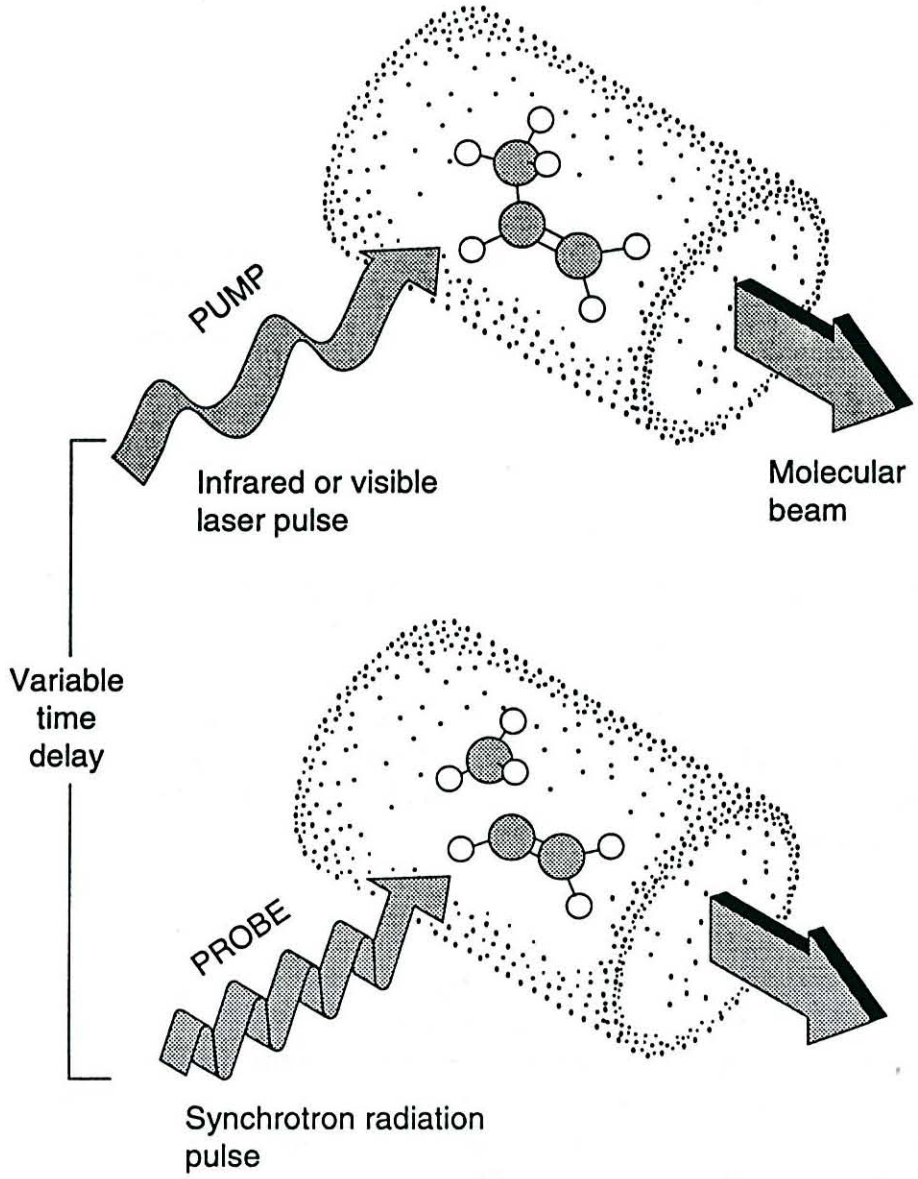


Figure 2-2. A diagram of a "two-color" pump-probe study illustrates one of several classes of research that require multiple tightly focuses, high-resolution beams at different wavelengths. (XBL 9012-6761B)

Service to the user community, viewed as an important factor in scientific productivity at the CDRL, is an integral part of the facility. The CDRL will strengthen national chemical physics research capabilities by serving a broad range of qualified users, including scientists from other national laboratories and investigators based in universities and industry.

A scientific users program is proposed to make use of the CDRL's IRFEL, chemical physics beamlines, and lasers to conduct experiments pertinent to the DOE mission. Users may use existing CDRL experimental stations or propose to develop their own apparatus for the experiments, or they may join LBL projects to conduct defined experiments leading to findings and publications.

A Program Review Panel will review all scientific proposals to use the facility. This panel will have a rotating and interdisciplinary membership to cover the major issues in chemistry and combustion relevant to the CDRL focus. The panel will advise the LBL Director and will provide him, through the CDRL Director, specific recommendations on all proposals.

2.1.1 Research Description

Infrared Multiphoton Excitation (IRMPE). IRMPE and dissociation under collision-free conditions will be made much more widely applicable by the IRFEL. Thus far, this powerful technique has been applicable only to molecular species that can be excited by a CO_2 laser, which has limited tunability. An IRFEL, with its broad tunability, will expand the range of applicability across the entire periodic table, providing experimental access to practically all molecular species. Using the IRFEL, chemists and surface scientists will be able to probe basic molecular dissociation processes and produce unusual transient species such as organic free radicals, reactive intermediates, and radical-containing clusters.

Important IRMPE applications using the IRFEL include

- Studies of dissociation dynamics and reaction mechanisms of aromatic hydrocarbons, which are abundant in low-grade fuels.
- Selective decomposition of undesirable minor species of molecules in gaseous matter.
- Separation of isotopes.
- Regioselective chemistry, in which vibrational modes at specific sites in a molecule are excited by a properly chosen IRFEL wavelength; these experiments might be combined with photoionization initiated by a VUV beam from the ALS.

Chemistry and Spectroscopy of Surfaces. These studies, which will also be enhanced by the IRFEL, are significant because surfaces play an important role in many chemical processes in the combustion cycle, including particulate formation and the creation and destruction of pollutants. Optical techniques, being nondestructive and widely applicable, are very attractive for this research.

A relatively new, yet fully developed, technique for surface vibrational spectroscopy —detection of a coherent output whose frequency is the sum of the laser input frequencies—provides vibrational "fingerprints" of surfaces and selective detection of adsorbed molecular species. However, one of the advantages of the technique, its high degree of surface specificity, also hampers its use—another handicap resulting from the narrow tuning range of the presently available IR lasers. The IRFEL would be a major breakthrough in this technique, allowing the study of any molecule or radical. A particularly exciting application, for which few other techniques exist, is spectroscopy of buried interfaces. The picosecond time structure of the beam would also make this technique extremely useful for studies of surface dynamics, as well as for following reaction paths step by step, which is necessary for truly understanding a reaction. The technique is not limited to gas-solid interactions; any interfaces accessible to light could be studied.

Prospects for the IRFEL in semiconductor studies include "hole-burning" experiments, performed with infrared and visible laser light, that would allow the first direct measurements of the coupling between electronic and vibrational degrees of freedom. Another possibility is real-time dynamic study of excitation and relaxation phenomena associated with defects in semiconductors, using the IRFEL and standard lasers.

Vibrational Dynamics of Reactions in Solution. It is currently not feasible to probe these phenomena on an extremely fine time scale because of the lack of high-power IR sources at the appropriate vibrational frequencies. The IRFEL, in combination with existing lasers and the ALS VUV beamline, would allow direct studies of these phenomena, greatly increasing our understanding of how chemical reactions proceed in solution.

Two-Color Threshold Photoelectron Spectroscopy. The CDRL would enable investigation of a set of asymmetric vibrational modes of ground state ions that cannot be excited directly from the vibrational ground state of the neutral molecule; the energy of these modes is unknown for many ions, even some as simple as CO_2^+. The IRFEL beam would be used to excite an infrared mode of the molecule; subsequent ionization by an ALS beam (to which the IRFEL beam is synchronized) would produce the new vibrational state.

Two-Color Fluorescence Studies. Superexcited molecules can dissociate not only into ions, but also into other entities, including electronically excited neutral fragments; this form of decay is usually the sole route below the ionization limit and can compete with ionization even several eV above it. Population of a specific vibrational-rotational state with IR laser light, followed by further excitation with synchrotron light, can produce a superexcited state whose dispersed neutral decay products fluoresce. This means of studying excited dissociation channels has been established at other synchrotron facilities as a powerful tool in the understanding of predissociation dynamics, and would be enhanced significantly at the CDRL because of higher resolution and, especially, rotational selectivity.

Spectroscopy of Gas-Phase Free Radicals. This research would benefit greatly from the combined availability of the ALS and the IRFEL; in fact, the combination could be referred to as a "universal free-radical spectrometer." In these experiments, a cold molecular beam containing a small concentration of radicals will be excited by intense light, tunable across the absorption spectrum, from the IRFEL. Since the density of radicals in the beam is not high enough to allow the measurement of direct absorption, a VUV beam from the ALS will be used for the detection of IR-photon-excited states of molecules by selectively ionizing the vibrationally excited radicals. (The VUV photons will not ionize the ground-state radicals.) Then, narrow-line-width IR lasers will be used for higher-resolution studies at frequencies found with the tunable "search" beam from the IRFEL.

Cluster Energetics and Dynamics. Neutral and ion clusters are formed by pulsed laser desorption of solid material followed by nucleation and cooling in a high-pressure flow of He gas. After expansion through a nozzle, the pulse of clusters is intersected by the photon beam from the ALS and ionized; the ionization thresholds can then be found. Alternatively, the IRFEL excites the clusters which can subsequently be dissociated or ionized by the ALS or a high-power laser. Spectroscopy and structural information can then be extracted. Similar measurements allow determination of bond strengths in clusters. The ALS photon beam is aligned in a collinear fashion, and the clusters are photodissociated. The lifetime of the photoexcited state depends strongly on both the cluster size and the binding energy of the fragment to the cluster; accurate (~0.1 eV) binding energies can be calculated from the data.

These measurements interact in a very helpful way. After measurement of the ionization potentials of the neutral clusters and the bond dissociation energies of the ionic clusters, a simple thermodynamic-cycle calculation yields the bond dissociation energies of the neutral clusters, an important quantity that cannot be measured by any other available means.

These studies can dramatically enrich our fundamental understanding of matter interactions, bridging the gap between the gas-phase properties of atoms and molecules and the very different worlds of aerosols, liquids, and solids. The structure, energetics, and kinetics of carbonaceous clusters have important consequences for modeling soot-producing flames. Metal clusters can also be studied in this way; metal clusters are of great fundamental importance and have possible energy-oriented applications in catalysis and other areas.

Intermediate-Energy Molecular Excited States. Molecular excited states in the intermediate energy region of 6–12 eV could be studied at the ALS in a variety of ways. Double-resonance experiments, combining synchrotron radiation with laser light in two-color, state-selected excitation schemes, would combine VUV synchrotron radiation from the ALS with light from any of several laser sources that have comparable time structures. This would generalize the existing experimental efforts in high-energy molecular structure and dynamics.

PEPICO Experiments. At the CDRL, PEPICO (photoelectron photoion coincidence) experiments could be carried out with an unprecedented combination of fine energy resolution (the ALS would provide a fiftyfold improvement) and narrow thermal energy distribution of the sample gas.

Threshold Photoelectron Spectroscopy (TPES). In this technique, which has been established as one of the most effective methods for obtaining high-resolution photoelectron spectra, the energy of the photoelectrons is measured by determining their time of flight. The time structure of the ALS in the 8-bunch mode should easily allow 1-meV energy resolution, in a 200-ps time window, for zero-energy photoelectrons gathered with a 2-V/cm electric field. This technique can be integrated into a two-color TPES experiment.

Optical Diagnostics. At present, optical techniques are recognized as best for probing reacting media in a nonperturbing way. Their application is limited, however, by the fact that the spectroscopic data base necessary for their application exists for only a very few species containing more than two atoms. In the CDRL, unparalleled resources can be brought to bear on spectroscopic investigations of radicals and other transient species important in combustion. The IRFEL will, for example, allow scientists to excite the internal modes of transient species in a way that simulates the combustion environment. The information obtained will be useful in its own right in expanding our understanding of the properties of these species, but it will also provide a crucial data base necessary for the development of optical diagnostic probes for species in flames. Collaborations between staff and visitors at the CDRL and those at SNL will result in rapid development of optical diagnostics for polyatomic species.

2.1.2 Coupling to Theoretical and Computational Chemistry

Highly productive chemical physics research requires broad and vigorous interaction between theorists and experimentalists. This interaction encompasses a wide range of efforts in two areas of particular relevance to the CDRL: developing new ways of determining Born-Oppenheimer potential-energy surfaces and developing new dynamical methods for describing molecular processes on these potential surfaces. Such research in the CDRL scientific program emphasizes relevance to the effort to understand combustion.

Advances in computer technology have produced workstations with computational power rivaling that of mainframe computers. At the CDRL these workstations will form the backbone for first-order calculations and development of new computational techniques. These efforts will be augmented by full-scale modeling using remote access to advanced supercomputing facilities. This combination of computational power can be applied to various quantum methods for obtaining accurate potential-energy surfaces. It is also applicable to dynamical models of tunneling, transition processes, and inelastic and reactive scattering processes related to the experimental investigations described earlier. An example of the long-range benefits is substantial improvement in the modeling of turbulent reactive flows; this could result in more effective pollutant avoidance and clean waste-disposal schemes.

Experimental output from the CDRL will be strongly coupled to computational and modeling efforts in the Advanced Combustion Modeling Environment Program (ACME). ACME is being proposed to the DOE as part of the High Performance Computing and Communications Initiative. ACME investigators will incorporate detailed chemistry into models of turbulent reacting flows to study the interaction of combustion and turbulence on pollutant emissions.

Combustion chemistry at the CDRL and combustion modeling in ACME will have a synergistic relationship. For example, it was long thought that the mechanism by which acetylene burned was well understood. However, direct measurement of the C–H bond strength in acetylene by LBL and SNL researchers established that the thermochemical properties assumed for the strength of that bond were incorrect. When the correct bond strength was substituted into the models, theoretical predictions no longer matched the combustion experiments, causing the models to be reevaluated. It is, in part, this iterative feedback among microscopic chemistry, combustion modeling, and experiments that furthers understanding, and that will ultimately yield the ability to develop predictive models which will be of great value to industry in producing low-emission, high-efficiency designs.

2.1.3 Resource Requirement

The research described above will require the simultaneous use of unique facilities like the ALS UV beamlines, the IRFEL, advanced conventional lasers, and molecular-beam experimental stations. In general, the proposed research will benefit from having high wavelength resolution from all the photon sources. In addition, it imposes special requirements on the IRFEL if its full promise is to be realized in pursuing combustion-related fundamental research.

The key characteristics required of the IRFEL include:

- Tunability from at least 3 to 20 microns
- Wavelength stability equal to a fraction of the resolution
- High peak and average power
- Picosecond pulse duration
- Capability to be continuously scanned over any 20% of the tuning range
- Synchronizable to the pulse train of other sources

Tunable, intense infrared radiation on a picosecond time scale will ultimately allow many different molecules to be examined over a wide range of reaction times. The CDRL will greatly enhance the possibilities by providing a UV and VUV synchrotron-radiation source and a tunable, high-intensity IRFEL that can be synchronized with it, as well as state-of-the-art molecular beam apparatus. Details of a conceptual design that meets the needs of the research are described in the following sections.

2.1.4 Scientific Horizons for the CDRL

In conclusion, besides providing unique and important opportunities for understanding the dynamics of combustion, the facilities will advance the broader field of chemical dynamics in general, and the opportunities for related benefits to science and society are considerable. Combustion studies will benefit from techniques and spectroscopic information derived from experiments designed to study dynamic processes in the condensed phase, in novel solid-state materials, semiconductors, metal clusters, inorganic crystals, and polymers. These experiments broaden the utility of the facilities and will provide unmatched U.S. leadership in the study of dynamic chemical processes for many years to come.

2.2 Special Research Facilities

This section describes the special research facilities to be built or installed as part of the CDRL These special research facilities are discussed in the following four subsections:

2.2.1 Infrared Free-Electron Laser (IRFEL)

2.2.2 ALS Insertion Devices and Bending Magnet Radiation

2.2.3 ALS Beamlines

2.2.4 Experimental Systems including Experimental Stations and Advanced Lasers

2.2.1 Infrared Free-Electron Laser (IRFEL)

A free-electron laser consists of an electron accelerator, an undulator, and an optical cavity, which in this case is made with a pair of mirrors, as shown schematically in Figure 2-3. The accelerator provides an energetic electron beam of the required qualities. The beam receives a periodic transverse kick in the magnetic field of the undulator so that the electrons' kinetic energy can be transferred to the radiation field. The role of the optical cavity is to trap the radiation and provide amplification to the optical beam via the electron beam at each successive traversal.

FELs provide intense, coherent radiation whose wavelength can be tuned by changing either the electron energy or the undulator magnetic field. Such capability will open up new scientific opportunities in the infrared region, where tunable coherent radiation is not available from the usual laser techniques based on atomic and molecular resonances. Here, we summarize the design of a tunable IRFEL for the CDRL that can be operated in synchronism with the ultraviolet radiation pulses from the ALS.

The principles of FEL operation have been amply demonstrated, and several IRFELs have been shown to work. The IRFEL for the CDRL will be similar to existing IRFELs, but it has to meet more stringent requirements on reliability and stability. It must be reliable enough for frequent, extensive use, and various forms of instability—for example, jitter in intensity, wavelength, direction, etc.—must be reduced to an unusually low level. These requirements call for a careful examination of all accelerator/FEL components.

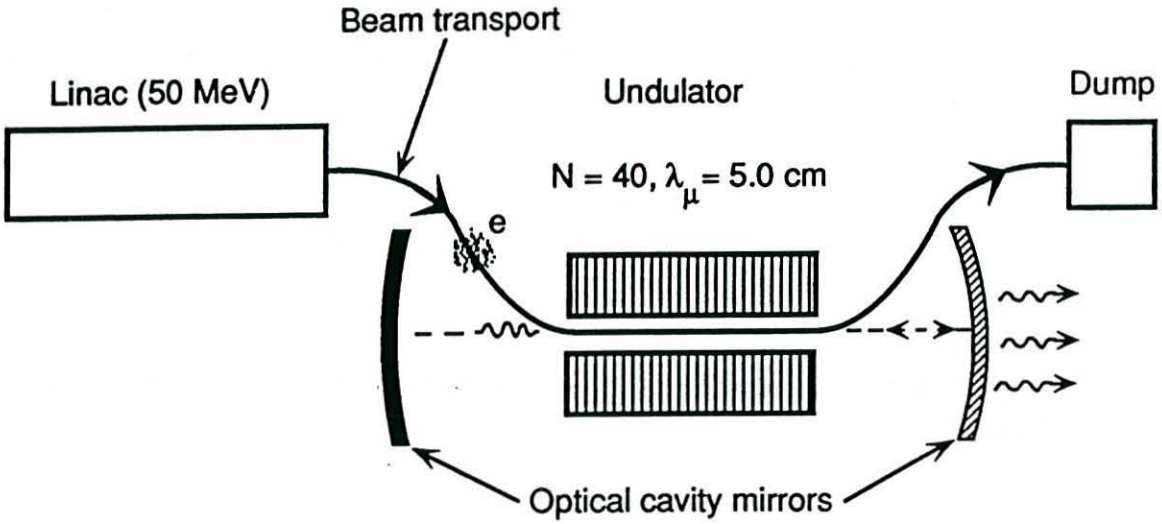


Figure 2-3. Schematic of an IRFEL. (XCG 899-4700)

The FEL proposed as part of the CDRL addresses the needs of the chemical sciences community for a high-brightness, tunable source covering a broad region of the infrared spectrum—from 3 to 50 μm. The technical approach adopted in the design makes use of superconducting radio-frequency (SCRF) accelerating structures. The primary motivation for adopting this approach was to meet the user requirement for wavelength stability equal to one part in 10^4. Previous studies concluded that a wavelength stability of only one part in 10^3 could be achieved with currently available room-temperature technology. In addition, the superconducting design operates in a continuous wave (cw) mode and hence offers considerably higher average optical output power. A summary of the comparative performance attainable with room-temperature and superconducting designs is given in Table 2-1.

The FEL provides a continuous train of 30-ps micropulses, with 100 μJ per micropulse, at a repetition rate of 6.1 MHz. The device can also deliver pulses with a peak power of 50 μJ at a cw repetition rate of 12.3 MHz. In both cases, the average optical output power can exceed 600 W. The length of the micropulse can also be varied. For shorter micropulse lengths (from 30 ps to below 2 ps), chirping techniques can be used that will still provide up to 100 μJ per micropulse. Grating techniques can be used to provide longer pulse lengths, up to ~100 ps, but only at the expense of a linear decrease in output power.

A layout of the proposed FEL is shown in Figure 2-4. The injector prepares a properly bunched beam at 6 MeV that matches the phase space requirements of

Table 2-1. Performance Characteristics of FELs Based on Room-Temperature and Superconducting Linacs.

	Room-temperature linac	Superconducting linac
Accelerator		
Type	SW side coupled	SCA
Frequency [MHz]	1300	500
Maximum energy [MeV]	~50	~55
General properties		
Wavelength, λ [μm]	3–50	3–50
Line width	Transform limited	Transform limited
Wavelength stability, $\delta\lambda/\lambda$	10^{-3}	10^{-4}
Intensity stability	0.1	≤0.1
Average optical power [W]	≤20	≥600
Micropulse properties		
Energy [μJ]	100 (at 50 MeV)	100
Duration [ps]	10–25	30 (≤2 via pulse compression)
Repetition rate [MHz]	36.6	6.1
Macropulse properties		
Energy [J]	0.36	cw
Duration	100 μs	>10 ms
Repetition rate	60 Hz	Flexible to cw

the accelerator section. The injector includes a thermionic gun; two subharmonic, room-temperature buncher cavities; and a single-cavity, 500-MHz SCRF accelerating module. The accelerator section consists of two dual-cavity, 500-MHz SCRF modules that accelerate the beam to ~30 MeV in a single pass. In both the injector and the accelerator sections, the SCRF cavities are designed to operate with a nominal accelerating gradient of 5 MV/m.

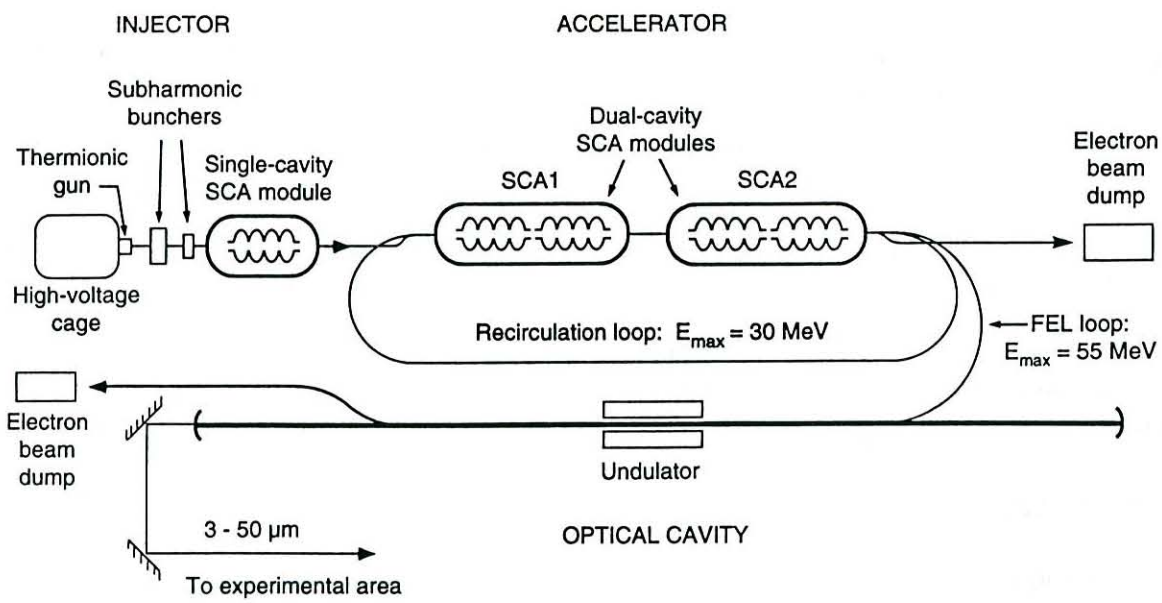


Figure 2-4. Schematic plan view of the infrared free electron laser, located in the basement vault of the Chemical Dynamics Research Laboratory building.

An achromatic and isochronous beam transport section then recirculates the beam for a second pass through the accelerator section for further acceleration to ~55 MeV. A similar beam transport system then delivers the fully accelerated beam to a 2-meter undulator that forms part of a 24-meter-long optical cavity. Optical power is outcoupled through a hole in one of the cavity end mirrors and transported to the experimental area.

As shown in Figure 2-5, the FEL is housed in a concrete vault that also serves as part of the foundation of the CDRL building. The walls and roof of this vault will be formed with approximately 10 feet of conventional, poured-in-place concrete, and access to this area will be carefully controlled and monitored. Systems that require occasional tuning or maintenance during operation are located outside the shielded vault area. Components inside the shielded vault include the injector and accelerator sections, all electron beam transport components, the undulator and optical cavity, and the electron beam dumps.

Separate shielding is provided at one end of the the vault for a closed-loop water system used to operate two beam dumps. These dumps are identical and designed to safely absorb a 55-MeV beam with 800 kW of power. They are housed inside separate concrete bunkers within the main vault. One of these dumps is located near the exit of the accelerator and will be used primarily for commissioning, development, and debugging. The second dump is located near the point where the electron beam exits the optical cavity; this dump will become

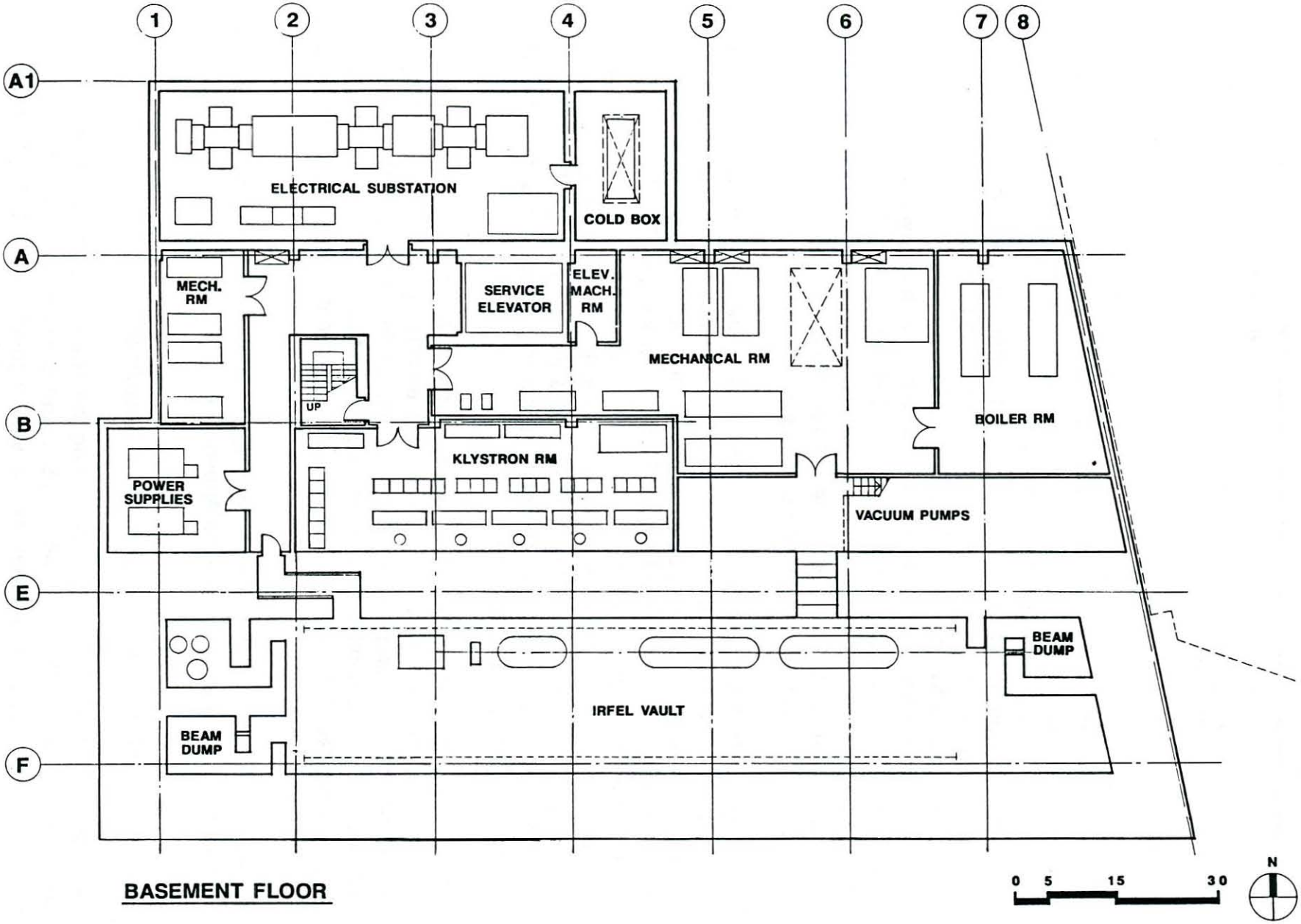


Figure 2-5. Plan view of the basement level of the proposed CDRL building.

the primary dump once routine operation is established. Access to the beam dumps will be required only infrequently. They will therefore be kept under separate lock and key, and access will be permitted only to persons accompanied by a designated safety officer.

Space is also required outside the vault for a variety of power, control, and cryogenic systems, together with their associated equipment racks. Most of these systems are shown in Figure 2-5. Five commercially available 500-MHz power amplifiers, each utilizing two klystrons, are located in a 20 × 50 foot room just outside the shielding wall adjacent to the SCRF cavities. This room also houses the associated equipment racks, the klystron crowbar system, and water control systems for thermal stabilization of the room-temperature subharmonic bunchers. The power supplies for these bunchers are located nearby in a separate 20 × 20 foot room Power from the amplifiers is transmitted to the cavities by means of waveguides. Circulators and "magic tees" are used to prevent reflected power from damaging the klystron amplifiers. An electrical substation that supports all of the building electrical systems (including the FEL) is also located in the basement level of the building, as can be seen at the top of Figure 2-5.

The cryogenic systems provide both helium at 4 K and liquid nitrogen at 80 K. Commercially purchased liquid nitrogen will be delivered by a house supply line from a nearby storage tank to points throughout the building. The helium will be generated on site by a 600-W refrigerator/compressor system. The helium system consists of the refrigerator/compressor, gaseous helium storage, and connecting cryogenic plumbing. The refrigerator is located in the basement level of the building approximately 70 feet from the cryostats in the vault (see Fig. 2-5). To isolate both noise and vibration, the compressor is located in a separate utility building approximately 200 feet away.

Equipment racks for other systems, primarily the electron beam transport system, are located on the basement level beneath an elevated platform used to support mechanical vacuum pumps servicing equipment in the experimental hall on the main floor. The FEL control room is also located on the main floor of the building, directly above the FEL, and is adjacent to the experimental hall to promote good communications with the users.

A detailed description of the FEL has been produced as a separate design document; a copy is included here as Appendix A.

2.2.2 ALS Insertion Devices, Radiation, and Beamlines

Two beamlines from the ALS will be among the key special research facilities of the CDRL. One beamline will deliver broadband radiation from a bending magnet in the ALS storage ring; another will provide high-intensity VUV light from an insertion device—the U10.0 undulator—in a straight section of the ring. The

undulator and its beamline have been tailored to meet the specific requirements of the chemical-sciences user community. This work builds on substantial expertise developed over the past several years by the ALS project team. This chapter provides both general background information and specific discussions of U10.0, along with some information on bending-magnet radiation; later it describes the beamlines for these two sources.

2.2.2.1 Insertion Devices and Radiation Characteristics

Undulators and wigglers, collectively referred to as insertion devices, are periodic magnetic structures placed in the straight sections of storage rings. The periodic field causes the electrons to move sinusoidally in the horizontal plane. Figure 2-6 illustrates the concept, and Figure 2-7 qualitatively shows the characteristics of synchrotron radiation from undulators, wigglers, and bending-magnet sources.

Undulator radiation consists of a series of narrow peaks, at the fundamental wavelength and its harmonics, radiated in a narrow cone in the forward direction

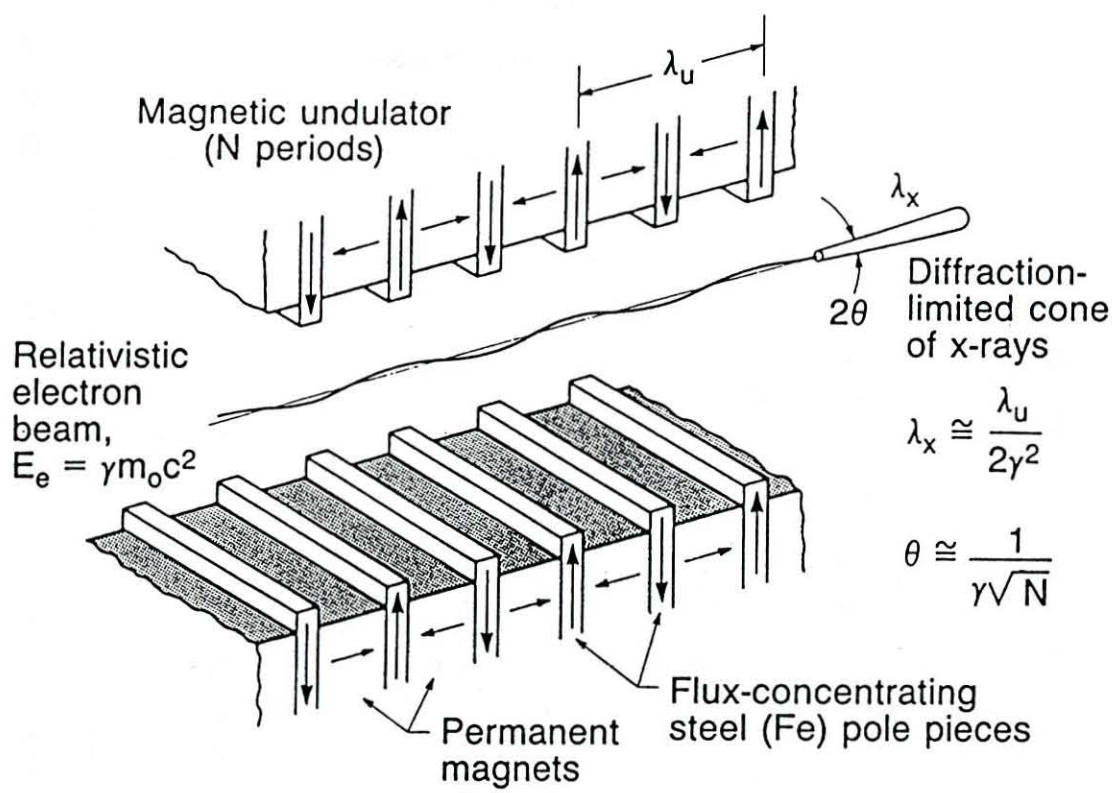
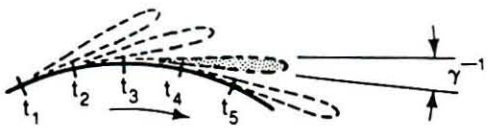
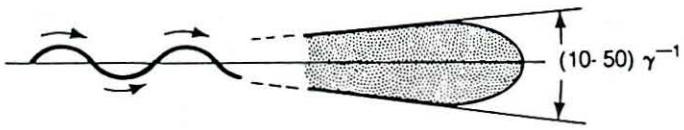


Figure 2-6. A schematic drawing of an undulator. The structure has *N* magnetic periods of wavelength λ_u. The periodic magnetic field causes the electron beam to oscillate in the horizontal plane as it passes through the device, producing a radiation beam of high spectral brightness. (XBL 865-6279)



Bending Magnet — A "Sweeping Searchlight"



Wiggler — Incoherent Superposition

$$\frac{dP}{d\Omega} \propto N$$

Undulator—Coherent Interference

$$\frac{dP}{d\Omega} \propto N^2$$

$$\Omega \propto \frac{1}{N}$$

$$P \propto N$$

N = number of magnetic periods (~100)

$$\gamma^{-1} = \frac{m_o c^2}{E_e} = \frac{0.511}{E_e(\text{GeV})} \text{ mrad}$$

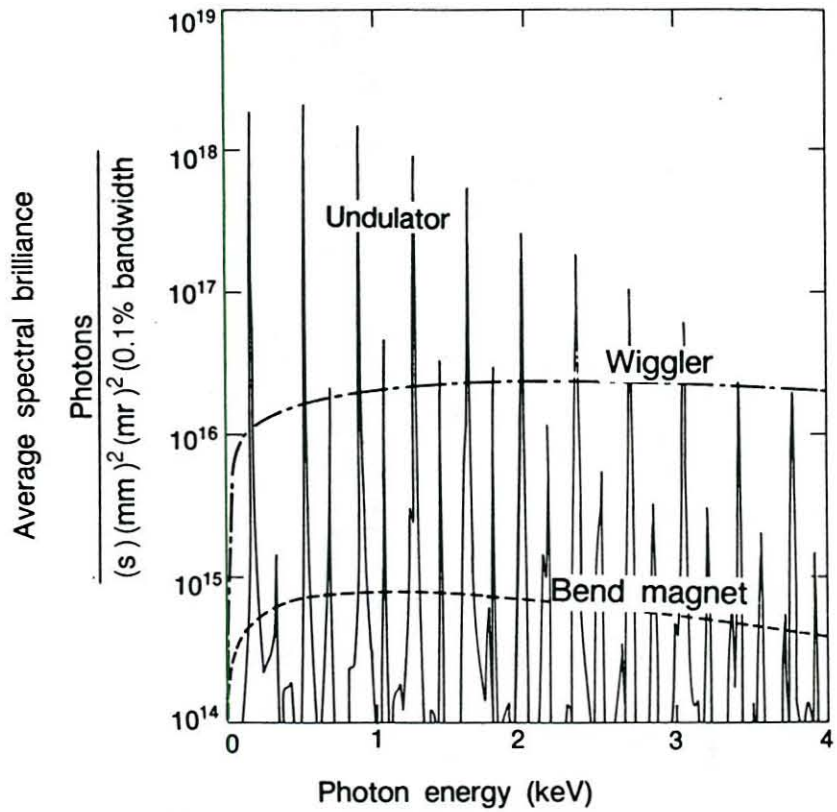


Figure 2-7. Bending magnets, undulators, and wigglers produce synchrotron radiation of different characteristics. The CDRL will use one undulator beam and one bending-magnet beam. The bending magnet beam will be a high-brightness, broadband source of radiation. The undulator beam will be considerably higher in both intensity and spectral brightness, with sharp spectral peaks at the undulator's fundamental wavelength and its harmonics. (XBL 8311-4541A, left, and XBL 827-909A)

from the electron's overall trajectory. Wigglers and bending magnets, on the other hand, produce broad-spectrum radiation; for this purpose, a wiggler may be thought of as a number of bending magnets in series.

The narrow spectral peaks from an undulator may be tuned by changing the electron energy and by changing the magnetic field of the undulator. For the high-performance permanent-magnet undulators planned for the ALS, the field is changed by varying the gap between the top and bottom halves of the periodic magnetic structure.

The ALS, operating at 1.5 GeV, is optimized for insertion-device operation in the VUV and soft-x-ray regions of the spectrum, encompassing the range of U10.0. On a time-averaged basis, an ALS undulator will have the highest spectral brightness of any available source in that energy range.

Table 2-2 summarizes the parameters of U10.0 and gives definitions and further information about its performance in the storage ring . These parameters were selected on the basis of the user community's requirements, including the following:

- Wide range of tunability; U10.0 provides photon energies of 6–25 eV, with a low end that overlaps conventional laser sources and a high end that covers interesting valence-shell processes in molecules.
- High intensity, greater than 10^{15} photons per second per 0.1% bandwidth, as required for a wide variety of measurements such as sampling of molecular beams containing low concentrations of radicals, clusters, or complexes.
- High brightness, important for two-color synchrotron radiation/laser experiments in which beams are tightly focused onto interaction volumes that could be as small as 50 μm on a side.
- High resolution; for instance, exploring the rovibrational structure of molecules calls for a resolving power of greater than 50 000.

The expression for the fundamental wavelength produced by an undulator is

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad ,$$

where λ_u is the period of the magnet, γ is the electron energy divided by mc^2 (roughly 3000 for the ALS), and K is the undulator deflection parameter, given by

$$K = \frac{\lambda_u eB}{2\pi mc} \quad .$$

In practical units of B in teslas and λ_u in cm, $K = 0.934B$. Note that the equation above gives the fundamental wavelength; the undulator also produces significant radiation at harmonics of that wavelength.

The output wavelength can be tuned by changing γ or K. At the ALS, the permanent-magnet undulators will use gap tuning to change B and hence K.

Figure 2-8 shows the spectral flux of U10.0, and Fig. 2-9 illustrates the spectral brightness. The figures show an envelope that includes the fundamental and the first and third harmonics.

As a rough guide, the useful operating range of an undulator is considered to lie between the energy of the fundamental at the largest achievable K, which is typically ≤ 10 for an undulator, and the energy of the third harmonic at $K = 0.5$. The

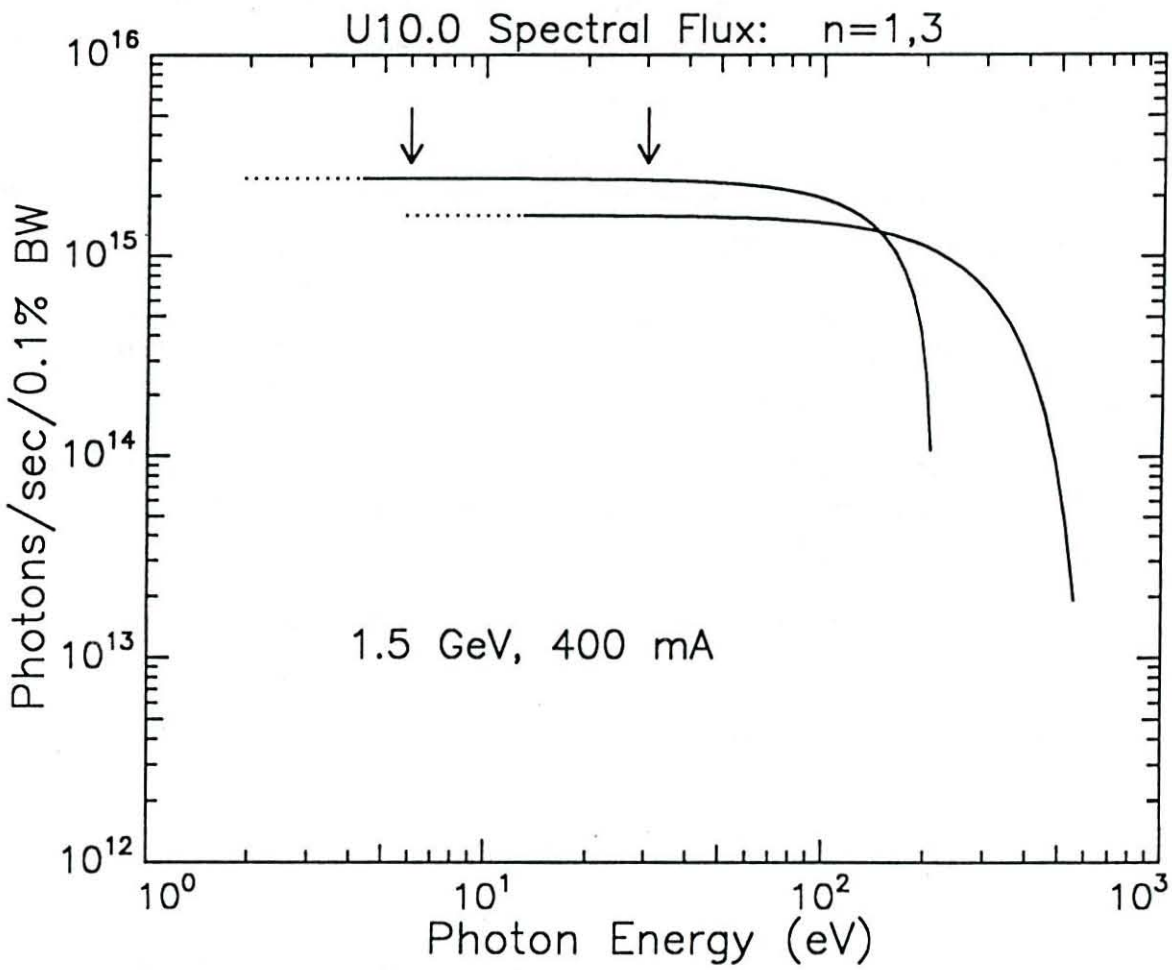


Figure 2-8. Spectral flux as a function of photon energy for U10.0. Each undulator curve is the locus of a narrow peak of radiation, tuned by altering the undulator gap and thus the magnetic field B. (XBL 901-241)

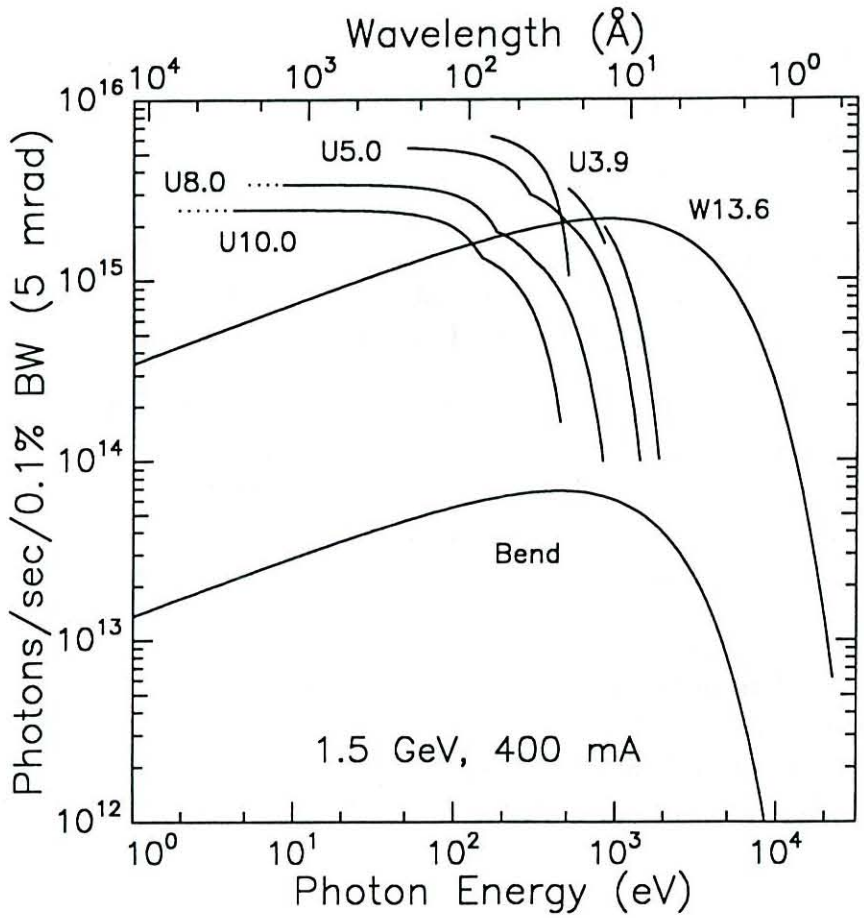


Figure 2-9. Spectral brightness as a function of photon energy for U10.0. Also shown for comparison are the curves for other ALS undulators, a bend magnet, and a wiggler. Each undulator curve is the locus of a narrow peak of radiation, tuned by altering the undulator gap. Shown here are the fundamental and the first and third harmonics (and the fifth harmonic as well except in the case of U10.0). The dotted extensions represent the performance when the undulator field exceeds the bending-magnet field; U10.0 could be operated in this way, but such use might compromise storage-ring operation, and anticipated CDRL user experiments would not call for it. (XBL 901-242)

spectral flux within the central cone increases as a function of K, but so does the higher-harmonic flux and thus the power loading of optical systems at wavelengths that may not be of interest.

The choice of a 10-cm period for the CDRL undulator has several advantages. First, the photon energy range of interest can be covered by using only the fundamental wavelength, as indicated by Figure 2-8, in which the arrows show the

spectral coverage required by the users. In the figure, the solid lines are the loci of the narrow undulator spectral peak as *K* is varied. The dotted lines represent operation of U10.0 when *B* exceeds the bending-magnet field. This condition, while possible for U10.0, is not necessary for the spectral coverage desired and it may compromise the beam dynamics of the storage ring. The fact that the higher harmonics are not really necessary allows a relaxed random-error tolerance for the device. This relaxation makes design and construction less expensive and places them well within the present state of the art for undulators built at LBL and by private industry. (However, U10.0 must still meet the strict field-integral tolerances that follow from the ALS storage-ring performance requirements.)

Figure 2-9 indicates a modest trend toward lower peak intensity as the period of the undulator increases. It can also be seen, however, that only U10.0 can span the spectral range needed for the CDRL with its fundamental. This tradeoff between intensity and tuning range is intrinsic to the use of undulators, and the design of U10.0 attempts to reconcile these factors.

Note also that there is significant third-harmonic output from U10.0. This is another intrinsic feature of undulators, The third and higher harmonics can be viewed either as undesirable spectral contamination that must be eliminated (and that causes a heat load on optical elements) or as sources of future spectral capability. Section 2.2.3, "ALS Beam Lines," discusses these issues in greater detail.

Table 2-2 (following pages). Detailed performance characteristics of U10.0 (Table 2-2b) and of an Advanced Light Source bending magnet (Table 2-2c), both at an electron-beam energy of 1.5 GeV. For the undulator, characteristics are given for the fundamental and the first and third harmonics for several values of *K* within the design range. The magnetic performance statements assume an Nd-Fe hybrid structure. Table 2-2a, below, describes the symbols used in the subsequent tables.

Table 2-2a. Symbol Definitions for Tables 2-2b and 2-2c.[1]

BO (T)	Peak magnetic field for undulators and wigglers.
BRI	Spectral brightness, i.e., flux per unit phase-space area [photons/(s-mm^2-mr^2-0.1% bandwidth)].
E (GeV)	Beam energy.
ECR (keV)	Critical energy for wigglers and bending magnets.
EP (keV)	Photon energy.
F	Spectral flux. For undulators the flux in the central cone; for wigglers and bending magnets, the flux within a 5-mr horizontal angle and all vertical angles [photons/(s-0.1% bandwidth)].
FDEN1	Spectral flux per unit horizontal angle [photons/(s-mr-0.1% bandwidth)].
FDEN2	Spectral flux per unit solid angle [photons/(s-mr^2-0.1% bandwidth)].
I (A)	Beam current.
K	Peak deflection parameter for undulators.
LAMDW (cm)	Period length of undulators and wigglers.
N	Number of magnet periods (undulators and wigglers).
n	Harmonic number for undulator radiation.
NPOLE	Number of wiggler poles.
PCEN (W)	Power transmitted through a pinhole whose angular size is equal to that of the central angular cone at the fundamental frequency.
PDEN1	Power emitted (all frequencies) per unit horizontal angle [W/mr].
PDEN2	Power emitted (all frequencies) per unit solid angle [W/mr^2].
PTOT (kW)	Total power (all angles and all frequencies) emitted by undulators and wigglers.
RHO (m)	Radius of curvature of electron beam in a bending magnet.
SIGPX (mr)	Horizontal rms beam divergence in the straight section.
SIGPY mr)	Vertical rms beam divergence in the straight section.
SIGX (mm)	Horizontal rms beam size in the straight section.
SIGY (mm)	Vertical rms beam size in the straight section.
XLEN (m)	Length of undulators and wigglers.

[1]Excerpted from *An ALS Handbook*, Lawrence Berkeley Laboratory PUB-643 Rev. 2, page 43.

Table 2-2b. Characteristics of Undulator U10.0.

E(GeV)	I(Amp)	SIGX(mm)	SIGY(mm)	SIGPX(mr)	SIGPY(mr)	N	LAMBDW(cm)	XLEN(m)
1.50	0.400	0.330	0.063	0.030	0.016	45	10.00	4.5

****

K	B0(T)	PTOT(KW)	PDEN2(W/(mr**2))	PCEN(W)
0.09	0.01	2.56E-04	2.08E+00	2.41E-02

n	EP(KeV)	F(#/s,0.1%BW)	FDEN2	BRI
1	2.13E-01	2.23E+13	1.91E+15	1.43E+16
3	6.38E-01	7.10E+08	1.17E+11	8.91E+11

.....

K	B0(T)	PTOT(KW)	PDEN2(W/(mr**2))	PCEN(W)
1.20	0.13	4.23E-02	1.22E+02	2.12E+00

n	EP(KeV)	F(#/s,0.1%BW)	FDEN2	BRI
1	1.24E-01	1.69E+15	9.61E+16	7.10E+17
3	3.73E-01	4.08E+14	5.05E+16	3.82E+17

.....

K	B0(T)	PTOT(KW)	PDEN2(W/(mr**2))	PCEN(W)
3.50	0.37	3.60E-01	3.68E+02	2.26E+01

n	EP(KeV)	F(#/s,0.1%BW)	FDEN2	BRI
1	3.00E-02	2.45E+15	3.97E+16	2.66E+17
3	9.00E-02	1.53E+15	6.66E+16	4.86E+17

.....

K	B0(T)	PTOT(KW)	PDEN2(W/(mr**2))	PCEN(W)
8.32	0.89	2.03E+00	8.79E+02	2.57E+02

n	EP(KeV)	F(#/s,0.1%BW)	FDEN2	BRI
1	6.00E-03	2.50E+15	8.48E+15	4.01E+16
3	1.80E-02	1.64E+15	1.63E+16	1.01E+17

.....

K	B0(T)	PTOT(KW)	PDEN2(W/(mr**2))	PCEN(W)
9.80	1.05	2.82E+00	1.04E+03	4.15E+02

n	EP(KeV)	F(#/s,0.1%BW)	FDEN2	BRI
1	4.36E-03	2.50E+15	6.19E+15	2.62E+16
3	1.31E-02	1.64E+15	1.20E+16	6.98E+16

.....

Table 2-2c. Characteristics of ALS Bending Magnet Radiation.[2]

E(GeV)	I(Amp)	ETAX(m)	SIGE
1.50	0.400	0.094	1.00E-03

EMTX(mm*mr)	EMTY(mm*mr)	BETAX(m)	ALPHAX	BETAY(m)	ALPHAY
1.00E-02	1.00E-03	8.55E-01	3.97E-01	1.46E+00	1.08E-01

RHO(m)	B0(T)	ECR(keV)	PDEN1(W/mr)	PDEN2(W/(mr**2))
4.81	1.04	1.56	5.90E+00	1.14E+01

EP(keV)	F	FDEN1	FDEN2	BRI
5.000E-04	1.081E+13	2.161E+12	1.599E+11	3.509E+12
1.000E-03	1.359E+13	2.717E+12	2.585E+11	6.832E+12
5.000E-03	2.295E+13	4.590E+12	7.557E+11	2.326E+13
1.000E-02	2.860E+13	5.719E+12	1.199E+12	3.743E+13
5.000E-02	4.608E+13	9.217E+12	3.477E+12	1.095E+14
1.000E-01	5.492E+13	1.098E+13	5.445E+12	1.715E+14
5.000E-01	6.753E+13	1.351E+13	1.367E+13	4.301E+14
1.000E+00	5.995E+13	1.199E+13	1.717E+13	5.392E+14
1.556E+00*	4.802E+13	9.603E+12	1.735E+13	5.433E+14
5.000E+00	7.862E+12	1.572E+12	5.335E+12	1.642E+14
1.000E+01	4.177E+11	8.354E+10	4.114E+11	1.234E+13
2.000E+01	9.159E+08	1.832E+08	1.300E+09	3.716E+10
5.000E+01	6.870E+00	1.374E+00	1.390E+01	3.651E+02
1.000E+02	1.475E-13	2.949E-14	4.104E-13	9.556E-12

*This is the critical energy.

2.2.2.2 U10.0 Mechanical Description

The overall mechanical design of U10.0, which is generic to ALS insertion devices, is shown in Figure 2-10. The undulator consists of three principal assemblies: a magnetic structure, a support/drive system, and a vacuum system.

The magnetic structure is of the hybrid configuration and is much like the wigglers that LBL designed and built for Beamlines VI and X at SSRL. U10.0 and the other ALS insertion devices will use a relatively new permanent-magnet material, neodymium-iron-boron (Nd-Fe-B), as the permanent-magnet material and vanadium permendur as the pole material. To achieve the intended magnetic performance, six-block arrays of Nd-Fe-B blocks are used, extensive block sorting is required during assembly, and all pole faces must be coplanar to within 0.001 inch (25 μm). Provisions for additional field correction capabilities will be built in; the field can be corrected by adding permanent-magnet studs and/or by using the dipole magnet and steering coil provided.

[2]Excerpted from *An ALS Handbook*, Lawrence Berkeley Laboratory PUB-643 Rev. 2, page 47.

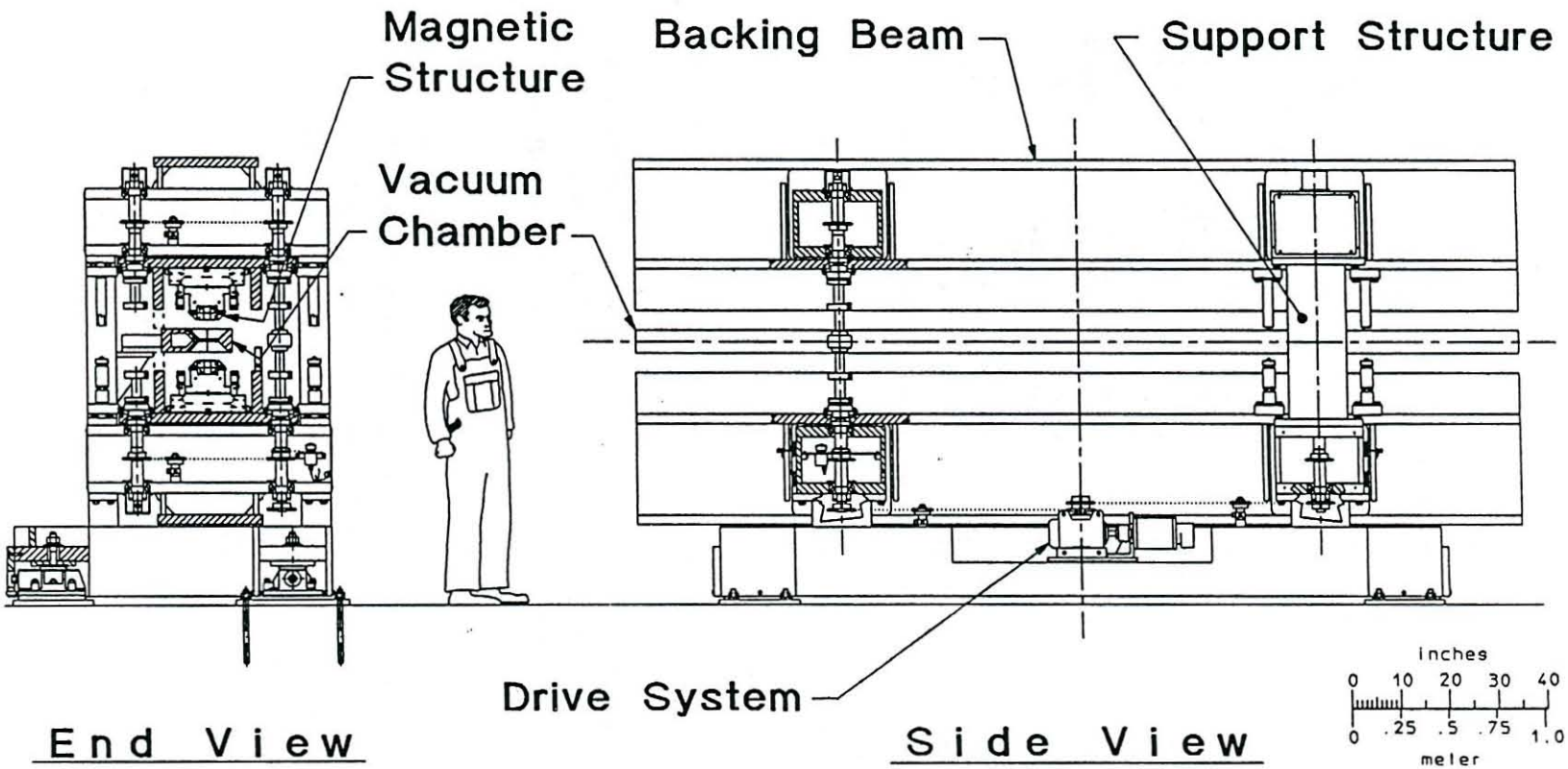


Figure 2-10. This drawing of the U10.0 undulator shows the main structural features, which are similar to those of all other ALS insertion devices. (XBL 901-278)

Figure 2-11 shows the proposed mechanical configuration of the pole assemblies, the pole mount, mount adjusters and the backing beam. The configuration illustrated is made up of a series of keeper subassemblies on a pole mount, which is bolted to one of the two backing beams; each keeper subassembly consists of a keeper, a pole, and appropriately oriented permanent-magnet material. In addition to details of the magnetic structure configuration, Figure 2-11 shows the corresponding quarter-period magnetic-flux plot.

Figure 2-12 gives a typical magnetic performance curve (magnetic field as a function of the variable gap) for such an undulator, in this case the LBL-SSRL-Exxon undulator for Beamline X. Field end correction will be provided by permanent-magnet rotors.

The support/drive system is identical to those of the other ALS undulators. A four-post support structure is used, and springs compensate for the gap-dependent magnetic load. The backing beams are stout enough to keep the maximum gap deflection less than 50 μm under peak field conditions, thus helping to meet a user requirement by minimizing line-width broadening. The maximum structure height is 94 inches, set by the 96-inch height of the storage-ring tunnel.

A roller-screw/chain drive mechanism much like the one on the SSRL wigglers will be used. Four right-handed roller-screw/nut assemblies on the upper half, and four left-handed ones on the lower half, are coupled by four drive shafts. This arrangement is driven by a stepper motor and a gear reduction unit via a roller chain and sprocket mechanism. Magnet-gap information is provided by a rotary encoder. Limit switches and mechanical stops protect the system.

Figure 2-13 shows the vacuum system, which includes the vacuum chamber and the pumping system. The vacuum chamber, 4.886 m in length, is machined from 5083 H321 aluminum alloy and welded. Since this vacuum chamber will be installed some time after the ALS has been commissioned,[3] the chamber will have a minimum vertical aperture of 1.0 cm; magnetic gaps as small as 1.4 cm can be employed during actual operation.

2.2.3 ALS Beamlines: An Introduction

In the 40 years or so of scientific experiments using synchrotron radiation, the development of dedicated storage rings and insertion devices has greatly advanced light-source technology. During these years, there have also been

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[3]The significance of this fact is that some other ALS insertion-device vacuum chambers to be installed earlier (and which are not associated with the CDRL) will have larger minimum gaps to make ALS commissioning easier.

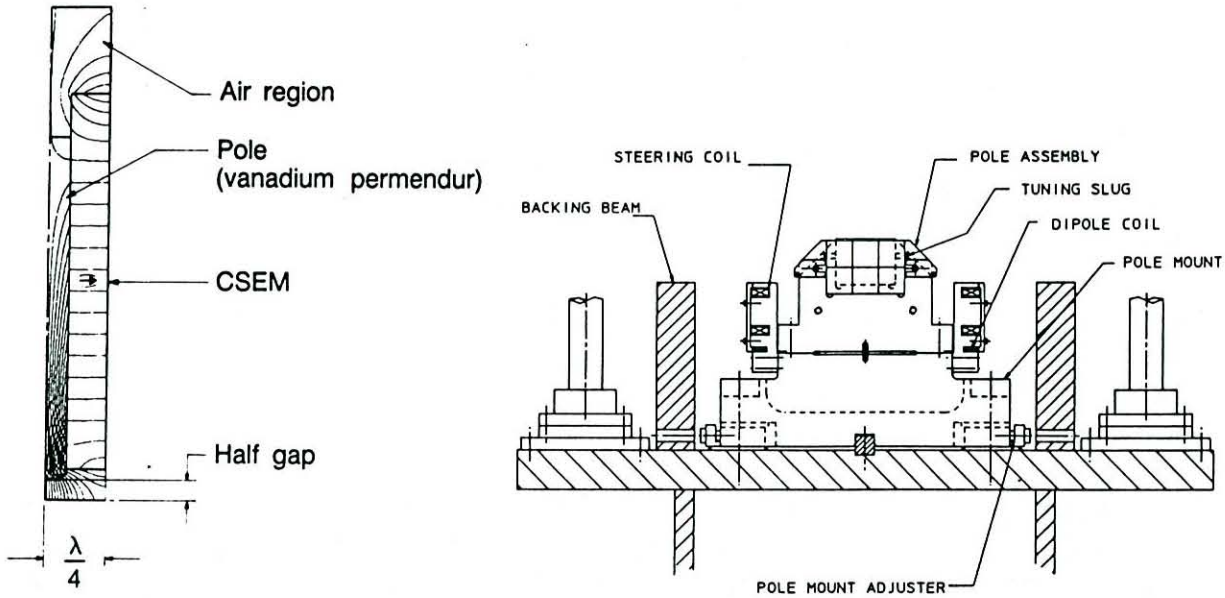


Figure 2-11. Details of the magnetic structure configuration, along with the corresponding quarter-period magnetic-flux plot, for an ALS hybrid insertion device such as U10.0. The current-sheet-equivalent material, or CSEM, is Nd-Fe-B. (XBL 855-2343A, left, and XBL 901-238)

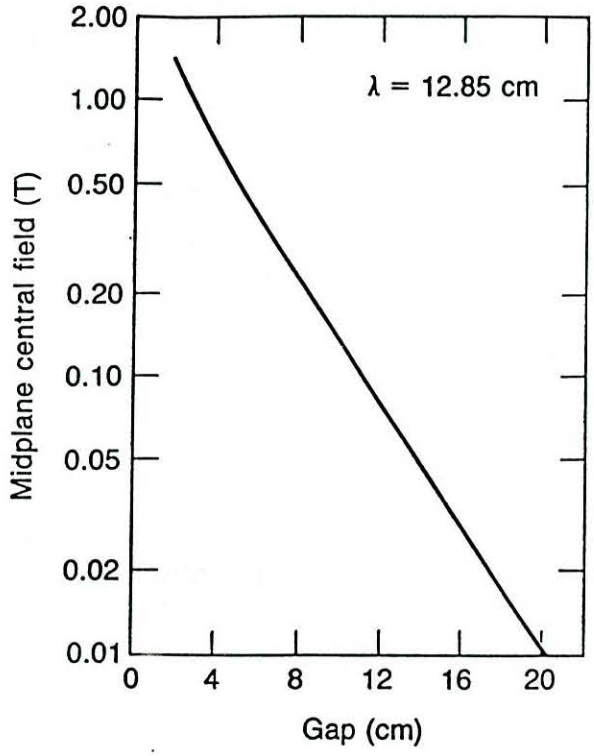


Figure 2-12. The magnetic performance of the Beam Line X wiggler, plotted here, is qualitatively similar to the expected performance of U10.0. (XBL 866-6298)

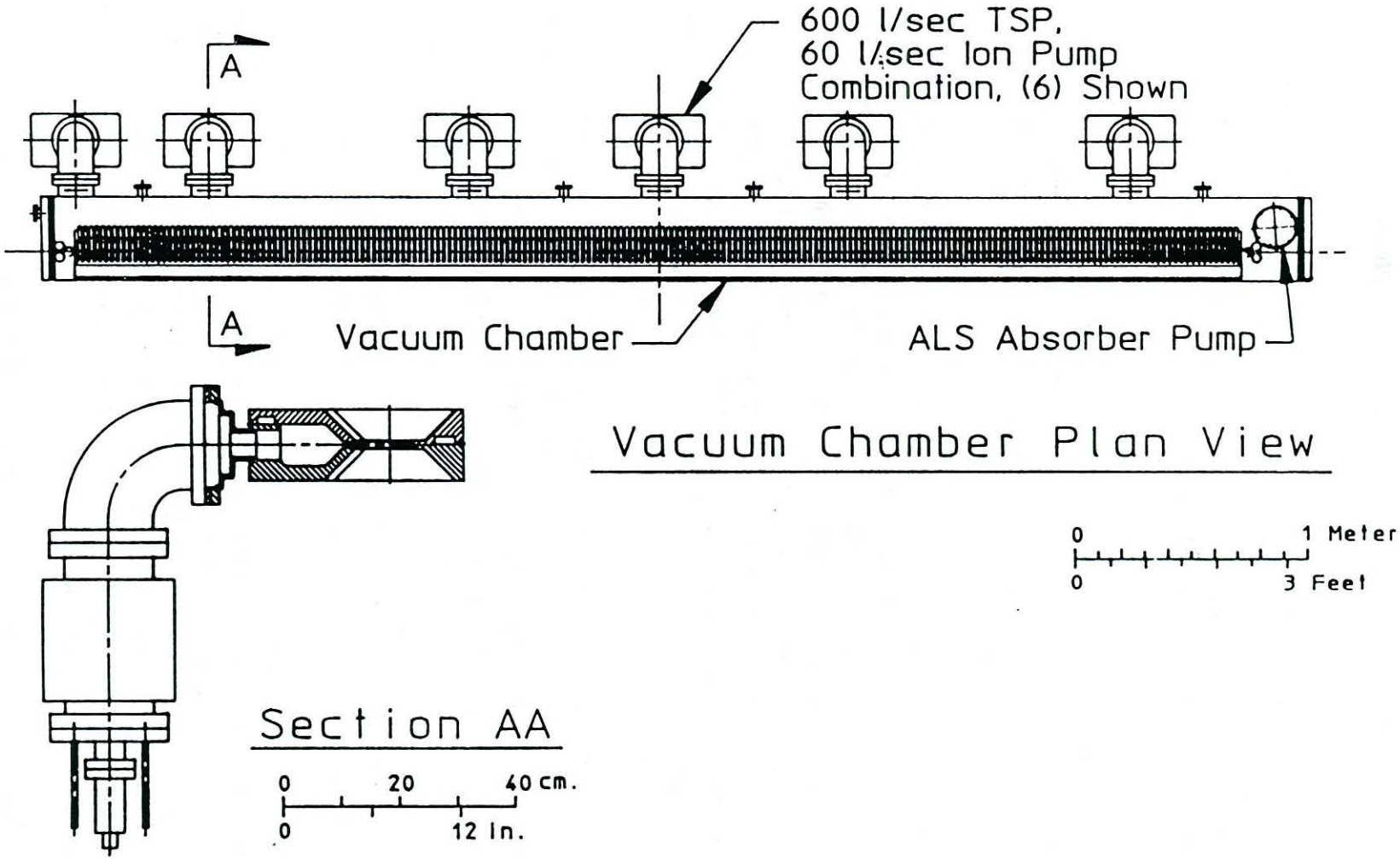


Figure 2-13. Vacuum system associated with undulator U10.0. (XBL 901-244)

corresponding developments in optical systems for handling the photon beams. These advances have created new challenges for the optical designer, especially in two areas:

- The source size has become smaller, so relay optics require tighter tolerances to avoid loss of light. The use of smaller slits also becomes practical, so monochromator components also need tighter tolerances to avoid loss of resolution. These tolerances apply to both the figure and the finish of optical components.

- The photon beam power has increased to the point that, in addition to satisfying more stringent surface tolerances, optical components must be cooled to control thermal distortions and stresses. This complicates the design and limits the choice of materials.

These factors, combined with the spatial separation of the ALS and the CDRL building and the exacting user requirements, make beamline design a particular challenge. LBL has played a leading role in the design and use of both high-power wigglers and undulators, which led to its involvement with Exxon and SSRL in the construction of a 54-pole wiggler, together with the beamline needed to exploit this device, at the SPEAR storage ring at Stanford. The chief conclusion from that exercise, confirmed by studies at LBL and elsewhere related to next-generation synchrotron radiation sources, was that when a large heat load is present it dominates the design and cost of the beamline.

The difficulties of dealing with large heat loads have increased the level of interest in the properties of undulators, which usually generate lower total power than wigglers. In addition, because undulator radiation is largely coherent, most of the unwanted power can be dumped in a robust, non-optical component (a pinhole, for example), which is a great advantage. For the ALS beamlines, including those feeding the CDRL, the power problem is usually quite moderate and, at worst, is similar to that of the 54-pole wiggler beamline. Our strategy for dealing with it is to use pinholes where appropriate, plus active water cooling of the optics.

The most serious problem now faced by the optical designer addressing the design of synchrotron-light-source beamlines is optical fabrication tolerances. It has been observed that even in present-generation storage rings, such as the National Synchrotron Light Source and the Berlin Electron Synchrotron, the fabrication accuracy of aspheric optical surfaces (paraboloids, ellipsoids, toroids, etc.) for use in mirrors, monochromators, and other applications is inadequate for taking full advantage of the source properties.

Although manufacturing methods are improving, the only sure way to address this problem would be to avoid the use of aspheric surfaces altogether and to build beamlines entirely with plane and spherical surfaces. All the important optical technologies for figuring, finishing, and measuring work best in these cases.

Furthermore, one can infer from the demonstrated resolution of certain existing spectrometers that fabrication tolerances below one microradian have been achieved for standard spherical gratings. This would be the ideal solution, but it lacks some of the flexibility that aspheric optics provide, thus placing significant limitations on the options for laying out the CDRL beamlines. We have thus adopted a compromise philosophy, banning aspheric surfaces from *resolution-determining* optical elements only.

2.2.3.1 Beamline Design and Optical Components

With that as background, we go on to discuss the specific design of the beamlines' specifications and critical components. The beamline layout is discussed in the next section.

The wavelength coverage, resolution, flux, and polarization requirements of the various user groups were studied when designing U10.0 and its beamline. The four principal requirements are:

- Photon energy range of 6-25 eV in the first harmonic. The low-energy end of this range overlaps the capabilities of intense laser sources; the high end allows exploration of valence-shell processes in molecules.
- Intensity of at least 10^{12} photons per second at 0.1% bandwidth. This is required for a wide variety of measurements that involve sampling of dilute molecular-beam targets for studies of radicals, clusters, and complexes.
- High brightness combined with a tightly focused beam; for instance, some "two-color" experiments involving the ALS beam and a laser beam will involve an interaction volume whose linear dimensions are on the order of 50 μm.
- Resolving power of at least 50 000 for studying the rovibrational structure of molecules.

Great spectral purity is also needed for many experiments; the ratio of the third harmonic to the first harmonic, I_3/I_1, must be less than 1×10^{-5}.

These requirements must be satisfied within certain practical constraints, many of which arise from the undulator. To obtain wide spectral coverage, one must use a wide range of undulator K values (defined in Section 2.2.2.1). For large K, the undulators generate substantial radiation flux at high harmonics (the higher orders scale as K^3), and the beamline optics must be able to handle this extra radiation. The undulator must not be longer than 450 cm. For reasons associated with ALS beam dynamics, the maximum magnetic field required for producing the photon characteristics outlined above must be less than the bending-magnet field (1.04 T). The U10.0 undulator will meet the user requirements by producing radiation that

has the following characteristics *at the source* (central cone, diffraction-limited, at 1550 Å):

- Beam size σ_H =800 μm, σ_V = 220 μm.
- Divergence ($\sigma_{H'}$, $\sigma_{V'}$) = 450 microradians.
- Brightness = 5.7×10^{16} photons/s/mm^2/mrad^2 at 0.1% bandwidth.

To meet the user requirements and take advantage of the characteristics of ALS radiation, the U10.0 and bending-magnet beamlines are designed for high throughput, high resolving power, small focused image, and wide energy range. Tables 2-3, 2-4a, and 2-4b list the parameters of the optical components within the beamlines.

Table 2-3. Parameters of Monochromator Gratings in the U10.0 and Bending-Magnet Beamlines*

	G1	G2	G3
Grating groove density (lines/mm)	600	1200	2400
Grating radius (m)	5	5	5
Reciprocal linear dispersion (Å/mm)	3.36	1.69	0.85
Slit-width-limited resolution, first-order, with 10-μm slits (Å)	0.033	0.016	0.008
Maximum wavelength (Å) at 10° from λ = 0**	5766	2883	1441

*Table applies to both beamlines, since the first mirror should have no effect on these parameters. Each monochromator is equipped with two gratings. Considering the wavelengths available from the sources, G2 and G3 would be good choices for the undulator beamline, and G1 and G3 would be appropriate for the bending-magnet beamline.

**Ten degrees is a typical choice for the scan range of this type of monochromator.

Table 2-4a. Parameters of the Mirrors in the U10.0 Beamline.

	M1	M2	M3	M4	M5
Shape	tor.	sph.	flat	tor.	tor.
Tangential radius (m)	42.0	2.75	∞	21.0	21.0
Sagittal radius (m)	0.33	2.75	∞	0.63	0.63
Length (mm)	200	50	50	0.63	300
Width (mm)	50	50	50	80	80
Incidence angle (deg.)	85	85	5	80	80
Magnification factor	0.12	0.25	n/a	1.0	1.0
Inward conjugate (m)	17	0.60	n/a	3.64	3.64
Outward conjugate (m)	2.05	0.15	n/a	3.64	3.64
Focusing plane	Both	V	–	Both	Both
Coating	C	C	SiC	C	C

Table 2-4b. Parameters of the Mirrors in the Bending-Magnet Beamline.

	M1	M2	M3	M4	M5
Shape	tor.	sph.	flat	tor.	tor.
Major radius (m)	62.58	1.41	∞	7.20	7.20
Minor radius (m)	0.52	1.41	∞	0.22	0.22
Length (mm)	150	50	100	500	500
Width (mm)	200	50	200	75	75
Incidence angle (deg)	85	80.2	5.0	80.0	80.0
Magnification factor	0.83	0.25	n/a	1	1
Inward conjugate (m)	6.00	0.60	n/a	2.5	2.5
Outward conjugate (m)	5.0	0.15	n/a	2.5	2.5
Coating	SiC	SiC	SiC	SiC	SiC

2.2.3.2 Beamline Optical Design and Layout

Two example beamline designs have been developed to show the feasibility of this program and to provide an indication of the level of performance that can be expected. (The beamlines actually implemented will be comparable in their basic configuration, but further refinement in details is likely to occur.) One of the designs is for the undulator U10.0 and the other is for a bending-magnet source. The two beams can be used simultaneously for different experiments. The capabilities they give are somewhat complementary: the bend magnet gives wider spectral coverage and greater polarization control than the undulator, at a cost of about a

factor of 30 in flux for comparable operating conditions. Both beamline designs are supported by detailed ray-tracing studies.

Bending Magnet Beamline. The way to collect radiation across a large horizontal angle from an ALS bending magnet is to place a mirror (M1) close to the storage ring (inside the shielding wall) and use sagittal (transverse) focusing. This implies the use of a toroidal mirror, and, since good image quality is required, the toroid must be operated at unity magnification. To achieve the required resolution of $\Delta\lambda/\lambda$ = 1/50 000, and to obtain the best suppression of higher diffracted orders, it is desirable to use a normal-incidence monochromator of large grating radius.

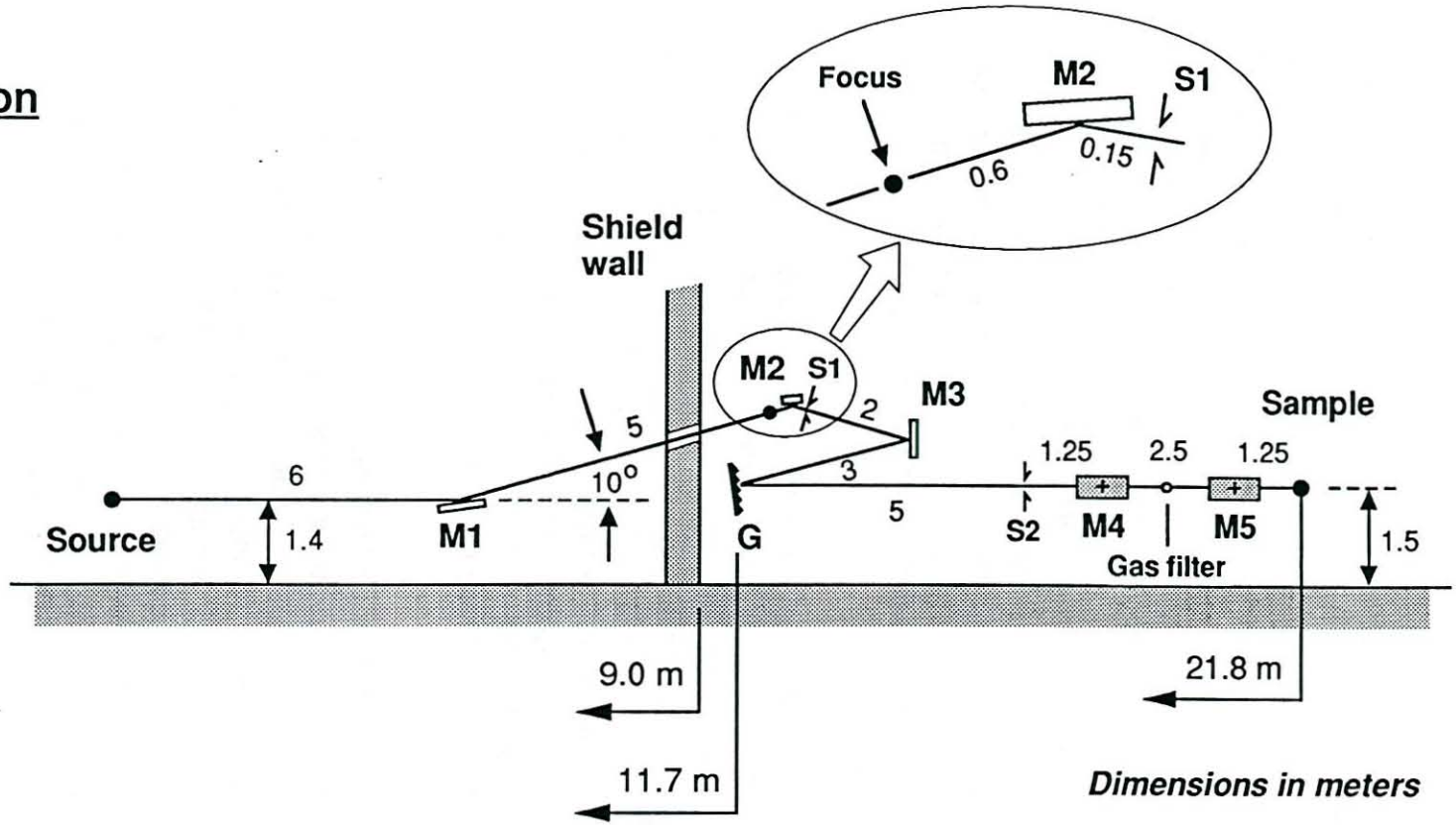
As an example, we choose a system of the McPherson type, which has been operated at the Hamburg, Daresbury, and National Institute for Standards and Technology synchrotron-light sources and which can be obtained commercially from several different vendors. We use a common variant of this scheme, incorporating a flat folding mirror (M3) that sends the beam in the desired direction after passage through the monochromator.

Figure 2-14 shows a layout in which the real image from the toroidal mirror M1 is demagnified (in the vertical direction only) by the small spherical mirror M2 to match the 20-μm slits that are required to get $\Delta\lambda/\lambda$ = 1/50 000 with the proposed monochromator. The monochromator is assumed to have a 5-m radius and a 2400 lines/mm grating. The remaining two mirrors M4 and M5 are a coma-correcting symmetric pair that delivers the beam with the proper direction, location and spot size. The fabrication tolerances required for the resolution-determining components, the grating and flat folding mirror, are about 1 μrad. This is challenging, but published spectra bear witness that it has been achieved.

Undulator Beamline. The undulator beamline design is based on similar requirements and uses essentially the same monochromator system as the bending magnet line. The main differences are due to the smaller divergence angle of the beam and its greater power. Consequently there are two grazing incidence mirrors (M1 and M2 in Figure 2-15) whose role is partly to condense the beam onto the entrance slit and partly to absorb the large power which will be present in the undulator beam at photon energies outside the range needed for this program. The monochromator for this beamline differs from that used for the bending magnet beamline only in the size of the displacement produced by the folding mirror M3.

The mirrors M1 and M2 and the normal incidence mirror M3 absorb sufficient power that the grating G does not need to be water-cooled. This allows both monochromators to be standard commercial items. Once again the two condensing mirrors, M4 and M5, are needed to deliver the monochromatic beam of the required spot size to the sample at the right location in three dimensions.

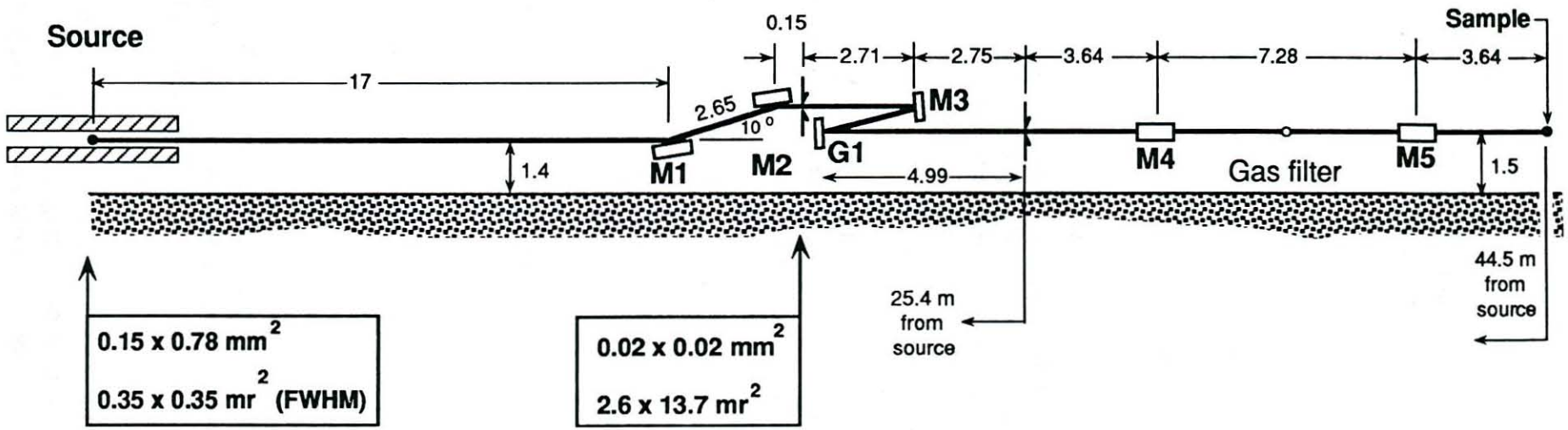
Elevation



Name	Shape	Magnification	Focusing Direction
M1	Toroid	1	Both
M2	Sphere	0.25	V
M3	Flat	-	-
G1, G2	Sphere	~1	Both
M4	Toroid	1	Both
M5	Toroid	1	Both

Figure 2-14. Layout of the bending-magnet beamline. (XCG 8910-4707)

Elevation



Dimensions in meters

NAME	SHAPE	MAGNIFICATION	FOCUSING DIRECTION
M1	Toroid	0.12	Both
M2	Sphere	0.25	V
M3	Flat	-	-
G1	Sphere	~1	Both
M4	Toroid	1	Both
M5	Toroid	0.5	Both

Figure 2-15. Layout of the U10.0 beamline. (XCG 8912-4755)

2.2.3.3 Output Flux and Geometry

The phase space of the photon beam at the interaction region provided by the two beamlines, when they are set for a slit-width-limited resolution of 0.016 Å with a 1200 lines/mm grating (10-μm slits), is as follows:

	Bending magnet	**Undulator**
Vertical	0 .09 x 12 mm mrad	0.011 x 4.9 mm mrad
Horizontal	0.78 x 22 mm mrad	0.1 x 2.8 mm mrad

These figures are the Gaussian optics values, which are expected to be good in general, but in some cases the astigmatic focal line length may be larger than the quoted horizontal spot size. As described in the next section, this can be corrected if it is considered important. The effects of optical fabrication tolerances and aberrations have not been allowed for, and might be expected to produce some degradation of the quoted values of the vertical spot size.

For the photon fluxes emitted by the two ALS sources, the output does not vary greatly over the spectral range involved in this work. The same is roughly true for the reflecting efficiency of the C and SiC coatings proposed. It is therefore reasonable to quote a single figure for the photon flux expected from each of the two beamlines.

For the optical systems described here, with the ALS operating at 400 mA and 1.5 GeV, we obtain:

Undulator beamline	$\Delta\lambda/\lambda$ = 1/50 000	3×10^{11} photons/second
Undulator beamline	$\Delta\lambda/\lambda$ = 1/44	3×10^{14} photons/second
Bending magnet beamline	$\Delta\lambda/\lambda$ = 1/50 000	1×10^{10} photons/second

2.2.3.4 Special Issues

Some of the issues that guided the design decisions bear further explanation. They include astigmatism, suppression of unwanted higher-order radiation, and dealing with the high heat loads associated with synchrotron radiation beamlines.

Astigmatism. The main aberration of the monochromator sytems described above is astigmatism. This means that, instead of producing a focal point at the exit slit, the system produces a focal line. This defect does not affect resolution, but it must

be taken into account in matching the focal spot from the ALS to an interaction region defined by a molecular beam. For both beamlines, calculations show that the length of the focal line reaches its maximum value (1/13 of the length of the illuminated part of the grating grooves) at the maximum output wavelength. For the undulator beamline, this means that the line length is always less than 0.5 mm and usually much less. For many purposes this will be negligible.

For the bending magnet beamline, the uncorrected focal line length increases from 1.1 mm at 30% of maximum wavelength to 8 mm at 100%. Such variation can be approximately corrected by use of a holographic grating, by making the grating surface slightly toroidal, or by a small departure from stigmatism in the refocusing optics. It could be exactly corrected by using an adaptive optical element in the horizontal focusing scheme; the ALS experimental systems group have already demonstrated a technique for accomplishing this.

Higher-Order Suppression. The requirement for higher diffracted orders to be less than 10^{-5} times the intensity of the first order cannot be met with any conceivable design based on optical considerations alone. The problem is particularly serious for the spectral region addressed in this program because, at the ALS electron energy, undulators must be operated at high magnetic fields to generate low-energy photons in the first harmonic. As a consequence, the higher-order radiation is generally more intense than is the desired radiation. A similar argument applies to the bending-magnet source, which also produces more higher-order than first-order radiation because of the value of the ALS critical energy (1.56 keV).

Nonetheless, we have made the best possible use of the optical factors that can be used to discriminate against higher orders: that is reflection filtering and use of a laminar grating with a mark-to-space ratio of unity. This is quite effective near the normal-incidence reflectance threshold of the silicon carbide reflection surfaces that are used on most of the optical components. However, it becomes so ineffective at wavelengths greater than twice threshold that second and third order may be as much as 10% of the total output. To obtain an improved rejection of the higher orders it is necessary to employ absorption filters. For a windowless beamline like this one, that means the use of gas filters.

In order to implement such a scheme, we first note that there is in any case a need to have considerable differential pumping between the sample chamber, which contains the sample species in gaseous form, and the beamline, which needs to be at ultrahigh vacuum. The introduction of gas filtration thus appears as an aspect of the design of the resident differential pumping system. The absorber gas, which will be one of the noble gases, is introduced into one of the three, sealed, rectangular apertures and is kept at a pressure of, say, 0.5 Torr. A system with the geometry shown transmits less than 10^{-6} of the incoming high order photons provided the correct choice of gas for the prevailing spectral region is made.

Heat Loads. The heat loads on the first mirror of the undulator beamline have been calculated, assuming that only the central-cone radiation from the undulator is needed (radiation outside the central cone is not accepted) and that the undulator gap is set to give a first harmonic photon energy of 6 eV. This is the worst case from a beam-power point of view. As a result, although the total output power of the undulator is 1.98 kW, the beamline accepts only 96 W, and 93 W of that is absorbed by the first mirror. We can therefore assume that the thermal design issues posed by this beamline are similar to, or easier than, the ones already resolved by the ALS engineering staff for other beamlines.

2.2.4 Experimental Systems

The experimental stations are the heart of the CDRL, where beams from the facility's various photon sources converge to allow new and unique experiments to be performed in combustion chemistry, chemical dynamics, and spectroscopy. These stations will be fully equipped with molecular beam machines, beam sources, apparatus for kinetics studies, ultrahigh vacuum apparatus, and automated data acquisition and control systems.

Because of the breadth and complexity of the potential CDRL research program, it is not presently possible to determine the exact configuration of the experimental stations. Details of the stations will evolve and be refined through continuing planning and discussion among the core research groups, the participating user groups, and several scientific and technical workshops that will be held between now and the project completion date. However, many general principles and guidelines can be laid out at this time, and certainly the large experimental station apparatus and special lasers must be designed in advance; these topics are the focus of this section. There is a total of seven experimental stations and three advanced lasers included in the CDRL.

The main components that distinguish one experimental station from another are the vacuum chamber and its peripherals. Each vacuum chamber, also called a "sample cell," is designed for a specific class of experiments, and quite often the different classes have different needs. They will be designed so that attachments to each apparatus, such as beam sources, detectors, and window flanges, can be fitted universally to many of the main chambers. We describe here the main features of three representative vacuum chambers.

2.2.4.1 Representative Experimental-Station Vacuum Chambers

Funding is being requested for seven major experimental stations based on five representative chamber designs. It is anticipated that the stations initially built will be modified over time, and that additional equipment will be built through the lifetime of the facility.

Each of the stations will be equipped with the data acquisition capability to take full advantage of the unique research facilities. Each station will also have one or more standard laser systems, in addition to the advanced lasers described later in this section, primarily for producing and preparing the experimental samples.

In order to protect against accidental contamination of the beamline optics and the expensive and delicate components upstream in the storage ring of the ALS, oil-free pumping systems will be employed wherever possible. A network of vacuum forelines is designed for the experimental hall with the roughing pumps located in the basement of the building to maintain the cleanliness and reduce the noise level in the hall.

Example #1: Chemical Physics. The first example chamber is being proposed by the chemical physics Participating Research Team of the ALS.[4] It is a multipurpose experimental chamber that could be used for a number of studies of critical interest to combustion chemistry and chemical dynamics, such as photoionization spectroscopy, threshold photoelectron spectroscopy, and photoelectron-photoionization-coincidence studies of normal molecules and free radicals. A standard source chamber with skimmers to produce a beam of normal molecules and/or ions in a free jet expansion will be attached to the experimental chamber. A special source chamber for making carbonaceous clusters and metal clusters will be built to match this apparatus. The source chamber will require a pumping speed of 2000–2500 liters per second. For the main chamber, 1000 l/s will suffice. The machine will be equipped with a time-of-flight ion detector with a quadrupole mass selector, an electron energy analyzer that has excellent magnetic field suppression, fluorescence detectors, etc. High speed detection electronics with a rise time of ~100 picoseconds are especially important for this station; they are a key to the unique ultrahigh resolution (sub-milli-electron-volt) photoelectron detection capability made possible by the undulator beamline.

Example #2: Fundamental Surface Processes. The second example is a chamber for experiments on fundamental processes that take place on surfaces, including photon-stimulated desorption, and dynamic processes on impure carbon surfaces and pure single crystals, that are important to understanding combustion and high-technology industrial processes. The facilities available at the CDRL can make a substantial impact in this field. For studies of this type, the apparatus consists of two components: a surface preparation chamber and a large multipurpose scattering chamber. The preparation chamber is essential for pure crystal studies

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[4]A Participating Research Team (PRT) is an experimental group that makes significant contributions toward construction of an ALS beamline in exchange for a guaranteed share of the beam time. See *An ALS Handbook* (Lawrence Berkeley Laboratory publication PUB-643 Rev. 2) for further details.

and contains surface diagnostic probes necessary to prepare, orient and characterize the substrates. Provisions for crystal etching, annealing, Auger spectroscopy, and LEED diagnostics will be attached. The main chamber will be equipped with a x-y-z-motion sample manipulator and has sufficient space to accommodate rotation of a time-of-flight ion/electron analyzer for angle-resolved detection of products desorbed from the sample surface. It will also be designed to accommodate a differentially-pumped molecular beam source for gas surface-scattering and surface-photochemistry experiments.

An ultrahigh vacuum of $< 5 \times 10^{-11}$ Torr is essential to maintain a clean surface for long periods of operation. This will be achieved using oil-free mechanical pumps and turbo pumps for initial evacuation. Ultimate UHV will be obtained by using high temperature baking, and a combination of an ion pump and a sublimation pump.

Example #3: Universal Crossed Molecular Beam Apparatus. A third experimental station might include a universal crossed-molecular-beam apparatus, an advanced version of one in operation in Prof. Y.T. Lee's laboratory. This apparatus will be most suitable for investigating primary photochemical processes and the dynamics and reactivity of polyatomic molecules, ions and clusters, using photofragmentation translational spectroscopy. These studies are of primary interest to combustion chemistry as well as fundamental chemical dynamics.

The detector in this apparatus comprises a high-efficiency electron bombardment ionizer, quadrupole mass filter, scintillation ion counter, and gated scaler synchronized with the beam modulation. The ionizer is nested within three chambers, each pumped by a separate turbomolecular pump; the innermost is attached to a liquid-helium-cooled trap. The design causes molecules that are not ionized to fly into another differentially pumped region before hitting a surface. The entire detector unit, including pumps and traps, will be mounted on a rotatable platform, which forms the lid of the main chamber. The beam sources also comprise modular units, mounted in differentially pumped side chambers inserted into ports in the main chamber. A high-speed multichannel scaler consisting of dual data scalers, onboard random access memory, a trigger counter, and a sweep counter with sub-microsecond counting time per channel will be used for data collection.

Example #4: Chemical Kinetic Station. The chemical kinetics experimental station will facilitate studies of the kinetics and mechanisms of reactions critical to combustion and pollution abatement. Both single-step and multiple-reaction processes will be investigated. The apparatus will utilize optical, mass, and photoelectron spectroscopies to characterize reactant and product concentrations in chemical flows. The information derived will serve as direct input into computer models of combustion processes. The extensive vacuum, laser, and detection

equipment requested in the proposal is critical to the construction of this next-generation chemical kinetics facility.

Example #5: Chemical Dynamics Imaging Station. The development of a large crossed-molecular-beam apparatus with several stages of differential pumping in order to obtain the intense, high-repetition-rate, pulsed molecular beams is necessary to perform bimolecular reaction dynamics experiments. This apparatus will require large roots blower pumps for the source chambers as well as turbo pumps for the reaction chambers. The apparatus will be equipped with state-of-the-art imaging detectors in order to detect ions and electrons. To complement the apparatus, a high-repetition rate, intense UV laser source with multiple frequency outputs will be constructed. This will allow researchers to perform stand alone as well as double-resonant experiments utilizing either the ALS or the IRFEL.

2.2.4.2 Advanced Laser Systems

Some of the lasers needed for the CDRL are fairly standard "off-the-shelf hardware" and, to a substantial degree, can be purchased commercially and used without modification. However, some experiments will also need laser systems whose performance and sophistication surpasses the state of the art in commercial systems from any single manufacturer. The preliminary specifications given here for these lasers are based on performance reported by researchers in various laser development laboratories. The final performance specifications will be developed and refined in workshops before CDRL construction begins.

Note that these advanced lasers will be very substantial in size; they will remain in the experimental hall and their beams will be transported to the experimental chamber as required, as opposed to the standard lasers, which could be moved close to each experiment as needed.

Three advanced laser systems will be constructed; the specifications of each one given here serve as examples of what capabilites are anticipated.

- A near-transform-limited source operating in the nanosecond regime will provide high-power tunable photons from 4 μm to 70 nm with exceptional frequency resolution. This laser, the IRFEL, and the ALS undulator beamline are all high-intensity sources, and they complement each other's spectral capabilities. Together, they provide complete coverage "at the user's fingertips" of the entire portion of the spectrum that is most important to chemical dynamics and combustion chemistry investigations.

- A laser operating in the sub-picosecond regime, providing tunable photon pulses that are time-synchronized to the pulse trains from the ALS beamlines and from the IRFEL. This laser will be suitable for pump-probe experiments

involving the micropulses from the accelerator-based systems. The sub-picosecond system will be designed to produce intense visible and UV pulses, each several hundred femtoseconds long, at a rate of 1000 pps; this feature is primarily envisioned for use in ALS-related experiments. The laser could be used with either the ALS or the IRFEL at the micropulse repetition rate.

- A picosecond laser that, like the sub-picosecond laser, will provide tunable pulses that can be synchronized to IRFEL or ALS pulse trains and will be useful for pump-probe experiments. The picosecond system will operate at 50 Hz in the high-power mode, synchronized with the macropulse timing of the IRFEL.

The three systems are described in greater detail below.

Near-Transform-Limited Tunable Laser System. This system is an improved version of one that is now in operation at LBL. It has a nearly transform-limited bandwidth of < 100 MHz in the visible region for a 7-ns (FWHM) pulse. It also has a high pulse energy, typically around 100 mJ in the visible and 30 mJ in the UV, with good beam quality; this allows efficient conversion into the VUV and XUV regions. With the use of frequency tripling and mixing techniques it is continuously tunable over a broad range in the VUV and XUV, producing fluxes of $>10^{11}$ photons/pulse in a bandwidth of 250 MHz (0.008 cm^{-1}). Difference frequency generation in $LiNbO_3$ or $LiIO_3$ extends the tunability to the infrared. A total useful tuning range of 4 μm to 70 nm is expected. A schematic of the system is shown in Figure 2-16.

The basic technique used in the construction of this laser system is pulse-amplification of a single-mode dye laser. We describe here the aspects of the design and performance of our system that significantly distinguishes this laser in providing a source of exceptionally high spectral brightness and versatility.

The system consists of a pair of identical subsystems. In each subsystem, we start with a narrowband continuous-wave ring dye laser (Coherent model 699-29 Autoscan ring dye laser) pumped by an argon ion laser. This gives a well-characterized light beam of 1-MHz bandwidth continuously tunable over the whole visible spectrum. The pulses are then amplified by the second harmonic of a Nd:YAG laser, using a three-stage, four-pass dye amplifier chain similar to one that has been built in our laboratory. The dye laser is optically isolated from the amplifier chain with a permanent-magnet Faraday isolator to prevent mode-hopping induced by the feedback of amplified spontaneous emission (ASE) from the amplifiers. The beam of pulsed visible photons is then sent through a frequency-doubling crystal, and the UV photons thus generated are used to make VUV and XUV radiation via third-harmonic generation or four-wave mixing in a pulsed atomic or molecular beam.

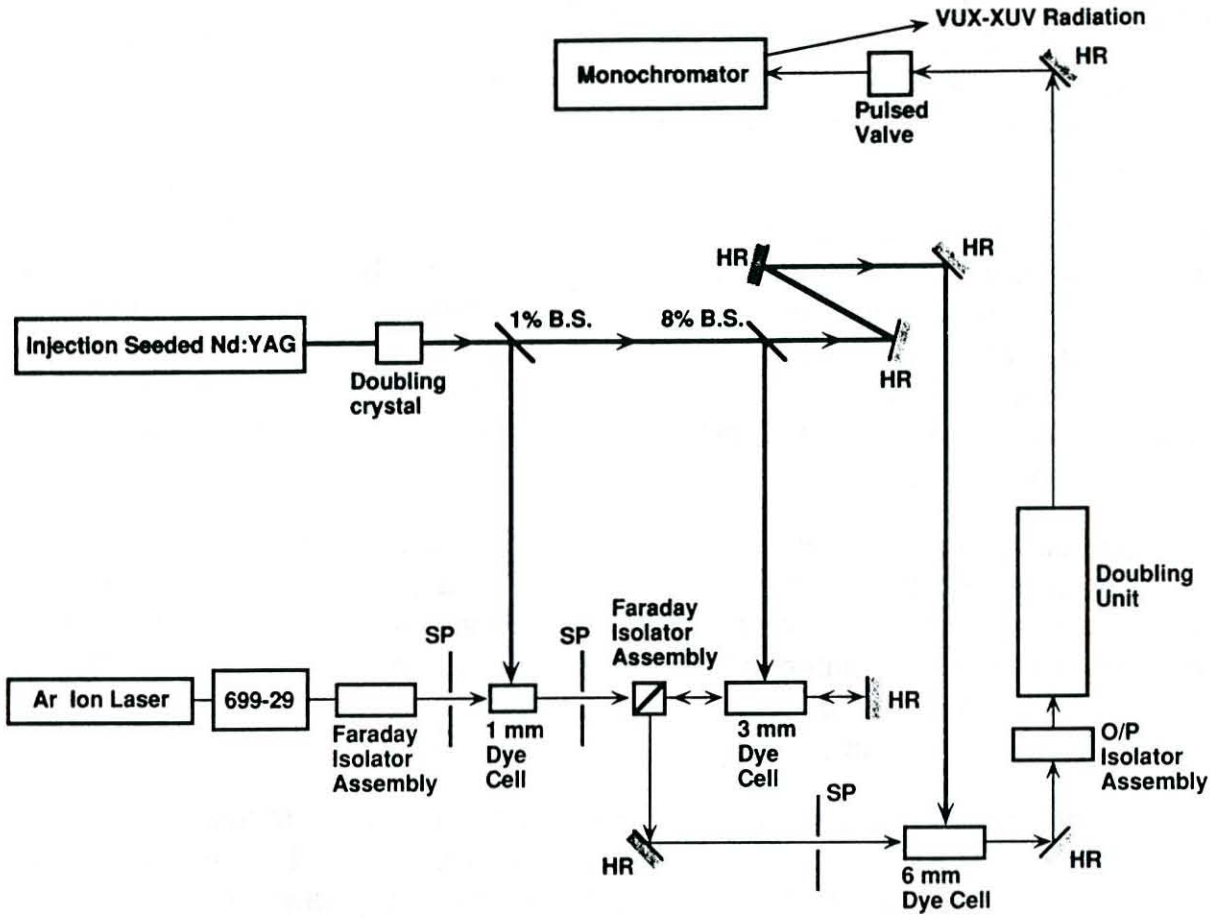


Figure 2-16. Schematic of existing LBL VUV laser system. BS = beam splitter, HR = high reflecting mirror, and SP = spatial filter/telescope. (XCG 8911-4723)

Some critical components of the subsystem call for further explanation, including the injection-seeded Nd:YAG laser. An important limiting factor on the bandwidth of the system is the temporal profile of the amplified dye laser pulse. This, in turn, is determined mainly by the profile of the pump pulse. By utilizing injection seeding, thereby obtaining output in single longitudinal mode from the Nd:YAG laser, the temporal profiles of both the pump laser and the dye lasers are made as smooth as possible, resulting in the narrowest bandwidth. Use of the injection-seeded Nd:YAG laser also gives more stability in UV and XUV power. This is again due to the single-mode operation, which eliminates the mode-beating induced modulations seen in the temporal profile of multimode lasers.

The dye cells used are similar to the prism cells developed by D.S. Bethune for an excimer pumped dye laser. These are side-pumped cells, with the pump beam being internally reflected into the dye. The prism-type dye cell has certain advantages; for example, the dye is pumped from all sides so the gain can be

made uniform to preserve the spatial quality of the seeding beam; there is no window damage by the pump laser because of the large pumping area; and finally, the amplified beam's spatial profile is decoupled from that of the pump beam, enabling the system to be used with pump sources that have very different beam shapes.

Three dye amplifiers are used in our design. The first cell has a bore of 1 mm diameter × 20 mm length. The second cell, which is double-passed, is 3 mm × 30 mm; the final amplifier is 6 mm × 60 mm. By adjusting the dye concentration such that one dye absorption depth at the pump wavelength equals approximately the bore diameter, the best output beam profile and power combination can be obtained. In this design the amplifier gain is changed by varying the pump beam intensity at each stage.

Lens-pinhole-lens combination telescopes with magnifying powers of ×l, ×3 and ×2 are used to shape the cw dye laser's beam profile to fill the bores of the first, second and third amplifiers respectively. The pinholes serve as spatial filters to maintain a diffraction-limited profile for the dye beam. A Faraday isolator is inserted between amplifiers 1 and 2 to prevent the growth of ASE, which could deplete the gain in the amplifiers.

VUV generation is done in a pulsed jet of atoms or molecules. In this design, there are no exit windows for the tripled light, so there is no short-wavelength cutoff. Second, the length of the tripling region is not necessarily greater than the confocal parameter of the beam, so the tripling medium does not have to be negatively dispersive. Finally, for the shorter wavelengths the problem with self-absorption is reduced. An LBL-fabricated valve (operated with a 1-mm-diameter nozzle) allows for a larger throughput than commercial valves to give nearly a factor-of-ten increase in density in the tripling medium, which in turn results in a greatly improved tripling efficiency. Here the two subsystems are combined to provide for resonance-enhanced four-wave mixing in VUV generation.

A modified 1-m normal incidence monochromator (McPherson model 225) separates the photons of different wavelengths present in the laser beam. While the monochromator reduces the VUV-XUV beam intensity by a large factor, it introduces a tremendous amount of experimental versatility, making it an invaluable component in the laser system. The monochromator is modified to use a 1.2-m Roc grating. This monochromator offers two major conveniences. First, it separates out the fundamental light beams, permitting the use of VUV and XUV photons without interference from the powerful UV and/or visible beams. Second, the curved grating recollimates the VUV-XUV beam, allowing an optimal spatial overlap of the photon beam with the molecular beam in the end station. Optical damage to the grating is minimized by expanding the UV beam to fill the size of the grating.

Tables 2-5 and 2-6 and Figures 2-17 through 2-20 show the characteristics of the existing VUV laser system. The new system will be expanded to meet and exceed these characteristics.

Table 2-5. Examples of Wavelengths Generated.

λ (nm)	υ (cm^{-1})	υ_{vis} (cm^{-1})	Amp. Dye	υ_{uv} ($2\upsilon_{vis}$) energy (mJ)	Generating medium	Generating scheme
123.6	80 917	17 578	R590	35*	$3x\upsilon_{uv}$	CO
117.8	84 910	16 982	Kiton Red	30	$(2x\upsilon_{uv})+\upsilon_{vis}$	Xe
116.5	85 847	17 169	R610 (basic)	20	$(2x\upsilon_{uv})+\upsilon_{vis}$	Xe
100.1	99 894	16 649	R640	15	$3x\upsilon_{uv}$	Ar
98.2	101 868	16 978	Kiton Red	30	$3x\upsilon_{uv}$	Ar
95.1	105 146	17 524	R590	35	$3x\upsilon_{uv}$	Xe
80.4	124 344	υ=17 768	R590	4‡	$2x\upsilon_{uv}+\upsilon'_{uv}$	Xe
		υ'=17 242†	R590	15		
74.2	134792	17768	R590	4‡	$3x\upsilon_{uv}$	Xe

*$\upsilon_{uv} = \upsilon_{ir} + \upsilon_{vis}$ (υ_{ir} is the Nd:YAG fundamental)

†Second laser

‡$\upsilon_{uv} = 2\upsilon_{vis} + \upsilon_{ir}$

Table 2-6. Laser System Performance.

	Visible	UV	VUV-XUV
Energy	>100 mJ	>30 mJ	>10^{11} photons/pulse (measured at 98 nm)
Bandwidth (FWHM)	91 MHz	<140 MHz (est.)	250 MHz
Pulse Length	7 ns	<7 ns	<7 ns
Present Tuning Range	562–680 nm	281–340 nm 210–260 nm	71–170
Temporal Profile	near-Gaussian	near-Gaussian	near-Gaussian

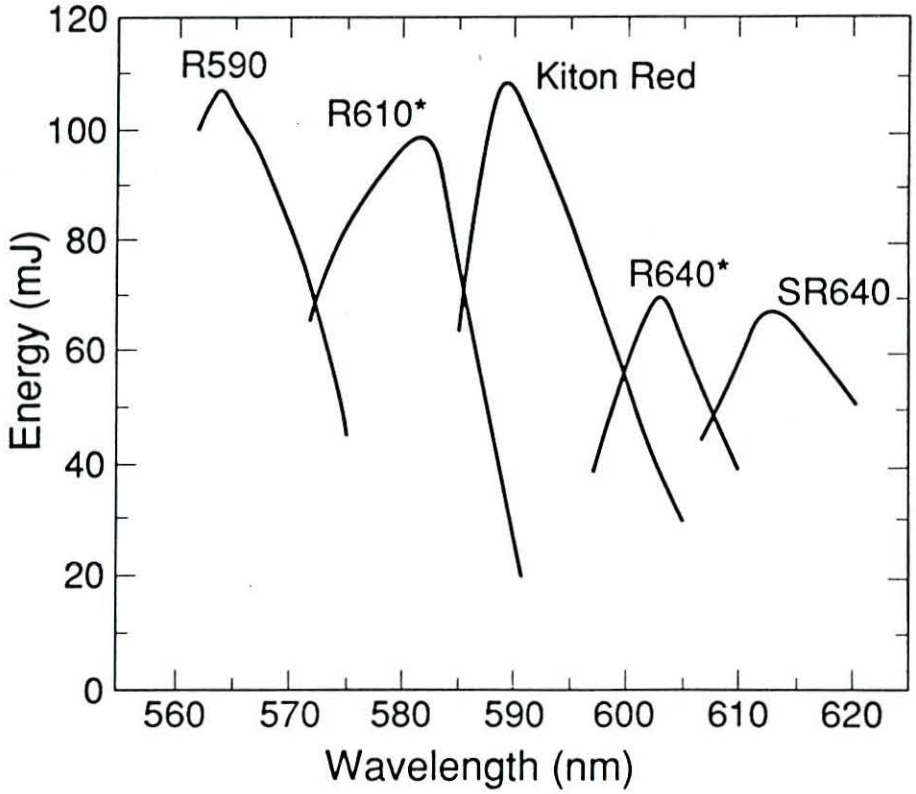


Figure 2-17. Dye-laser output response curves for various dyes; asterisk denotes basic solution. (XBL 902-5410)

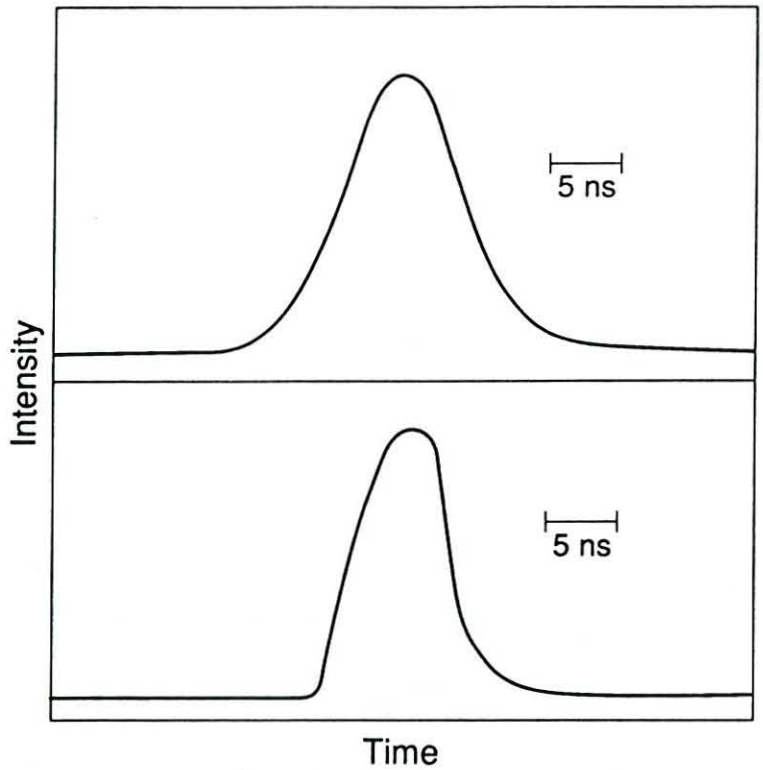


Figure 2-18. Upper trace: Temporal profile of the injection seeded Nd:YAG laser pulse; FWHM = l0 ns. Lower trace: Temporal profile of the dye laser pulse; FWHM = 7 ns. (XBL 902-5411)

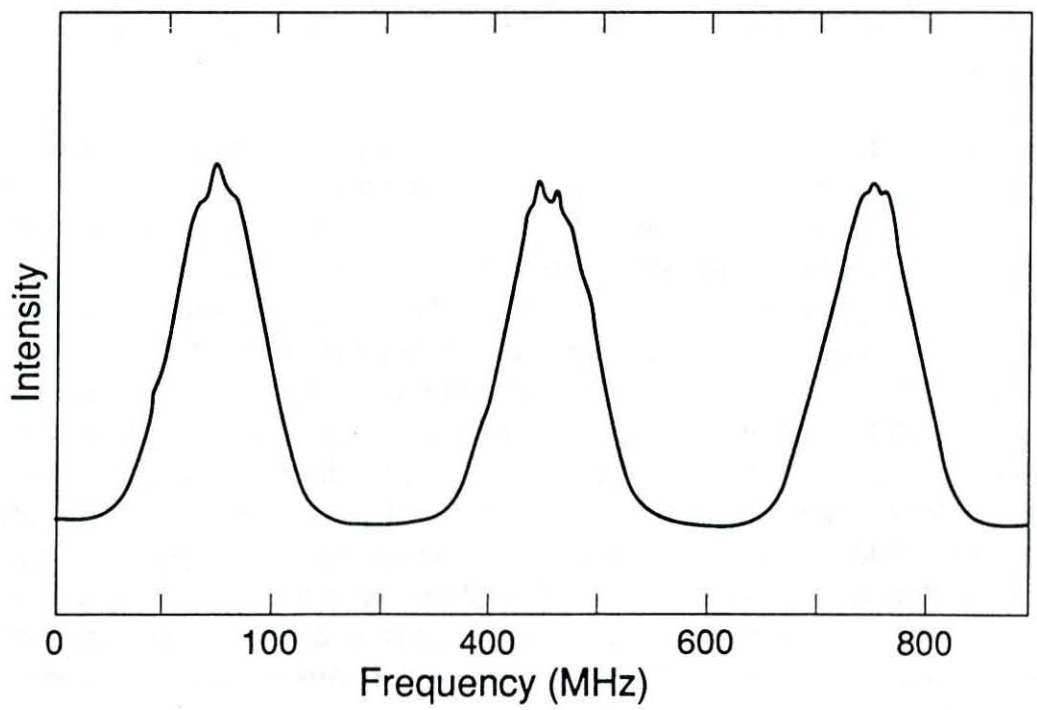


Figure 2-19. Scan of pulsed dye laser through a 300 MHz etalon with R590 dye in the amplifiers; FWHM = 91 MHz. (XBL 902-5412)

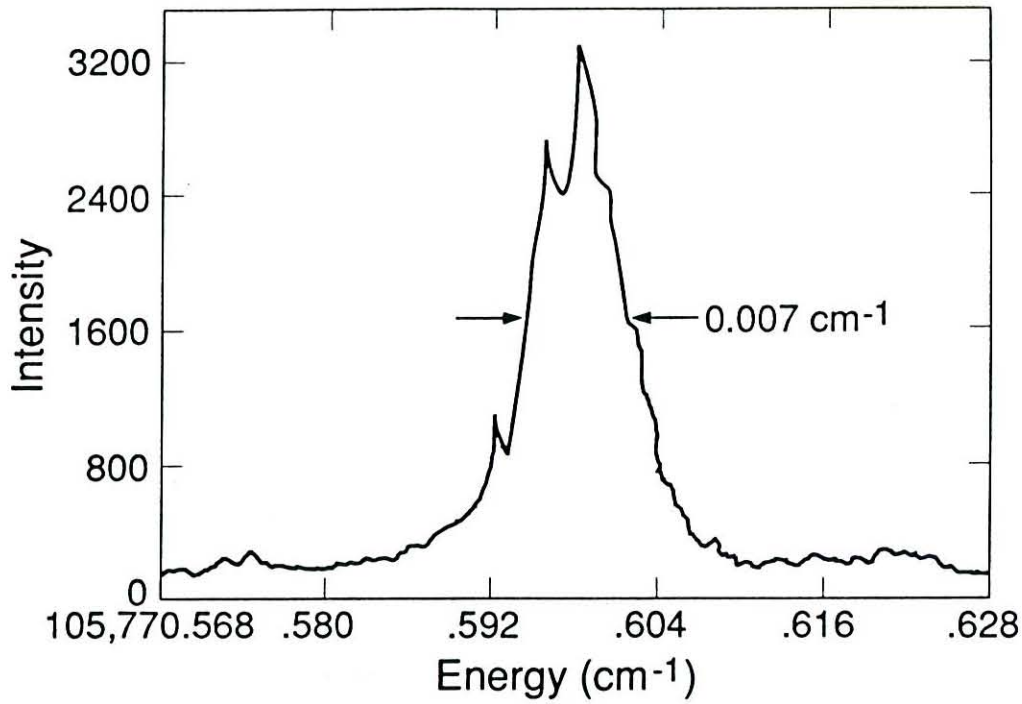


Figure 2-20. Scan of the 4p-7s $^2P_{3/2}$ (J = 1) transition of Kr at 94.5 nm. FWHM = 210 MHz (0.007 cm^{-1}). (XBL 902-5413)

Sub-picosecond and Picosecond Tunable Laser Systems. These systems are similar in their basic concepts to the near-transform-limited laser system described above. We therefore point out only the main features and the significant components.

Each system will have a dye laser oscillator stage, a high-power amplification stage, and a nonlinear optical wavelength extension stage. For the sub-picosecond system, the basic oscillator will be a mode-locked, frequency-doubled Nd:YAG laser synchronously pumping a group-velocity-dispersion-compensated dual-jet dye laser, providing pulses in the 100-femtosecond range. The significant part is that the mode-locked laser will be driven externally by rf at 36.56 MHz derived from the ALS rf oscillator, thus synchronizing the dye laser pulses to the ALS and the IRFEL pulses. The laser operating at this repetition rate will have low pulse energy (~2 nJ) and is functional in the visible from ca. 570 nm to 850 nm. Infrared pulses from the mode-locked Nd:YAG laser will be regeneratively amplified at a 1-kHz repetition rate and frequency-doubled to yield 1 mJ/pulse at 532 nm. A double-pass dye amplification stage, with a cavity dumper in the dye laser, will provide up to 5-10 mJ of visible energy in a sub-picosecond pulse. At this power level, frequency doubling and mixing are efficient and will permit extension of the wavelengths into the ultraviolet and infrared. A schematic of the sub-picosecond system is shown in Figure 2-21.

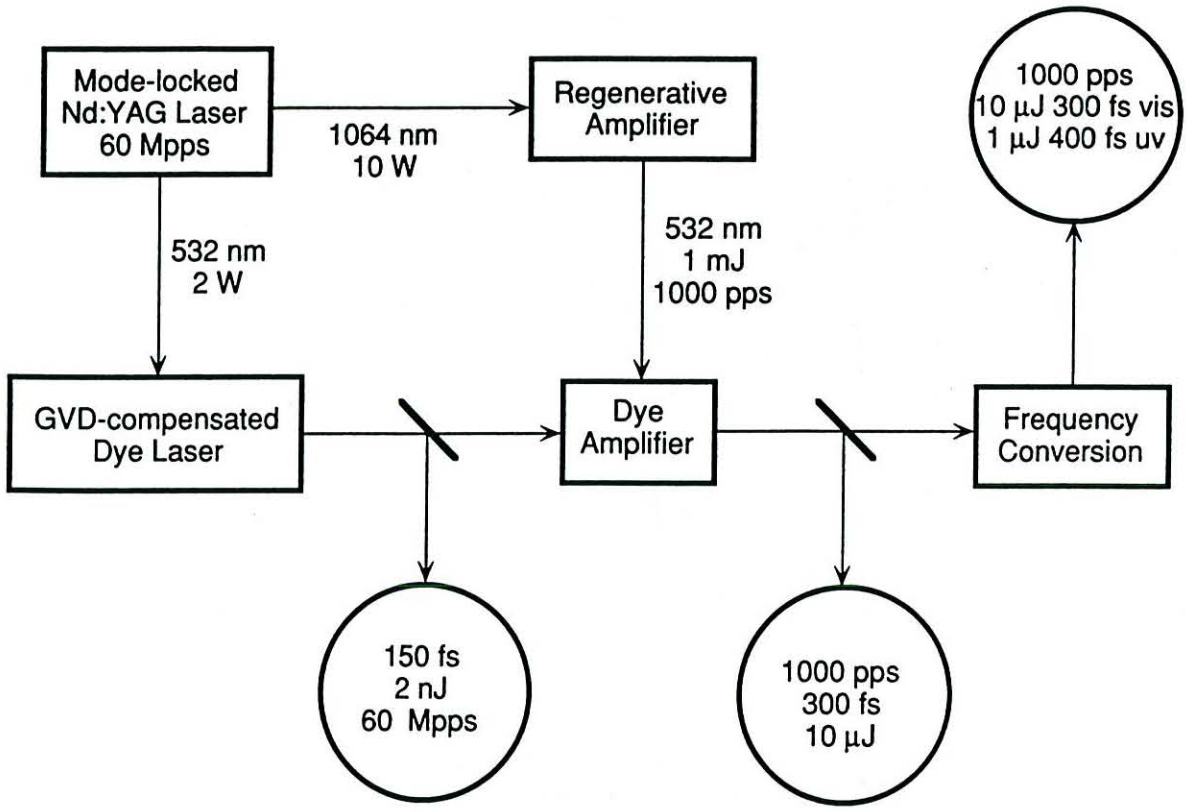


Figure 2-21. Schematic of the sub-picosecond laser system. (XCG 8912-4760)

The picosecond tunable system has essentially the same dye oscillator stage as the sub-picosecond system. The main difference is that there will be two dye laser oscillators pumped by the same Nd:YAG laser. Neither dye laser will have dispersion compensation. This results in two separately tunable dye pulses, each with approximately 1 nJ energy and 1 ps in duration, synchronized with each other to within a few ps. "Multicolor" experiments requiring three and even four different wavelengths at high repetition rates can be planned involving the ALS, IRFEL, and these dye lasers.

The picosecond system also is meant to be used with the macropulses of the IRFEL. A 50-pps regenerative amplifier will be used to boost the Nd:YAG laser's pulse power to pump dye laser amplifiers similar to those described for the transform-limited laser. The advantages of using the regeneratively amplified pump instead of a Q-switched laser pump are twofold: the dye pulses will be synchronized to the Nd:YAG laser pulses, which will facilitate frequency mixing and pump-probe experiments requiring those pulses; and amplified stimulated emission in the dye amplifiers will be reduced. The projected performance and layout of this system are shown in Figure 2-22.

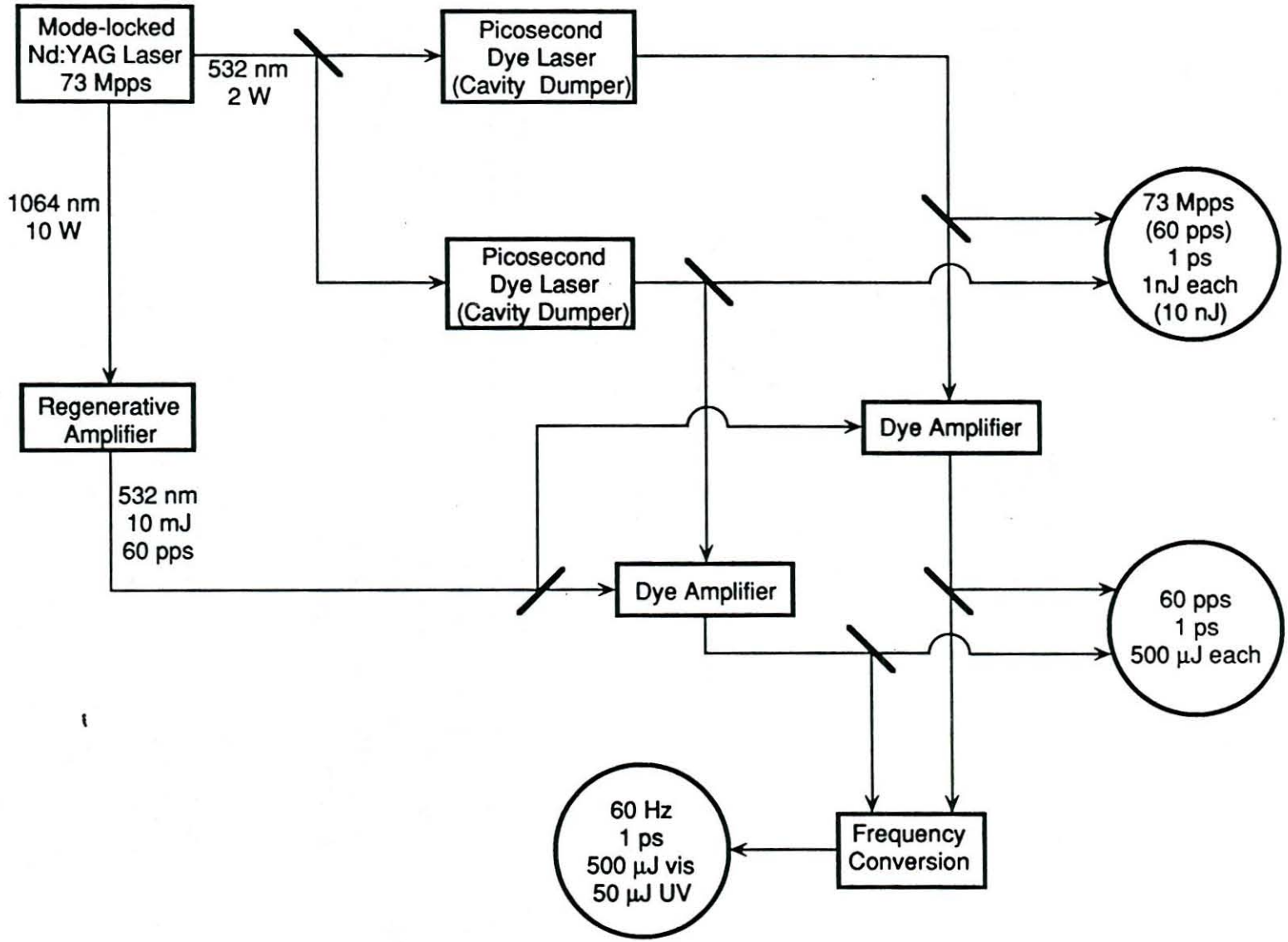


Figure 2-22. Schematic of the picosecond laser system. (XCG 8912-4759)

Conventional Facilities

The conceptual design for the conventional facilities includes site improvements, building, and mechanical and electrical utilities.

The Chemical Dynamics Research Laboratory will be located in a new building directly adjacent to the ALS facility. The three story, 46,600 GSF braced steel frame structure with full basement will house a large high-bay heavy laboratory experimental hall, eight related support laboratories and 40 offices to accommodate 50-60 researchers and visiting scientists plus 35-40 graduate students. The schedule of net square foot areas, and the building design criteria are included in this section.

The high-bay experimental hall will be equipped with a 5-ton crane and will be contiguous with the ALS experimental area. In addition to the experimental hall, a support lab, a wet lab, a control room and offices will be located on the first floor. The second floor will be occupied by six support laboratories and offices. The third floor will be dedicated to offices, and computer, conference and seminar rooms. The basement will house the Infrared Free Electron Laser (IRFEL) in a radiation shielded vault and mechanical and electrical equipment supporting the research and the building. The IRFEL vault will be equipped with a 5-ton hoist.

The CDRL building was designed using the Integrated Building System incorporating an interstitial level, or service zone. Interstitial level is a permanent walk-on platform which houses mechanical and electrical equipment and distribution and provides an easy access for construction and maintenance. In the CDRL it is located in the truss space between the two laboratory floors which it serves. This concept provides a highly flexible, adaptable and efficient laboratory space.

The laboratory areas are designed in compliance with the requirements for the H-7 occupancy as defined by the Uniform Building Code. All code stipulated mitigation measures for handling and storage of hazardous materials are incorporated.

The HVAC system features a separate zone with 100% outside air supply for the experimental hall and each laboratory. An energy efficient variable air volume system is proposed for offices and other support spaces. Constant air volume systems are planned for the IRFEL vault, Klystron Room and Power Supply Room. Mechanical equipment will be located in the basement and on the interstitial level. All equipment will be mounted on isolators and/or inertia blocks to minimize the vibration impact on the structure. Laboratories and the experimental hall will be equipped with fume hoods, vented chemical storage cabinets, vacuum, liquid nitrogen, natural gas, compressed air, deionized water, low conductivity water, industrial water and acid drain systems. Low conductivity water for equipment cooling systems will be provided by a new cooling tower of 4 MW capacity which will be an extension of existing cooling tower structure in the vicinity of the site.

The building will be served by a 5,500 kVA dedicated electrical substation located in the basement. A 300 kVA emergency generator will be located on a pad outside of the building. The building will be served by 480/277 V and 208/120 V distribution systems with, branch circuit panels and step-down transformers located in dedicated electrical rooms on each floor. The building will be equipped with telephone, communications and fiber optic data circuits. Lighting controls will be zoned and automated and integrated with the LBL Energy Management and Control System.

Architecturally, the three story building will be modulated by terracing of upper floors which will optically diminish the mass of the building. The terraces will function as usable extension of office space for informal interaction between scientists. The exterior finishes of preformed metal siding, extruded aluminum windows, and heat absorbing tinted glass will be compatible and complementary to the ALS building exterior treatment which in turn matches the finishes and proportions of the original, historically significant 184 Inch Cyclotron Building.

Site improvements will include preservation and protection of mature trees in the vicinity of the site which will provide an attractive green shielding for the building. New planting will be provided in planters along the edges of roof terraces and in separation strips between the building and the road. New concrete stairs on grade will provide a direct connection to the nearest LBL shuttle stop. Ten (10) parking spaces will be adjacent to the building, and an additional 16 spaces will be provided on a built-up structural platform extension of Cyclotron Road.

The Lawrence Berkeley Laboratory is committed to providing a safe working environment for its personnel, and negligible adverse impact to the environment and the general public. In recent years, the average annual dose equivalent to radiation workers who received detectable whole body doses has been between 25 and 50 mrem. The average annual dose equivalent at the site boundary due to accelerator operation has been about one (1) mrem.

Shielding design criteria for the proposed electron accelerator are such that these historically low levels of radiation will not be compromised by its operation. For personnel protection the shielding thickness is based on the conservative assumption of operation at 50 kW of beam power at 100% use factor for a 2000 hour shift year. It is further assumed that the areas above the roof shield and outside the lateral shielding will have unlimited access. Under these conditions, the dose equivalent design goal exterior to the shield is 250 mrem per shift year (2,000 hours) from both giant photonuclear dipole resonance neutrons and from bremsstrahlung photons. This value, although already small enough to accommodate an anticipated increase in neutron quality factor, is small compared to the DOE design goal for new installations of 1 rem per year to personnel. Experience has shown that because of the mitigating effects of distance, actual occupancy time near the shield, and realistic operating schedules, personnel on average will receive only a small fraction of the 250 mrem per year limit.

CHEMICAL DYNAMICS RESEARCH LABORATORY

SCHEDULE OF NET AREAS

Space	Net Area - Sq. Ft. Labs	Lab Offices	Other
Experimental Hall	6,240		
Support Laboratories	6,090		
4 @ 860			
1 @ 1,120			
1 @ 830			
1 @ 700			
Wet Laboratory		400	
Lab Offices	5,050		
30 @ 120			
4 @ 150			
3 @ 100			
3 @ 90			
1 @ 280			
Conference Room			150
Seminar Room		550	
Computer Room		290	
Reception		120	
Lobby	340		
IRFEL Vault		2,600	
Control Room			300
Klystron Room			600
Screen Room			220
Electronic Racks Room			340
Linac Cooling			150
Vacuum Pump Rooms			1,600
Storage of Hazardous Chemicals			80
	17,720	3,960	3,440
Total Net Area	25,120 Sq. Ft.		

Gross Areas

Basement Floor	13,980
First Floor	11,320
Interstitial Level	3,990
Second Floor	9,490
Third Floor	7,220
Roof Penthouse	600
Total Gross Area	46,600 Sq. Ft.
Efficiency Ratio:	0.54

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES DESIGN CRITERIA

A. General

1. Life Expectancy of the Building: 40 years.

2. Design in compliance with the LBL Long Range Development Plan approved by DOE in 1991.

3. Environmental Safety: In compliance with DOE, OSHA, State of California, and LBL standards.

B. Architectural

1. Occupancy: 50-60 researchers plus 35-40 graduate students.

2. Occupancy Classification: Mixed

   a. Laboratories: H-7

   b. Chemical Storage: H-2

   c. Offices: B-2

   d. Basement: Used exclusively for service functions to support both research and building needs.

3. Construction Type: II - 1 hr.

4. Fire Resistive Requirements:

   a. One hour at external walls, one hour at structural frame, noncombustible construction.

   b. Occupancy Separation: 1 hr.

5. Maximum Total Allowable Floor Area: 54,000 sq. ft.

6. Maximum Allowable Building Height: 65 ft.

7. Code Compliance: 1991 Uniform Building Code.

8. Handicapped Requirements: In compliance with Federal Register CFR 41, DOE Order 6430.1A, ANSI Standard A117.1, California Administrative Code Title 24.

C. Civil/Structural

1. Vertical Load System

   a. Roof: 2-1/2" mesh reinforced light-weight concrete on 2-inch, 18 gauge metal deck supported on structural steel beams and columns.

   b. Third Floor: Same as roof.

   c. Second Floor: Same as roof except 3" mesh reinforced light-weight concrete instead of 2-1/2 inch light-weight concrete.

   d. Interstitial Floor: Same as Second Floor.

   e. First Floor: Cast-in-place reinforced concrete one-way slabs supported on 18 inches minimum cast-in-place reinforced concrete walls.

   f. Foundation: Cast-in-place reinforced concrete mat foundation.

2. Lateral Force System

   a. Vertical concentric braced structural steel frames.

   b. Roof diaphragm of 2-1/2 inch mesh reinforced light-weight concrete and 2-inch, 18 gauge metal deck.

   c. Other floor bracing systems consist of horizontal structural steel bracing trusses.

3. Design Live Loads: (Pounds per square foot)

Roof:	50
Third Floor:	50
Second Floor:	150
Interstitial Level:	75
First Floor:	250

4. Lateral Forces

   a. Wind: 20 lbs. per square foot.

   b. Seismic: V (base shear) = 0.20 times the building dead load weight plus equipment loads plus code required portion of live load.

5. Foundation Design

   a. Cast-in-place reinforced concrete mat foundation.

b. Allowable Design Soil Bearing Pressures

Dead Load	=	4,000 lbs per sq ft
Dead plus Live Load	=	4,500 lbs per sq ft
Dead plus Live plus Seismic Loads	=	5,000 lbs per sq ft

6. Codes

   a. 1991 Uniform Building Code.

   b. LBL "Lateral Force (Wind and Earthquake) Design Criteria," August 15, 1989.

7. Soils Criteria: See Section 9, Detailed Supporting Data, Geotechnical Report by Geo/Resources Consultants, Inc.

D. Mechanical

1. Room Temperature

   a. Laboratories: 75°F ± 2°F, no humidity control.

   b. Offices: Winter 72°F, Summer 78°F, no humidity control.

   c. IRFEL Vault and Klystron/Screen Room: 75°F ± 2°F, no humidity control.

2. HVAC Air Handling System

   a. Laboratories: H-7 Occupancy, 4 CFM/sq. ft. constant volume, 100% outside air, fume hoods with face velocity controllers.

   b. Offices: Variable air volume, minimum 15% outside air.

   c. IRFEL Vault and Klystron/Screen Room: Constant air volume, minimum 15% outside air.

3. Automatic Control System: Digital.

4. Fire Protection

   a. Sprinkler system, Ordinary Hazard, Group 3.

   b. Double interlock pre-action sprinkler system in IRFEL vault, Power Supply Room, Computer Room and Control Room.

5. Utilities Provided

Low conductivity water
Treated water
Potable cold water
Domestic cold and hot water
Heating water
HVAC chilled water
Cold and hot deionized water
Sanitary drain
Acid drain and neutralization system
Compressed air
Natural gas
Vacuum
Liquid Nitrogen

E. Electrical

1. Power and Lighting

a. Substation: 5500 kVA, 12.47 kV to 480 V, 30, 60 Hz.

b. Large Process Loads: 480 V.

c. Area Lighting: 277 V.

d. Emergency Generator: 300 kVA.

e. Interior Lighting: fluorescent.

2. Lighting Levels

a. Laboratories: 50° FC.

b. Offices: 50° FC.

c. Lobby and Corridors: 10° FC.

d. Conference Rooms: 30° FC to 50° FC with dimming controls.

e. Equipment Rooms: 30° FC.

f. Exterior Lighting: 2 FC, HID.

3. Communications

a. Integrated Communications System (ICS).

b. Closed-circuit intercom.

c. Local paging system.

4. Energy Monitoring and Control System

5. Computer System

6. Fire Alarm and Security

   a. Smoke detection system.

   b. Fire call boxes.

   c. Alarm bell system.

   d. Card key system.

APPLICABLE CODES AND DESIGN REFERENCES

Applicable requirements and recommendations in the following codes and references will be followed in the design. These codes, as listed, should be included in the construction specifications. Codes and references will be the latest editions except where specifically noted otherwise:

A. Codes

1. 10 CFR Part 435 Energy Conservation Voluntary Energy Performance Standards (Mandatory for Federal Buildings)

2. 29 CFR Part 1926, Safety and Health Regulations for Construction, Department of Labor

3. 29 CFR Part 1910, Occupational Safety and Health Standards, Department of Labor

4. 40 CFR Parts 264 and 265, Environmental Protection Agency

5. National Fire Codes, National Fire Protection Association (NFPA)

6. National Electrical Safety Code, ANSI C2

7. National Electric Code, NFPA 70 (NEC-1990) latest edition

8. Safety Code for Building Construction, ANSI A10.2

9. California Code of Regulations, Title 8, General Industrial Safety Orders, Construction Safety Orders

10. California Code of Regulations, Title 19 - Public Safety, Chapter 1; Title 24, Part 2 - California Building Code; and Title 24, Part 3 - California Electrical Code

11. Uniform Building Code

12. Uniform Mechanical Code

13. Uniform Fire Code

14. Uniform Plumbing Code

15. Occupational Safety and Health Act

16. Federal, state, and local air-pollution and water-pollution control regulations

17. AMCA Fan Test Code

18. NBSIR 78-1305A Test Procedures

19. LBL Lateral Force (Wind and Earthquake) Design Criteria, August 15, 1989

B. Design References

1. Department of Energy General Design Criteria Manual, DOE 6430.1A

2. Rules and Procedures for the Design and Operation of Hazardous Research Equipment, LBL Pub 3001

3. LBL Long Range Site Development Plan

4. NBS Handbook 135, Life Cycle Cost Manual for the Federal Energy Management Program

5. The ASHRAE Handbook and Product Directory:

   a. HVAC Systems and Applications Volume: 1987
   b. Fundamentals Volume: 1989
   c. Equipment Volume: 1988
   d. Refrigeration Volume: 1986

6. Standards for Natural and Mechanical Ventilating, ASHRAE Standard 62-73 (ANSI B194.1-1977)

7. Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) Standards

8. Standards and Codes of the American Society of Mechanical Engineers (ASME)

9. American Water Works Association (AWWA) Standards

10. National Environmental Balancing Bureau (NEBB)

11. American Welding Society Handbook and Standards (AWS)

12. Standards of the American Society for Testing and Materials (ASTM)

13. American National Standard Specifications for Making Buildings and Facilities Accessible and Usable by the Physically Handicapped. ANSI A117.1-1961. REAF-1971

14. Recommended Outdoor Design Temperatures, Northern California Golden Gate Chapter, ASHRAE, November 1977

15. Industrial Ventilation Manual by the American Conference of Governmental Industrial Hygienists (ACGIH)

16. Earthquake-Resistive Construction for Mechanical Systems, Light Fixtures, and Ceilings, Ayres & Hayakawa, July 1972

17. Guidelines for Seismic Restraints of Mechanical Systems and Plumbing Piping Systems, SMACNA, October 13, 1982

18. Design Evaluation Guidelines for DOE Facilities Subject to Natural Phenomena, UCRL 15910, Draft May 1989

19. American National Standards Institute (ANSI) Standards

20. National Electrical Manufacturers' Association (NEMA) Standards

21. Institute of Electrical and Electronics Engineers (IEEE) Standards

22. Underwriters' Laboratories, Inc. (UL) Standards and "Building Materials, Fire Protection Equipment, and Fire Resistive Directories"

23. Factory Mutual Engineering Corp. (FM) Approval Guide and FM Loss Prevention Data

24. Insulated Cable Engineers' Association (ICEA) Standards

25. National Electrical Testing Association (NETA) Standards

26. Illuminating Engineering Society (IES) Lighting Handbook

27. Department of Energy Electrical Safety Criteria for Research and Development Activities, DOE/EV-0051/1, August 1979

28. Standard for Fire Protection of DOE Electronic Computer/Data Processing Systems, Jan 1984 (DOE/EP-0108, Formerly Wash 1245-1). See paragraph 101.4.

29. A Building Planning Guide for Communication Wiring, International Business Machines Corp., G320-8059-1, March 1984

30. American Institute of Steel Construction, Manual of Steel Construction, eighth edition

31. American Concrete Institute, ACI Manual of Concrete Practice, Parts 1 through 5, latest edition

32. ANSI/IES RP7 "Practice for Industrial Lighting"

33. LBL Building Automation System Design Criteria and Design Guidelines

QUALITY ASSURANCE PROCEDURES FOR DESIGN, CONSTRUCTION, FACILITY ACCEPTANCE AND PROJECT CLOSEOUT

Quality assurance procedures during project development, design, and construction assure that all safety, operational and Subcontract requirements will be met. The established system to review, inventory, and document facility construction, acceptance, and project closeout includes the following elements:

- Engineering

  - The LBL Plant Engineering Department assisted by selected consultants provides quality control and assurance measures during design and construction.

  - The Plant Engineering Department includes a multidisciplinary Design Management Group and a Project Management Group. Each significant project is assigned to a Project Manager (PM) who is responsible for the management of cost, scope and schedule. The PM is also responsible for quality assurance during project formulation and implementation, and is assigned a staff including a Project Architect or Engineer (PA/E), a multidisciplinary support team, a construction manager if necessary, a contract administrator, and a construction inspector. The PA/E is responsible for design and technical quality control. The work of each member of the PA/E's support team is reviewed by the appropriate Section Leader from the Design Management Group. The PM develops a Project Management Plan which is reviewed and approved by Plant Management and DOE/SF.

  - Design and cost estimates are reviewed and a plan check carried out by LBL at completion of schematics and during and after Title I and Title II designs are completed. An independent third party plan check is made of the seismic design and an independent cost estimate is made by a consulting cost estimator at completion of Title I and Title II to compare with the A/E's cost estimates. Plans and specifications are also reviewed by the LBL Fire Protection Engineer, the LBL Fire Marshal, the LBL Environment, Health and Safety (EH&S) Division, the LBL Energy Conservation Engineer, and the LBL Construction and Maintenance Department at each stage of design development. When applicable, a consulting geotechnical firm provides appropriate geotechnical data and reviews the design at each stage of design and during construction.

  - An internal sign-off sheet covering all LBL design disciplines, PA/E, PM, Fire Protection Engineer, Fire Marshal, EH&S, Plant Management, third party reviews, and the Client is completed at the end of Title I, Title II and Title III. (A sample form follows.)

- Construction

  - Subcontract documents are reviewed by LBL's technical staff for compliance with DOE and LBL design criteria.

  - The Construction Inspector reviews and the Executive Architect/Engineer (A/E of Record) and Plant Engineering's staff of engineers accept or reject all materials and workmanship in accordance with Subcontract documents.

  - A submittal control system for materials, shop drawings, test reports, and certifications assures that all necessary reviews for compliance with specifications, codes, environmental mitigation measures and other requirements including provisions for the handicapped and energy conservation have been made.

  - A Construction Inspector observes construction activities and reports discrepancies to LBL's Project Manager (or Construction Manager, if applicable) and the Project Architect/Engineer. Daily inspection reports are maintained in a file or a project logbook.

  - A Contract Administrator (from the Purchasing Department) reviews documentation for compliance with Subcontract provisions.

  - A Safety Inspector (from LBL's Environment, Health and Safety Division) and the Fire Marshal make periodic inspections of construction to assure compliance with safety and fire codes and regulations.

  - Specialty inspections are made of rebar, structural steel, welding, concrete, and geotechnical conditions to assure compliance with codes and specifications. Appropriate testing laboratories are utilized for support as necessary. The A/E of Record is required to inspect the construction during appropriate times and provide interpretation of the Subcontract documents whenever necessary.

  - Subcontract Change Orders

    - Reviewed in accordance with UCLBL Construction Subcontracting Manual.

    - If project contingency funds are involved, the proposed change is reviewed to ensure that it is due to unforeseen, uncertain, and/or unpredictable conditions or incomplete design.

- Final Inspection and Acceptance

  The following items are accomplished by the Inspector and the A/E of Record working together:

  - Preliminary inspection and list of incomplete work.

  - Equipment testing and operational instruction of LBL personnel.

- Final inspection walk-through and punch list.
- Inspection of correctional and completion work (punch list work).
- Inventory of all operational manuals, instructions, guarantees.
- Internal sign-off sheet: Acknowledgment of completion and acceptance of all work under construction Subcontract by the LBL project team and all interested parties, i.e., Fire Marshal, EH&S, etc.
- Subcontract Changes Orders
  - The LBL A/E team and Executive Architect/Engineer review any proposed change and provide justification and an independent cost estimate. The Subcontractor's proposed cost is evaluated relative to LBL's cost estimate, and a Subcontract price is negotiated. Availability of project funds is verified. If all project and Subcontract requirements are met, a Change Order is executed.

- Project Closeout
  - After final acceptance of the facility, LBL audits all charges to assure that all costs are in proper accounts.
  - LBL sends the cost closing statement to DOE/SF.
  - Project authorization closed by DOE/SF.

PROJECT REVIEW AND APPROVAL
(Projects ≥ $250K TEC)

_____
Project Title

_____
Job Number | Subcontract No/PB No | Documents Prepared By:

☐ PRELIM (TITLE I) ☐ FINAL (TITLE II) ☐ CONSTR COMPLETE (TITLE III)

☐ SPECIFICATIONS ☐ DRAWINGS

1. DESIGN MANAGEMENT

Design Team		Section Leaders	
Proj A/E	_____		
Arch	_____	Arch	_____
Civil	_____	Civil	_____
Mech	_____	Mech	_____
Elec	_____	Elec	_____
Energy	_____	Energy	_____
FP Engr	_____		

2. PROJECT MANAGEMENT

Project Manager _____

Inspector _____

3. PURCHASING

Contract Admin _____
(Titles II & III only)
(Last to sign for Title III)

4. Environment, Health and Safety Division	Date	9. Third Party Structural Review or Recommendation (Memo Attached)	Date
5. Fire Marshal	Date	10. Quality Assurance	Date
6. Construction and Maintenance Dept	Date	11. Value Engineering Coordinator	Date
7. Disabled Barriers Review	Date	12. Client/Division Head	Date
8. Third Party Hazardous Material Review or Recommendation (Memo Attached)	Date	13. Plant Engineering Dept	Date

Sign-offs (Title I) indicate that project scope and criteria fully define Title II design requirements.

Sign-offs (Title II) indicate that construction documents comply with applicable sections of DOE General Design Criteria Manual 6430.1A and that they're complete and ready for construction.

Sign-offs (Title III) indicate that work was completed in accordance with construction documents.

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 10 , Office

Other Projects Affecting this Category: ALS Life Sciences Center, Human Genome Laboratory, Envir Mon & Indus Hyg Bldg , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	577,400	in SF or other unit.
B.	The total existing assets in this category:	460,300	SF,
C.	Less amount of existing, substandard assets:	353,700	SF,
D.	Equals amount of existing, adequate assets:	106,600	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(470,800)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	9,600	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	2,500	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	7,100	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(461,200)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	(110,000)	SF. (B plus H minus A)

2/2491
CDRL

Figure III-5
Facility Utilization Data

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 73 , Light Lab

Other Projects Affecting this Category: Human Genome Lab, ALS Life Sciences Center, Envir Mon & Indus Hyg Bldg , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	366,200	in SF or other unit.
B.	The total existing assets in this category:	278,700	SF,
C.	Less amount of existing, substandard assets:	186,900	SF,
D.	Equals amount of existing, adequate assets:	91,800	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(274,400)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	12,000	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	9,900	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	2,100	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(262,400)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	(85,400)	SF. (B plus H minus A)

2/2491
CDRL

Figure III-5
Facility Utilization Data

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 74 , Heavy Lab

Other Projects Affecting this Category: Induction Linac Systems Experiment , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	359,300	in SF or other unit.
B.	The total existing assets in this category:	343,000	SF,
C.	Less amount of existing, substandard assets:	114,800	SF,
D.	Equals amount of existing, adequate assets:	228,200	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(131,100)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	11,600	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	2,000	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	9,600	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(119,500)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	(6,700)	SF. (B plus H minus A)

Figure III-5
Facility Utilization Data

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 67 , Computer

Other Projects Affecting this Category: _____ , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	40,900	in SF or other unit.
B.	The total existing assets in this category:	40,400	SF,
C.	Less amount of existing, substandard assets:	24,100	SF,
D.	Equals amount of existing, adequate assets:	16,300	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(24,600)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	500	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	0	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	500	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(24,100)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	0	SF. (B plus H minus A)

2/2491
CDRL

Figure III-5
Facility Utilization Data

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 40 , Storage

Other Projects Affecting this Category: ALS Life Sciences Center, Advanced Light Source, Ph. II , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	100,500	in SF or other unit.
B.	The total existing assets in this category:	93,900	SF,
C.	Less amount of existing, substandard assets:	55,200	SF,
D.	Equals amount of existing, adequate assets:	38,700	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(61,800)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	200	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	600	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	(400)	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(61,600)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	(7,000)	SF. (B plus H minus A)

2/2491
CDRL

Figure III-5
Facility Utilization Data

SUPPLEMENTARY PROJECT DATA
FACILITY UTILIZATION

Title and Location of Project CHEMICAL DYNAMICS RESEARCH LABORATORY Project No. 94-LBL

Lawrence Berkeley Laboratory, Berkeley, California

Site-wide Requirements/Assets for CATEGORY 80 , Miscellaneous

Other Projects Affecting this Category: Human Genome Lab, ALS Life Sciences Center, Envir Mon & Indus Hyg Bldg , etc.

Unit of Measure: GSF (square feet (SF) or other unit)

UTILIZATION OF EXISTING ASSETS (FACILITIES) IN THIS CATEGORY:

A.	Total requirement for this category:	187,800	in SF or other unit.
B.	The total existing assets in this category:	161,900	SF,
C.	Less amount of existing, substandard assets:	117,700	SF,
D.	Equals amount of existing, adequate assets:	44,200	SF.
E.	Existing adequate assets, less total requirement for this category equals excess/(deficiency) of adequate assets:	(143,600)	SF. (D minus A)

CHANGES TO ASSET LEVELS RESULTING FROM THIS PROJECT:

F.	The additional assets created in this category by the project:	12,700	SF,
G.	Less assets removed from this category by the project through excessing, demolition, etc.:	1,500	SF,
H.	Equals net increase/(decrease) of assests in this category due to the project:	11,200	SF. (F minus G)

PROJECTED ASSET STATUS AFTER COMPLETION OF THIS PROJECT:

I.	Existing excess or (deficiency) of adequate assets, plus this project's increases, equal excess or (deficiency) of adequate assets projected for this category:	(130,900)	SF. (E plus F)
J.	Total existing assets, plus net increase/(decrease) of assets in this category due to the project, less total requirement, equal total excess/(deficiency) of assets projected for this category:	(14,700)	SF. (B plus H minus A)

2/2491
CDRL

Figure III-5
Facility Utilization Data

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 3

BASIS OF COST ESTIMATE

The Cost Estimate is based upon the conceptual design and project schedule developed by the Lawrence Berkeley Laboratory (LBL) with the assistance of qualified consultants. The estimate for the Special Research Facilities is based on FY 1992 costs; the estimate for the Conventional Facilities is based on FY 1990 costs.

The cost estimate for the Special Research Facilities was prepared using a carefully organized procedure based on a Work Breakdown Structure (WBS). An engineering cost estimating team was charged with the responsibility to develop reliable cost estimates at the most detailed WBS level, typically level 6 or 7, including an estimate for ED&I and contingency. Material and labor costs were separately estimated and entered into a computer data base. Standardized craft codes and rates were used in estimating labor costs. In developing the cost estimate, the estimating team used past history, recent experience, catalogue prices and vendor quotes. Current experience with the Advanced Light Source (ALS) project proved to be extremely valuable in assuring the accuracy of many of the estimates. In cases where relevant comparable costs occurred before FY 1992, a set of uniform escalation rates was used to convert the data to FY 1992 dollars. All cost estimates, including ED&I and contingency were carried out "from the bottom up" using the WBS format.

The cost estimate for the Conventional Facilities was prepared by Lee Saylor, Inc., Construction Consultants, and was reviewed by Derek Daniels, LBL's professional estimator. The estimate is based upon quantity take-offs from conceptual design drawings and outline specifications prepared by the architectural, civil, structural, mechanical and electrical design sections of LBL's Plant Engineering Department. The unit price data used in the estimate are based upon Lee Saylor, Inc., Construction Data Base. The construction cost estimate is divided into two lump-sum bid packages, one for the site preparation work and one for the building construction. It is proposed that the building construction bid package be incrementally funded, in order to provide a more acceptable overall funding profile.

The cost estimate summary and contingency analysis are included in this section; details of the cost estimate are included in Section 9. Both the Cost Estimate Summary and the Details of Cost Estimate have been correlated with the Work Breakdown Structure (WBS).

Escalation is based upon DOE's "Anticipated Economic Escalation Rates" updated August 1991. Costs for the Conventional Facilities have been escalated to the midpoint of construction separately for Phase I and Phase II. Costs for the Special Research Facilities and Project Management have been escalated on a year-by-year basis using the projected distribution of costs. Escalation analysis is shown later in this section.

Analysis of ED&I costs is included in Section 9.

DEPARTMENT OF ENERGY
FY 1994 FIELD BUDGET PROCESS
PROJECT DATA SHEETS
ENERGY SUPPLY RESEARCH & DEVELOPMENT: PLANT & CAPITAL EQUIPMENT
BASIC ENERGY SCIENCES

(Tabular dollars in thousands. Narrative material in whole dollars.)

1. Title and Location of Project: Chemical Dynamics Research Laboratory
Lawrence Berkeley Laboratory, Berkeley, California

2. Project Number: 94-LBL

3a. Date A-E Work Initiated: 2nd Qtr., FY 1994
3b. A-E Work (Titles I & II) Duration: 21 months

4a. Date Physical Construction Starts: 4th Qtr., FY 1994
4b. Date Construction Ends: 3rd Qtr., FY 1998

5. Previous Cost Estimate: none
Date:

6. Current Construction Cost Estimate: TEC: $104,600
(Date: February 6, 1992) TPC: $124,600

7. Financial Schedule:

Fiscal Year	Appropriations	Obligations	Costs
1994	11,740	11,740	6,700
1995	28,160	28,160	20,140
1996	29,750	29,750	32,630
1997	24,420	24,420	33,380
1998	10,530	10,530	11,750
Total	104,600	104,600	104,600

2/28/92
PE:CDRL:CDR

Figure III-3
Project Data Sheet

DEPARTMENT OF ENERGY
FY 1994 FIELD BUDGET PROCESS
PROJECT DATA SHEETS
ENERGY SUPPLY RESEARCH & DEVELOPMENT: PLANT & CAPITAL EQUIPMENT
BASIC ENERGY SCIENCES

(Tabular dollars in thousands. Narrative material in whole dollars.)

1. Title and Location of Project: Chemical Dynamics Research Laboratory
Lawrence Berkeley Laboratory, Berkeley, California

2. Project Number: 94-LBL

10. Details of Cost Estimate[a]:

Chemical Dynamics Research Laboratory			$104,600
A. Engineering, Design, and Inspection			$14,830
(1) Special facilities construction at 31% of construction costs, item C.1		$11,870	
(2) Conventional facilities construction at 15% of construction costs, item C.2.		$2,960	
B. Project management costs at 10% of construction cost total, item C.			$5,890
C. Construction Costs			$58,640
(1) Special facilities construction		$38,610	
(a) IRFEL User Facility, including accelerator, transport system, undulator, optical cavity, controls, survey and alignment and safety systems.	$18,480		
(b) ALS Chemical Physics beamlines, including undulator and beamline, bend magnet beamline.	$6,520		
(c) Experimental Systems including Experimental Stations and Advanced Lasers	$13,610		
(2) Conventional facilities		$20,030	
(a) Improvements to land	$420		
(b) Building[b] (@ approx. $309/gsf)	$14,250		
(c) Special building facilities (Schedule II)	$1,830		
(d) Utilities	$3,530		
D. Standard equipment, including office and laboratory furnishings (Schedule III)			$5,720
E. Contingencies at 23% of the above costs[c]			$19,520

[a]Cost estimates are based on a preliminary conceptual design. Escalation calculations were based on DOE inflation estimates: FY93, 3.9%; FY94, 4.7%; FY95, 4.8%; FY96, 4.9%; FY97, 4.9%; and FY98, 4.9%.

[b]Building costs include radiation shielding needed for the IRFEL.

[c]Contingencies were estimated separately for special facilities and associated ED&I (28%), for project management (15%), and for conventional facilities and associated ED&I (16%).

DEPARTMENT OF ENERGY
FY 1994 FIELD BUDGET PROCESS
PROJECT DATA SHEETS
ENERGY SUPPLY RESEARCH & DEVELOPMENT: PLANT & CAPITAL EQUIPMENT
BASIC ENERGY SCIENCES

(Tabular dollars in thousands. Narrative material in whole dollars.)

1. Title and Location of Project: Chemical Dynamics Research Laboratory
Lawrence Berkeley Laboratory, Berkeley, California

2. Project Number: 94-LBL

Schedule I

Special Building Facilities

Laboratory Benches	$256
Chemical Storage Cabinets	$12
Fume Hoods	$283
Liquid Nitrogen Distribution System	$300
Vacuum Systems	$128
Acid Drain Systems	$76
Laser Safety Control Systems	$39
Vacuum Control Systems	$46
Chemical Detection Systems	$283
Instrument Racks	$64
Data Acquisition System	$343
Total	$1,830

2/28/92
PE:CDRL:CDR

Figure III-3: Project Data Sheet
Page 3 of 4

DEPARTMENT OF ENERGY
FY 1994 FIELD BUDGET PROCESS
PROJECT DATA SHEETS
ENERGY SUPPLY RESEARCH & DEVELOPMENT: PLANT & CAPITAL EQUIPMENT
BASIC ENERGY SCIENCES

(Tabular dollars in thousands. Narrative material in whole dollars.)

1. Title and Location of Project: Chemical Dynamics Research Laboratory
Lawrence Berkeley Laboratory, Berkeley, California

2. Project Number: 94-LBL

Schedule II

Standard Building Equipment

Standard Laser Systems	$1,258
Diagnostic and Detection Systems	$600
Office Furniture and Equipment	$135
Personal Computers	$196
Computer Workstations	$1,042
Streak Camera System	$182
Miscellaneous Instrumentation	$37
Equipment for SNL Upstairs Lab	$2,270
Total	$5,720

Figure III-3: Project Data Sheet
Page 4 of 4

rev. Feb 7 1992

Chemical Dynamics Research Laboratory

Cost Estimate Summary (Then Year k$)

1 Chemical Dynamics Research Laboratory				104,620
1.1 Project Management and Administration			5,890	
1.2 Special Research Facilities			50,480	
1.2.1 ED&I		11,870		
1.2.1.1 IRFEL	5,680			
1.2.1.2 ALS beamlines	1,990			
1.2.1.3 Exper. Systems	4,200			
1.2.2 Construction		38,610		
1.2.2.1 IRFEL	18,480			
1.2.2.2 ALS beamlines	6,520			
1.2.2.3 Exper. Systems	13,610			
1.3 Conventional Facilites			28,710	
1.3.1 ED&I		2,960		
1.3.2 Construction		20,030		
1.3.2.1 Improvements to land	420			
1.3.2.2 Building	14,250			
1.3.2.3 Special building facilites	1,830			
1.3.2.4 Site utilities	3,530			
1.3.3 Standard Equipment		5,720		
1.4 Contingency			19,540	
1.4.1 Project management contingency		850		
1.4.2 Special research facilities contingency		14,060		
1.4.2.1 IRFEL	6,530			
1.4.2.2 ALS beamlines	2,190			
1.4.2.3 Exper. Systems	5,340			
1.4.3 Conventional facilities contingency		4,630		

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

CONSTRUCTION COST ESTIMATE SUMMARY

PHASE I (SITE PREPARATION) AND PHASE II (BUILDING CONSTRUCTION)
(TY $K)

		Improvements to Land	Building	Special Facilities	Utilities
PHASE I (SITE PREPARATION)					
Improvements to Land	180	180			
Building	850		850		
Special Facilities	-			-	
Utilities	1,690				1,690
PHASE II (BUILDING CONST)					
Improvements to Land	240	240			
Building	13,400		13,400		
Special Facilities	1,830			1,830	
Utilities	1,840				1,840
	20,030	420	14,250	1,830	3,530

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE SUMMARY

PHASE I - SITE PREPARATION		Improvements to Land	Building	Utilities
Building Demolition		123,650		
Shoring/Underpinning			348,300	
Basement Excavation			246,640	
Modifications to Existing Systems				1,187,510
Subtotal Direct Cost		123,650	594,940	1,187,510
General Conditions/Mobilize	6%	7,420	35,700	71,250
Estimating Contingency		*In Project Contingency.*	*In Project Contingency*	*In Project Contingency*
		131,070	630,640	1,258,760
Bond	2%	2,620	12,610	25,180
Prime Contractor OH & Fee	10%	13,110	63,060	125,880
Total Estimated Construction Cost at December 1989		146,800	706,310	1,409,820
Total Escalated Construction Cost to April 1995	19.8%	175,870	846,160	1,688,960

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE SUMMARY

PHASE II - BUILDING CONSTRUCTION		Improvements to Land	Building
Site Work		158,520	
Concrete			1,625,160
Metals			952,700
Wood and Plastic			47,280
Thermal and Moisture Protection			581,500
Doors and Windows			297,990
Finishes			1,020,400
Specialties			34,990
Energy Management System			190,000
Conveying Systems			376,860
Mechanical			2,217,920
Electrical			1,427,130
Subtotal Direct Cost		158,520	8,771,930
General Conditions/Mobilize	6%	9,510	526,320
Estimating Contingency		*In Project Contingency*	*In Project Contingency*
		168,030	9,298,250
Bond	2%	3,360	185,970
Prime Contractor OH & Fee	10%	16,800	929,830
Total Estimated Construction Cost at December 1989		188,190	10,414,050
Total Escalated Construction Cost to September 1996	28.7%	242,200	13,402,880

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE SUMMARY

PHASE II - BUILDING CONSTRUCTION		Special Building Facilities
Laboratory Benches		167,440
Chemical Storage Cabinets		7,800
Fume Hoods		184,800
Liquid Nitrogen Distribution		196,000
Vacuum Systems		84,000
Acid Drain System		50,030
Laser Safety Control Systems		25,500
Vacuum Safety Control Systems		30,000
Chemical Safety Control Systems		185,000
Instrument Racks		42,000
Data Acquisition System		224,000
Subtotal Direct Cost		1,196,570
General Conditions/Mobilize	6%	71,790
Estimating Contigency		*In Project Contingency*
		1,268,360
Bond	2%	25,370
Prime Contractor OH & Fee	10%	126,840
Total Estimated Construction Cost at December 1989		1,420,570
Total Escalated Construction Cost to September 1996	28.7%	1,828,270

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE SUMMARY

PHASE II - BUILDING CONSTRUCTION		Utilities
Water Distribution		17,310
Gas Distribution		17,310
Sewerage/Drainage		3,000
Cooling Tower Extension		1,047,820
LCW Connection		32,690
Treated Water Connection		32,690
15kV Power Service		53,500
Subtotal Direct Cost		1,204,320
General Conditions/Mobilize	6%	72,260
Estimating Contingency		*In Project Contingency*
		1,276,580
Bond	2%	25,530
Prime Contractor OH & Fee	10%	127,660
Total Estimated Construction Cost at December 1989		1,429,770
Total Escalated Construction Cost to September 1996	28.7%	1,840,110

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE SUMMARY

Standard Equipment			
Standard Laser Systems		930,000	
Diagnostic and Detection Systems		444,000	
Office Furniture and Equipment		100,000	
Personal Computers		145,000	
Electronic Balance		4,000	
Computer Stations		770,000	
Cassettometer		5,000	
Streak Camera		135,000	
Vacuum Leak Detector		18,000	
Subtotal Direct Cost		2,551,000	
Storage, Handling, Delivery and Set-up	5%	127,550	
Total Estimated Construction Cost at December 1989		2,678,550	
Equipment for SNL Laboratory			1,773,000
Total Escalated Construction Cost to September 1996 (LBL)	28.7%	3,447,290	
Total Escalated Construction Cost for SNL Equipment	28%		2,269,440
Total Escalated Construction Cost		5,716,730	

CHEMICAL DYNAMICS RESEARCH LABORATORY

SPECIAL RESEARCH FACILITIES AND PROJECT MANAGEMENT

ESCALATION ANALYSIS

Based on DOE "Anticipated Economic Escalation Rates" (updated August 1991)

	FY92	FY93	FY94	FY95	FY96	FY97	FY98	Total
Cost Schedule in FY92 M$*			4.87	13.85	16.13	15.25	8.92	59.02
• Project Management			0.77	1.03	1.03	1.03	1.03	4.89
• Special Research Facilities			3.11	9.90	11.81	11.10	5.87	41.79
• Contingency on Project Management			0.10	0.15	0.15	0.15	0.15	0.70
• Contingency on Special Research Facilities			0.89	2.77	3.14	2.97	1.87	11.64
DOE Escalation Rates	0.0%	3.9%	4.7%	4.8%	4.9%	4.9%	4.9%	
Cumulative Escalation Factor	1.000	1.039	1.088	1.140	1.196	1.255	1.317	
Cost Schedule in Then-Year M$			5.32	15.77	19.31	19.13	11.75	71.28

*For supporting data, see "Schedule of Costs (FY92 $M)" in Section 9, page 9-95

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESCALATION ANALYSIS

Based on DOE "Anticipated Economic Escalation Rates" (updated August 1991).

Phase I - Site Preparation

Start Construction:	December 1994
Construction Period:	9 Months
Finish Construction:	August 1995
Midpoint Construction:	April 1995
Estimate Date:	December 1989

										%		
FY	1990	Dec	1989	-	Sep	1990	10	mo	@	2.8	=	2.3
FY	1991	Oct	1990	-	Sep	1991	12	mo	@	2.6	=	2.6
FY	1992	Oct	1991	-	Sep	1992	12	mo	@	2.5	=	2.5
FY	1993	Oct	1992	-	Sep	1993	12	mo	@	3.9	=	3.9
FY	1994	Oct	1993	-	Sep	1994	12	mo	@	4.7	=	4.7
FY	1995	Oct	1994	-	Mar	1995	6	mo	@	4.8	=	2.4

Total Compounded Escalation: 19.8

Phase II - Building Construction

Start Construction:	October 1995
Construction Period:	24 Months
Finish Construction:	September 1997
Midpoint Construction:	September 1996
Estimate Date:	December 1989

										%		
FY	1990	Dec	1989	-	Sep	1990	10	mo	@	2.8	=	2.3
FY	1991	Oct	1990	-	Sep	1991	12	mo	@	2.6	=	2.6
FY	1992	Oct	1991	-	Sep	1992	12	mo	@	2.5	=	2.5
FY	1993	Oct	1992	-	Sep	1993	12	mo	@	3.9	=	3.9
FY	1994	Oct	1993	-	Sep	1994	12	mo	@	4.7	=	4.7
FY	1995	Oct	1994	-	Sep	1995	12	mo	@	4.8	=	4.8
FY	1996	Oct	1995	-	Sep	1996	12	mo	@	4.9	=	4.9

Total Compounded Escalation: 28.7

Chemical Dynamics Research Laboratory

Schedule of Obligations (Then year M$)

	Revised Cost FY92M$ (ref)	FY94	FY95	FY96	FY97	FY98	Total Oblig. TYM$
1. CDRL	**86.600**	**11.74**	**28.17**	**29.76**	**24.42**	**10.53**	**104.62**
1.1 Project management	**4.890**	**0.84**	**1.17**	**1.23**	**1.29**	**1.36**	**5.89**
1.2 Spec. research facilities	**41.788**	**3.89**	**14.03**	**12.54**	**13.12**	**6.90**	**50.48**
1.2.1 ED&I	9.894	1.78	2.55	2.67	2.80	2.07	11.87
1.2.1.1 IRFEL	4.765	0.91	1.24	1.29	1.36	0.88	5.68
1.2.1.2 ALS beamlines	1.655	0.30	0.45	0.48	0.52	0.24	1.99
1.2.1.3 Exper. Systems	3.474	0.57	0.86	0.90	0.92	0.95	4.20
1.2.2 Construction	31.894	2.11	11.48	9.87	10.32	4.83	38.61
1.2.2.1 IRFEL	15.386	1.50	5.95	4.90	4.90	1.23	18.48
1.2.2.2 ALS beamlines	5.307	0.00	1.90	1.72	1.70	1.20	6.52
1.2.2.3 Exper. Systems	11.201	0.61	3.63	3.25	3.72	2.40	13.61
1.3 Conventional facilities*	**23.768**	**4.82**	**7.73**	**10.54**	**5.62**	**0.00**	**28.71**
1.3.1 ED&I	2.430	2.10	0.40	0.23	0.23	0.00	2.96
1.3.2 Construction	16.628	2.72	7.33	8.16	1.82	0.00	20.03
1.3.3 Standard equipment	4.710	0.00	0.00	2.15	3.57	0.00	5.72
1.4 Contingencies	**16.154**	**2.19**	**5.24**	**5.45**	**4.39**	**2.27**	**19.54**
1.4.1 Project management	0.700	0.11	0.17	0.18	0.19	0.20	0.85
1.4.2 Special res. facilities	11.643	1.30	3.82	3.58	3.29	2.07	14.06
1.4.2.1 IRFEL	5.443	0.75	1.59	1.88	1.67	0.64	6.53
1.4.2.2 ALS beamlines	1.795	0.10	0.61	0.52	0.48	0.48	2.19
1.4.2.3 Exper. Systems	4.405	0.45	1.62	1.18	1.14	0.95	5.34
1.4.3 Conventional facililities*	3.811	0.78	1.25	1.69	0.91	0.00	4.63

*From revised BA/BO schedule

Chemical Dynamics Research Laboratory

Schedule of Costs (Then Year M$)

	Revised Cost FY92M$ (ref)	FY94	FY95	FY96	FY97	FY98	Total Cost TYM$
1. CDRL	**86.600**	**6.70**	**20.15**	**32.64**	**33.38**	**11.75**	**104.62**
1.1 Project management	**4.890**	**0.84**	**1.17**	**1.23**	**1.29**	**1.36**	**5.89**
1.2 Spec. research facilities	**41.788**	**3.39**	**11.28**	**14.15**	**13.93**	**7.73**	**50.48**
1.2.1 ED&I	9.894	1.78	2.55	2.67	2.80	2.07	11.87
1.2.1.1 IRFEL	4.765	0.91	1.24	1.29	1.36	0.88	5.68
1.2.1.2 ALS beamlines	1.655	0.30	0.45	0.48	0.52	0.24	1.99
1.2.1.3 Exper. Systems	3.474	0.57	0.86	0.90	0.92	0.95	4.20
1.2.2 Construction	31.894	1.61	8.75	11.46	11.13	5.66	38.61
1.2.2.1 IRFEL	15.386	1.10	4.55	5.72	5.62	1.49	18.48
1.2.2.2 ALS beamlines	5.307	0.00	1.12	2.08	1.75	1.57	6.52
1.2.2.3 Exper. Systems	11.201	0.51	3.08	3.66	3.76	2.60	13.61
1.3 Conventional facilities*	**23.768**	**1.19**	**3.77**	**11.48**	**12.27**	**0.00**	**28.71**
1.3.1 ED&I	2.430	1.19	1.05	0.36	0.36	0.00	2.96
1.3.2 Construction	16.628	0.00	2.72	10.07	7.24	0.00	20.03
1.3.3 Standard equipment	4.710	0.00	0.00	1.05	4.67	0.00	5.72
1.4 Contingencies	**16.154**	**1.28**	**3.93**	**5.78**	**5.89**	**2.66**	**19.54**
1.4.1 Project management	0.700	0.11	0.17	0.18	0.19	0.20	0.85
1.4.2 Special res. facilities	11.643	0.98	3.15	3.75	3.72	2.46	14.06
1.4.2.1 IRFEL	5.443	0.58	1.58	1.76	1.73	0.88	6.53
1.4.2.2 ALS beamlines	1.795	0.07	0.40	0.63	0.56	0.53	2.19
1.4.2.3 Exper. Systems	4.405	0.33	1.17	1.36	1.43	1.05	5.34
1.4.3 Conventional facililities*	3.811	0.19	0.61	1.85	1.98	0.00	4.63

*From revised BA/BO schedule

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

OBLIGATIONS AND COSTS SCHEDULE DETAIL
(TY $K)

DESCRIPTION	TOTAL	FY1994 O	FY1994 C	FY 1995 O	FY 1995 C	FY 1996 O	FY 1996 C	FY 1997 O	FY 1997 C	FY 1998 O	FY 1998 C
LBL Activities											
EDI											
TIte I	150	150	150								
Title II	340	120	120	220	220						
Title III	280			80	80	100	100	100	100		
Inspection	290			80	80	105	105	105	105		
Consultants	95	25	25	20	20	20	20	30	30		
Subtotal	1,155	295	295	400	400	225	225	235	235		
Architect/Engineer											
Title I	540	540	540								
Title II	905	905	355	0	550						
Title III	360	360	0	0	95	0	130	0	135		
Subtotal	1,805	1,805	895	0	645	0	130	0	135		
Construction											
Phase I-Site Dev											
Improv to Land	180	180	0	0	180						
Building	850	850	0	0	850						
Utilities	1,690	1,690	0	0	1,690						
Phase II-Bldg Const											
Improv to Land	240							240	240		
Building	13,400			5,490	0	7,910	7,980	0	5,420		
Spec Bldg Fac	1,830			0	0	250	250	1,580	1,580		
Utilities	1,840			1,840	0	0	1,840				
Subtotal	20,030	2,720	0	7,330	2,720	8,160	10,070	1,820	7,240		
Standard Equipment	5,720					2,150	1,050	3,570	4,670		
Subtotal	28,710	4,820	1,190	7,730	3,765	10,535	11,475	5,625	12,280		
Contingency (16%)	4,630	780	190	1,250	605	1,695	1,855	905	1,980		
TOTAL	33,340	5,600	1,380	8,980	4,370	12,230	13,330	6,530	14,260		

Project Management Cost included in Overall Project Management Cost (WBS 1.1).

CHEMICAL DYNAMICS RESEARCH LABORATORY
SPECIAL RESEARCH FACILITIES AND PROJECT MANAGEMENT

BA/BO SCHEDULE
(TY $K)

WBS NO.	WBS ELEMENT	TOTAL BUDGET	FY 1994				FY 1995				FY 1996				FY 1997				FY 1998			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
			O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S
1.1	PROJECT MANAGEMENT	5890		840/840				1170/1170				1230/1230				1290/1290				1360/1360		
1.2	SPECIAL RESEARCH FACILITIES																					
1.2.1	ED&I																					
1.2.1.1	IRFEL	5680			910/910				1240/1240				1290/1290				1360/1360			880/880		
1.2.1.2	ALS BEAMLINES	1990			300/300				450/450				480/480				520/520			240/240		
1.2.1.3	EXPERIMENTAL SYSTEMS	4200			570/570				860/860				900/900				920/920			950/950		
1.2.2	CONSTRUCTION																					
1.2.2.1	IRFEL	18480				1500/1100				5950/4550				4900/5720				4900/5620		1230/1490		
1.2.2.2	ALS BEAMLINES	6520								1900/1120				1720/2080				1700/1750		1200/1570		
1.2.2.3	EXPERIMENTAL SYSTEMS	13610				610/510				3630/3080				3250/3660				3720/3760		2400/2600		
	Contingency by Year	14910/14910	1410 / 1090				3990 / 3320				3760 / 3930				3480 / 3910				2270 / 2660			
	Total BA/BO by Year	71280/71280	6140 / 5320				19190 / 15790				17530 / 19290				17890 / 19130				10530 / 11750			
	Current Funding Plan	71280	6140				19190				17530				17890				10530			

PE:CDR:CDRL:CDR:BABO/CDRL
2/11/92

CHEMICAL DYNAMICS RESEARCH LABORATORY
CONVENTIONAL FACILITIES

BA/BO SCHEDULE
(TY $K)

WBS NO.	WBS ELEMENT	TOTAL BUDGET	F Y 1994				F Y 1995				F Y 1996				F Y 1997			
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
			O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S	O N D	J F M	A M J	J A S
1.3.1	ED&I																	
1.3.1.1	LBL ACTIVITIES																	
1.3.1.1.1	TITLE I ENGINEERING	150		150/150														
1.3.1.1.2	TITLE II ENGINEERING	340			120/120			220/220										
1.3.1.1.3	TITLE III ENGINEERING	280							80/80				100/100				100/100	
1.3.1.1.4	INSPECTION	290						80/80				105/105				105/105		
1.3.1.1.5	COLSULTANTS	95			25/25				20/20				20/20				30/30	
1.3.1.2	ARCHITECT/ENGINEER																	
1.3.1.2.1	TITLE I	540		540/540														
1.3.1.2.2	TITLE II	905			905/355			0/550										
1.3.1.2.3	TITLE III	360		360/0					0/95			0/130				0/135		
1.3.2	CONSTRUCTION																	
1.3.2.1	PHASE I (SITE PREPERATION)																	
1.3.2.1.1	IMPROVEMENTS TO LAND	180		180/0				0/180										
1.3.2.1.2	BUILDING	850		850/0					0/850									
1.3.2.1.3	UTILITIES	1690		1690/0				0/1690										
1.3.2.2	PHASE I (BUILDING CONSTRUCTION)																	
1.3.2.1.1	IMPROVEMENTS TO LAND	240															240/240	
1.3.2.1.2	BUILDING	13400								5490/0		7910/7980				0/5420		
1.3.2.1.3	SPECIAL FACILITIES	1830											250/250				1580/1580	
1.3.2.1.4	UTILITIES	1840								1840/0		0/1840						
1.3.3	STANDARD EQUIPMENT	5720												2150/1050		3570/4670		
	Contingency by Year	4630/4630	780 / 190				1250 / 605				1695 / 1855				905 / 1980			
	Total BA/BO by Year	33340/33340	5600 / 1380				8980 / 4370				12230 / 13330				6530 / 14260			
	Current Funding Plan	33340	5600				8980				12230				6530			

PE:CDR:CDRL:CDR:BA/BO/CDRL
2/28/92

Revised 2/92

Chemical Dynamics Research Laboratory
Contingency Analysis (FY92k$)

WBS Element	Base costs (k$)			Contingency rate	Contingency costs (k$)		
1 Chemical Dynamics Research Laboratory			86,600				16,154
1.1 Proj. Management & Administration			4,890	15%			700
1.2 Special Research Facilities			41,788				11,643
1.2.1 ED&I		9,894				2,758	
1.2.1.1 EDI, IRFEL	4,765			27%	1,268		
1.2.1.2 EDI, ALS beamlines	1,655			27%	455		
1.2.1.3 EDI, Exper. Systems	3,474			30%	1,035		
1.2.2 Construction		31,894				8,885	
1.2.2.1 IRFEL		15,386				4,175	
1.2.2.1.1 Acceler. Systems	7,568			30%	2,235		
1.2.2.1.2 Electron Beam Trnsprt	3,825			25%	940		
1.2.2.1.3 Und & Optical systems	2,130			25%	535		
1.2.2.1.4 Electron Bm Dump	296			25%	75		
1.2.2.1.5 Control system	823			25%	205		
1.2.2.1.6 Safety Systems	282			25%	70		
1.2.2.1.7 Accel/FEL Physics	462			25%	115		
1.2.2.2 ALS beamlines		5,307				1,340	
1.2.2.2.1 U10 Undulator	1,411			25%	350		
1.2.2.2.2 Undulator beamline	2,338			25%	595		
1.2.2.2.3 Bend Mag. Beamline	1,558			25%	395		
1.2.2.3 Experimental Systems		11,201				3,370	
1.2.2.3.1 Experimental Stations	8,214			30%	2,445		
1.2.2.3.2 Advanced Lasers	2,691			30%	820		
1.2.2.3.3 Laser safety/controls	127			35%	45		
1.2.2.3.4 User Cntrl Interface	169			35%	60		
1.3 Conventional Facilities			23,768				3,811
1.3.1 ED&I		2,430		16%		395	
1.3.1.1 LBL Activities		950				158	
1.3.1.1.1 Engineering	630			20%	126		
1.3.1.1.2 Consultants	80			10%	8		
1.3.1.1.3 Inspection	240			10%	24		
1.3.1..2 A/E Activities		1,480		16%		237	
1.3.2 Construction		16,628				2,898	
1.3.2.1 Phase I (site preparation)		2,396		20%		479	
1.3.2.2 Phase II (building constr.)		14,232		17%		2,419	
1.3.3 Standard Equipment		4,710		11%		518	
1.4 Contingency			16,154				
1.4.1 Project management		700					
1.4.2 Special research facilities		11,643					
1.4.3 Conventional facilities		3,811					

DEPARTMENTAL PRICE CHANGE INDEX

FY 1993 GUIDANCE

ANTICIPATED ECONOMIC ESCALATION RATES

DOE CONSTRUCTION PROJECTS

FISCAL YEAR	ENERGY RESEARCH AND NUCLEAR		FOSSIL		CONSERVATION/SOLAR		DEFENSE PROGRAMS, EP & GENERAL CONSTRUCTION	
	INDEX	%CHANGE	INDEX	% CHANGE	INDEX	% CHANGE	INDEX	%CHANGE
1991	1.000	NA	1.000	NA	1.000	NA	1.000	NA
1992	1.025	2.5	1.022	2.2	1.023	2.3	1.023	2.3
1993	1.065	3.9	1.064	4.1	1.062	3.8	1.061	3.7
1994	1.115	4.7	1.115	4.8	1.111	4.6	1.106	4.2
1995	1.168	4.8	1.168	4.7	1.164	4.7	1.157	4.6
1996	1.225	4.9	1.225	4.9	1.220	4.8	1.211	4.7
1997	1.286	4.9	1.286	4.9	1.280	4.9	1.267	4.6

Based on the materials and labor data contained in the Energy Supply Planning Model and appropriate escalation rates forecasted by Data Resources, Incorporated, it would be expected that DOE projects conform to those rates shown above. DOE Order 5700.3C requires that any local rates different from those above be submitted to the ICE Office for approval, prior to their use. Additional advice and assistance can be obtained from the Office of Procurement, Assistance and Program Management, Program/Project Management Division (FTS 896-1190).

DEPARTMENTAL PRICE CHANGE INDEX

ICE FY 1991 GUIDANCE

HISTORICAL AND ANTICIPATED ECONOMIC ESCALATION RATES FOR DOE CONSTRUCTION PROJECTS

FISCAL YEAR	ENERGY RESEARCH AND NUCLEAR	FOSSIL	CONSERVATION/SOLAR	DEFENSE PROGRAM, EP, & GENERAL CONSTRUCTION
Historical				
1974	10.4	11.3	10.7	9.6
1975	14.5	15.4	15.3	13.0
1976	6.1	6.0	5.7	5.2
1977	6.2	6.3	6.0	6.0
1978	7.1	7.3	6.8	7.3
1979	9.1	9.6	9.1	8.9
1980	9.7	10.1	10.7	9.7
1981	9.2	9.4	9.1	8.1
1982	6.8	6.6	6.5	6.3
1983	3.0	2.6	2.9	3.1
1984	2.4	2.2	2.4	2.4
1985	2.1	1.9	2.0	1.6
1986	1.3	0.6	1.3	1.1
1987	1.9	1.8	1.8	1.8
1988	4.0	4.7	4.0	3.2
1989	4.2	4.4	4.5	3.2
1990	2.8	2.3	2.9	2.3
1991	2.6	2.2	2.7	2.5
Anticipated				
1992	2.5	2.2	2.3	2.3
1993	3.9	4.1	3.8	3.7
1994	4.7	4.8	4.6	4.2
1995	4.8	4.7	4.7	4.6
1996	4.9	4.9	4.8	4.7
1997	4.9	4.9	4.9	4.6
1998	5.0	5.0	4.9	4.8
1999	5.1	5.2	5.1	5.0
2000	5.2	5.2	5.1	5.0
2001	5.3	5.3	5.3	5.0

Based on the materials and labor data contained in the Energy Supply Planning Model and appropriate escalation rates forecasted by Data Resources, Incorporated (DRI), it would be expected that DOE projects would generally conform to those rates shown above. DOE Order 5700.3C requires that any local rates different from those above be submitted to the ICE Office for approval, prior to their use. Additional advice and assistance can be obtained from the Office of Procurement, Assistance and Program Management, Program/Project Management Division (FTS 896-1190).

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 4

BASIS OF PROJECT TIME SCHEDULE

The Project Time Schedule shown on the following bar chart is based upon the assumption that the funding will be available on January 1, 1994.

Prior to this date LBL will:

1. Prepare a Project Management Plan.

2. Define in detail the program and scope of the project.

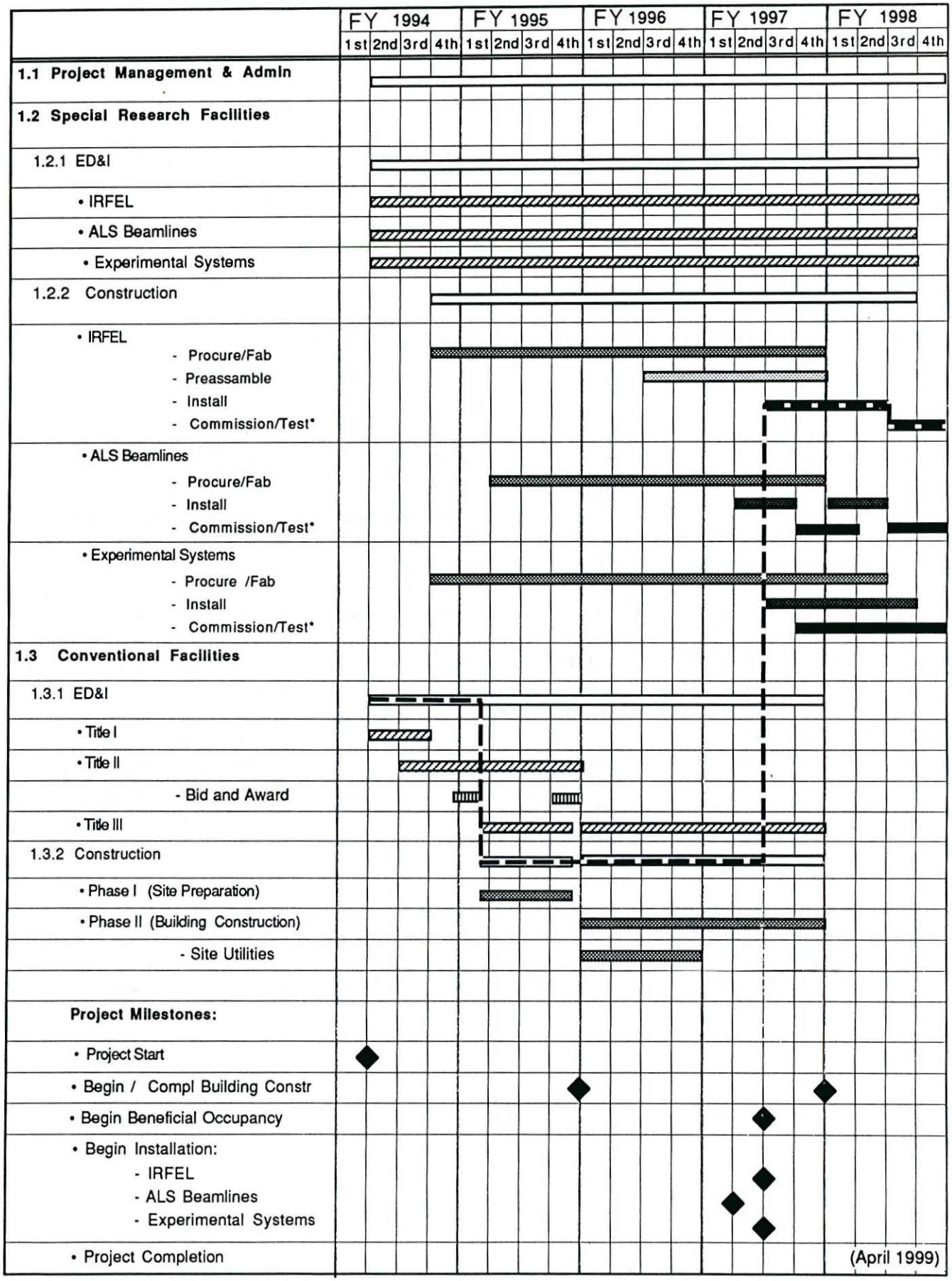
3. Complete the A/E selection.

4. Evaluate environmental considerations and prepare recommendations for NEPA documentation, beginning in October 1992 for completion by January 1994. It is anticipated that an Environmental Assessment (EA) will find no significant impact, however a sufficient contingency is built into the schedule to permit preparation of an Environmental Impact Statement if required.

The schedule for the Special Research Facilities is based largely upon the experience with ALS systems. The goal is to have the Special Research Facilities available to the users and operating in a reliable manner at the conclusion of the project. Procurement activities for the IRFEL will begin in the final quarter of FY 1994. Procurement activities for the ALS bend magnet beamline and one experimental station will begin in FY 1995. It will be fast tracked to take an earliest advantage of the ALS operation which is projected to start in FY 1993. Installation of the remainder of the beamlines and experimental systems will begin in the third quarter of FY 1997, following beneficial occupancy of the experimental hall. A substantial pre-assembly and pre-alignment period for the IRFEL is provided to ensure that installation and commissioning can be complete as efficiently as possible following the beneficial occupancy of the IRFEL vault.

Construction activities for the Conventional Facilities are scheduled in two steps. Phase I, Site Preparation, will include the demolition of Building 10, excavation, grading and utilities relocation. Phase II, Building Construction, will include the building foundations, the building structure, special building facilities and utilities.

CHEMICAL DYNAMICS RESEARCH LABORATORY
PROJECT SCHEDULE



* Funded by R&D Operations

The critical path is shown as a dashed line

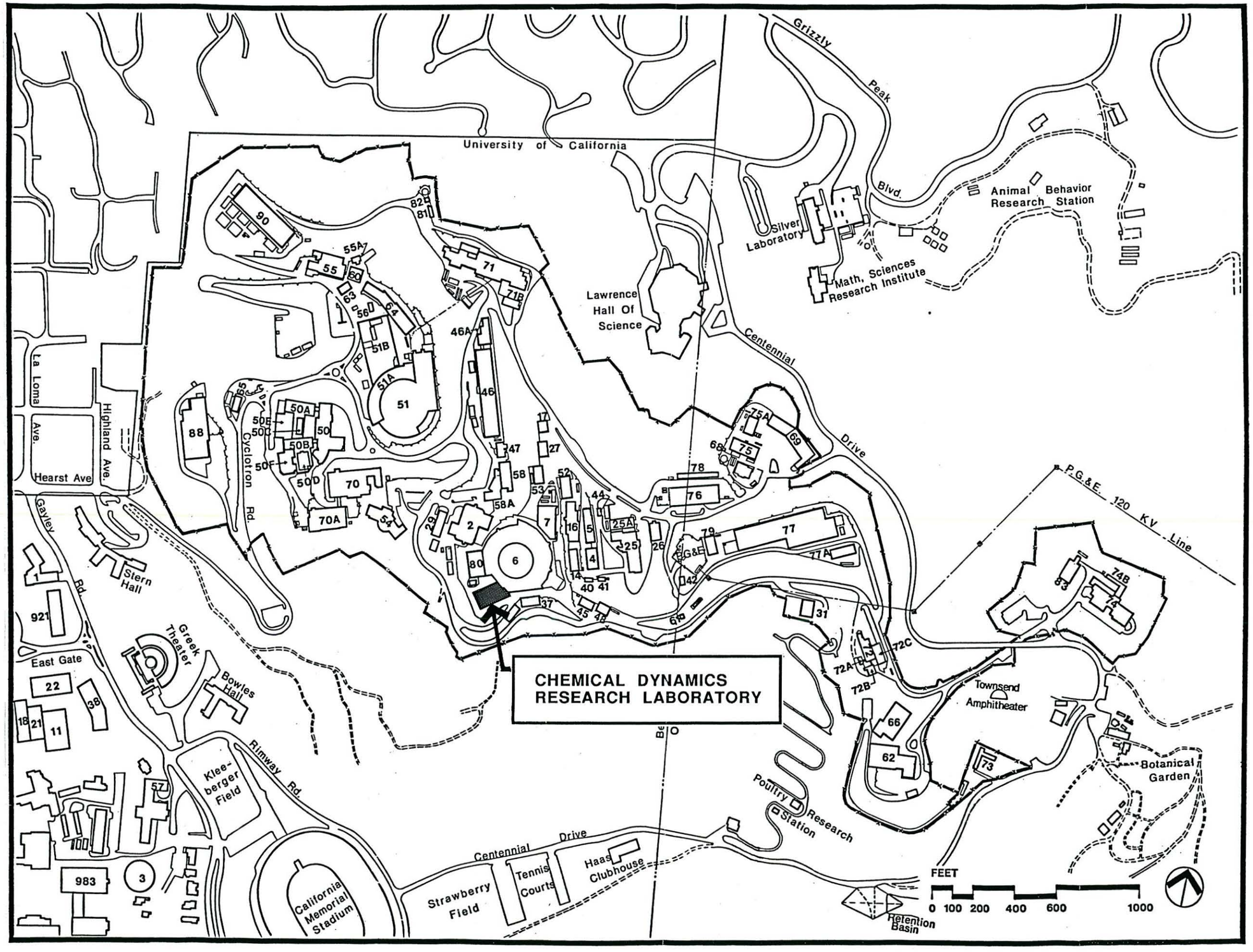
February 15, 1991

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 5

SCHEDULE OF DRAWINGS

T-1	Location Plan
T-2	Site Plan
T-3	Site Mechanical Utilities Plan
T-4	Site Electrical Utilities Plan
A-1	Basement Floor Plan
A-2	First Floor Plan
A-3	Interstitial Level Plan
A-4	Second Floor Plan
A-5	Third Floor Plan
A-6	Roof Plan
A-7	Building Sections
A-8	Building Elevations
S-1	Foundation Plan
S-2	First Floor Framing Plan
S-3	Interstitial Level Framing Plan
S-4	Second Floor Framing Plan
S-5	Top Chord Bracing Plan
S-6	Third Floor Framing Plan
S-7	Roof Framing Plan
S-8	Wall Framing Elevations and Column Schedule
M-1	Basement Mechanical Plan
M-2	First Floor Mechanical Plan
M-3	Interstitial Level Mechanical Plan
M-4	Second Floor Mechanical Plan
M-5	Third Floor Mechanical Plan
M-6	Roof Mechanical Plan
M-7	Building Composite HVAC Flow Diagram
M-8	HVAC Control Diagram
E-1	Single Line Diagram
E-2	Riser Diagram

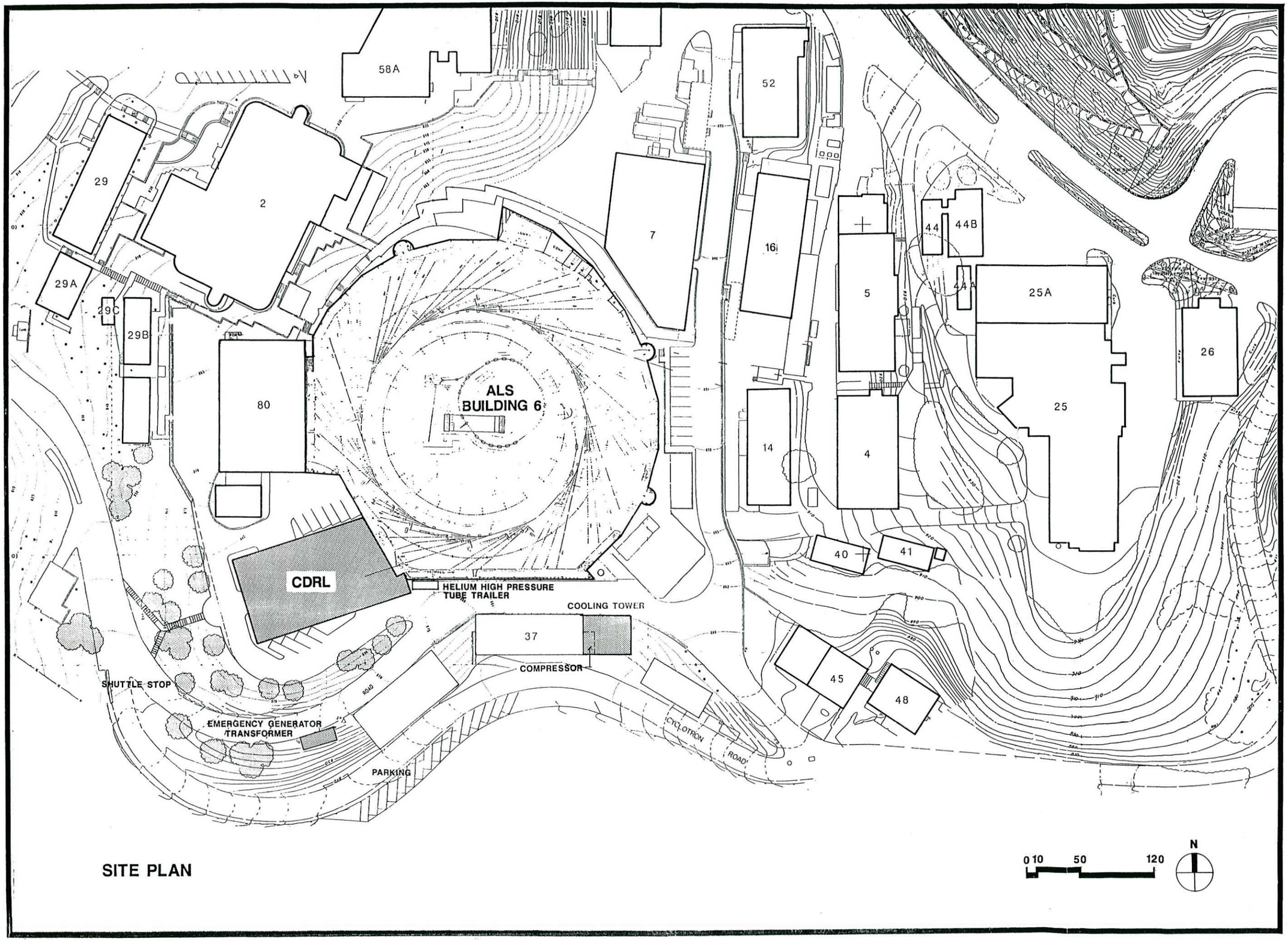


T-1

CHEMICAL DYNAMICS RESEARCH LABORATORY

LOCATION PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



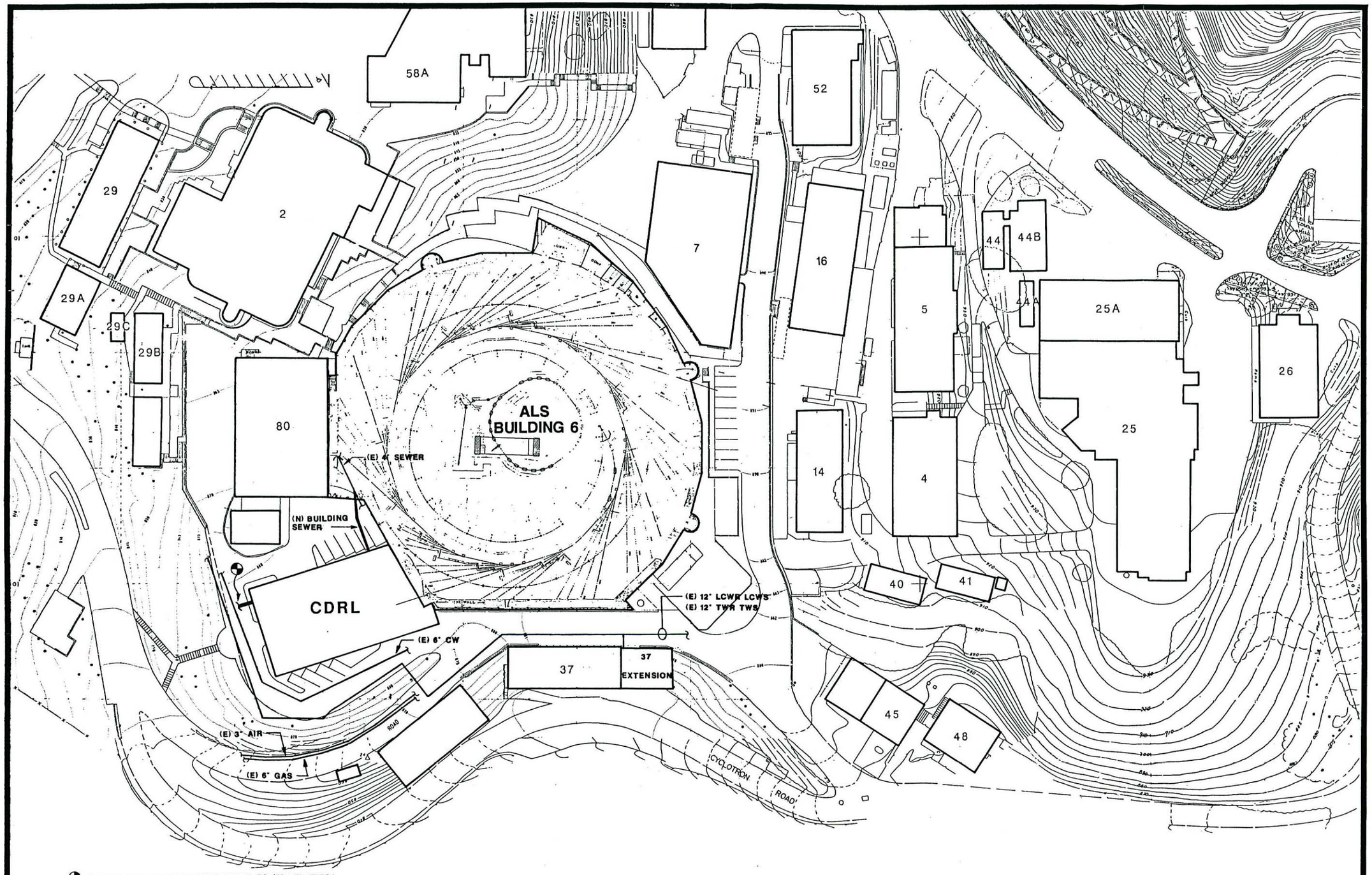
SITE PLAN

T-2

CHEMICAL DYNAMICS RESEARCH LABORATORY

SITE PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



(N) BUILDING UTILITY CONNECTIONS TO (E) UTILITIES:
LCWR, LCWS, TWR, TWS, CA, CW, F, G
(N) = NEW (E) = EXISTING
(ALSO SEE M-1 FOR SYMBOLS & LEGEND)

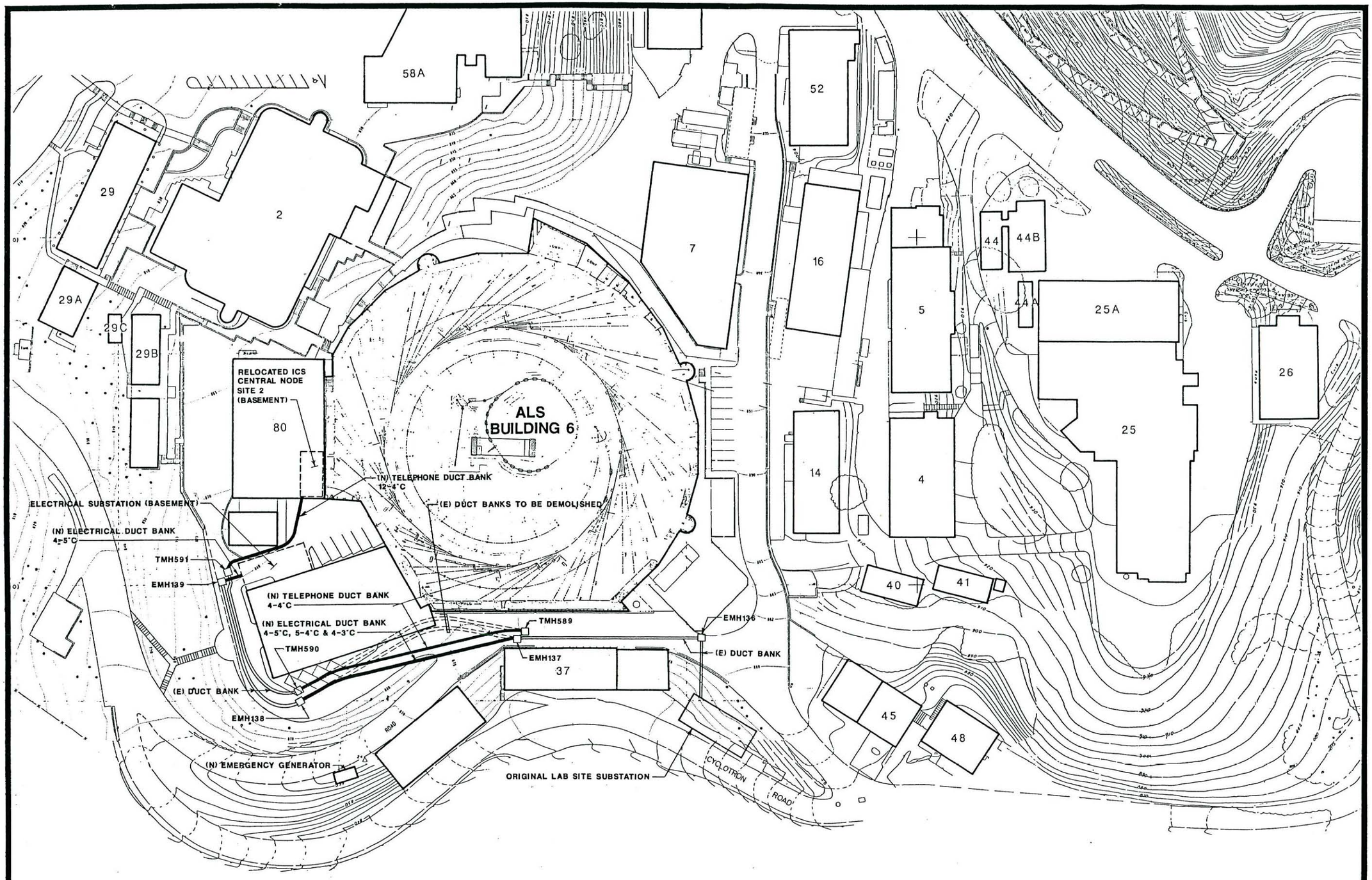
SITE MECHANICAL UTILITIES PLAN

T-3

CHEMICAL DYNAMICS RESEARCH LABORATORY
SITE MECHANICAL UTILITIES PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

DIETERICH POST RECORDER NO. 123543



SITE ELECTRICAL UTILITIES PLAN

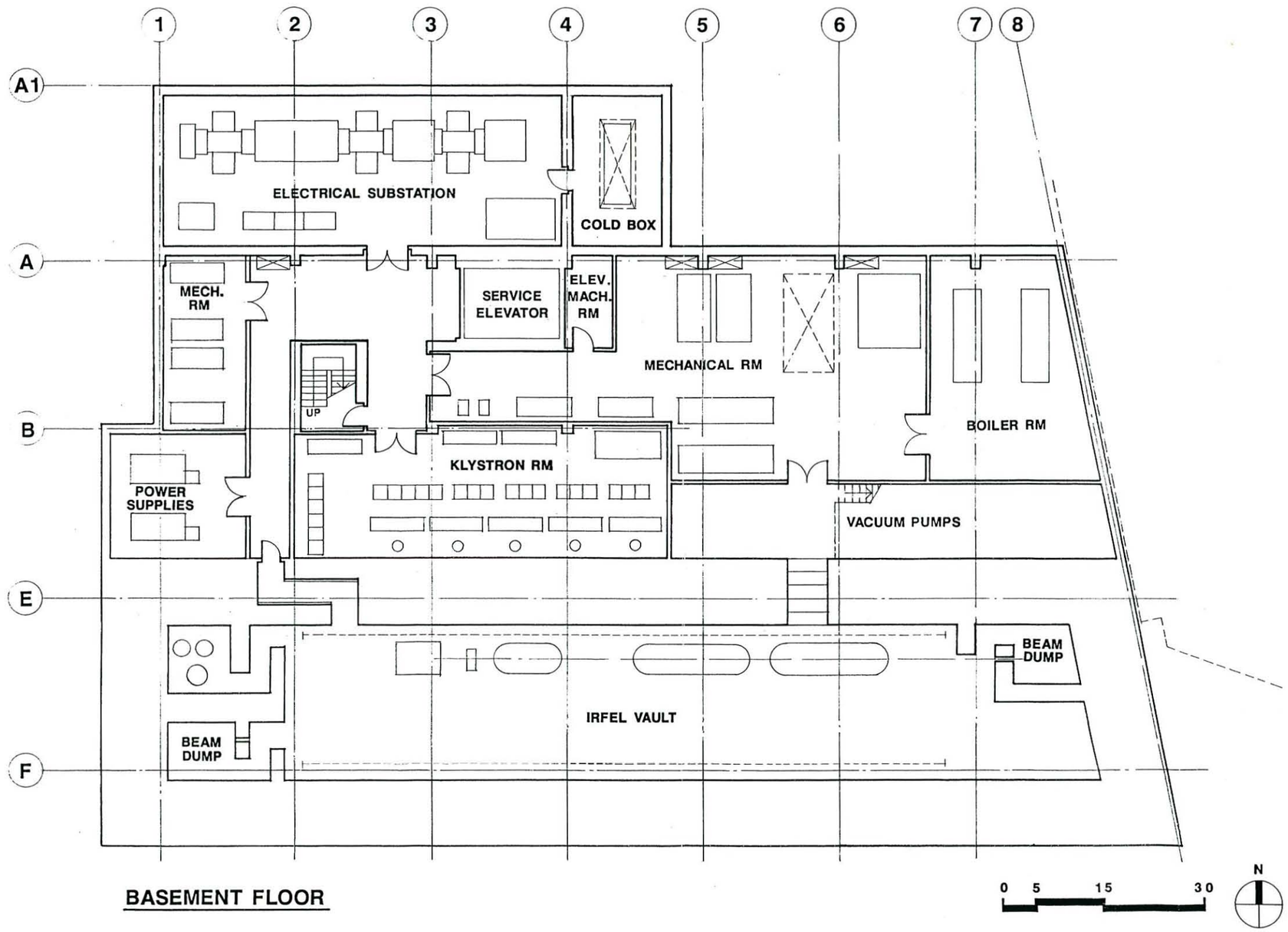
T-4

CHEMICAL DYNAMICS RESEARCH LABORATORY

SITE ELECTRICAL UTILITIES PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

DIETERICH POST REORDER NO. 132542



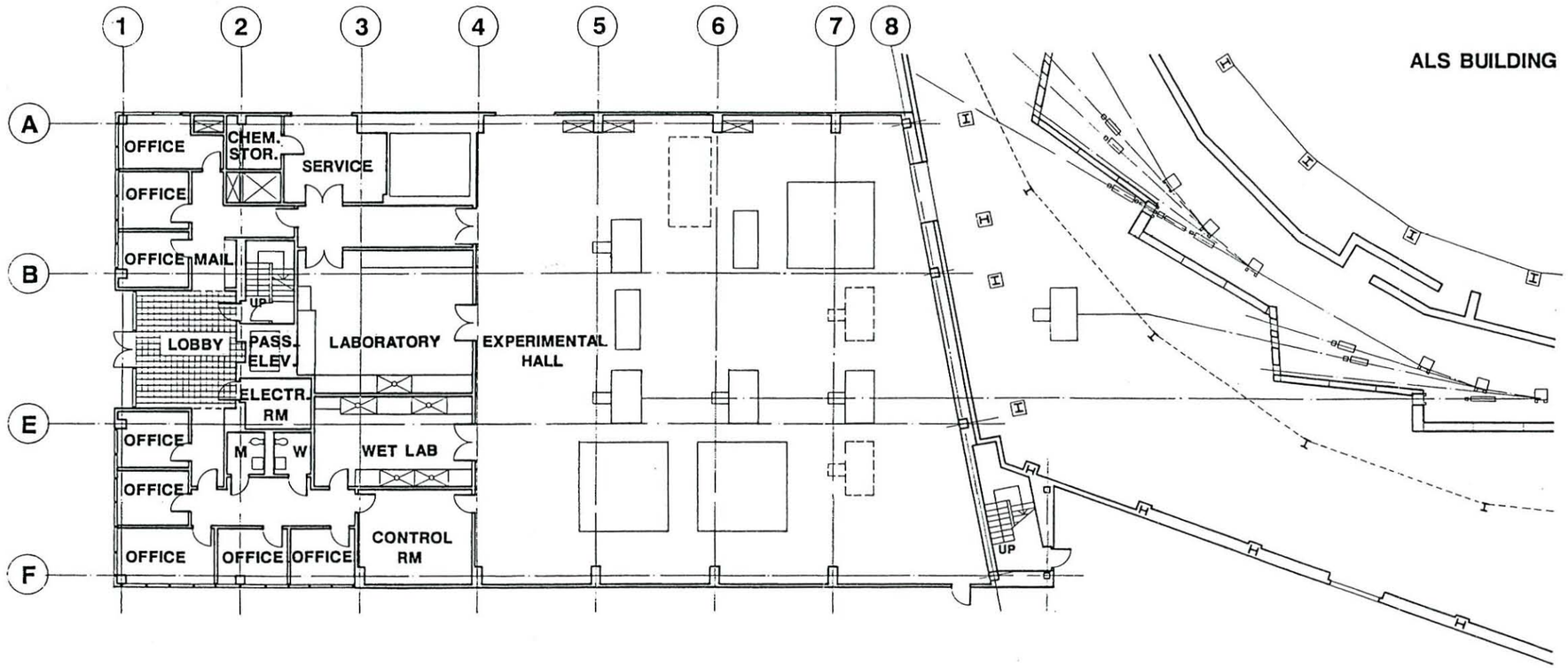
BASEMENT FLOOR

A-1

CHEMICAL DYNAMICS RESEARCH LABORATORY

BASEMENT FLOOR PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



FIRST FLOOR PLAN

0 5 15 40

N

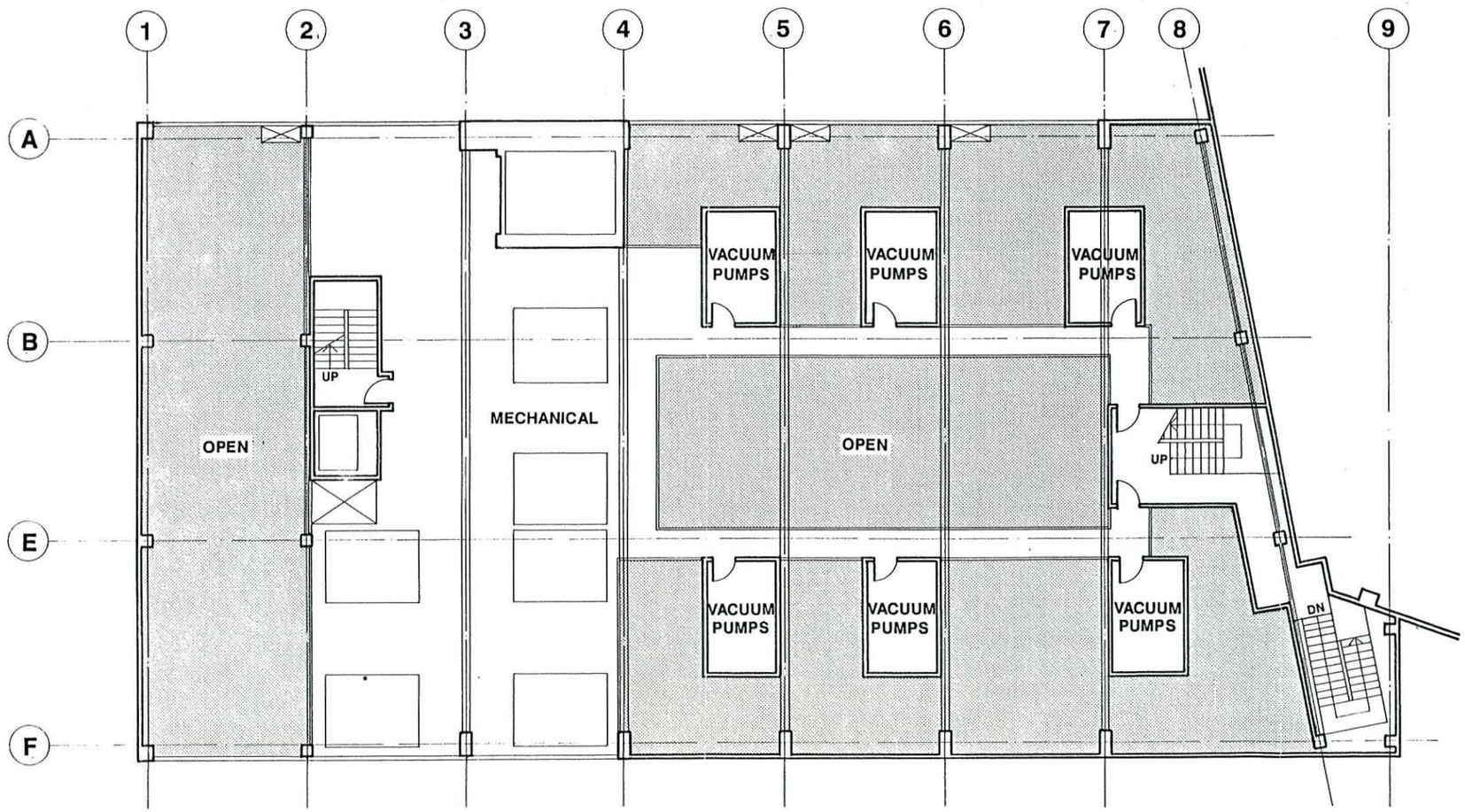
A-2

CHEMICAL DYNAMICS RESEARCH LABORATORY

FIRST FLOOR PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

DIETERICH POST REORDER NO. 132543



INTERSTITIAL LEVEL PLAN

A-3

CHEMICAL DYNAMICS RESEARCH LABORATORY

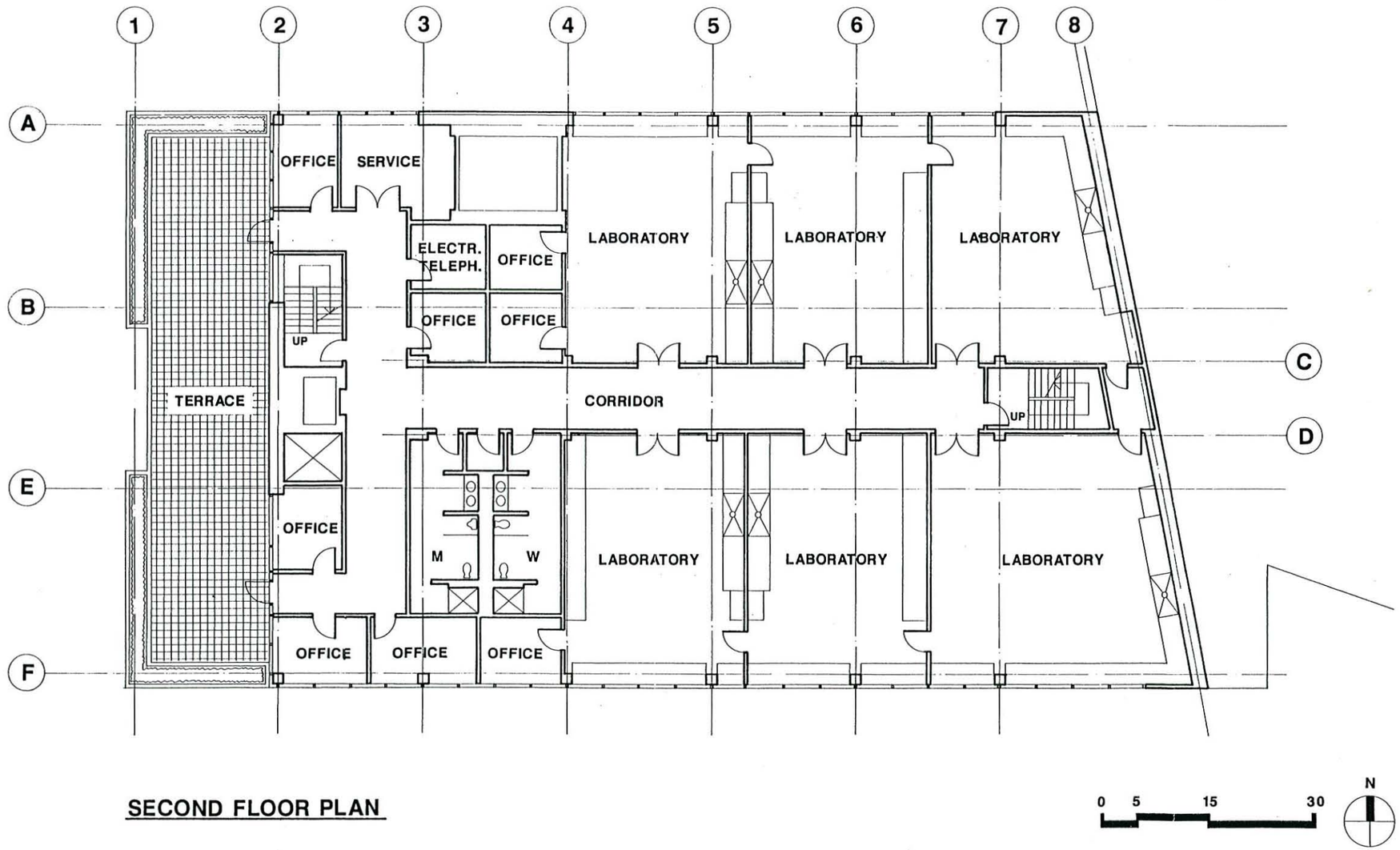
INTERSTITIAL LEVEL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

CHEMICAL DYNAMICS RESEARCH LABORATORY

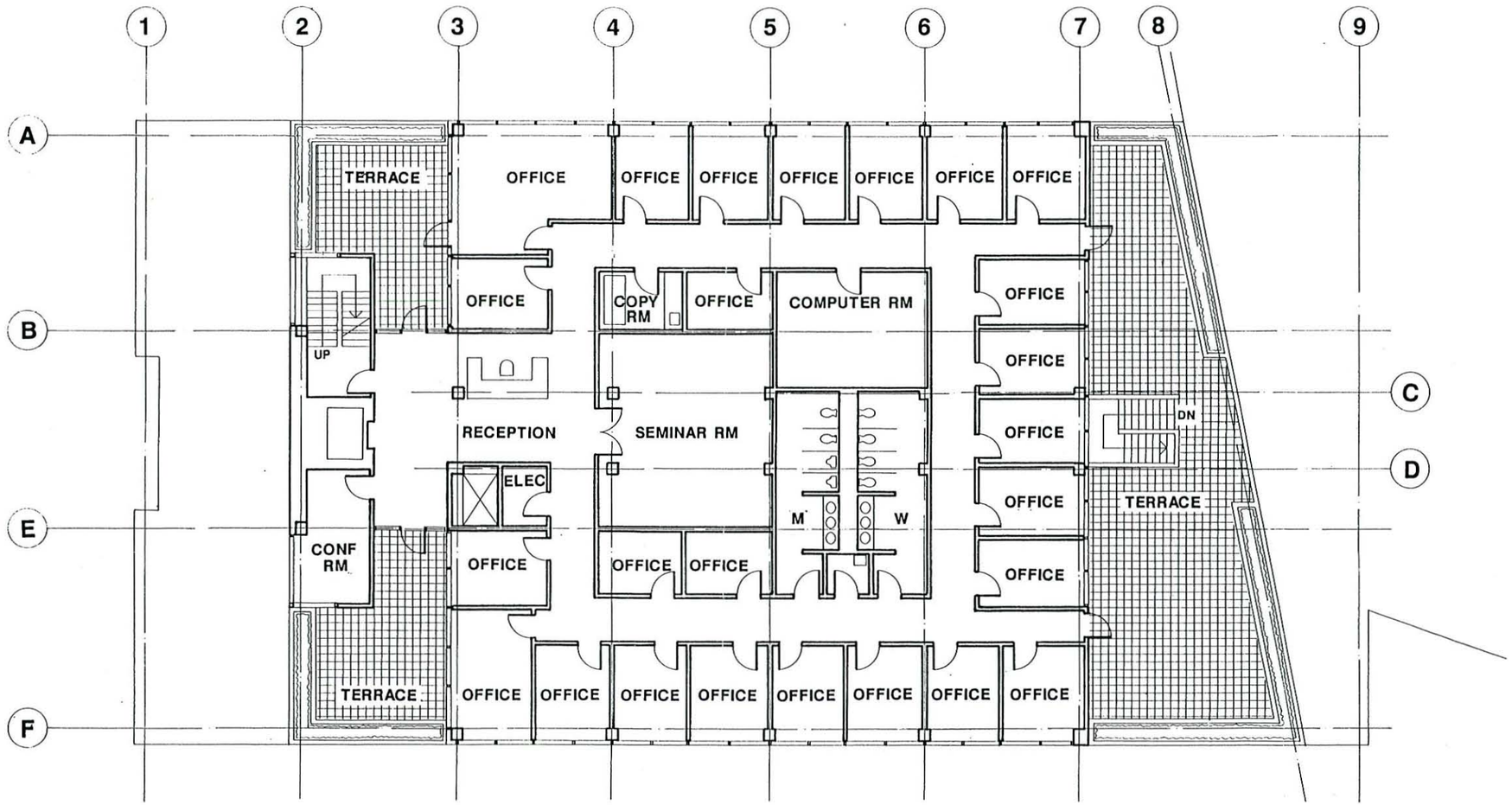
SECOND FLOOR PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



SECOND FLOOR PLAN

A-5



THIRD FLOOR PLAN

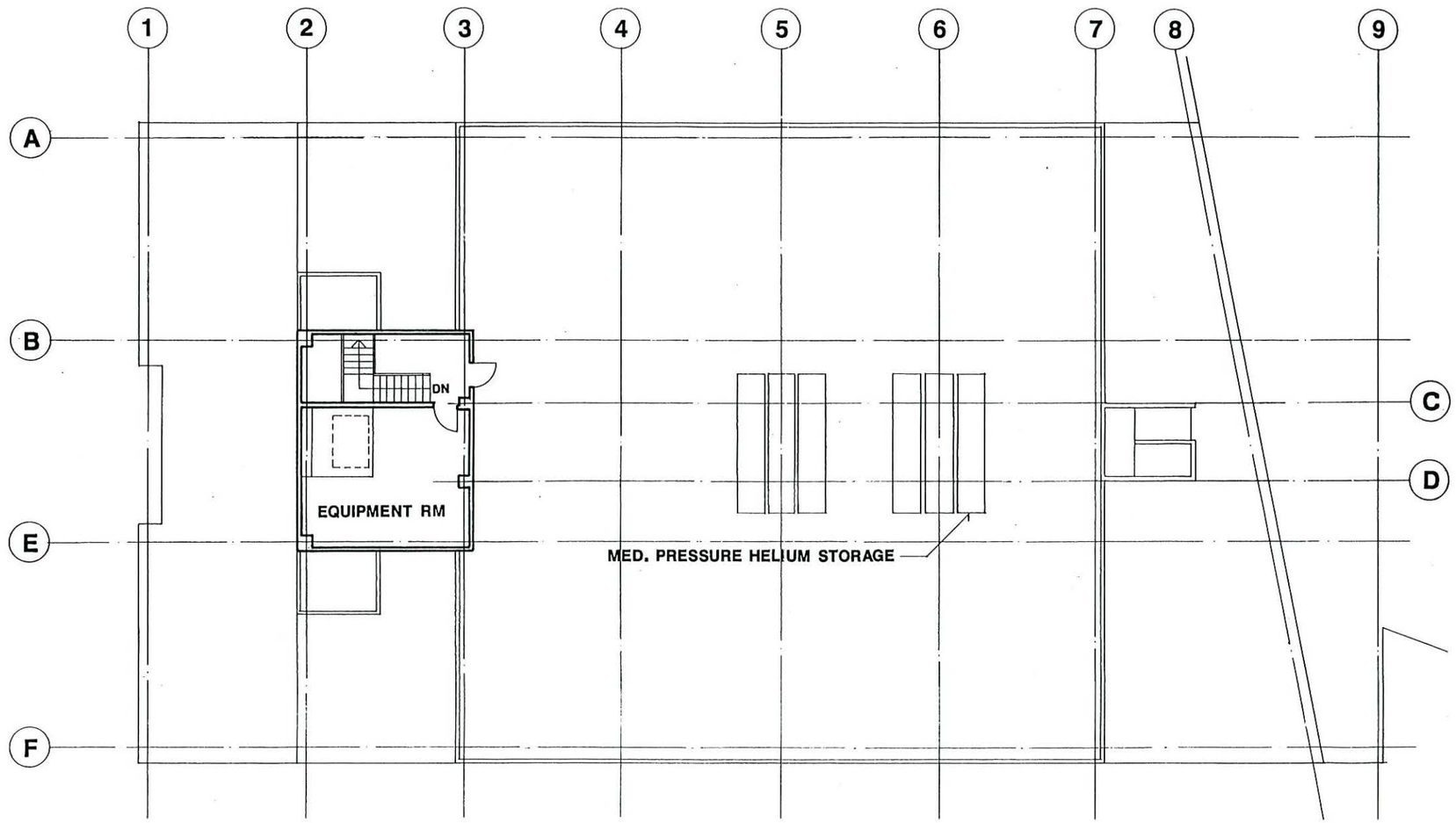
0 5 15 30

N

CHEMICAL DYNAMICS RESEARCH LABORATORY

THIRD FLOOR PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



ROOF PLAN

0 5 15 30

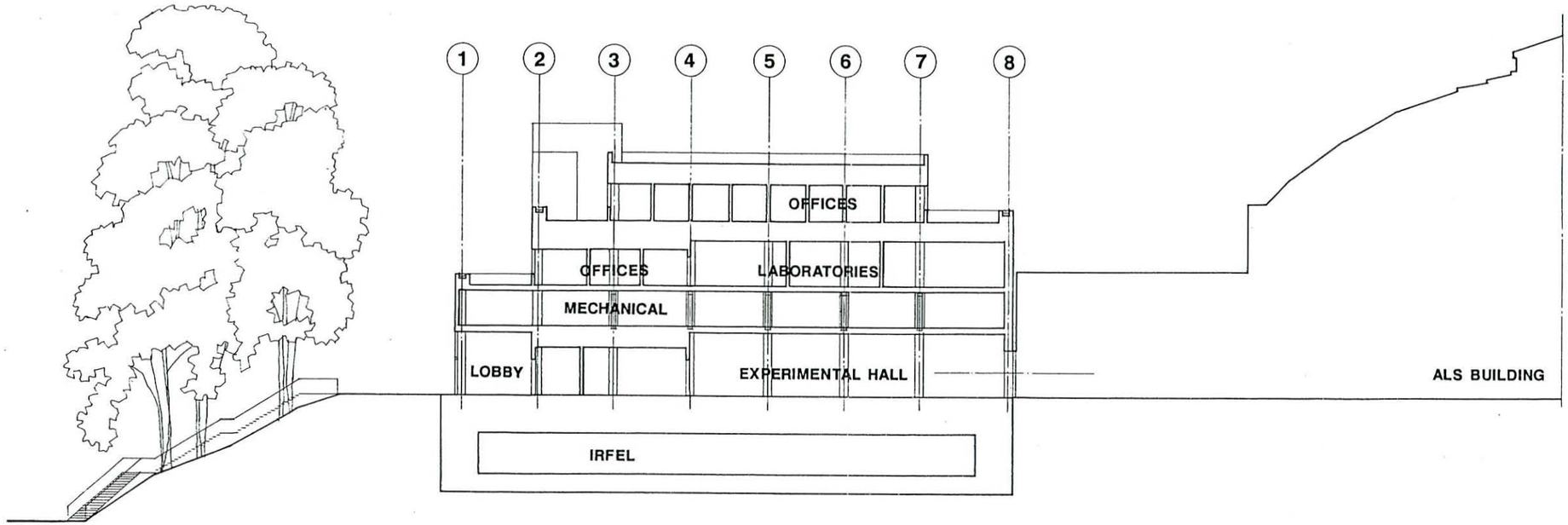
N

A-6

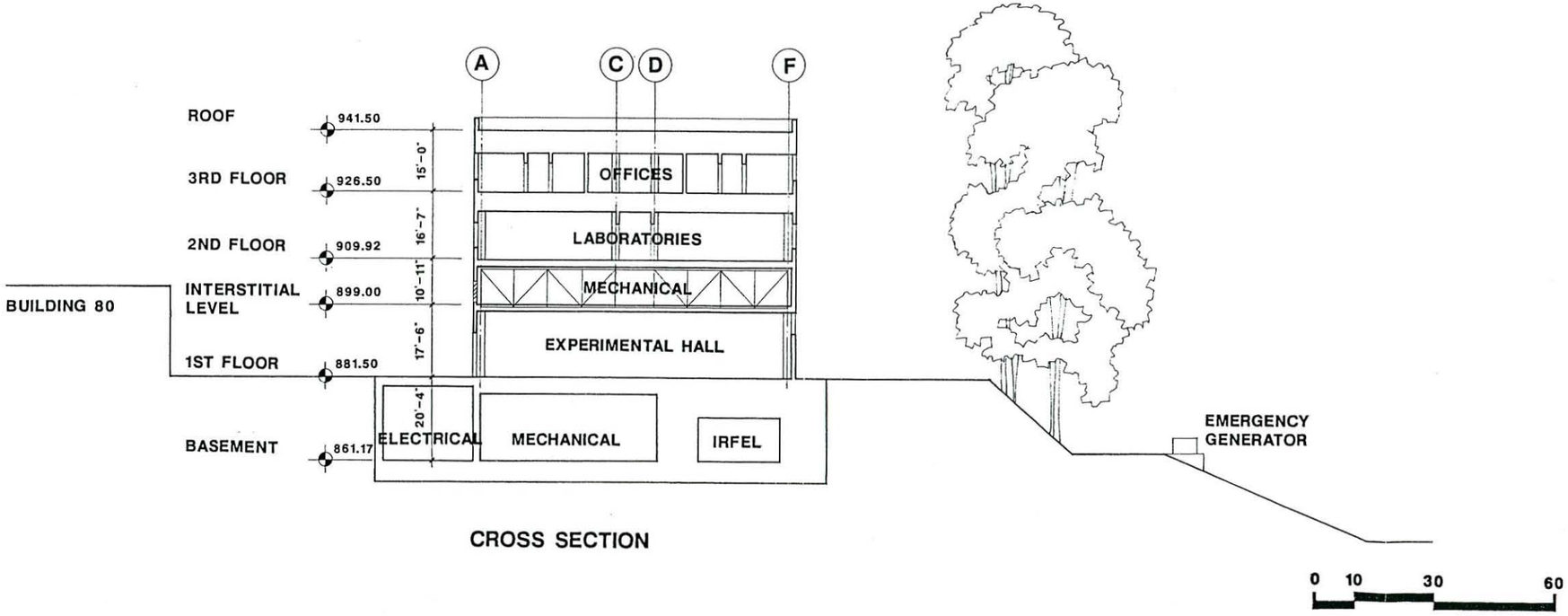
CHEMICAL DYNAMICS RESEARCH LABORATORY

ROOF PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



LONGITUDINAL SECTION



CROSS SECTION

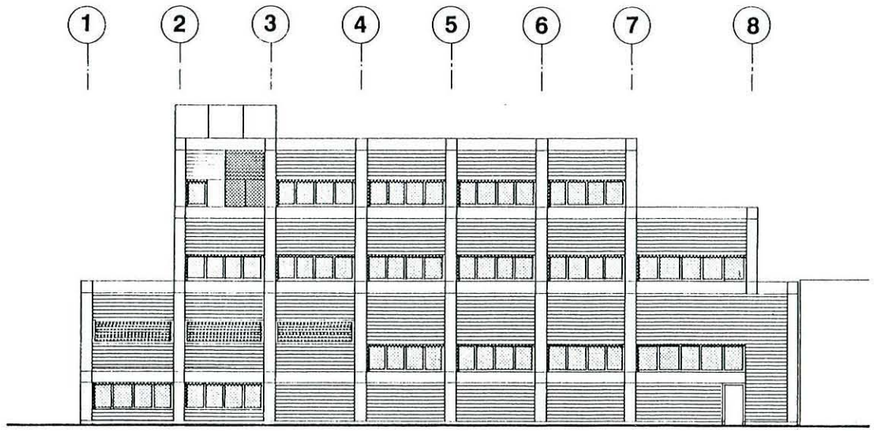
A-7

CHEMICAL DYNAMICS RESEARCH LABORATORY

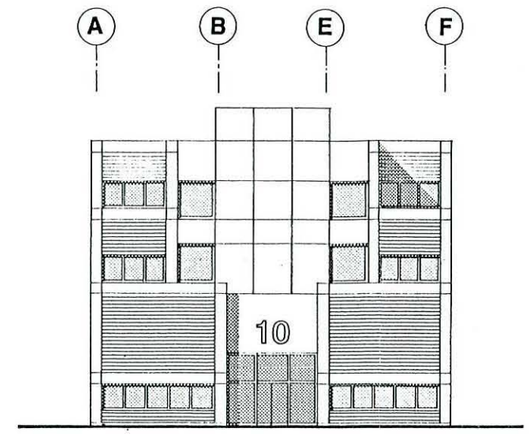
BUILDING SECTIONS

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

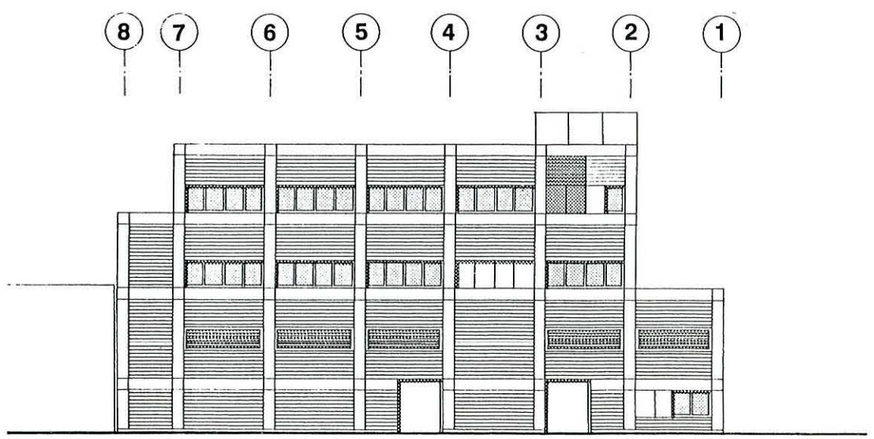
A-8



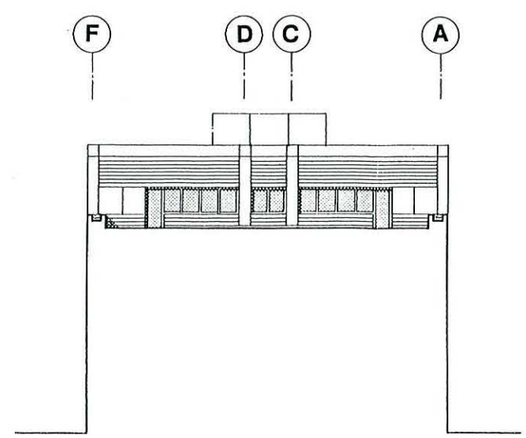
SOUTH ELEVATION



WEST ELEVATION



NORTH ELEVATION



EAST ELEVATION

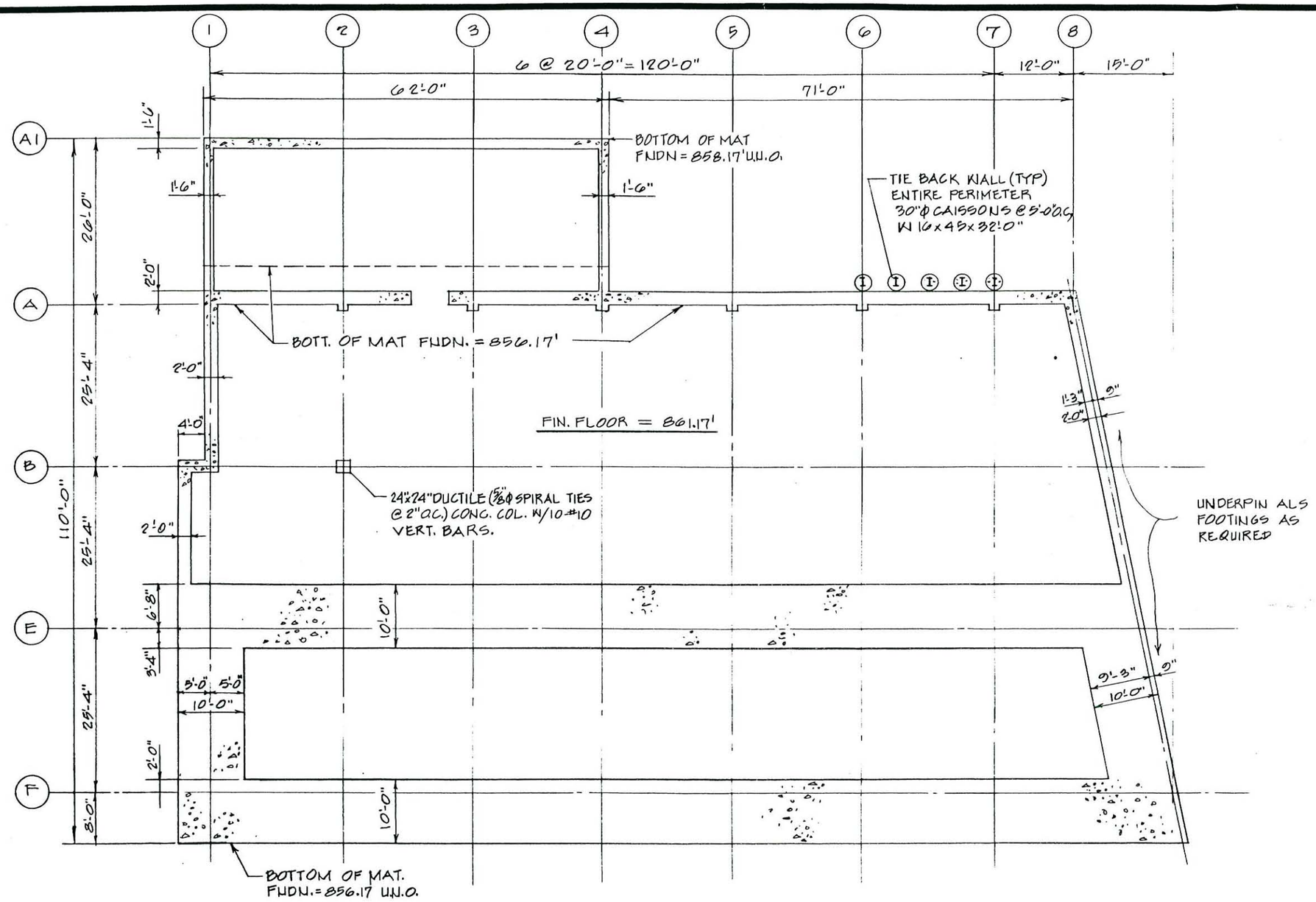
0 10 30 60

CHEMICAL DYNAMICS RESEARCH LABORATORY

BUILDING ELEVATIONS

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

DIETERICH POST REORDER NO. 122542



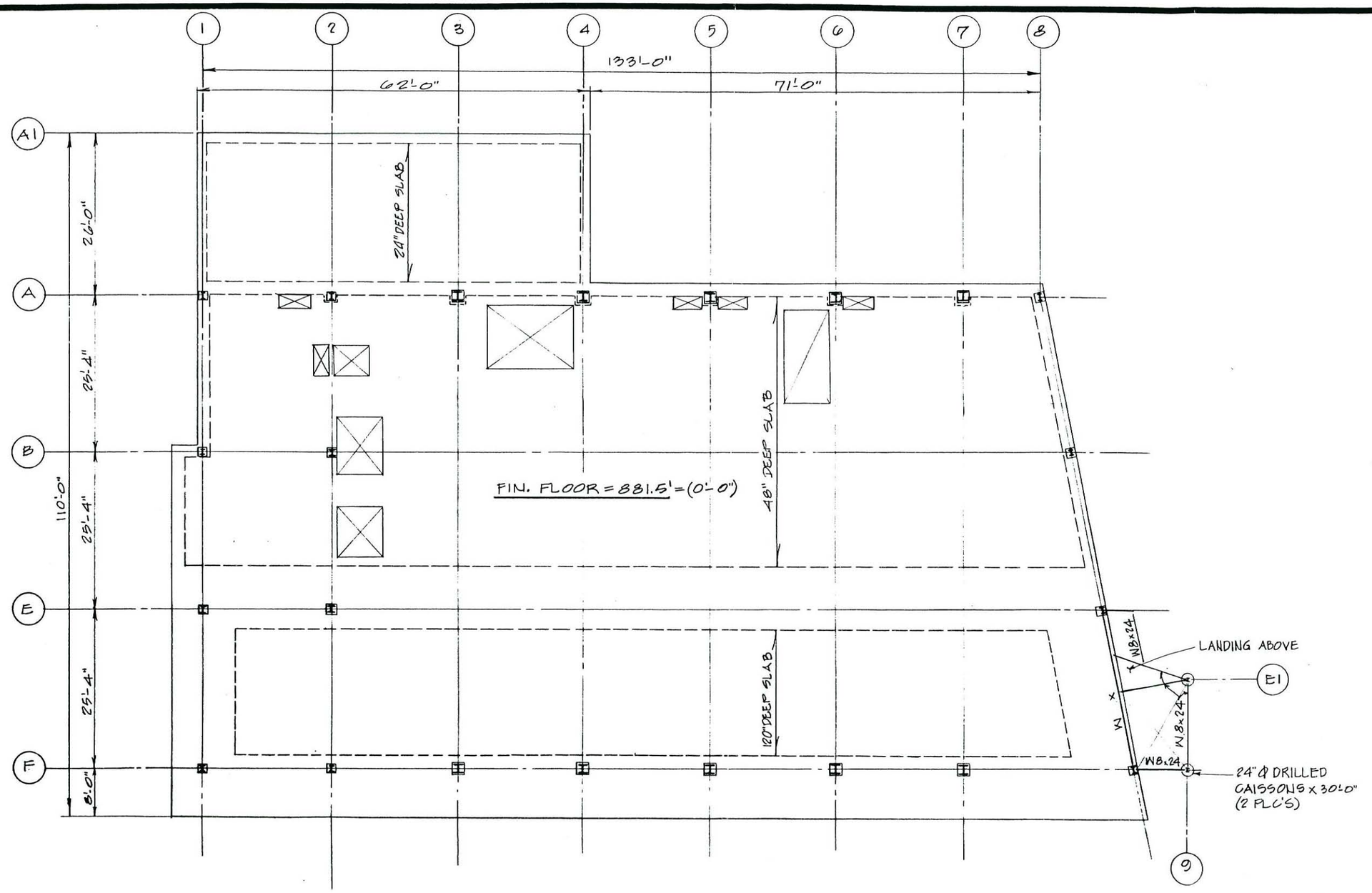
FOUNDATION PLAN

0 5 10 30
FEET

S-1

CHEMICAL DYNAMICS RESEARCH LABORATORY
FOUNDATION PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



FIRST FLOOR FRAMING PLAN

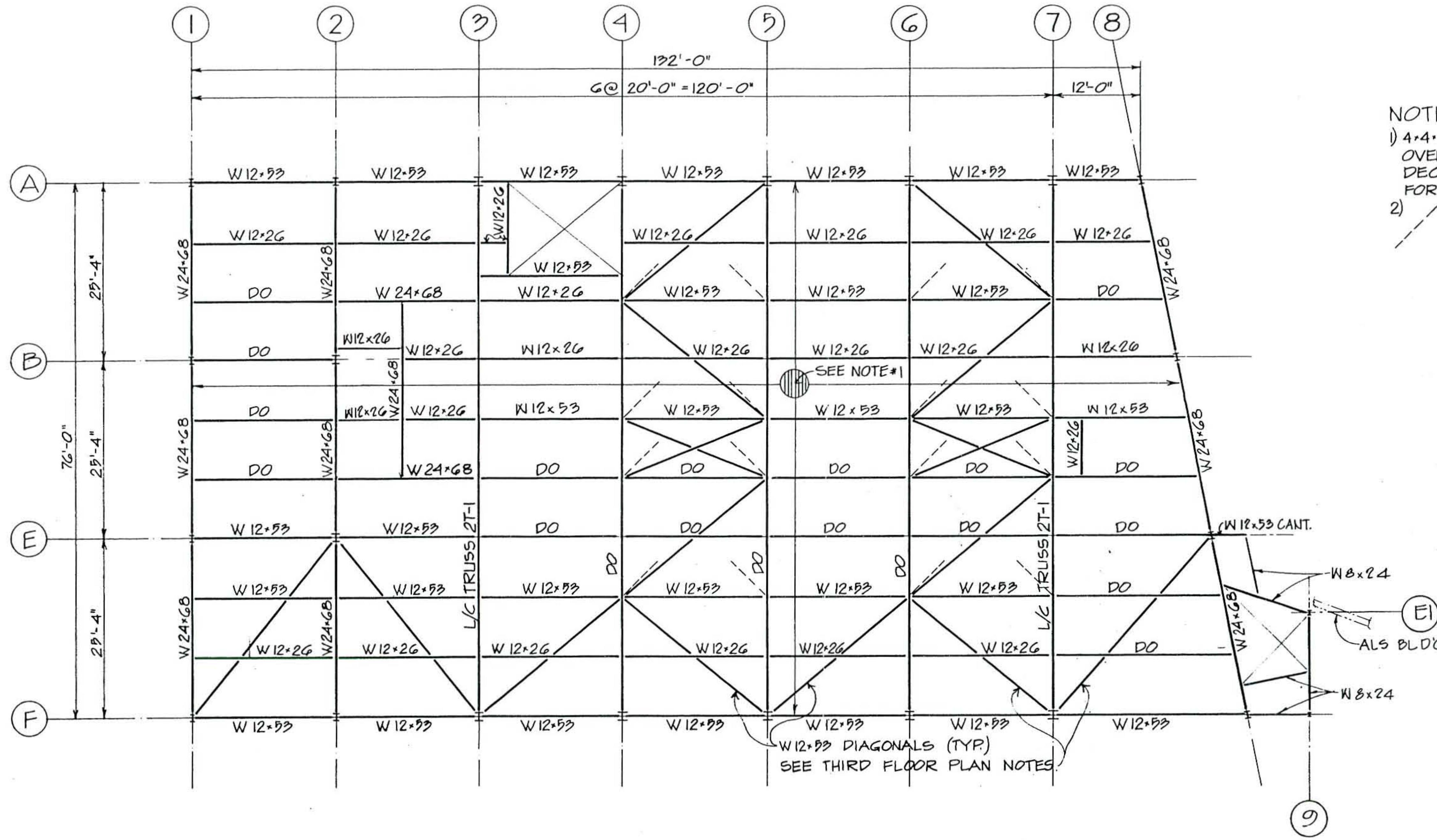
0 5 10 30
FEET

S-2

CHEMICAL DYNAMICS RESEARCH LABORATORY

FIRST FLOOR FRAMING PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTES:
1) 4×4×1.5×1.5 MESH 3" LT.WT. CONC. OVER 2"×18 GA METAL DECK. SEE ARCH. DWGS FOR EXTENT.
2) VERTICAL = BRACING W 12×40

INTERSTITIAL LEVEL FRAMING PLAN

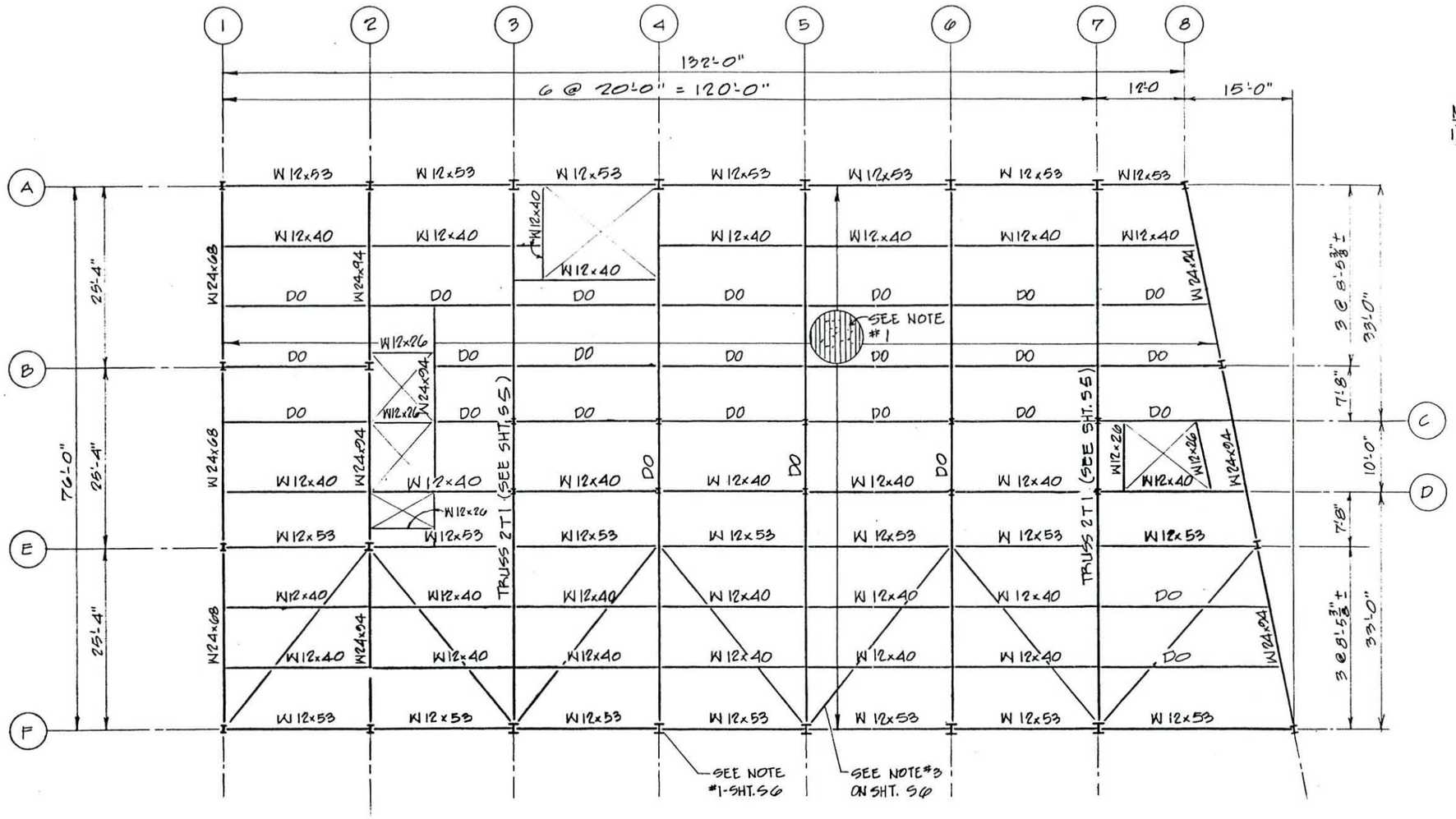
TOP OF STEEL (+17'-1 3/8")

0 5 10 30
FEET

S-3

CHEMICAL DYNAMICS RESEARCH LABORATORY
INTERSTITIAL LEVEL FRAMING PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTES

1) 4x4x1.5x1.5 MESH IN 3" LT. WT. CONC. OVER 2"x18ga. METAL DECK.

SECOND FLOOR FRAMING PLAN

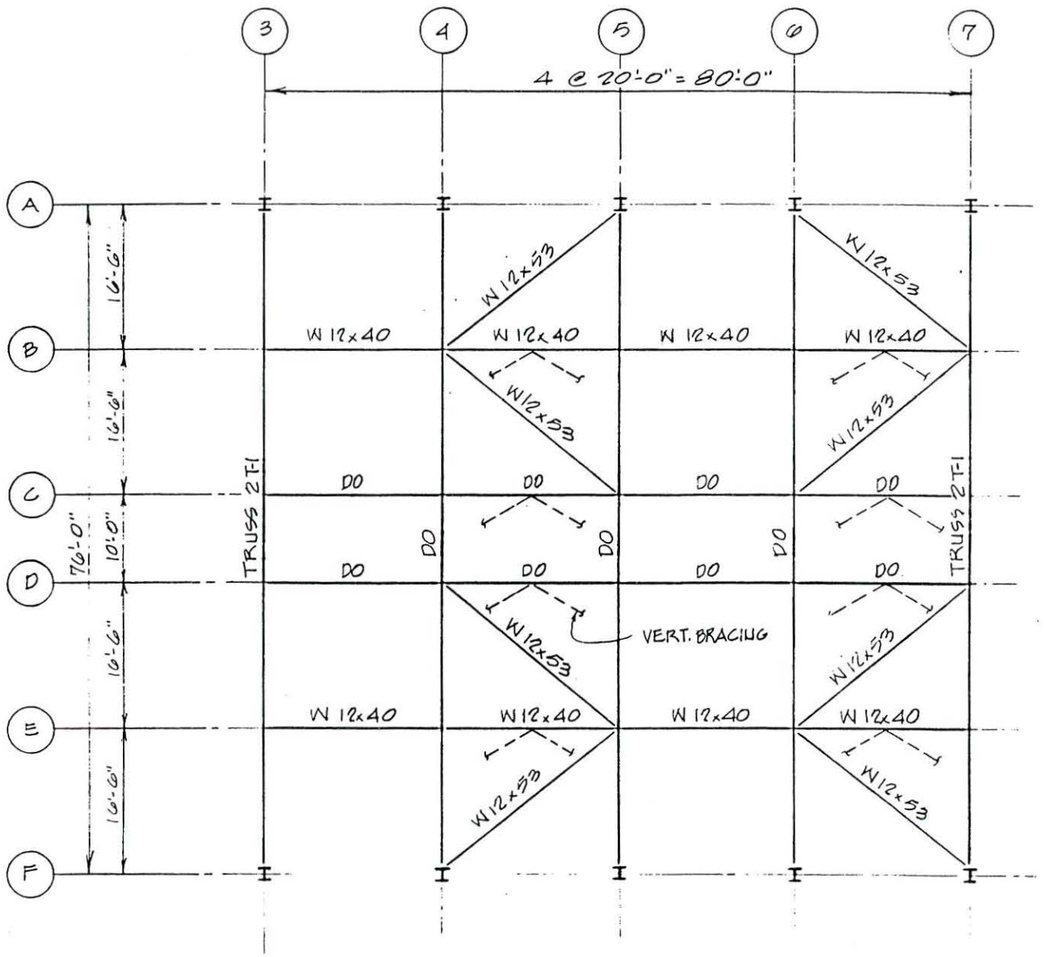
TOP OF STEEL (+28'-0")

0 5 10 30
FEET

S-4

CHEMICAL DYNAMICS RESEARCH LABORATORY
SECOND FLOOR FRAMING PLAN

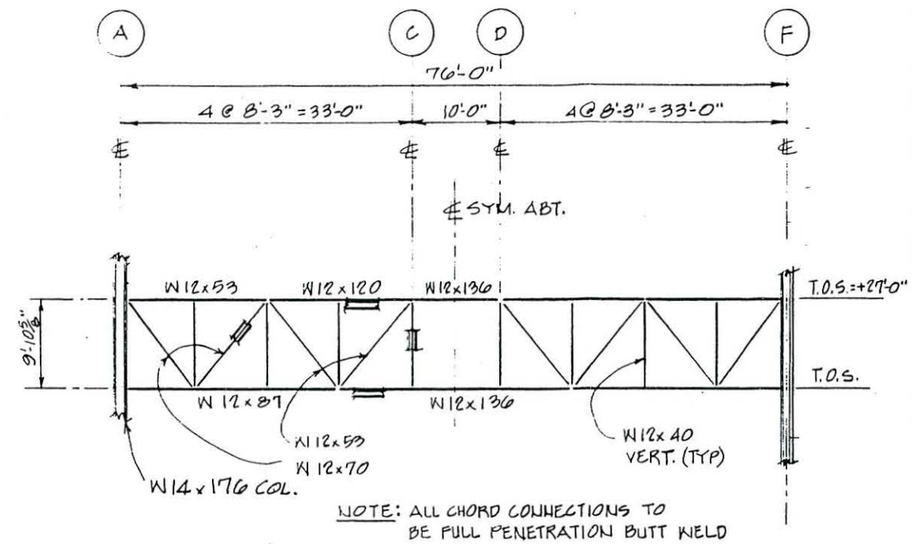
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTE: W12x40 VERT. BRACING (TYP)
ELEV. +26'-6" TO +16'-7 3/8"

TOP CHORD BRACING PLAN

TOP OF STEEL (+27'-0")



NOTE: ALL CHORD CONNECTIONS TO BE FULL PENETRATION BUTT WELD

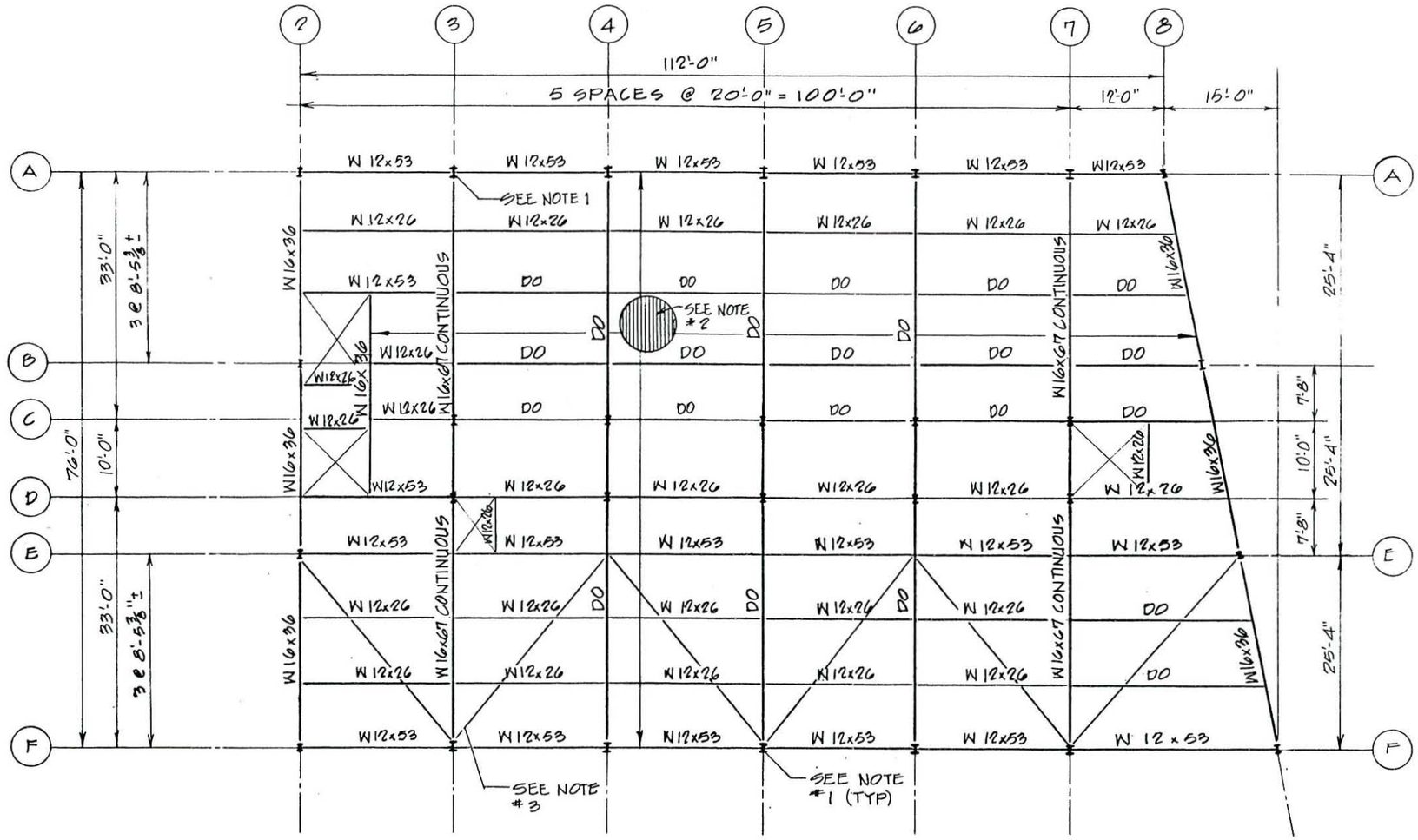
TYPICAL TRUSS 2T-1 ELEVATION

0 5 10 30
FEET

S-5

CHEMICAL DYNAMICS RESEARCH LABORATORY
TOP CHORD BRACING PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTES:

1.) FOR COLUMNS SIZE, SEE COLUMNS SCHEDULE AT SHEET S 8

2.) 4x4x1.5x1.5 MESH, 2 1/2" LT. WT. CONC. OVER 2"x18ga. METAL DECK.

3.) HORIZONTAL TRUSS DIAGONAL BRACING TO BE: W12x53 W/COMPLETE PENETRATION WELDS AT CONNECTIONS.

THIRD FLOOR FRAMING PLAN

TOP OF STEEL (+44'-7 1/2")

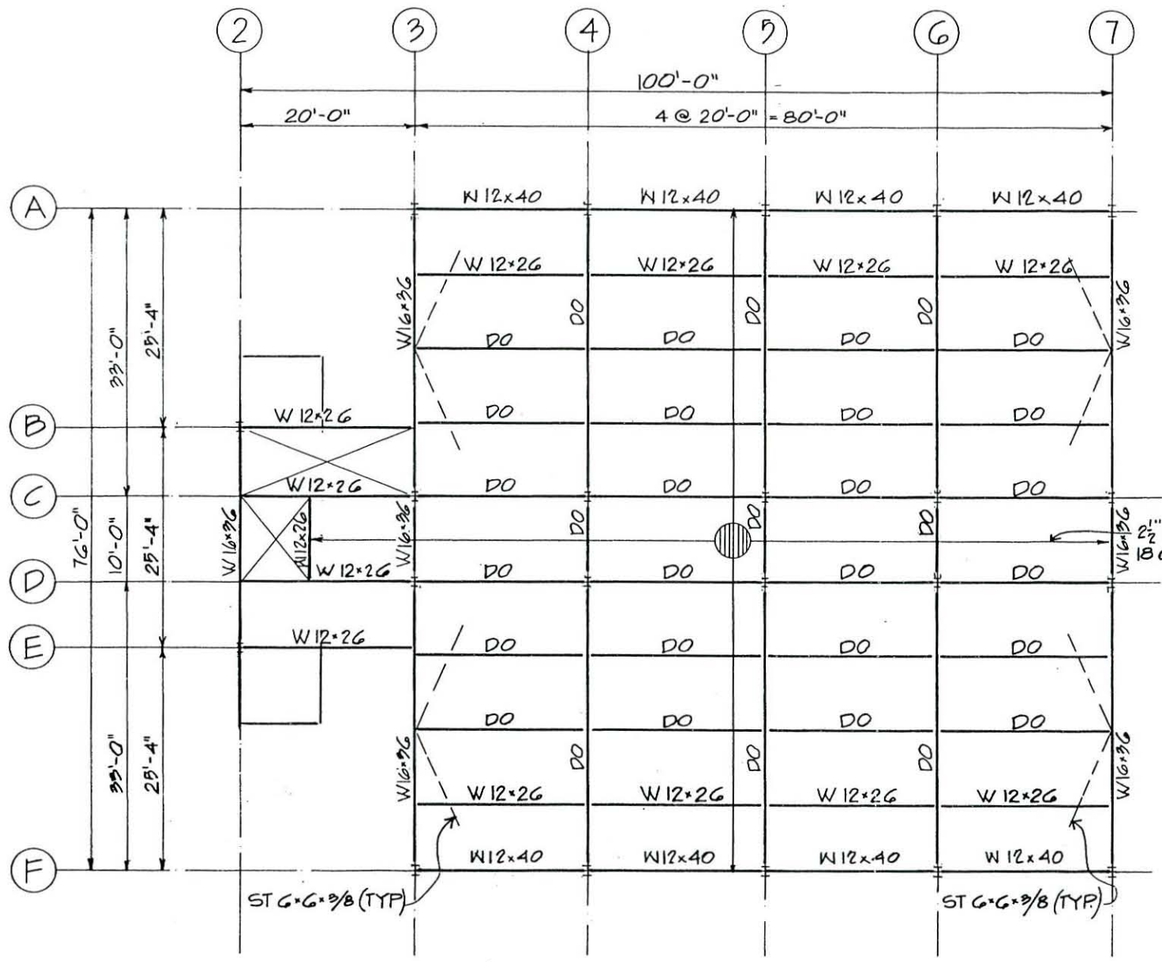
0 5 10 30
FEET

S-6

CHEMICAL DYNAMICS RESEARCH LABORATORY

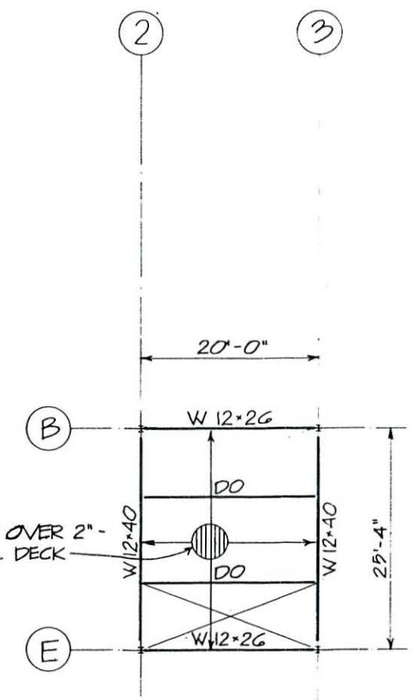
THIRD FLOOR FRAMING PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



ROOF FRAMING PLAN

TOP OF STEEL (+59'-7 1/2")



PENTHOUSE ROOF FRAMING PLAN

TOP OF STEEL (+66'-7 1/2")

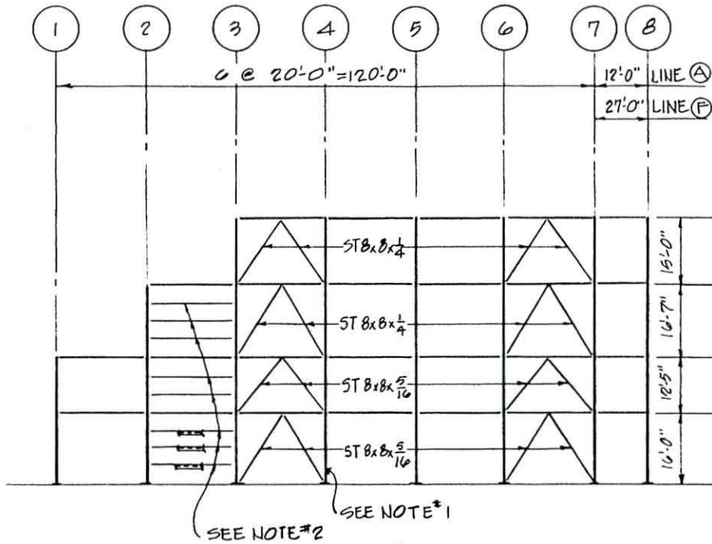
0 5 10 30
FEET

S-7

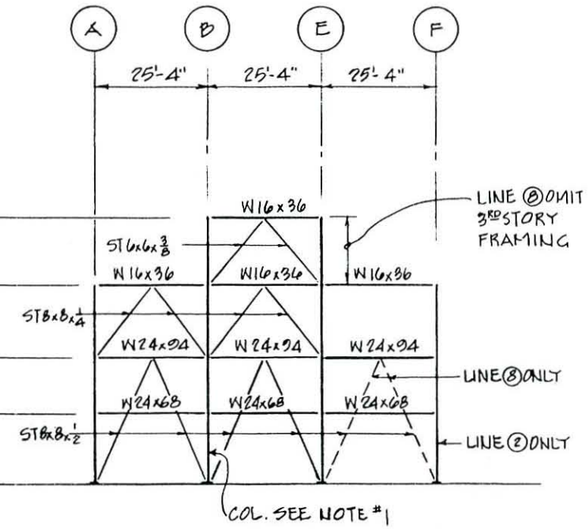
CHEMICAL DYNAMICS RESEARCH LABORATORY

ROOF FRAMING PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



WALL FRAMING ELEVATION
LINES A&E



FRAMING ELEVATION
LINE 2 SHOWN, LINE 8 SIMILAR

NOTES:

1.) SEE COLUMN SCHEDULE FOR COLUMN SIZES
2.) PROVIDE WIND GIRTS C 8x11.5 @4'-0" VERTICAL SPACING. LINES A, F, 1 & 8 NOT SHOWN COMPLETELY.

COLUMN SCHEDULE

	A-1, B-1, C-1, D-1	A-2, F-2	B-2, E-2	B-3, E-3	A-3,4,5,6,7; F-3,4,5,6,7	C-3,4,5,6,7; D-3,4,5,6,7	A-8, B-8, E-8, F-8	E1, F9
PENTHOUSE ROOF +67'-0"								
ROOF +60'-0" (7'-0")			W18x24	W18x24				
3RD FLR +45'-0" (15'-0")			W12x40		W14x61	W12x40		
2ND FLR +28'-5" (16'-7")		W12x40					W12x40	
INTER. +16'-0" (12'-5")	W12x40	W12x53	W12x65		W14x176		W12x53	
1ST FLR. 0'-0" (16'-0")								W18x31

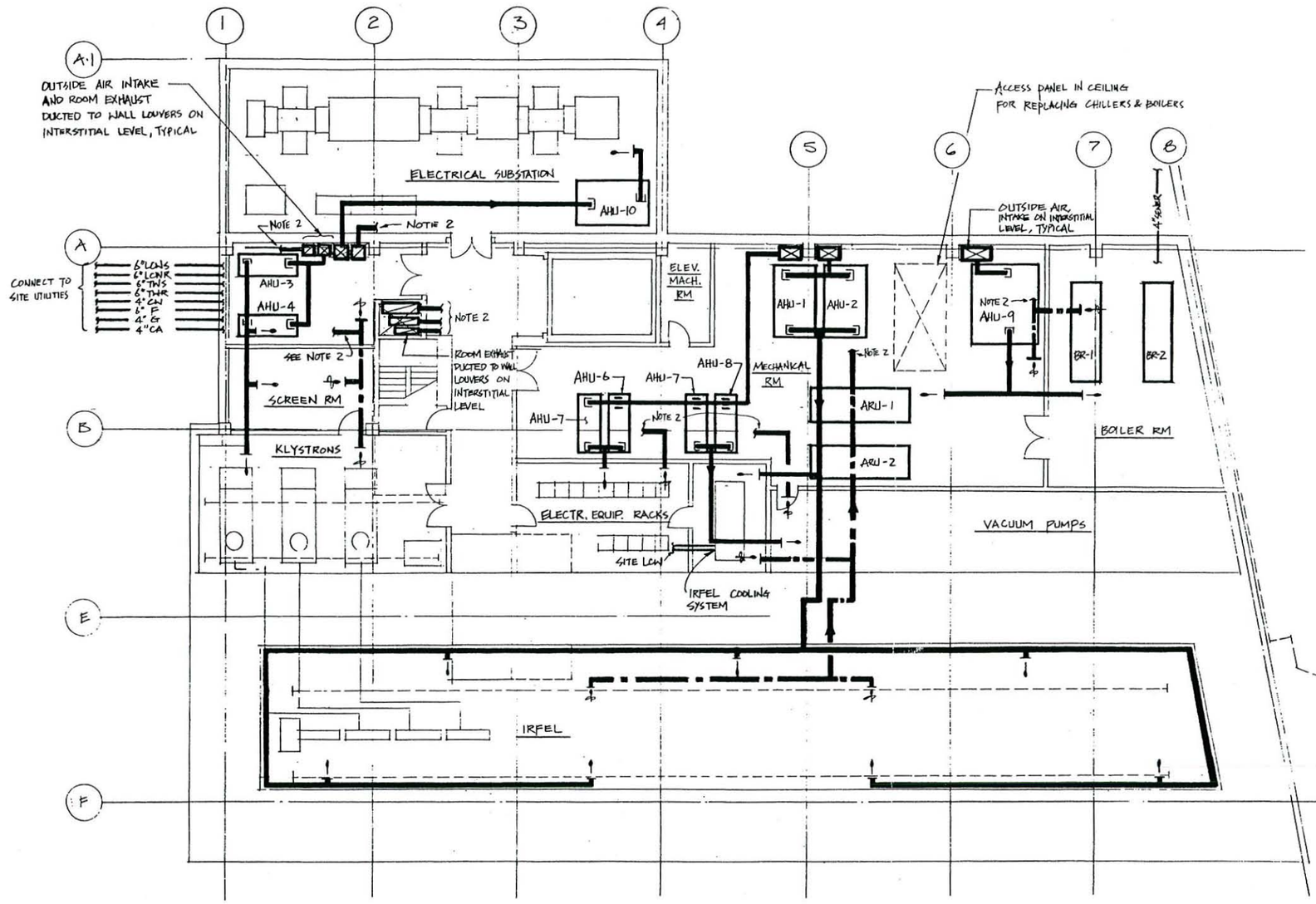
0 10 20 40
FEET

S-8

CHEMICAL DYNAMICS RESEARCH LABORATORY

WALL FRAMING ELEVATIONS & COLUMN SCHEDULE

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



BASEMENT MECHANICAL PLAN

0 5 15 30

N

NOTES:

1. EACH HVAC SYSTEM INCLUDES AIR HANDLING UNIT(S), AIR DUCTS AND ASSOCIATED RETURN/EXHAUST FAN(S). SEE DRAWINGS M-7 AND M-8.
2. THIS DRAWING HAS BEEN PREPARED FOR CONCEPTUAL PRESENTATION; THE RETURN/EXHAUST FAN(S) AND AIR DISTRIBUTION DETAILS ARE NOT SHOWN IN THIS ISSUE.
3. BASEMENT IS USED EXCLUSIVELY FOR BUILDING SERVICES AND EQUIPMENT PLACEMENT.

SYMBOLS & LEGEND:

	SUPPLY AIR
	RETURN / EXHAUST AIR
	RECTANGULAR DUCT CONNECTION DOWN TO EQUIPMENT
	ROUND DUCT CONNECTION DOWN TO EQUIPMENT
	SUPPLY AIR DUCT SECTION
	EXHAUST AIR DUCT SECTION
	RETURN AIR DUCT SECTION
	VARIABLE AIR VOLUME BOX WITH COOLING AND HEATING COILS
AHU	AIR HANDLING UNIT
BL	FAN (EXHAUST OR RETURN/EXHAUST)
CA	COMPRESSED AIR
CW	COLD WATER
F	FIRE WATER
G	NATURAL GAS
IRFEL	INFRARED FREE ELECTRON LASER
LCWR	LOW CONDUCTIVITY WATER RETURN
LCWS	LOW CONDUCTIVITY WATER SUPPLY
TWR	TREATED WATER RETURN
TWS	TREATED WATER SUPPLY

EQUIPMENT SCHEDULE

EQUIPMENT NO.	AREA SERVED	DESCRIPTION
AIR HANDLING UNITS		
AHU-1, 2	IRFEL VAULT	EACH 6,000 CFM, 5 HP, BOTH OPERATING
AHU-3, 4	KLYSTRON / SCREEN ROOMS	EACH 2,500 CFM, 2 HP, BOTH OPERATING
AHU-5, 6	EQUIPMENT RACKS ROOM	EACH 2,500 CFM, 2 HP, BOTH OPERATING
AHU-7, 8	VACUUM PUMP ROOM	EACH 2,500 CFM, 2 HP, BOTH OPERATING
AHU-9	MECHANICAL ROOM	15,000 CFM, 10 HP
AHU-10	ELECTRICAL SUBSTATION	7,500 CFM, 5 HP
BOILERS		
BR-1, 2	HOT WATER FOR BUILDING HEATING AND GENERATING DOMESTIC HOT WATER	GAS-FIRED HOT WATER BOILERS 3,700 KBTUH OUTPUT EACH BOTH OPERATING
CHILLERS		
ARU-1, 2	CHILLED WATER FOR BUILDING COOLING	FACTORY-ASSEMBLED CHILLERS 200 TONS EACH, BOTH OPERATING

M-1

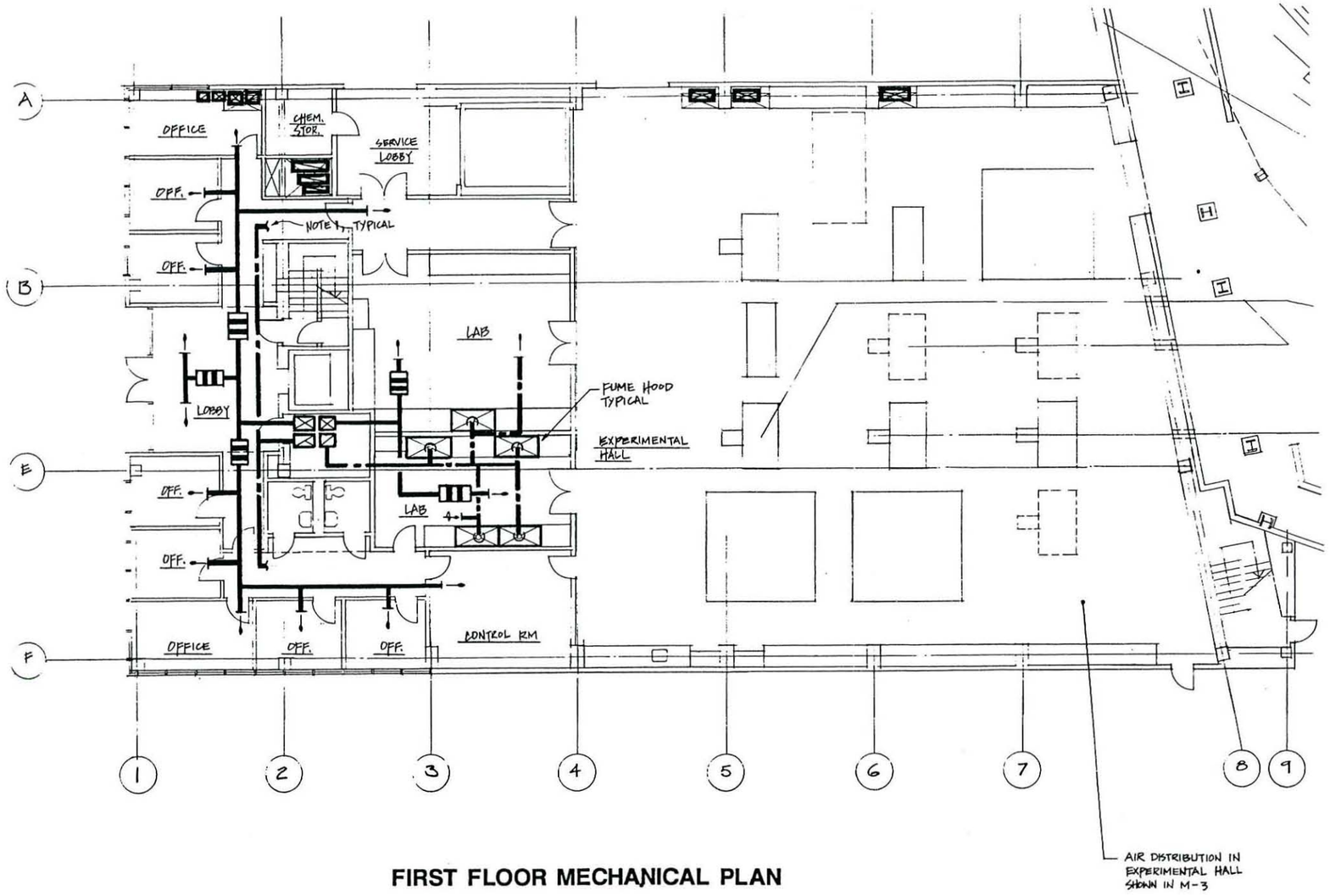
CHEMICAL DYNAMICS RESEARCH LABORATORY

BASEMENT MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

NOTES:

1. FOR GENERAL NOTES, SYMBOLS AND LEGEND, SEE DRAWING M-1.



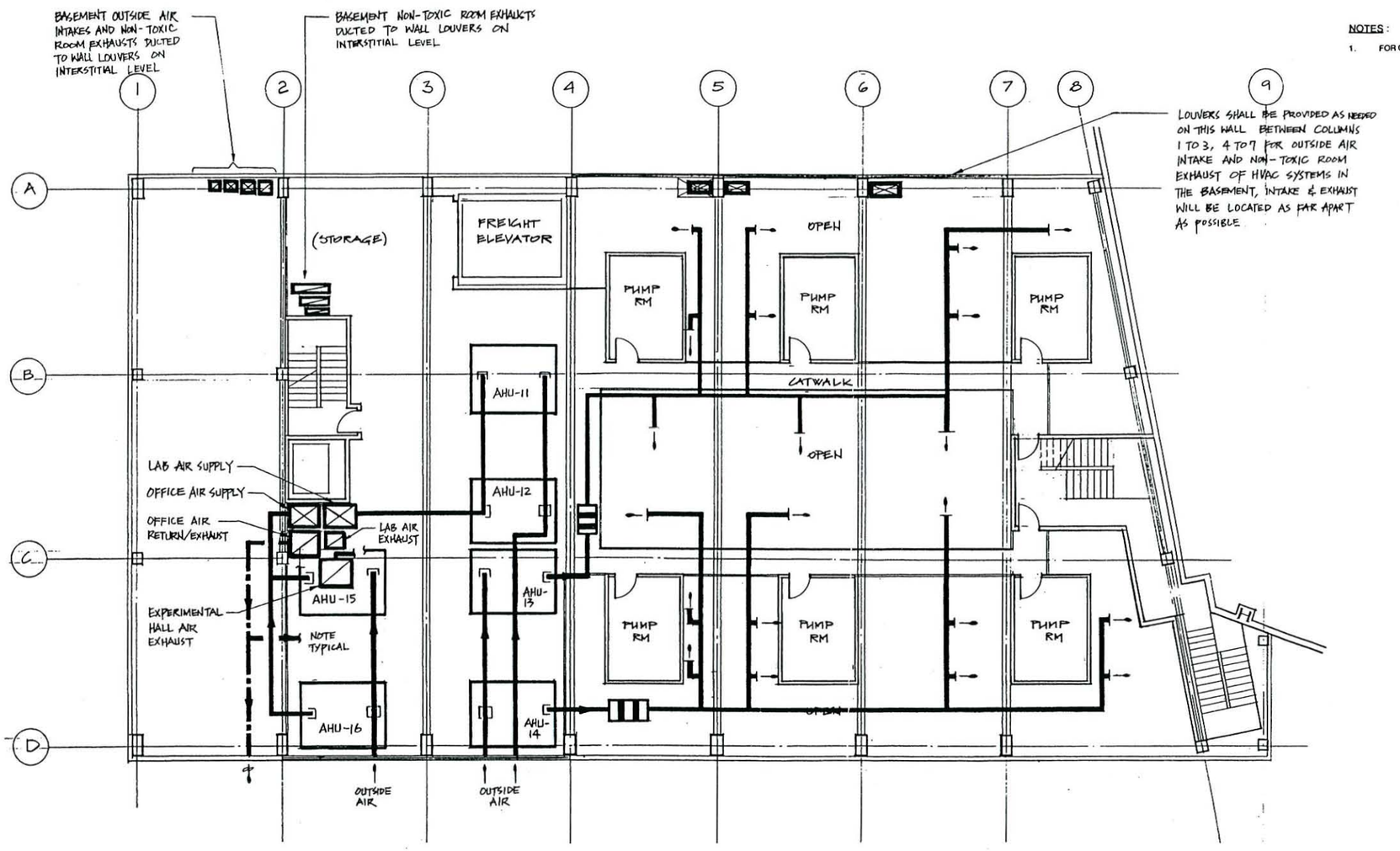
FIRST FLOOR MECHANICAL PLAN

M-2

CHEMICAL DYNAMICS RESEARCH LABORATORY

FIRST FLOOR MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTES:

1. FOR GENERAL NOTES, SYMBOLS AND LEGEND, SEE DRAWING M-1.

INTERSTITIAL LEVEL MECHANICAL PLAN

0 5 15 30

N

EQUIPMENT SCHEDULE

EQUIPMENT NO.	AREA SERVED	DESCRIPTION
AIR HANDLING UNITS		
AHU-11, 12	LABORATORIES	EACH 15,000 CFM, 10 HP, BOTH OPERATING
AHU-13, 14	EXPERIMENTAL HALL	EACH 13,000 CFM, 10 HP, BOTH OPERATING
AHU-15, 16	OFFICES	EACH 13,000 CFM, 15 HP, BOTH OPERATING

M-3

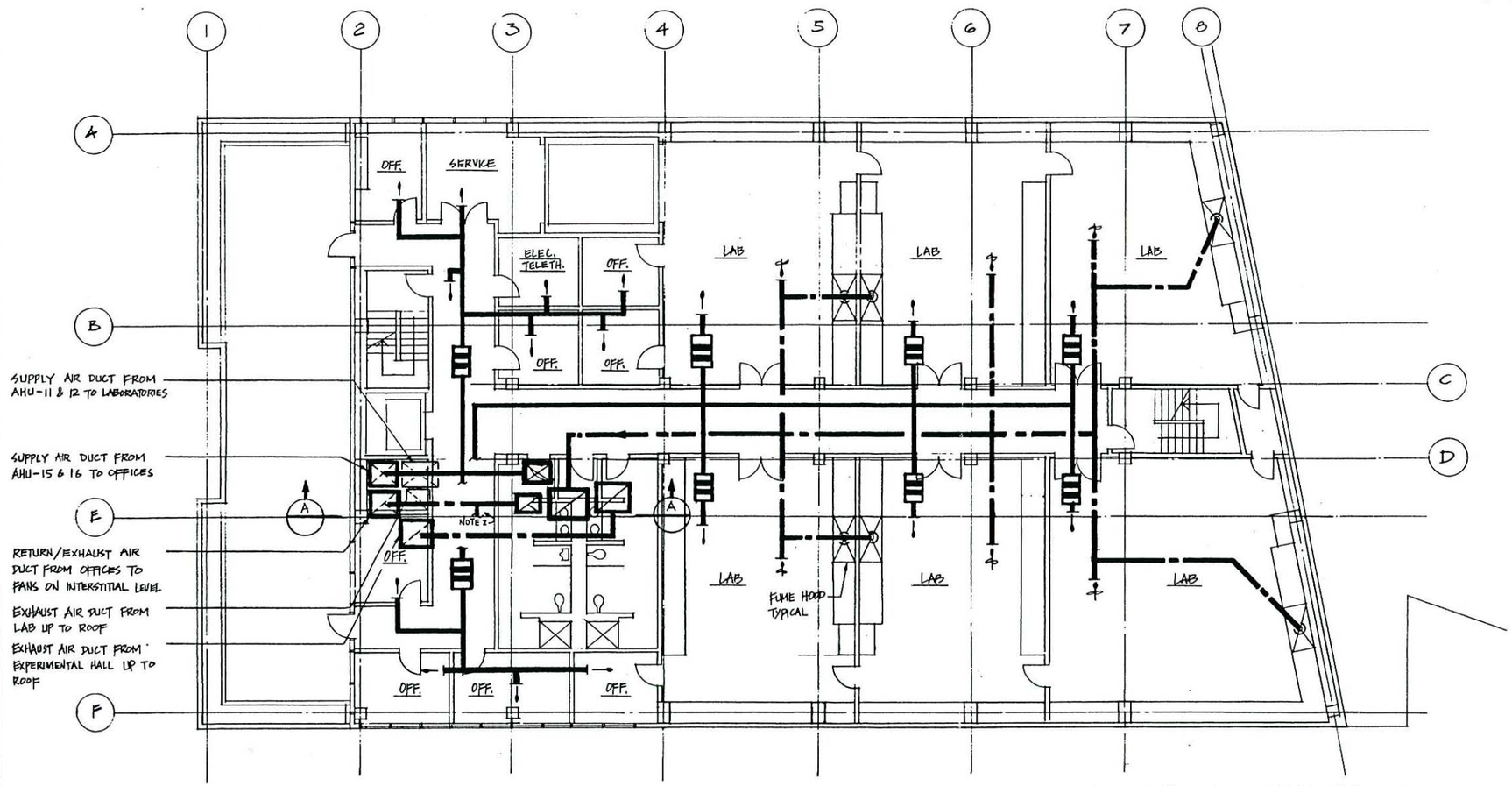
CHEMICAL DYNAMICS RESEARCH LABORATORY

INTERSTITIAL LEVEL MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

NOTES :

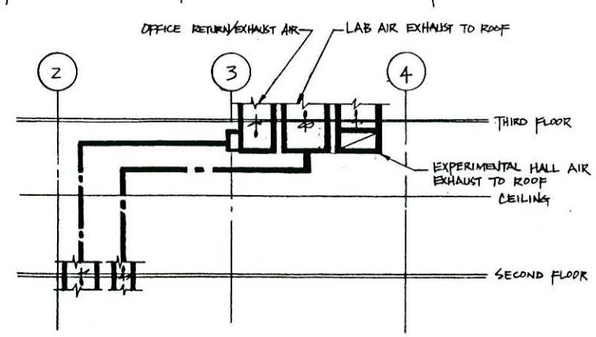
1. FOR GENERAL NOTES, SYMBOLS AND LEGEND, SEE DRAWING M-1.



SECOND FLOOR MECHANICAL PLAN

0 5 15 30

N



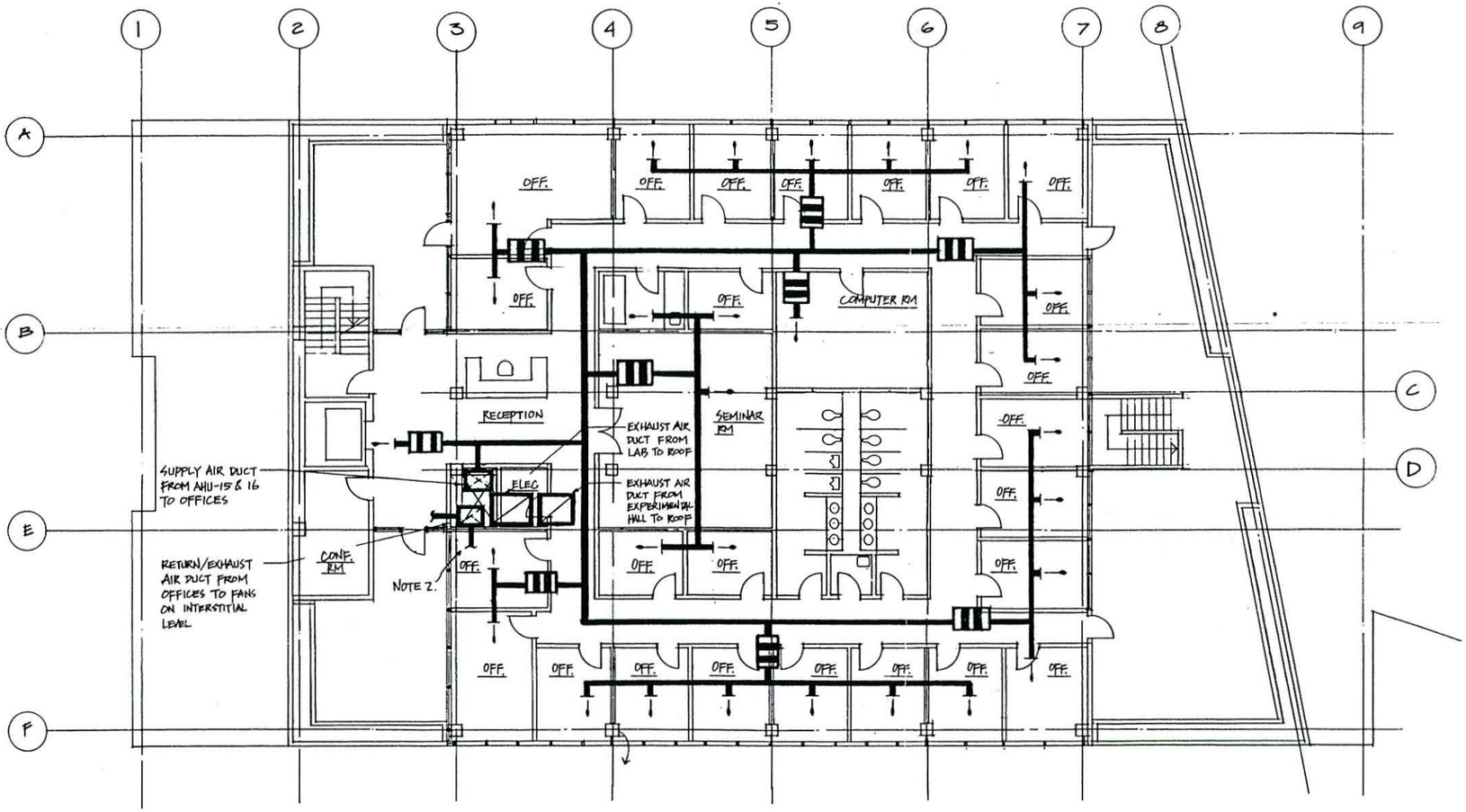
SECTION A-A

M-4

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECOND FLOOR MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



THIRD FLOOR MECHANICAL PLAN

0 5 15 30

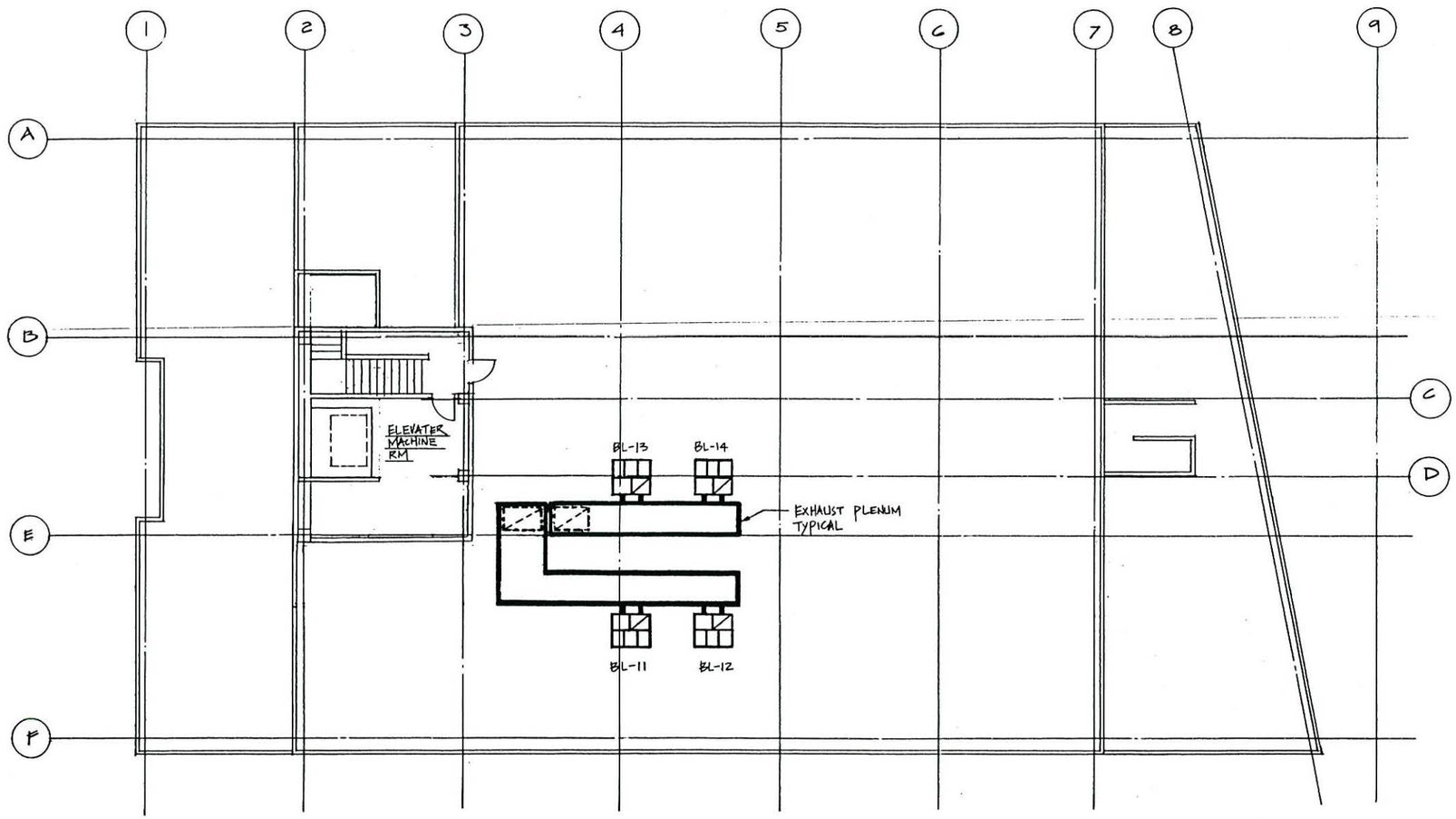
N

M-5

CHEMICAL DYNAMICS RESEARCH LABORATORY

THIRD FLOOR MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



NOTES :

1. FOR GENERAL NOTES, SYMBOLS AND LEGEND, SEE DRAWING M-1.

ROOF MECHANICAL PLAN

0 5 15 30

N

EQUIPMENT SCHEDULE

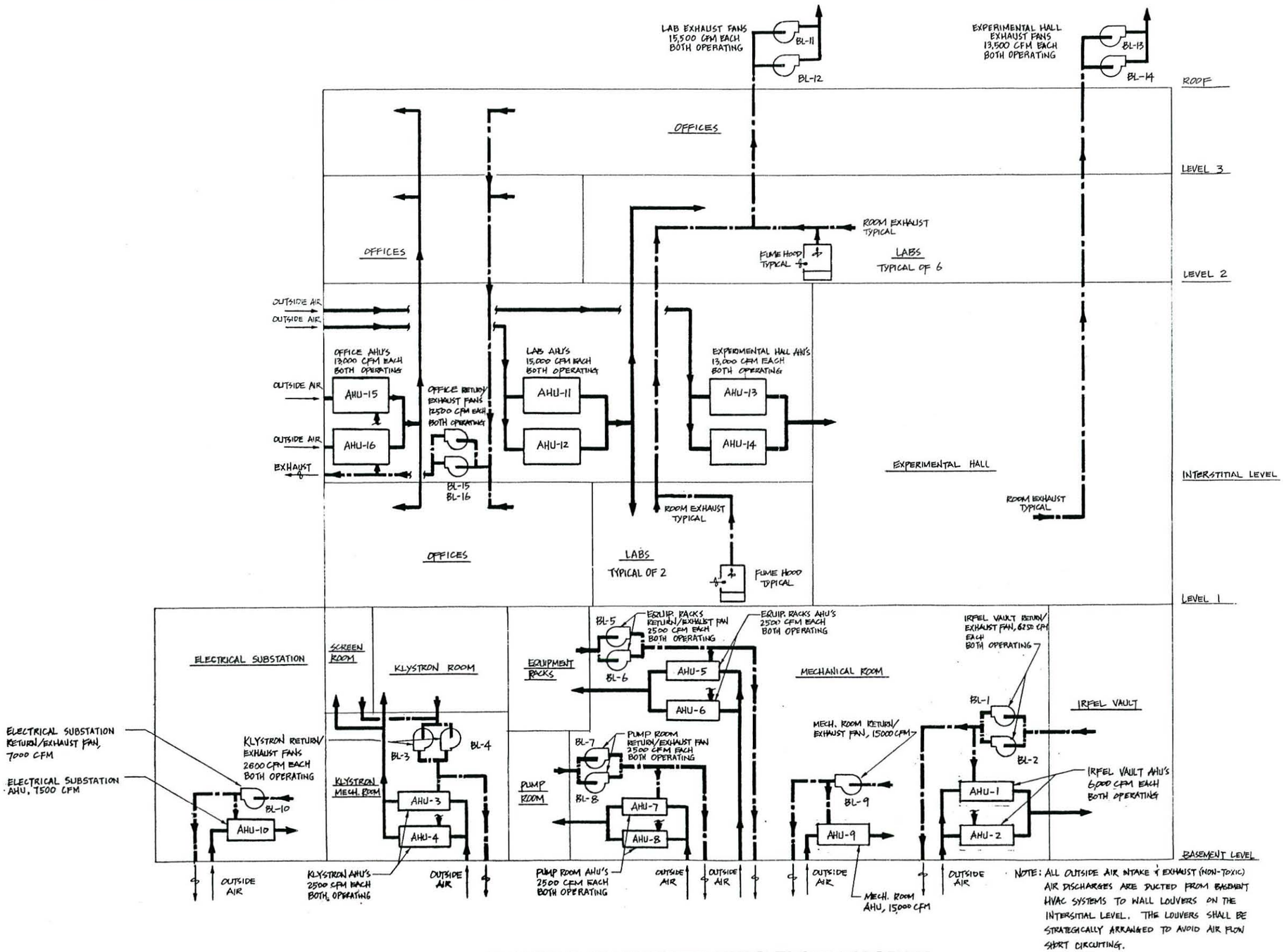
EQUIPMENT NO.	AREA SERVED	DESCRIPTION
EXHAUST FANS		
BL-11, 12	LABORATORIES	EACH 15,500 CFM, 7.5 HP, BOTH OPERATING
BL-13, 14	EXPERIMENTAL HALL	EACH 13,500 CFM, 7.5 HP, BOTH OPERATING

M-6

CHEMICAL DYNAMICS RESEARCH LABORATORY

ROOF MECHANICAL PLAN

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



BUILDING COMPOSITE HVAC FLOW DIAGRAM

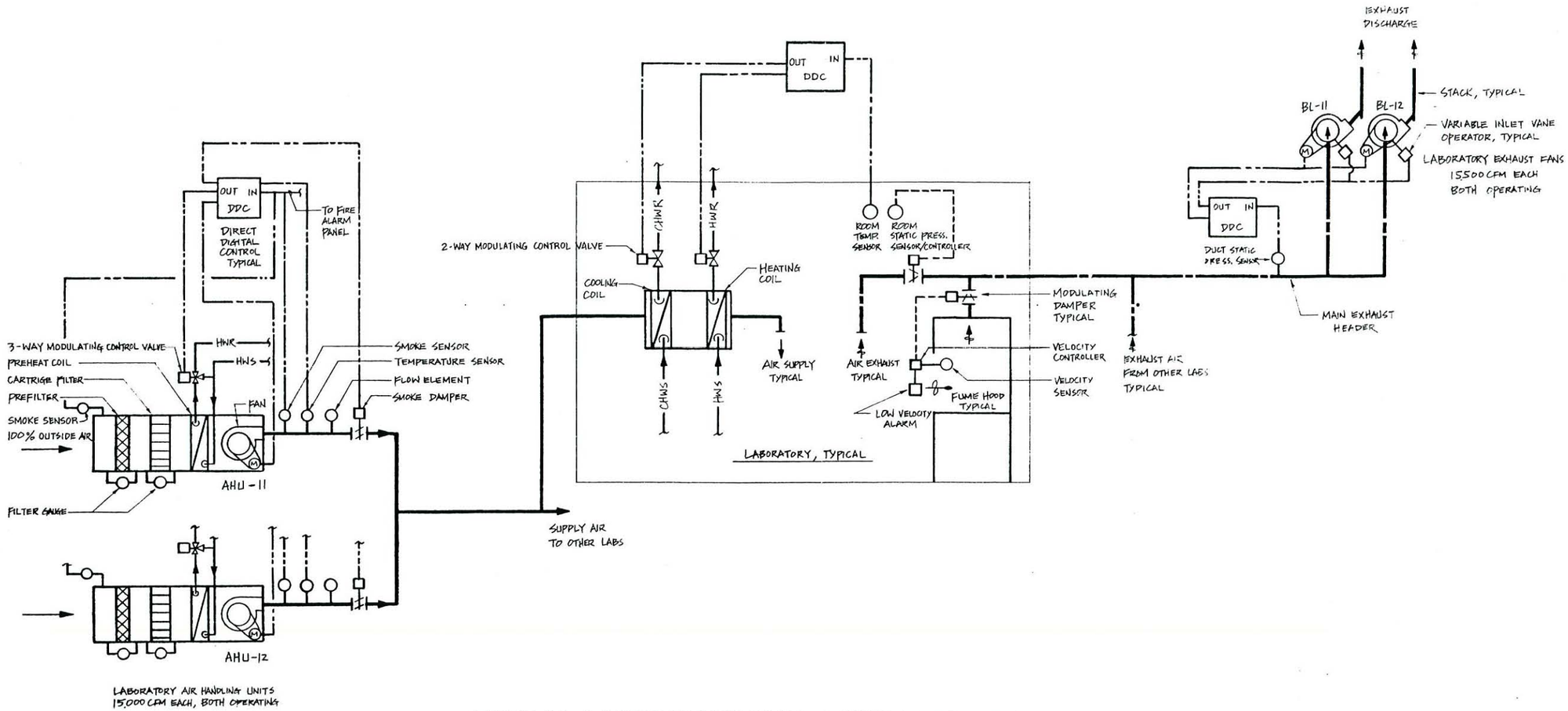
SCALE: NONE

M-7

CHEMICAL DYNAMICS RESEARCH LABORATORY

BUILDING COMPOSITE HVAC FLOW DIAGRAM

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



TYPICAL LABORATORY HVAC CONTROL DIAGRAM

SCALE: NONE

SEQUENCE OF OPERATION

GENERAL
CONTROLS FOR THE EXPERIMENTAL HALL HVAC SYSTEM IS SIMILAR TO THE SYSTEM SHOWN. THE SUPPLY FANS AND EXHAUST FANS SHALL BE ENERGIZED MANUALLY AND SHALL OPERATE CONTINUOUSLY. AIR SUPPLY TO THE AREA SHALL BE CONSTANT VOLUME.

FUME HOOD AIR FLOW CONTROL
THE FUME HOOD FACE VELOCITY SENSOR AND CONTROLLER SHALL MODULATE THE HOOD EXHAUST DAMPER TO MAINTAIN THE DESIRED HOOD FACE VELOCITY.

LABORATORY STATIC PRESSURE CONTROL
SPACE STATIC PRESSURE BETWEEN EACH LABORATORY AND THE ADJACENT CORRIDOR SHALL BE MAINTAINED BY ROOM STATIC PRESSURE SENSOR/CONTROLLER THAT MODULATES THE DAMPER IN THE ROOM AIR EXHAUST DUCT.

DIRECT DIGITAL CONTROLLER (DDC) WITH THE ASSOCIATED STATIC PRESSURE SENSOR IN THE MAIN EXHAUST DUCT HEADER SHALL MODULATE THE VARIABLE INLET VANES IN THE EXHAUST FANS TO MAINTAIN THE DESIRED PRESSURE IN THE MAIN EXHAUST HEADER.

* ALTERNATE CONTROLS
FOR PROJECT COST ESTIMATION, INCLUDE VARIABLE FREQUENCY CONTROLS (VFC) FOR LABORATORIES AND EXPERIMENTAL HALL SUPPLY AND EXHAUST FANS, IN CASE DESIGN IS CHANGED TO A VARIABLE AIR VOLUME SYSTEM.

HEATING
DIRECT DIGITAL CONTROLLER (DDC) WITH THE ASSOCIATED TEMPERATURE SENSOR IN THE MAIN AIR SUPPLY DUCT SHALL MODULATE THE THREE-WAY VALVE ON THE PREHEAT COIL TO MAINTAIN THE SUPPLY AIR AT A DESIRED TEMPERATURE ABOVE FREEZING AND TO PREVENT CONDENSATION ON THE DUCT. FOR EACH LABORATORY, DIRECT DIGITAL CONTROLLER (DDC) WITH THE ASSOCIATED ROOM TEMPERATURE SENSOR SHALL MODULATE THE TWO-WAY VALVE ON THE HEATING COIL TO MAINTAIN THE LABORATORY AT A DESIRED TEMPERATURE.

COOLING
FOR EACH LABORATORY, DIRECT DIGITAL CONTROLLER (DDC) WITH THE ASSOCIATED ROOM TEMPERATURE SENSOR SHALL MODULATE THE TWO-WAY VALVE ON THE COOLING COIL TO MAINTAIN THE LABORATORY AT A DESIRED TEMPERATURE.

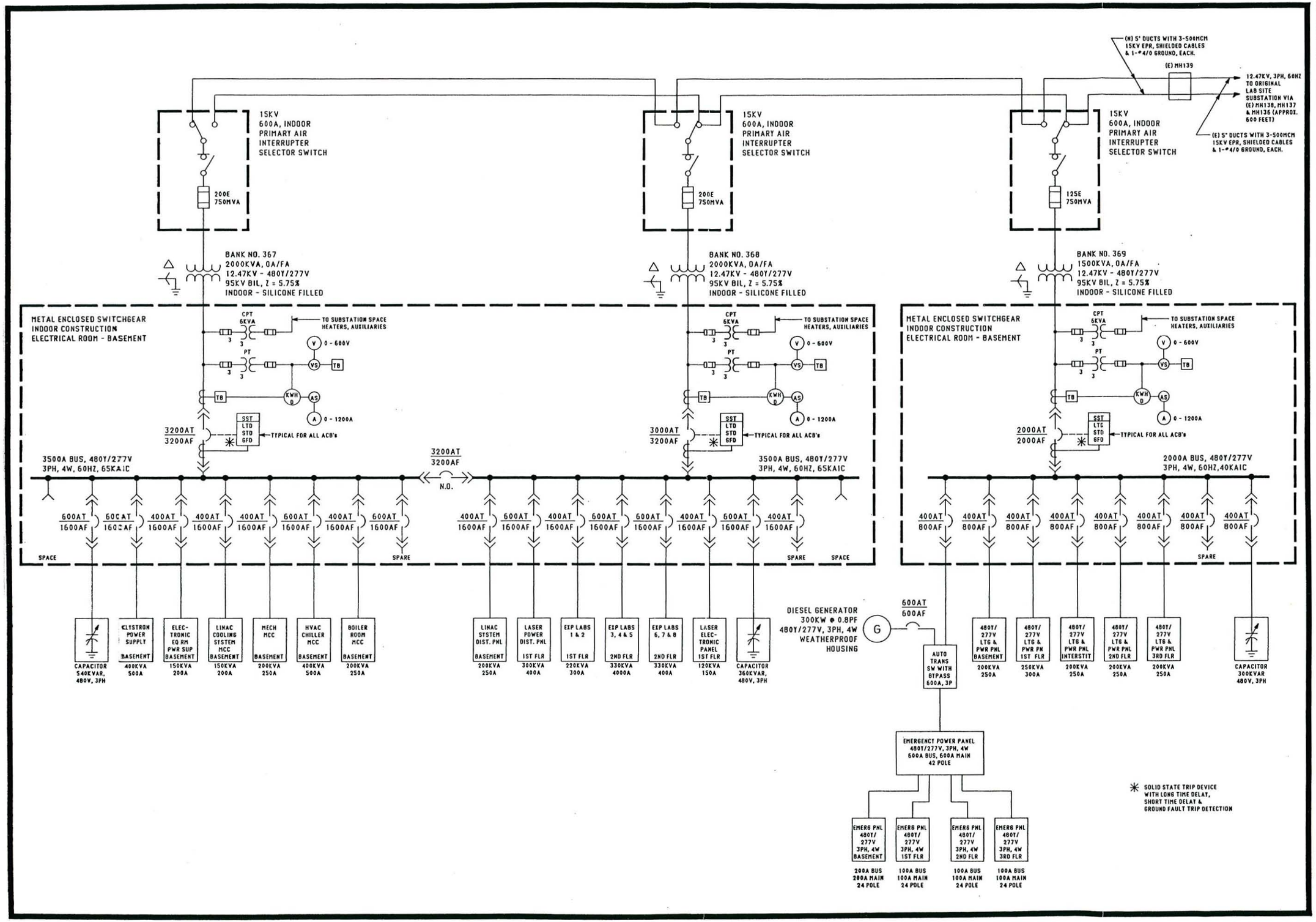
SAFETY
SMOKE SENSORS SHALL BE FURNISHED AT THE INTAKE AND DISCHARGE OF EACH SUPPLY FAN. THE SENSORS SHALL BE INTERLOCKED WITH THE FIRE ALARM PANEL. A SMOKE DAMPER SHALL BE FURNISHED AT THE DISCHARGE OF THE SUPPLY FAN.

THE VELOCITY CONTROLLER IN EACH FUME HOOD SHALL BE EQUIPPED WITH AN ALARM THAT SHALL BE ACTIVATED WHEN THE FUME HOOD FACE VELOCITY FALLS BELOW A SET POINT.

M-8

CHEMICAL DYNAMICS RESEARCH LABORATORY
HVAC CONTROL DIAGRAM

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

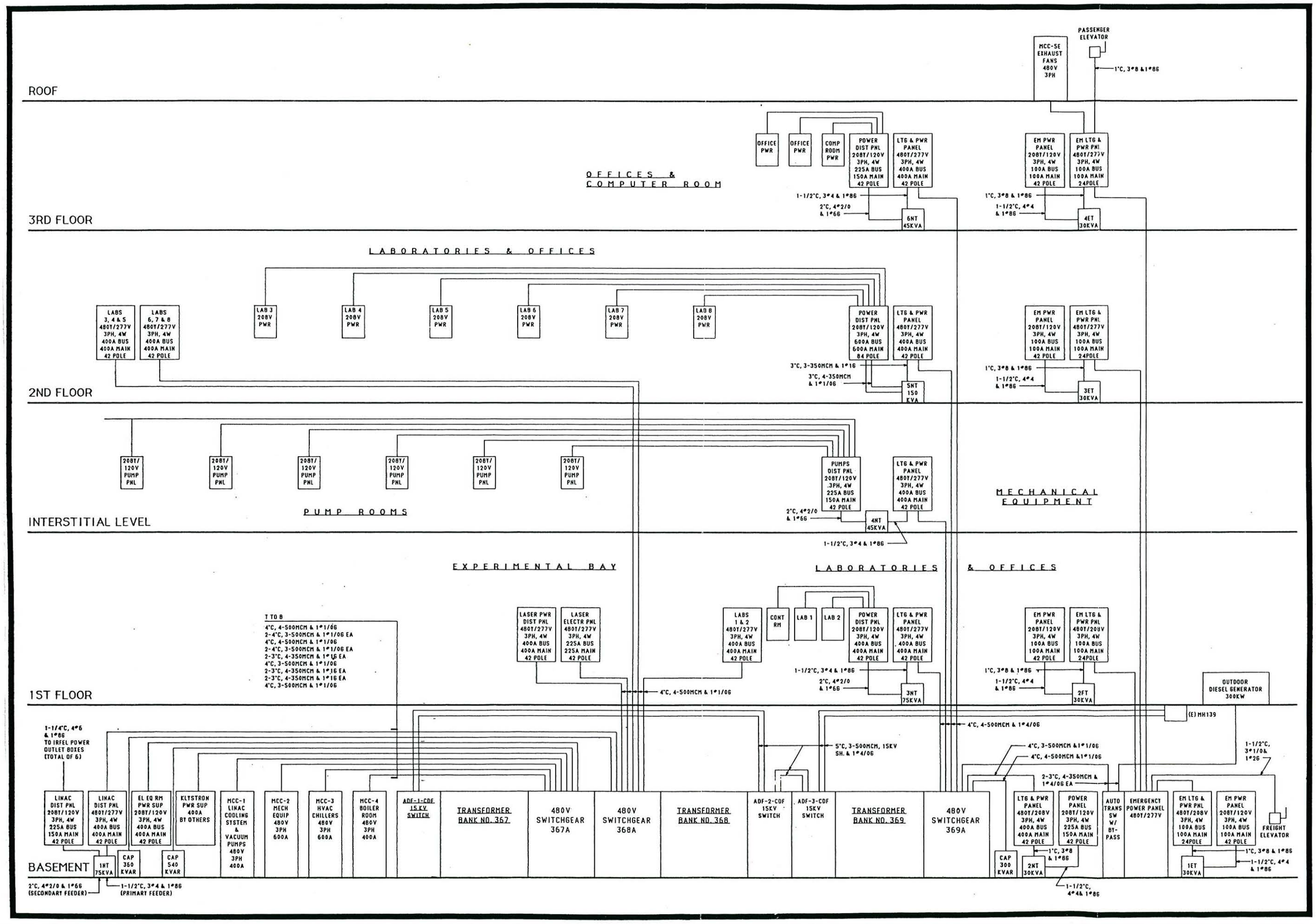


E-1

CHEMICAL DYNAMICS RESEARCH LABORATORY

SINGLE LINE DIAGRAM

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA



E-2

CHEMICAL DYNAMICS RESEARCH LABORATORY

RISER DIAGRAM

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 6

OUTLINE SPECIFICATIONS

Division 0	NOT APPLICABLE	
Division 1	GENERAL REQUIREMENTS	
	01060	Regulatory Requirements
	01200	Project Meetings
	01300	Submittals
	01400	Quality Control
	01510	Temporary Utilities
	01525	Construction Aids
	01530	Barriers
	01590	Field Offices and Sheds
Division 2	SITE WORK	
	02050	Demolition
	02200	Earthwork
	02510	Asphalt Paving
	02600	Pipe Utility Systems
	02605	Manholes
	02710	Site Drainage
	02780	Underground Electrical Utilities
	02810	Landscape Irrigation
	02920	Landscape Grading
	02950	Trees, Plants and Ground Cover
Division 3	CONCRETE	
	03100	Concrete Formwork
	03200	Concrete Reinforcement
	03250	Concrete Accessories
	03300	Cast-In-Place Concrete
Division 4	NOT APPLICABLE	
Division 5	METALS	
	05120	Structural Steel and Miscellaneous Metal
	05310	Steel Deck
	05500	Metal Fabrications

Division 6	WOOD AND PLASTICS	
	06410	Custom Casework
Division 7	THERMAL AND MOISTURE PROTECTION	
	07210	Building Insulation
	07420	Composite Metal Building Panels
	07525	Modified Bitumen Roofing
	07900	Sealants
Division 8	DOORS AND WINDOWS	
	08110	Steel Doors and Frames
	08213	Plastic Faced Wood Doors
	08331	Overhead Coiling Doors
	08520	Aluminum Windows
	08710	Door Hardware
	08800	Glazing
Division 9	FINISHES	
	09110	Metal Stud Framing System
	09260	Gypsum Board System
	09310	Ceramic Tile
	09330	Quarry Tile
	09510	Suspended Acoustical Ceilings
	09650	Resilient Flooring
	09680	Carpet
	09730	Elastomeric Liquid Flooring
	09900	Painting
Division 10	SPECIALTIES	
	10100	Chalkboards and Tackboards
	10160	Metal Toilet Compartments
	10210	Metal Wall Louvers
	10800	Toilet and Bath Accessories
Division 11	EQUIPMENT	
	11660	Laboratory Equipment
Division 12	FURNISHINGS	
	12510	Horizontal Louver Blinds

Division 13	SPECIAL CONSTRUCTION	
	13810	Energy Monitoring and Control System—New Construction
Division 14	CONVEYING SYSTEMS	
	14200	Elevators
Division 15	MECHANICAL	
	15010	Basic Mechanical Requirements
	15260	Piping Insulation
	15290	Ductwork Insulation
	15310	Fire Protection Piping
	15325	Sprinkler Systems
	15410	Plumbing Piping
	15510	Hydronic Piping
	15540	HVAC Pumps
	15559	Steel Water Tube Boilers
	15684	Centrifugal Water Chillers
	15855	Air Handling Units with Coils
	15860	Centrifugal Fans
	15890	Ductwork
	15990	Testing, Adjusting and Balancing
Division 16	ELECTRICAL	
	16010	Basic Electrical Requirements
	16111	Conduit
	16114	Cable Tray
	16121	Medium Voltage Cable
	16123	Wire and Cable
	16170	Grounding and Bonding
	16311	Secondary Unit Substations
	16321	Distribution Transformers
	16410	Automatic Power Factor Correction
	16461	Dry Type Transformers
	16470	Panelboards
	16480	Motor Control Centers
	16481	Variable Frequency Drives
	16500	Lighting
	16700	Communications
	16721	Fire Alarm Detection Systems
	16915	Lighting Control System

SECTION 01060: REGULATORY REQUIREMENTS

A. Codes and Design References

1. Codes listed in Section 2 should be included in the construction specifications; codes and references shall be latest editions except where specifically noted otherwise.

2. Design Standards

   a. Earthwork

      1) Standard Specification, State of California, Department of Transportation, Division of Highways.

      2) ASTM standards for compaction.

   b. Concrete

      1) ACI-318 Building Code Requirements for Reinforced Concrete.

      2) ACI-347 Recommended Practice for Concrete Formwork.

      3) CRSI Manual of Standard Practice.

   c. Concrete Reinforcement

      1) ACI-301 Specification for Structural Concrete for Buildings.

      2) ACI-315 Manual of Standard Practice for Detailing Reinforced Concrete.

      3) ACI-318 Building Code Requirements for Reinforced Concrete.

      4) CRSI 59 Recommended Practice for Placing Reinforcing Rods.

      5) CRSI 63 Recommended Practice for Placing Bar Supports, Specifications and Nomenclature.

      6) ASTM Standards.

      7) AWS D12.1 Reinforcing Steel Welding Code.

d. Structural Steel

1) AISC Standard Specifications for the Design, Fabrication, and Erection of Structural Steel for Buildings.

2) AISC Code of Standard Practice for Steel Buildings and Bridges.

3) AWS Structural Welding Code D1.1.

4) AISC Specification for Structural Joints Using ASTM A325 or A490 Bolts.

5) ASTM Standards.

6) SSPC Steel Structures Painting Council.

e. Metal Decking

1) Steel Deck Institute - SDI Standard #1.

2) AISI Specification for the Design of Light Gauge, Cold Formed, Steel Structural Members.

3) American Welding Society Standards.

SECTION 01200: PROJECT MEETINGS

A. Preconstruction conference.

B. Billing meetings, at the last progress meeting each month.

C. Periodic progress meetings, twice each month.

D. Guarantees, bonds, and service and maintenance Subcontracts meetings.

SECTION 01300: SUBMITTALS

A. Schedules

1. Progress schedule.

2. Proposed cash-flow schedule.

3. Schedule of values.

4. Submittal schedule.

B. Product list.

C. Shop drawings, product data, and samples.

D. Certificates of compliance.

SECTION 01400: QUALITY CONTROL

A. Soils engineer's services.

B. Testing laboratory's services.

C. Testing agency's services.

SECTION 01510: TEMPORARY UTILITIES

A. Provide the following temporary utilities as part of the work of this Subcontract:

1. Heat and ventilation.
2. Sanitary facilities.
3. Telephone service.
4. Fire protection.

B. Water will be provided by the University.

SECTION 01525: CONSTRUCTION AIDS

A. Provide the following construction aids as part of the work of this Subcontract:

1. Construction elevators and hoists.
2. Temporary enclosures.
3. Swing staging.
4. Scaffolding and platforms.

SECTION 01530: BARRIERS

A. Fences.

B. Tree and plant protection.

C. Barricades.

SECTION 01590: FIELD OFFICES AND SHEDS

A. Field offices and sheds may be specially constructed for the work of this Subcontract, or they may be portable or mobile buildings.

DIVISION 2 - SITE WORK

SECTION 02050: DEMOLITION

PART 1 GENERAL

1.01 WORK INCLUDED

A. Removal of existing building as required to install the new work as shown on the drawings.

B. Protection of existing facilities remaining operational during the construction.

C. Removal of debris and off-site disposal.

D. Dust and noise control.

E. Salvage of existing items as directed by the University.

PART 3 EXECUTION

3.01 DEMOLITION REQUIREMENTS

A. Cutting of concrete or asphalt shall be done by power saw in sharp straight lines.

B. Exact location of utilities shall be field verified and due caution shall be exercised when working in or about these areas.

SECTION 02200: EARTHWORK

PART 1 GENERAL

1.01 WORK INCLUDED

A. Earthwork shall include all excavation, fill, and backfill, as well as site mobilization. Work also encompasses fine grading for pads and walls, street coarse preparation, backfilling of trenches, foundations, and retaining walls, and placement of base materials for slabs on grade and roadways.

B. All earthwork and related testing shall conform to ASTM standards.

C. Testing will be done by an independent laboratory selected by the Lawrence Berkeley Laboratory.

D. Shoring and lagging shall be the responsibility of the Subcontractor.

PART 2 PRODUCTS

2.01 MATERIALS

A. Base material under slabs on grade and roadways shall be Class 2 aggregate base/subbase, conforming to specifications of the State of California Division of Highways.

B. Backfill behind all retaining walls shall be previous materials.

C. All backfill shall be nonexpansive material, free of deleterious materials and large rocks. Materials of suitable composition excavated on site may be utilized as backfill material when approved by the Geotechnical Engineer.

PART 3 EXECUTION

A. All fill and backfill shall be compacted to a relative density of 90% (modified proctor) maximum optimum density. A relative density of 95% (modified proctor) of maximum optimum density will be required in areas so designated on the construction documents.

B. All temporary and finished cut slopes shall be configured as recommended by a Geotechnical Engineer familiar with the site geology.

C. Backfill shall be compacted by impact and/or vibration methods.

SECTION 02510: ASPHALT PAVING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Work includes all new paving and patch paving for roadways, pathways, curbs, roadside swales, and access driveways.

B. Materials, including paving materials, shall conform to the Standard Specifications of the State of California, Division of Highways.

PART 2 PRODUCTS

2.01 MATERIALS

A. Asphalt concrete surfacing shall consist of a two-inch minimum layer of Type B aggregate 85-100% penetration, steam-refined asphalt.

B. Penetration prime coat, asphalt paint binder, and seal coat shall conform to the standard specifications.

PART 3 EXECUTION

3.01 GENERAL REQUIREMENTS

A. Batching, placing, and compacting of asphalt concrete surfacing shall conform to the Standard Specifications.

SECTION 02600: PIPE UTILITY SYSTEMS

PART 1 GENERAL

1.01 GENERAL SCOPE

Plug existing utility lines, provide new relocated lines and new building service lines for the following piped utility systems:

A. Water (potable, industrial and fire): Ductile iron per ANSI A21.51, thickness Class 50, mortar lined per ANSI 421.4 with rodded and clamped joints.

B. Sanitary sewer: Cast iron soil pipe, vitrified clay or PVC drainage piping.

C. Compressed air: Black steel pipe, coated and wrapped.

D. Natural gas (high pressure): Polyethylene (PE) plastic pipe.

E. Low conductivity water: PVC pressure piping (Class 150) or aluminum piping.

F. Treated water: PVC pressure piping (Class 150).

SECTION 02605: MANHOLES

PART 1 GENERAL

1.01 WORK INCLUDED

A. Manholes and handholes for below-ground electrical and telephone service.

PART 2 PRODUCTS

2.01 MATERIALS

A. Precast or cast-in-place reinforced concrete boxes, sectional type manholes, and handholes for underground service, complete with cast iron cover, neck, ladders, cable racks and traffic lids.

PART 3 EXECUTION

3.01 INSTALLATION

A. Install manholes on a 6-inch base of crushed rock. Backfill around manholes shall be compacted sand to allow for drainage.

SECTION 02710: SITE DRAINAGE

PART 1 GENERAL

1.01 WORK INCLUDED

A. Work includes concrete-lined interceptor trench drains, installation of perforated pipe subsurface drains, erosion control sedimentation traps and basins, storm-water inlet structures and junction boxes, and all storm-water conduits.

PART 2 PRODUCTS

2.01 MATERIALS

A. Perforated pipe shall be corrugated galvanized pipe with a bituminous coating.

B. Manholes shall be precast heavy-duty type. Manhole sections, including riser sections, cones, and grade rims, shall conform to ASTM C-478 Specifications. Manhole frames and covers will sustain standard H-20 wheel loadings.

C. Catch basins, field inlet, and junction boxes shall be cast-in-place units. Precast units may be substituted as specified on the plans or as approved by the engineer. All lids and grading will sustain H-20 wheel loading for boxes susceptible to such loading.

D. Storm drain shall be cast iron soil pipe, concrete pipe or PVC drainage piping. Storm-water piping at depths greater than four feet or contained within a private street right of way shall be reinforced concrete pipe.

PART 3 EXECUTION

3.01 INSTALLATION

A. All piping shall be installed in sand-bedded trenches.

B. All piping installation shall be inspected before backfilling.

SECTION 02780: UNDERGROUND ELECTRICAL UTILITIES

PART 1 GENERAL

1.01 WORK INCLUDED

A. Furnish all labor supervision, materials, equipment, tools, transportation, and services required to disconnect, provide temporary services, install, tie in, relocate, and test existing high-voltage electrical/telephone conduits and related appurtenances.

PART 2 PRODUCTS

2.01 MATERIALS

A. New duct banks and related appurtenances.

B. Manholes and junction boxes.

C. Conduit.

D. Transmission cable as specified in Division 16, Electrical.

PART 3 EXECUTION

3.01 GENERAL REQUIREMENTS

A. Existing electrical/telephone conduit systems shall be relocated or adjusted to grade per the Lawrence Berkeley Laboratory Standard Specifications.

SECTION 02810: LANDSCAPE IRRIGATION

PART 1 GENERAL

1.01 WORK INCLUDED

A. Pipe and fittings, valves, outlets, bubblers, and accessories.

B. Connection to utilities.

C. Control system.

1.02 SYSTEM DESCRIPTION

A. Electric solenoid controlled underground irrigation system, with drain.

PART 2 PRODUCTS

2.01 MATERIALS

A. Pipe: PVC OR ABS.

B. Outlets: Bronze.

C. Spray Type Sprinkler Head: Pop-up head.

SECTION 02920: SOIL PREPARATION

PART 1 GENERAL

1.01 WORK INCLUDED

A. Final grade topsoil for finish landscaping.

PART 2 PRODUCTS

2.01 MATERIALS

A. Topsoil: Imported friable loam.

SECTION 02950: TREES, PLANTS AND GROUND COVER

PART 1 GENERAL

1.01 WORK INCLUDED

A. Trees.

B. Plants.

C. Ground cover.

SECTION 03100: CONCRETE FORMWORK

PART 2 PRODUCTS

2.01 MATERIALS

A. Form Lumber: Douglas fir, construction grade.

B. Plywood Forms: Douglas fir plywood, Grade B-B, Class 1, exterior type, 5/8 inch thick maximum.

C. Form Sealer: Nonbonding and nonstaining.

D. Form Accessories: Standard types, as required.

SECTION 03200: CONCRETE REINFORCEMENT

PART 2 PRODUCTS

2.01 MATERIALS

A. Reinforcing Steel: ASTM A615, Grade 40 for No. 4 bars and smaller, Grade 60 for No. 5 bars and larger.

B. Welded-Wire Fabric: ASTM A185 or ASTM A497.

C. Tie Wire: No. 16 AWG or heavier, black annealed.

D. Spirals: ASTM A82.

SECTION 03250: CONCRETE ACCESSORIES

PART 2 PRODUCTS

2.01 MATERIALS

A. Expansion-Joint Fillers

1. Exposed Joints: ASTM D1751.

2. Sealed Joints: ASTM D1752.

B. Water Stops: Preformed polyvinyl chloride, "Hydrocide Vinylstop," manufactured by Sonneborn-Contect, or equal.

PART 2 PRODUCTS

2.01 MATERIALS

A. Portland Cement Concrete

1. Compressive Strength, 28-day minimum

   a. All concrete: 4,000 psi.

2. Portland Cement: ASTM C150, Type II.

3. Aggregates: ASTM C33. Coarse aggregates shall be either granite or limestone.

4. Water: Clean and potable.

5. Admixtures: ASTM C494 or C290, as approved.

B. Concrete Curing

1. Liquid Membrane-Forming Compound: ASTM C309, Type I.

2. Sheet Materials: ASTM C171.

3. Clean, nonstaining burlap.

C. Patching Mortar: Concrete materials, except with coarse aggregate omitted.

D. Grout

1. Regular: Concrete materials, except with coarse aggregate omitted.

2. Metallic Nonshrink: "Embeco 153," manufactured by Master Builders, or approved equal.

PART 3 EXECUTION

3.01 CRACK CONTROL

For concrete sections over three feet (3'-0") thick the temperature gradient between the center and the surface of the section must not exceed 20°F during the first 10 days. Thermocouples are to be placed in the center and six inches (6") from the surface at several locations along the length of each thick concrete placement and at the corners. The thermocouples are to be monitored continuously and if the temperature gradient exceeds 20°F, insulating blankets shall be placed over the surface (on surfaces with protruding reinforcing, such as

the top of a wall, loose insulation will be used.) A three foot test cube of the concrete mix for the thick sections will be instrumented with thermocouples and monitored to determine whether the heat of hydration exceeds 150°F. If the temperature exceeds 150°F, standard aggregate cooling will be utilized and the mix retested.

SECTION 05120: STRUCTURAL STEEL AND MISCELLANEOUS METAL

PART 2 PRODUCTS

2.01 MATERIALS

A. All structural steel and miscellaneous metal, unless otherwise specified: ASTM A36.

B. Pipe: ASTM A53, Type S, Grade B.

C. High-Strength Bolts: ASTM A325.

D. Standard Bolts and Nuts: ASTM A307, Grade A.

E. Washers for Standard Bolts: ANSI B27.2 and B27.4.

F. Welding Electrodes: E70.

G. Welding: Shielded-arc method.

H. Galvanizing

1. Structural shapes and plates: ASTM A123.

2. Hardware and threaded components: ASTM A153.

I. Primer: Solvent-based, inorganic zinc paint.

SECTION 05310: STEEL DECK

PART 2 PRODUCTS

2.01 MATERIALS

A. H. H. Robertson Co., Inc., 3" deep x 3'-0" wide, or equal, conforming to ASTM A446 steel sheet, zinc coated, hot-dipped galvanizing, Grade A.

SECTION 05500: METAL FABRICATIONS

PART 2 PRODUCTS

2.01 MATERIALS

A. Prefabricated Stairs: Concrete filled metal pan stair construction with tubular steel railings.

B. Wall-Mounted Railings: Vinyl-covered aluminum extrusions, color as scheduled.

C. Metal Guardrails: Welded tubular steel as detailed, primed for paint.

D. Steel Bollards: Round steel tubes filled with concrete, embedded in concrete.

E. Catwalk Grating: Galvanized steel or aluminum.

SECTION 06410: CUSTOM CASEWORK

PART 1 GENERAL

1.01 WORK INCLUDED

A. Special fabricated cabinet units.

B. Countertops.

C. Cabinet hardware.

1.02 QUALITY ASSURANCE

A. Perform work in accordance with AWI Premium.

PART 2 PRODUCTS

2.01 MATERIALS

A. Cabinet Work: Flush overlay design. Plastic laminate on all exposed surfaces. Interior surfaces and edges to be finished with "Guardian Liner" or acceptable alternate.

2.02 CABINET HARDWARE

A. Hinges.

B. Shelf Brackets.

C. Drawer and Door Pulls.

D. Catches.

E. Drawer Slides.

PART 3 EXECUTION

2.01 Installation

A. Secure cabinet to floor and wall using appropriate angles and anchorages.

SECTION 07210: BUILDING INSULATION

PART 2 PRODUCTS

2.01 MATERIALS

A. Inorganic glass-fiber or mineral-fiber blankets, foil-faced.

B. Polystyrene insulation board, tapered.

SECTION 07420: COMPOSITE METAL BUILDING PANELS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Preformed wall metal panel siding system, related flashings and accessory components.

1.02 SYSTEM DESCRIPTION

A. Preformed and prefinished composite metal building panel system of horizontal profile.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Mor-Wal Panel Y36.

B. ASC Pacific HR-36.

2.02 MATERIALS

A. Galvanized Steel: Zinc coating; shop finished with fluorocarbon coating.

B. Internal and External Corners: Same material, thickness and finish as exterior sheets, profile to suit system to maintain continuity of profile.

C. Trim, Closure Pieces, Caps, Flashings: Same material, thickness and finish as exterior sheets; brake formed to required profiles.

2.03 FINISH

A. Exposed Exterior and Interior Surfaces: Color from manufacturer's standard range.

SECTION 07525: MODIFIED BITUMEN ROOFING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Insulation, membrane roofing and base flashings.

1.02 SYSTEM DESCRIPTION

A. Modified Bitumen Conventional Roofing System: Two-ply mineral surface cap sheet membrane system over rigid insulation.

PART 2 PRODUCTS

2.01 MANUFACTURERS - MEMBRANE MATERIALS

A. Garland Company.

B. Tarmac Roofing, Inc.

2.02 MATERIALS

A. Membrane: Asphalt and polymer modifiers (APP) A60+MILS.

B. Sheet Materials: Polyester felts; asphalt saturated and coated inorganic base sheet.

C. Bituminous Materials: Asphalt bitumen; asphalt primer.

D. Base Flashings: Flexible sheet flashing, modified bitumen; asphalt impregnated wood fiberboard fiber cant and tapered edge strips.

E. Insulation: Roof deck rigid insulation, tapered.

F. Surfacing: Mineral cap sheet.

SECTION 07900: SEALANTS

PART 2 PRODUCTS

2.01 MATERIALS

A. General Exterior Building Sealing: Two-component gun-grade non-sag rubber-based elastomeric; FS TT-S-00227E, Type II, Class A.

B. Traffic-Bearing Horizontal Surfaces: Two-part puncture-resistant polyurethane, durometer hardness 25 to 50 after 14 days.

C. Interior Building Sealing, Except as Otherwise Specified: Single-component gun-grade paintable acrylic-latex water-based; WOODMONT "Chem-Calk 600" or approved equal.

D. Acoustical Sealing: Permanently plastic non-skinning paintable synthetic-polymer-based; PRESSTITE "No. 579.64 Acoustical Sealant" or approved equal.

E. Sanitary Sealing: FS TT-S-001543A, Class A single-component primerless flexible mildew-resistant silicone rubber; DOW-CORNING "Dow-Corning Silicone Rubber Bathtub Caulk," Catalog no. 8640, or approved equal.

F. Sealant Backup: Compatible with sealant material.

DIVISION 8 - DOORS AND WINDOWS

SECTION 08110: STEEL DOORS AND FRAMES

PART 1 GENERAL

1.01 WORK INCLUDED

A. Hollow metal doors.

B. Rolled steel frames.

C. Interior light frames.

D. Louvers.

PART 2 PRODUCTS

2.01 MATERIALS

A. Doors: Flush construction, formed steel sheets, 18-gage.

B. Frames: Cold or hot rolled sheet steel, 16-gage. One piece welded construction.

C. Finish: Baked-on zinc chromate primer; baked enamel finish.

SECTION 08213: PLASTIC FACED WOOD DOORS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Interior plastic faced wood doors.

B. Louvers.

PART 2 PRODUCTS

2.01 MATERIALS

A. Doors: Flush face, solid core construction, fire rated.

SECTION 08331: OVERHEAD COILING DOORS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Fire rated overhead coiling doors, operating hardware, electric operation.

1.02 SYSTEM DESCRIPTION

A. Electric motor operated unit with manual override in case of power failure.

B. Fire rated door fusible link activated with automatic governed closing speed.

C. Within a framed opening.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Cookson.

B. Kinnear.

2.02 MATERIALS

A. Curtain: Fire rated, insulated, hot dipped galvanized steel interlocking flat face slats.

B. Electric Operator: Heavy-duty hoist-type totally enclosed gearhead motor, mechanical self-adjusting brake.

C. Curtain Finish: Precoated paint finish.

SECTION 08520: ALUMINUM WINDOWS

PART 1 General

1.01 WORK INCLUDED

A. Extruded aluminum windows with operating sash.

B. Glass and glazing.

C. Operating hardware and insect screens.

1.02 SYSTEM DESCRIPTION

A. Windows with top hinged outward projecting sash.

B. Exterior glazing.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Blomberg.

B. Fentron.

2.02 MATERIALS

A. Extruded aluminum.

2.03 FINISHES

A. Factory applied resinous coating.

SECTION 08710: DOOR HARDWARE

PART 1 GENERAL

1.01 WORK INCLUDED

A. Hardware for wood and hollow metal doors.

B. Thresholds.

C. Gasketting.

PART 2 PRODUCTS

2.02 MANUFACTURERS

A. Schlage.

B. Yale.

SECTION 08800: GLAZING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Glass and glazing.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Pittsburgh Plate Glass.

B. Libbey-Owens-Ford Co.

2.02 MATERIALS

A. Float glass.

B. Safety glass fully tempered.

C. Tinted heat absorbing and light reducing glass, color green ("SOLEX" by PPG).

SECTION 09110: METAL STUD FRAMING SYSTEM

PART 1 GENERAL

1.01 WORK INCLUDED

A. Formed metal stud framing.

B. Framing accessories.

1.02 SYSTEM DESCRIPTION

A. Metal stud framing for exterior wall infill.

B. Metal stud framing system for interior walls.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Dale Industries.

B. U.S. Gypsum.

SECTION 09260: GYPSUM BOARD SYSTEM

PART 1 GENERAL

1.01 WORK INCLUDED

A. Gypsum board.

B. Taping and joint treatment.

1.02 SYSTEM DESCRIPTION

A. Acoustic attenuation interior partitions.

B. Fire rated interior partitions and shaft walls.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. United States Gypsum.

B. Genstar.

2.02 MATERIALS

A. Gypsum board, 5/8 inch thick.

B. Type "X" fire rated gypsum board, 5/8 inch thick.

C. Moisture resistant gypsum board, 5/8 inch thick.

SECTION 09310: CERAMIC TILE

PART 1 GENERAL

1.01 WORK INCLUDED

A. Ceramic tile floor and base finish using the setting bed method.

B. Ceramic tile wall finish using the thin set method.

C. Thresholds at door openings.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Crown.

B. American Olean.

2.02 MATERIALS

A. Ceramic floor tile.

B. Ceramic wall tile.

C. Cove base to match floor tile.

D. Marble thresholds.

SECTION 09330: QUARRY TILE

PART 1 GENERAL

1.01 WORK INCLUDED

A. Quarry paver tile floor and base finish using the setting bed application method.

B. Thresholds at door openings.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Quarry Tile Co.

B. Murry.

2.02 MATERIALS

A. Quarry Tile.

B. Base to match paver.

SECTION 09510: SUSPENDED ACOUSTICAL CEILINGS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Suspended metal grid ceiling system.

B. Acoustical tiles and panels.

C. Lateral bracing of ceiling system.

D. Fire rated assembly with gypsum board boxes over light fixtures.

E. Perimeter trim.

PART 2 PRODUCTS

2.01 MANUFACTURERS - SUSPENSION SYSTEM

A. Donn Products.

B. Chicago Metallic.

2.02 MANUFACTURERS - ACOUSTICAL TILE

A. Armstrong.

B. Celotex.

SECTION 09650: RESILIENT FLOORING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Resilient sheet and tile flooring.

B. Resilient base.

C. Resilient stair nosings, treads and risers.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Armstrong.

B. Gaf.

2.02 MATERIALS

A. Vinyl Sheet Flooring.

B. Vinyl Composition Tile, 12 inches x 12 inches.

C. Vinyl Tile, 12 inches x 12 inches.

D. Rubber Tile, 12 inches x 12 inches.

E. Rubber Base, four (4) inches high.

SECTION 09680: CARPET

PART 1 GENERAL

1.01 WORK INCLUDED

A. Carpet finish using glue down method.

SECTION 09730: ELASTOMERIC LIQUID FLOORING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Fluid applied polyurethane elastometric flooring.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. 3M Company.

2.02 MATERIALS

A. Base Coat: Fluid applied polyurethane, standard color as selected.

B. Top Coat: Fluid applied polyurethane, clear color.

SECTION 09900: PAINTING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Surface preparation.

B. Surface finish schedule.

C. Color selection schedule.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Pratt and Lambert.

B. Fuller O'Brien.

SECTION 10100: CHALKBOARDS AND TACKBOARDS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Liquid chalkboards.

B. Tackboards.

PART 2 PRODUCTS

2.01 MATERIALS

A. Tackboard Covering: Vinyl coated fabric.

SECTION 10160: METAL TOILET COMPARTMENTS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Metal toilet compartments, ceiling hung.

B. Urinal screens, wall mounted.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Knickerbocker Products Corp.

B. Sanymetal Products Co., Inc.

2.02 MATERIALS

A. Steel, baked enamel finish.

B. Hardware: Chrome plated non-ferrous cast pivot hinges, gravity type, adjustable for door close positioning.

SECTION 10210: METAL WALL LOUVERS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Louvers and frames.

B. Bird and insect screens.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Airolite.

B. Construction Specialties, Inc.

2.02 MATERIALS

A. Louvers and Frames: Extruded aluminum, factory applied resinous coating.

B. Screens: Interwoven aluminum wire mesh, factory applied vinyl coating.

SECTION 10800: TOILET AND BATH ACCESSORIES

PART 1 GENERAL

1.01 WORK INCLUDED

A. Toilet and washroom accessories, recessed.

B. Attachment hardware.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Bobrick.

2.02 MATERIALS

A. Stainless Steel Sheet: ASTM A167, Type 304.

B. Tubing: stainless steel.

2.03 FINISH

A. Stainless Steel: satin luster finish.

SECTION 11660: LABORATORY EQUIPMENT

PART 1 GENERAL

1.01 WORK INCLUDED

A. Laboratory benches, wall cabinets, fume hoods, chemical storage cabinets; shop manufactured.

B. Installation including connection to utilities.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Hamilton.

B. Duralab.

2.03 MATERIALS

A. Sheet steel.

B. Plastic laminate.

C. Laminate backing sheets.

SECTION 12510: HORIZONTAL LOUVER BLINDS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Horizontal slat louver blinds.

B. Mounting accessories.

C. Operating hardware.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Levolor.

2.02 MATERIALS

A. Louvers: Aluminum one inch wide horizontal slats, factory applied plastic coating finish.

SECTION 13810: ENERGY MONITORING AND CONTROL SYSTEM - NEW CONSTRUCTION

PART 1 GENERAL

1.01 SECTION INCLUDES: FURNISH AND INSTALL

A. Building Automation System.

B. Software.

1.02 SYSTEM DESCRIPTION

A. The purpose of the project is control the "on/off" operation of specific lighting and air conditioning systems and to monitor the space temperature in selected rooms. The means of accomplishing this is through the installation of a fully distributed processing Building Automation System (BAS) with both supervisory control and Direct Digital Control (DDC) capabilities for automation of building energy-using systems, including heating, ventilation, air conditioning, and individual room lighting "occupancy sensors" to control the operation of the lighting. The sensors are interconnected to the digital inputs and outputs of the Energy Monitoring Control System (EMCS) to monitor and control the on/off operation of the HVAC units based on room occupancy.

B. The BAS shall be a fully independent programmable control system with full energy monitoring control and data acquisition capabilities, and remote communications capability for remote programming, monitoring, manual override, remote alarm indication and logging, and automatic collection and processing of historical data.

PART 2 PRODUCTS

2.01 EMCS MANUFACTURER

A. Barrington Systems StarView™ 4000, to match existing, provided by the Subcontractor and installed by the Subcontractor. The University has purchased a 'site-wide' license for Barrington Systems StarVIEW 4000™ software.

PART 3 EXECUTION

3.01 EMCS INSTALLATION

A. The Subcontractor shall install one or more field processing units (FPUs) and any required input/output interface devices, all in appropriate enclosures. Subcontractor shall provide and install all appropriate

appurtenances, devices and terminate wiring from the input/output subsystem and shall perform a comprehensive acceptance inspection and test, and prove connection and function for all input/output subsystem components. The EMCS Subcontractor shall develop, install, test, tune and prove, and thoroughly document all applications programs.

3.02 EMCS FIELD SERVICES

A. Perform a comprehensive acceptance inspection and test of all installation details and system operational validity, including but not limited to; inspection and verification of input/out sensor locations, control device location and connection, input/output point terminations, point-by-point proof of function for each input/output, and functional test of all application software.

SECTION 14200: ELEVATORS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Passenger Elevator: Geared traction, 3,000 lbs capacity, three stops.

B. Service Elevator: Oil hydraulic, 10,000 lbs capacity, four stops.

C. Elevator cars with two doors.

D. Hoistway entrances.

E. Machine room and hoistway equipment.

F. Signals and fixtures.

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Montgomery.

B. Westinghouse.

DIVISION 15 - MECHANICAL

SECTION 15010: BASIC MECHANICAL REQUIREMENTS

1.01 SECTIONS INCLUDE

Basic Mechanical Requirements specifically applicable to Division 15 Sections, in addition to Division 1 - General Requirements.

1.02 WORK BY UNIVERSITY

1.03 UNIVERSITY FURNISHED PRODUCTS

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A. Products furnished to the site and paid for by UNIVERSITY.

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1. Centrifugal chillers.

2. Hot water boilers, etc.

1.04 REFERENCES

1.05 SUBMITTALS

A. Submit under provisions of Section 01300, Submittals.

B. Proposed products list.

C. Submit shop drawings and product data grouped to include complete submittals of related systems, products, and accessories in a single submittal.

D. Mark dimensions and values in units to match those specified.

1.06 REGULATORY REQUIREMENTS

A. Building codes.

B. Fire protection codes.

C. Plumbing codes.

SECTION 15260: PIPING INSULATION

PART 1 GENERAL

1.01 WORK INCLUDED

A. Piping insulation.

B. Jackets and accessories.

PART 2 PRODUCTS

2.01 MATERIALS

A. Glass fiber insulation; 'k' value of 0.24 at 75°F; noncombustible.

B. Hydrous calcium silicate; rigid white; asbestos free; 'k' value of 0.44 at 300°F.

C. Cellular foam for chilled water pipes; flexible, plastic; 'k' value of 0.28 at 75°F.

D. Jackets

1. Interior applications

a. Vapor barrier jackets: Kraft reinforced foil vapor barrier with self-sealing adhesive joints.

b. PVC Jackets: One piece, premolded type.

c. Canvas jackets: UL listed treated cotton fabric, six (6) oz/sq yd.

2. Exterior Applications: aluminum jackets, 0.020 inch thick; smooth finish.

E. Accessories

1. Insulation Bands: 3/4 inch wide; 0.015 inch thick aluminum.

2. Metal Jacket Bands: 3/8 inch wide; 0.015 inch thick aluminum.

3. Fibrous Glass Cloth: Untreated; nine (9) oz/sq yd weight.

PART 3 EXECUTION

3.01 PREPARATION

A. Install materials after piping has been tested and approved.

3.02 INSTALLATION

A. Install materials in accordance with manufacturer's instructions.

B. Continue insulation with vapor barrier through penetrations.

C. In exposed piping, locate insulation and cover seams in least visible locations.

3.03 SCHEDULE

Piping	Pipe Size Inch	Type	Insulation Thickness Inch
Hot Water Supply (Domestic and Industrial)			
Chilled Water Supply and Return			
Heating Water Supply and Return			
Condenser Water (Treated Water)			

SECTION 15290: DUCTWORK INSULATION

PART 1 GENERAL

1.01 WORK INCLUDED

A. Ductwork insulation.

B. Insulation jackets.

PART 2 PRODUCTS

2.01 MATERIALS

A. Flexible glass fiber: Commercial grade; 'k' value of 0.29 at 75°F, foil scrim facing.

B. Indoor jacket: Presized glass cloth, minimum 7.8 oz/sq. yd.

C. Outdoor jacket: Coated glass fiber sheet, 30 lb/sq yd.

D. Vapor barrier jackets: Kraft reinforced foil vapor barrier with self-sealing adhesive joints.

E. Impale anchors: Galvanized steel, 12-gage, self-adhesive pad.

F. Tie wire: Annealed steel, 16-gage.

PART 3 EXECUTION

3.01 PREPARATION

A. Install materials after ductwork has been tested and approved.

B. Clean surfaces for adhesives.

3.02 INSTALLATION

A. Install materials in accordance with manufacturer's instructions.

B. Provide insulation with vapor barrier when air conveyed may be below ambient temperature.

C. Continue insulation with vapor barrier through penetrations.

3.03 SCHEDULE

Ductwork	Insulation Thickness Inch
(List by system)	

SECTION 15310: FIRE PROTECTION PIPING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Pipes, fittings, valves, and connections for standpipe and fire hoses.

PART 2 PRODUCTS

A. Sprinkler and standpipe piping, buried.

B. Sprinkler and standpipe piping, above ground.

C. Valves.

PART 3 EXECUTION

3.01 PREPARATION

3.02 INSTALLATION

SECTION 15325: SPRINKLER SYSTEMS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Wet-pipe sprinkler system.

B. System design, installation, and certification.

C. Fire Department connections.

PART 2 PRODUCTS

2.01 SPRINKLER HEADS

A. Suspended Ceiling: Concealed pendant type with matching escutcheon plate.

B. Exposed Area Type: Standard upright type with guard.

C. Sidewall Type: Horizontal sidewall type with matching escutcheon plate.

2.02 PIPING SPECIALTIES

A. Valves.

B. Alarms.

C. Water Flow Switch.

D. Excess Pressure Pump.

E. Fire Department connection.

PART 3 EXECUTION

3.01 PREPARATION

3.02 INSTALLATION

3.03 SYSTEM SCHEDULE

Location	System Type/Hazard
Offices	
Laboratories	
Computer Room	
IRFEL Vault	
Klystron Room	
Mechanical Rooms	

SECTION 15410: PLUMBING PIPING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Pipe and Pipe Fittings.

B. Valves.

PART 2 PRODUCTS

A. Sanitary sewer pipes, buried and above grade.

B. Domestic water pipes, buried and above grade.

C. Natural gas pipes, buried and above grade.

D. Fuel oil piping, buried and above grade.

E. Valves.

PART 3 EXECUTION

3.01 PREPARATION

3.02 INSTALLATION

3.03 APPLICATION

SECTION 15510: HYDRONIC PIPING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Pipes and pipe fittings.

B. Valves.

PART 2 PRODUCTS

A. Heating water pipes.

B. Chilled water pipes.

C. Condenser water and treated water pipes.

D. Low conductivity water pipes.

E. Deionized water pipes.

F. Flanges, unions and couplings.

G. Valves.

PART 3 EXECUTION

3.01 PREPARATION

3.02 INSTALLATION

3.03 APPLICATION

SECTION 15540: HVAC PUMPS

PART 1 GENERAL

1.01 WORK INCLUDED

A. In-line circulators.

B. Close coupled pumps.

C. Base mounted pumps.

PART 2 PRODUCTS

A. Type.

B. Casing.

C. Impeller.

D. Bearings.

E. Shaft.

F. Seal.

G. Drive and Motor.

SECTION 15559: STEEL WATER TUBE BOILERS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Water heating boiler, low pressure atmospheric natural gas fired.

PART 2 PRODUCTS

A. Boiler shell.

B. Hot water boiler trim.

C. Fuel burning system: gas train consistent with the Lawrence Berkeley Laboratory standards.

D. Control panel, consistent with the Lawrence Berkeley Laboratory standards.

E. Performance.

SECTION 15684: CENTRIFUGAL WATER CHILLERS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Factory assembled packaged chillers.

PART 2 PRODUCTS

A. Chiller Package.

B. Compressors.

C. Evaporators.

D. Condensers.

E. Purge System.

F. Controls.

SECTION 15855: AIR HANDLING UNITS WITH COILS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Packaged air handling units.

B. Fabricate draw-through type air handling units suitable for medium pressure operation.

C. Fabricate units with filter, coil section, fan plus accessories.

PART 2 PRODUCTS

A. Casing.

B. Mixing Boxes and Dampers.

C. Filters.

D. Coils.

E. Fans.

SECTION 15860: CENTRIFUGAL FANS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Backward inclined centrifugal fans.

PART 2 PRODUCTS

A. Housing.

B. Wheel and Inlet.

C. Motors and Drivers.

D. Belt Guards.

E. Access Doors.

F. Scroll Drains.

G. Accessories.

SECTION 15890: DUCTWORK

PART 1 GENERAL

1.01 WORK INCLUDED

A. Definition of low pressure ducts.

B. Definition of medium pressure ducts.

C. Definition of high pressure ducts.

D. Fibrous glass ducts.

PART 2 PRODUCTS

A. Materials, general.

B. Low pressure ducts.

C. Medium pressure ducts.

D. High pressure ducts.

E. Fibrous glass ducts.

PART 3 EXECUTION

3.01 INSTALLATION

3.02 CLEANING AND ADJUSTING

SECTION 15990: TESTING, ADJUSTING AND BALANCING

PART 1 GENERAL

1.01 WORK INCLUDED

A. Testing, adjustment, and balancing of HVAC systems.

B. Testing, adjustment, and balancing of hydronic systems.

C. Sound measurement of equipment operating conditions.

D. Vibration measurement of equipment operating conditions.

E. References

1. AABC - National Standards for Field Measurement and Instrumentation, Total System Balance.

2. ASHRAE - Systems Handbook: Testing, Adjusting and Balancing.

F. Submittals: Submit reports on AABC National Standards for Total System Balance forms.

DIVISION 16 - ELECTRICAL

SECTION 16010: BASIC ELECTRICAL REQUIREMENTS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Two new 15kV vacuum circuit breakers at the Original Labsite Substation.

B. New electrical duct bank, containing four to five inch conduits, from electrical manhole No. 138 to the CDF substation.

C. Two new 15kV feeder cables, with 1-500 MCM per phase + 1-#4/0 ground, from the Original Labsite Substation to the CDF substation.

D. Three 12.47kV to 480 volt transformer power centers (2-2,000 kVA and 1-1,500 kVA).

E. 480 volt power feeders between CDF substation and building 480 volt distribution system.

F. 480/270 volt and 208/120 volt distribution panels.

G. Interior power distribution system for experimental and normal building power.

H. Emergency power system with 300 kW diesel-generator.

I. Electrical system grounding and equipment grounding.

J. Power wiring to mechanical equipment.

K. Interior and exterior lighting, including emergency egress lighting.

L. Cables and raceways for the Lawrence Berkeley Laboratory Integrated Communication System (ICS).

M. Paging system equipment.

N. Building fire protection and alarm system.

O. Extensions to existing fire alarm system.

P. Power wiring for major research equipment.

Q. Rights-of-way and cable trays for experimental equipment control and instrumentation.

R. Wiring for Energy Monitoring and Control System.

SECTION 16111: CONDUIT

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Interior conduits, installed concealed whenever possible: 3/4 inch minimum electrical metallic tubing (EMT).

B. Conduit in floor slab or under floor: 3/4 inch minimum hot-dip galvanized, rigid steel.

C. Power and communication branch circuit conduits, below grade: Plastic, Carlon PVC, schedule 40, (Rigid steel conduit shall be used for 12kV ductbank located adjacent to a communication ductbank.

SECTION 16114: CABLE TRAY

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Interior wireways, for communication cables running down each hallway and connecting to the telephone closets: 8 inches x 8 inches minimum, lay-in square duct.

B. Interior wireways, for experimental equipment power, control and instrumentation cables in the IRFEL tunnel, and experimental hall and running down each hallway and connecting to laboratories: 12 inches x 4 inches minimum, aluminum ladder tray.

C. Laboratory Cable Trays: Aluminum, ladder tray, nine (9) inches wide.

SECTION 16121: MEDIUM-VOLTAGE CABLE

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Primary feeders: Three single conductor, copper, 15kV, shielded, 133% insulation level, ethylene propylene rubber (EPR) insulation with chlorinated polyethylene jacket.

SECTION 16123: WIRE AND CABLE

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Secondary, copper wire, 600 volts or less: No. 12 AWG minimum size for power wiring. Use No. 14 AWG for control wiring, No. 16 AWG for security, paging and fire alarm.

B. Conductors

1. No. 12 AWG and smaller: Solid copper.

2. No. 10 AWG and larger: Stranded copper.

C. Wire Types

1. No. 6 AWG and smaller: Type THWN.

2. No. 4 AWG and larger: Type THW or THWN.

SECTION 16170: GROUNDING AND BONDING

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Grounding System Resistance: five (5) ohms.

B. Conform to requirements of ANSI/NFPA 70.

C. Furnish products listed and classified by Underwriters' Laboratories (UL), Inc. as suitable for purpose specified and shown.

D. Provide service ground at main circuit breaker section of low-voltage switchgear.

E. Ground secondary neutral point of all transformers.

F. Provide building column grounding.

G. Ground all electrical equipment enclosures.

H. Provide a separate ground system for the IRFEL Klystrons and equipment.

SECTION 16311: SECONDARY UNIT SUBSTATIONS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Incoming section with high voltage, fused disconnect switch.

B. Transformer section.

C. Low voltage switchgear section.

1.02 INCOMING SECTION EQUIPMENT

A. Description: Air interrupter switch, selector switch.

B. Configuration: Two incoming lines, looped.

C. System Voltage: 12.47kV, three-phase, 60Hz.

D. Maximum Design Voltage: 15kV.

E. Basic Impulse Level: 95kV.

1.03 TRANSFORMER SECTION EQUIPMENT

A. Description: Oil-immersed type distribution transformer.

B. Refer to Section 16321, Distribution Transformers.

1.04 LOW VOLTAGE SWITCHGEAR EQUIPMENT

A. Description: 480/277 Volt, three-phase, four wire, indoor, metal enclosed, dead front power switchgear manufactured to NEMA SG 5.

B. Bus Material: Copper, sized in accordance with NEMA PB 2.

C. Power Circuit Breakers: NEMA SG 5; factory-assembled mechanically-operated, low-voltage air circuit breakers, drawout construction. Include electronic sensing, timing and tripping circuits for adjustable current, long-time pickup and long-time delay; ground-fault pickup and delay; adjustable instantaneous pickup; short-time pickup and delay. Ground fault sensing shall be integral with circuit breaker.

1.05 MAIN BREAKER SECTION INSTRUMENTS

A. Ammeters.

B. Voltmeter.

C. Ammeter Transfer Switch.

D. Voltmeter Transfer Switch.

E. Watt-hour Demand Meters.

SECTION 16321: DISTRIBUTION TRANSFORMERS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Liquid filled distribution and power transformers.

B. Transformers shall be designed and tested in accordance with the applicable ANSI/IEEE, NEMA and ASTM standards.

C. Liquid-Filled Transformers: ANSI C57.12.00; three-phase, self-cooled transformer unit.

D. Primary Voltage: 12.47kV, delta connected; provide standard primary taps, with externally-operated, no-load tap changer. The tap changer shall have a handle with provision for padlocking.

E. Secondary Voltage: 480 volts, wye connected, solidly grounded.

F. Impedance: 5.75%.

G. Basic Impulse Level: 95kV, HV; 30kV, LV.

H. Cooling and Temperature Rise: ANSI C57.12.22; Class OA/FA, 55°C, self-cooled.

I. Liquid: Silicone with a fire point liquid not less than 30°C. Insulating liquid shall be shipped in the transformer tank.

SECTION 16410: AUTOMATIC POWER FACTOR CORRECTION

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Controllers: Factory-assembled and pre-wired equipment consisting of unit capacitors, power factor sensing and control equipment, and switching contactors to provide variable correction within discrete steps to maintain preset value of power factor.

B. Step Capacity: 50 kVAR at rated voltage and frequency.

C. Voltage: 480 volts, three-phase, 60 Hz.

D. Power Factor Range: 95% at rated kVAR.

SECTION 16461: DRY TYPE TRANSFORMERS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Dry Type Transformers: ANSI/NEMA ST 20; factory-assembled, air cooled dry type transformers.

B. Insulation system and average winding temperature rise for rated kVA as follows:

Rating (kVA)	Class	Rise (degree C)
1-15	185	115
16-500	220	80

C. Winding Taps, Transformers Less than 15 kVA: Two 5% below rated voltage, full capacity taps on primary winding.

D. Winding Taps, Transformers 15 kVA and Larger: ANSI/NEMA ST 20.

SECTION 16470: PANELBOARDS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Main and distribution panelboards.

B. Lighting and appliance branch circuit panelboards.

1.02 BUS AND HARDWARE

A. Panelboards shall be completely factory assembled and equipped with the type, size and number of branch circuit breakers, arranged and numbered as shown on the panel schedule. Use of at least 100 ampere breaker-connecting bus straps and mounting hardware.

B. All multi-pole breakers shall be common trip. Minimum Short Circuit Rating: 65,000 amperes rms symmetrical for 240 volt panelboards; 35,000 amperes rms symmetrical for 480 volt panelboards, or as shown on drawings.

C. Preinstalled locking devices shall be provided for locking each circuit breaker in the OPEN position, by means of a padlock.

1.03 CIRCUIT BREAKERS

A. Molded Case Circuit Breakers: Provide bolt-on type circuit breakers with integral thermal and instantaneous magnetic trip in each pole and common trip handle for all poles. Provide circuit breakers, UL listed as Type HACR, for air conditioning equipment branch circuits. Provide circuit breakers, UL listed as Type SWD, for lighting circuits. Provide UL Class A ground fault interrupter circuit breakers where scheduled.

B. The minimum width of one pole shall be 1-3/8 inches.

C. The minimum interrupting rating for 240 volt molded-case breakers shall be 65,000 amperes rms symmetrical, and the minimum interrupting rating for 480 volt molded-case breakers shall be 35,000 amperes rms symmetrical.

1.04 CABINETS

A. The cabinet shall have full-length hinged outer door designed to expose the wiring raceways and breakers, when open. Another, inner hinged door shall expose breakers only, when open, making this a door-in-door construction. Both doors shall open to the right. When the outer door is open, all gutter space shall be exposed.

B. All panelboards shall bear the Underwriters' Laboratories label.

SECTION 16480: MOTOR CONTROL CENTERS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Motor Control Centers: NEMA ICS 2; Class II, Type B.

B. Motor Starter Units: Plug-in combination starters with motor circuit protectors.

C. Feeder Tap Units: Molded case thermal-magnetic circuit breakers.

D. Voltage Rating: 480 volts, three-phase.

E. Horizontal Bussing: Copper, with a continuous current rating of 60 amperes. Include copper ground bus entire length of control center.

F. Vertical Bussing: NEMA ICS 2; copper.

G. Integrated Equipment Short Circuit Rating: 35,000 amperes rms symmetrical at 480 volts.

SECTION 16481: VARIABLE FREQUENCY DRIVES

PART 1 GENERAL

1.01 SECTION INCLUDES

A. Variable Frequency Drives.

B. Adjustable Frequency Controllers.

1.02 SYSTEM DESCRIPTION

A. Furnish and install Variable Frequency Drive(s) (VFD) and provide all wiring and interconnection, applications programming, and start-up and test services to provide variable speed fan/pump operation. It is the Subcontractor's responsibility to determine if the existing fan/pump motor is suitable for operation with VFD control.

PART 2 PRODUCTS

2.01 VARIABLE FREQUENCY DRIVE (VFD)

A. Saftronics Varispeed™, or MagnaTek™ GPD 503 Series.

2.02 ACCESSORIES

A. The VFDs shall include on-board self-diagnostics and indicators for troubleshooting of all operational problems.

PART 3 EXECUTION

3.01 INSTALLATION

A. The VFDs shall be totally enclosed in either wall-mounted or free-standing enclosures with a bypass panel.

SECTION 16500: LIGHTING

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Interior luminaires, lamps and accessories.

1. Offices and workstations - 50 fc.

2. Work areas - 30 fc.

3. Non-work areas and corridors - 10 fc.

B. Emergency lighting units

1. Fluorescent exit sign lights with battery backup.

2. Fluorescent egress lighting.

C. Fluorescent fixtures shall have specular reflectors, acrylic lenses and high-frequency electronic ballasts.

D. Fluorescent dimming ballasts and controls.

E. Provide task lighting, where required.

F. Provide ultrasonic occupancy sensors in restrooms and office spaces, where practical.

SECTION 16700: COMMUNICATIONS

PART 1 GENERAL

1.01 GENERAL SCOPE

A. Extend the Lawrence Berkeley Laboratory Integrated Communication System (ICS) cable raceway system into and throughout the building. Minimum conduit size: 3/4 inch. Telephone outlets: 4-11/16 inch spare boxes with plaster ring.

B. Wireways for data and communications cables, between telephone closet, computer room, IRFEL, Experimental Hall and laboratories shall be 8 inches x 8 inches minimum, lay-in square duct.

C. Speaker system in main conference room.

D. Building wide paging system with battery-powered amplifiers, surface mounted speakers. System shall connect to the Lawrence Berkeley Laboratory disaster-alert system.

E. Security-entry raceway system.

SECTION 16721: FIRE ALARM DETECTION SYSTEMS

PART 1 GENERAL

1.01 WORK INCLUDED

A. Flow switches to indicate sprinkler zone water flow.

B. Tamper switches on all sprinkler water valves.

C. Alarm signal, on sprinkler water flow, to central fire station.

D. Interrupt power to HVAC and electrical equipment upon flow of sprinkler water.

E. Heat and smoke detectors in major electronic equipment racks.

F. Manual fire call boxes.

G. Halon system for Control Room.

H. Building fire alarm bells.

I. Zone annunciation at Control Room.

J. Equipment must be compatible with existing Lawrence Berkeley Laboratory fire alarm system.

K. Supervision on all fire alarm circuits.

L. Provide very early smoke detection apparatus (VESDA).

PART 2 PRODUCTS

2.01 MANUFACTURERS

A. Equipment shall be as manufactured by the Pyrotronics Co., Division of Baker Industries: Multilarm VI and System 3, no substitutes.

SECTION 16915: LIGHTING CONTROL SYSTEM

PART 1 GENERAL

1.01 SECTION INCLUDES

A. Occupancy Sensors.

B. Power Supply.

C. Control Wiring.

D. Control Panels.

1.02 SYSTEM DESCRIPTION

A. The purpose of the project is control the "on/off" operation of specific lighting and space conditioning systems. The means of accomplishing this is through the installation of individual room lighting "occupancy sensors" to control the operation of the lighting and space conditioning systems utilizing both infrared and ultrasonic sensing technologies. Provide set of relay contacts for input to HVAC system.

PART 2 PRODUCTS

2.01 OCCUPANCY SENSOR

A. Combination infrared and ultrasonic ceiling mounted sensors with time-delay and a manual override shall be utilized.

PART 3 EXECUTION

3.01 INSTALLATION

A. Occupancy sensors shall be furnished for each room, ceiling-mounted and connect to both the lighting system and the Building Automation System.

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 7

ENERGY CONSERVATION

Project Overview

A. Total Projected Energy Usage: 36.65×10^9 BTU/YR.

General In-House Energy Management Requirements

A. Design Policy

1. The DOE and Lawrence Berkeley Laboratory (LBL) policy is to design buildings based on the lowest Life Cycle Cost.

B. Codes and Standards

1. DOE Order 6430.1A, General Design Criteria (especially Division I, Section 0110-12 Energy Conservation).

2. 10 CFR Part 435, Interim Rule (mandatory for LBL).

3. California Title 24.

C. Metering

1. In general, the metering to be provided in the facility shall comply with DOE Order 6430.1A, General Design Criteria, and 10 CFR Part 435 Interim Rule.

2. Each distinct utility provided energy service shall be metered to measure and record the amount of energy being delivered, based on energy content.

3. The energy delivery systems shall be arranged and metered to allow individual measurement of occupant lighting and outlet services, production processes, auxiliary systems, service water heating, space heating, space cooling, and HVAC delivery systems.

4. Provisions shall be made for the measurement of energy inputs and outputs (flow, temperature, pressure, etc.) to determine equipment energy consumption or installed performance capabilities and efficiencies of all heating, cooling, and HVAC delivery systems and equipment greater than 20kVA or 60,000 BTUH energy input.

D. Outline Specifications

The following specification outline is meant only as a guide. Additional specifications under other divisions may be required to fully provide the identified energy conservation measures. See Section 6, Outline Specifications.

1. Section 13810 Energy Monitoring and Control System - New Construction.

2. Section 16481 Variable Frequency Drives.

3. Section 16915 Lighting Control System.

Identified Energy Conservation Opportunities

The following is a list of identified energy savings opportunities that should be incorporated in the building design when cost effective. However, this list provides a starting point only and is not meant to exclude other energy conservation features.

A. Opportunity #1

1. Major User: Building/Process Systems

2. Alternative

Energy Monitoring and Control System (EMCS): All mechanical systems shall be monitored and controlled by an EMCS. The EMCS shall employ a multi-level distributed processing architecture connected by a local area network. A Central Operator's Terminal (COT) shall act as the "host" and perform the highest level of processing. It shall communicate with both the system operator and the Field Processing Unit (FPUs). The FPUs shall be microprocessor based and perform specified data acquisition and stand-alone control functions of timed events, conditional control sequences, and Proportional-Integral-Derivative (PID) control.

3. Justification

Centralized Energy Monitoring and Control Systems are proven energy savers. The entire LBL site is in the process of being connected to an EMCS.

B. Opportunity #2

1. Major User: Lighting Systems

2. Alternative

Occupancy Controlled Lighting and HVAC: Generally, occupancy sensors that combine both infra-red and ultrasonic technologies shall be used (in addition to local manual switches) to control lighting, and as an input to the EMCS for HVAC temperature control and override.

3. Alternative

   High Efficiency Lighting: Fluorescent fixtures shall utilize T-8 lamps with solid state high frequency ballasts.

4. Justification

   The combination of occupancy sensors and high efficiency lighting provide rapid payback periods since energy use by a building's lighting system is typically its largest single energy consuming system.

C. Opportunity #3

1. Major User: Pumps and Fans

2. Alternative

   Variable Frequency Drives (VFDs): Pump and fan motors shall be controlled by VFDs.

3. Justification

   VFDs are proven energy savers, provide enhanced control and process stability, and reduce motor wear.

D. Opportunity #4

1. Major User: Motors

2. Alternative

   High Efficiency Motors: Motors of one half horsepower and larger shall be 3-phase. All motors shall be highest efficiency available.

3. Justification

   High Efficiency Motors are proven energy savers and reduce motor wear.

E. Opportunity #5

1. Major User: Air Distribution

2. Alternative

   Variable Air Volume (VAV): VAV systems shall be utilized. Use fan powered VAV boxes or terminal cooling coils, reheat systems not allowed.

3. Justification

   VAV systems offer energy conservation by reducing heating and cooling energy and motor energy required by circulation pumps and fans.

F. Opportunity #6

1. Major User: Building Envelope

2. Alternative

   Increased Wall and Ceiling Insulation: Increase wall insulation to R-19 and ceiling to R-30.

3. Justification

   Life Cycle Cost effective.

G. Opportunity #7

1. Major User: Chiller

2. Alternative

   Turbomodulator Option or Staged Compressor Option: Provide staging or modulation as manufacturer allows to satisfy low load operation.

3. Alternative

   Heat Recovery System: A heat recovery system that will transfer energy within the chiller system.

4. Alternative

   Free Cooling Option: The free cooling option will allow bypass of the chiller compressor to save energy.

5. Justification

   Chiller operation will more closely match load requirements and save energy and wear on the chiller.

Special Cost Estimates

A. In addition, the Energy Conservation Measures relating to the chiller system in the Human Genome Laboratory are delineated with cost estimates as follows:

1. Free Cooling Option	$ 18,000
2. Heat Recovery System	42,000
3. Turbomodulator Option or Three Stage Compressor	61,000
	=========
Estimated Total	$121,000

These estimates are based upon single chiller with 400 tons of chilling capacity. Other arrangements or capacities can significantly impact the cost estimates.

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 8

SAFETY AND ENVIRONMENTAL CONSIDERATIONS

Safety Considerations

The research programs conducted in the Chemical Dynamics Research Laboratory (CDRL) will involve the use of hazardous materials above the exempt levels for B-2 occupancy as defined in the 1991 Uniform Building Code and Uniform Fire Code. As a result, the facility will be designed in compliance with H-7 occupancy requirements which incorporate mitigation measures for transportation, storage and utilization of hazardous materials. Research activities will also involve the use of ionizing radiation, radioisotopes and the use of lasers. Shielding design criteria utilized for conceptual design incorporate conservative safety assumptions which will provide a safe working environment for Lawrence Berkeley Laboratory (LBL) personnel and negligible impact to the general environment and the general public.

Operational Safety Procedures (OSPs) are mandatory for all potentially hazardous experiments, research and support activities at LBL. OSPs are reviewed by the Environment and Safety Hazards Control Department and the appropriate subcommittee(s) of the LBL Safety Review Committee. The LBL Fire Marshal, Fire Protection Engineer and Building Official provide a code compliance review with the support of a third-party review by a consultant expert in hazardous materials safety. A hazardous materials management plan including required emergency training and response plans will be implemented for operational safety.

Design of flammable-fluid-filled research equipment and all intended use of flammable gases and liquids are reviewed by the LBL Fire Marshal and the Environment, Health and Safety Division.

The building, experimental facilities, shielding blocks and non-structural building elements will be designed for a site specific maximum creditable earthquake on the nearby Hayward Fault and to special seismic criteria included in *LBL Health and Safety Manual,* PUB-3000. A third-party design review will be accomplished by a consulting structural engineer experienced in earthquake engineering.

As a standard procedure of the LBL safety program, all areas of the facility will be inspected routinely for compliance with OSHA, LBL Standards, DOE Order 6430A, General Design Criteria; 29 CFR 1926 and all federal and state life safety codes.

A Safety Analysis Document will be developed for DOE review and approval prior to operation of the facility which will incorporate mitigation measures designed to reduce any hazards to a "low hazard" classification.

Environmental Considerations

No significant environmental impacts are expected on or off site. Prompt radiation levels at the fenceline will be controlled to lower than DOE guidelines by a combination of shielding around the accelerator and control of beam parameters. Radiation associated with radioisotope releases will be controlled by the use of HEPA filters for particulate matter and activated filters and/or cryogenic traps for gaseous matter. Monitoring of radiation levels will be provided at the site boundary and at the stack discharge point. Cooling water for magnets and other heat sources will come from in-house closed systems; no waste water is discharged to the environment.

The LBL "Facility Operation Plan for Hazardous Waste" was approved by the State of California on July 25, 1983. In accordance with Section 66373, Title 22, State Administrative Code, a Part B permit to operate a hazardous waste facility to handle and store hazardous waste at LBL was granted.

In accordance with LBL policy, radioactive and chemical wastes will be collected at their points of generation. The chemicals will be segregated into compatible groups, placed in approved shipping containers and transported to an approved site for burial or recycling. No chemical wastes will be discharged to storm drains or streams.

Radioactive wastes will be collected, placed in approved drums and shipped off-site to an approved disposal site.

Runoff from rainfall on excavation spoils will be controlled by sand-bag dikes or other means to keep mud out of surface drains and storm sewers. No problems from runoff are anticipated. No disturbance to the geology of the area is expected.

The project will have no archaeological or historical impact in that it will be constructed on a site now occupied by an existing substandard Building 10 which will be demolished. The project will have no impact on the atmosphere or climate of the area, upon flora or fauna, on noise, or waste.

The facility will be occupied by 50-60 researchers and visiting scientists and 30-40 graduate students. Parking availability is planned for a maximum of 1.7 employees per parking space at the Laboratory as established in LBL's Long Range Site Development Plan, approved by DOE and the University (backed by CEQA document). The current parking space inventory in the Light Source and Engineering Area is 383 spaces. The current population of this functional planning area is 410 which will be reduced by 35 when current programs are moved from existing Building 10. LBL has planned for an addition of 250 users and operations staff for the ALS and would have an excess of 15 spaces to meet the 1.7 ratio but 10 parking places will be lost due to CDRL construction. The CDRL will be occupied by an additional 50-60 researchers (seven are in the area now) and visiting scientists and 30-40 graduate students. Graduate students will be required to use the LBL shuttle service and will not be provided with parking. To increase the parking availability to the 1.7 ratio, 26 new spaces are being proposed bringing the total to 399 (see analysis below).

Parking Space Analysis

383	Existing
(10)	Lost due to CDRL Construction
26	Added by CDRL Project
399	Total Spaces Available

Population Analysis

410	Existing
(35)	Removed from Building 10
250	ALS
53	DF (60 less 7 existing)
678	Total

399 Spaces Required to Maintain 1.7 Ratio

The project will incorporate the use of increased increments of electricity, gas and water and will be served by the capacity of existing utility systems serving the LBL site.

It is anticipated that an Environmental Impact Report (EIR) will be performed under the California Environmental Quality Act (CEQA) and an Environmental Assessment (EA) will be performed under NEPA with findings of no significant impact. However, the EA will be scheduled with sufficient schedule contingency to permit an Environmental Impact Statement to be prepared if necessary before construction is scheduled.

All of the changes will be on University-owned land. No effective alternative plans have been discovered.

CHEMICAL DYNAMICS RESEARCH LABORATORY

SECTION 9

DETAILED SUPPORTING DATA

Details of Cost Estimate

ED&I Analysis for Conventional Facilities

Geotechnical Report

Structural Calculations

Mechanical Data and Calculations

Electrical Data and Calculations

Detailed Cost Data - Sandia National Laboratory

Note: The "Chemical Dynamics Research Laboratory" (CDRL) is a new designation. The Conceptual Design Report was previously titled "Combustion Dynamics Facility/LBL" (CDF/LBL).

CHEMICAL DYNAMICS RESEARCH LABORATORY

Details of Cost Estimate

Chemical Dynamics Research Laboratory

Cost Estimate Summary (FY92k$)

1 Chemical Dynamics Research Laboratory					86,600
1.1 Proj. Management & Administration				4,890	
1.2 Special Research Facilities				41,788	
1.2.1 ED&I			9,894		
1.2.1.1 IRFEL		4,765			
1.2.1.2 ALS Beamlines		1,655			
1.2.1.3 Experimental Systems		3,474			
1.2.2 Construction			31,894		
1.2.2.1 IRFEL		15,386			
1.2.2.2 ALS Beamlines		5,307			
1.2.2.3 Experimental Systems		11,201			
1.3 Conventional Facilities				23,768	
1.3.1 ED&I			2,430		
1.3.2 Construction			16,628		
1.3.2.1 Phase I (site preparation)		2,396			
1.3.2.1.1 Improvements to land	156				
1.3.2.1.2 Building	748				
1.3.2.1.3 Utilities	1,492				
1.3.2.2 Phase II (building construction)		14,232			
1.3.2.2.1 Improvements to land	199				
1.3.2.2.2 Building	11,018				
1.3.2.2.3 Special Bldg Facilities	1,502				
1.3.2.2.4 Utilities	1,513				
1.3.3 Standard Equipment			4,710		
1.4 Contingency				16,154	
1.4.1 Project management			700		
1.4.2 Special research facilities			11,643		
1.4.2.1 IRFEL		5,443			
1.4.2.2 ALS beamlines		1,795			
1.4.2.3 Experimental Systems		4,405			
1.4.3 Conventional facilities			3,811		

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description			Material & Labor Total K$
** *				
1	Chemical Dynamics Research Laboratory			86,599.5
** **				
1.1	Project Management and Administration			4,889.8
** ***				
1.1.1	Project Direction and Management		2,466.8	
1.1.2	Project Office Services		1,722.9	
1.1.3	Incremental Indirects		700.0	
** **				
1.2	Special Research Facilities			41,787.3
** ***				
1.2.1	ED&I		9,894.0	
** ****				
1.2.1.1	ED&I for IRFEL	4,765.0		
** *****				
1.2.1.1.1	Accelerator Systems	2,385.0		
1.2.1.1.2	Electron Beam Transport	1,130.0		
1.2.1.1.3	Undulator and Optical System	675.0		
1.2.1.1.4	Electron Beam Dumping System	105.0		
1.2.1.1.5	Control System	245.0		
1.2.1.1.6	Safety Systems	85.0		
1.2.1.1.7	Accelerator/FEL Physics	140.0		
** ****				
1.2.1.2	ED&I for ALS Beamlines	1,655.0		
** *****				
1.2.1.2.1	U10 Undulator	420.0		
1.2.1.2.2	Undulator Beamline	740.0		
1.2.1.2.3	Bend Magnet Beamline	495.0		
** ****				
1.2.1.3	ED&I for Experimental Systems	3,474.0		
** *****				
1.2.1.3.1	Experimental Stations	2,425.0		
1.2.1.3.2	Advanced Lasers	930.0		
1.2.1.3.3	Laser Safety & Controls	51.0		
1.2.1.3.4	User Control Interface	68.0		

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description					Material & Labor Total K$
** ***						
1.2.2	Construction					31,893.3
** ****						
1.2.2.1	IRFEL				15,385.6	
** *****						
1.2.2.1.1	Accelerator Systems			7,567.7		
** ******						
1.2.2.1.1.1	Electron Gun		281.5			
1.2.2.1.1.2	GTL and Buncher Systems		1,034.8			
** *******						
1.2.2.1.1.2.1	Magnets and Power Supplies	152.7				
1.2.2.1.1.2.2	Subharmonic Bunchers	100.5				
1.2.2.1.1.2.3	Buncher RF System	478.2				
1.2.2.1.1.2.4	Vacuum System	150.1				
** ********						
1.2.2.1.1.2.4.1	Vacuum Chambers	48.8				
1.2.2.1.1.2.4.2	Pumping Systems	73.9				
1.2.2.1.1.2.4.3	Monitoring and Control	27.3				
** *******						
1.2.2.1.1.2.5	Cooling Systems	90.6				
1.2.2.1.1.2.6	Stands and Supports	17.5				
1.2.2.1.1.2.7	Installation	44.9				
** ******						
1.2.2.1.1.3	500 MHz Systems		5,394.1			
** *******						
1.2.2.1.1.3.1	Magnets and Power Supplies	241.4				
1.2.2.1.1.3.2	S.C. Accelerator Modules	1,800.0				
1.2.2.1.1.3.3	RF System	2,051.7				
** ********						
1.2.2.1.1.3.3.1	High Power Systems	1,796.8				
1.2.2.1.1.3.3.2	Low Power Systems	254.9				
** *******						
1.2.2.1.1.3.4	Cryogenic System	1,112.5				
** ********						
1.2.2.1.1.3.4.1	Cryostat Services	71.2				
1.2.2.1.1.3.4.2	He Refrigeration	682.8				

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description				Material & Labor Total K$
1.2.2.1.1.3.4.3	Transfer Line, Distribution Sys, Storage	358.5			
** *******					
1.2.2.1.1.3.5	Stands and Supports		59.8		
1.2.2.1.1.3.6	Installation		128.4		
** ******					
1.2.2.1.1.4	Timing System			66.9	
1.2.2.1.1.5	Diagnostics and Instrumentation			790.2	
** *******					
1.2.2.1.1.5.1	Electron Beam Position Monitor		80.5		
1.2.2.1.1.5.2	Wall Current Monitor		16.8		
1.2.2.1.1.5.3	Scintillators and TV Cameras		58.2		
1.2.2.1.1.5.4	X-Ray Monitors		18.0		
1.2.2.1.1.5.5	Scintillator Display and Analysis		44.9		
1.2.2.1.1.5.6	Equipment Racks		56.0		
1.2.2.1.1.5.7	6 MeV Bend Magnet		7.3		
1.2.2.1.1.5.8	Pinhole Emittance Insert		30.7		
1.2.2.1.1.5.9	Slow Deflector		25.0		
1.2.2.1.1.5.10	Temporal Analysis		136.5		
1.2.2.1.1.5.11	Control Room Instrumentation		201.0		
1.2.2.1.1.5.12	Spectrometer Instrumentation		15.0		
1.2.2.1.1.5.13	Hall Probe Field Analysis		20.0		
1.2.2.1.1.5.14	Feedback Instrumentation		80.0		
** *****					
1.2.2.1.2	Electron Beam Transport				3,825.2
** ******					
1.2.2.1.2.1	Transport Magnets and Power Supplies			1,998.6	
** *******					
1.2.2.1.2.1.1	Dipole Magnets & Power Supplies		625.5		
1.2.2.1.2.1.2	Quadrupole Magnets & Power Supplies		1,015.3		
1.2.2.1.2.1.3	Sextupole Magnets & Power Supplies		111.9		
1.2.2.1.2.1.4	Steering Magnets & Power Supplies		245.7		
** ******					
1.2.2.1.2.2	Vacuum System			404.2	
** *******					
1.2.2.1.2.2.1	Vacuum Chambers		260.8		
1.2.2.1.2.2.2	Pumping Systems		113.9		
1.2.2.1.2.2.3	Monitoring and Control		29.3		

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Work Breakdown Structure #	Description				Material & Labor Total K$
** ******					
1.2.2.1.2.3	Special Systems			177.8	
** *******					
1.2.2.1.2.3.1	High Power Slit		119.6		
** ********					
1.2.2.1.2.3.1.1	Fab/Buy Machined Parts & Subassy's	38.2			
1.2.2.1.2.3.1.2	Fab/Buy Vacuum Chamber & Supports	21.7			
1.2.2.1.2.3.1.3	Vac Pumping,Gauges,Controllers,P.S.	16.5			
1.2.2.1.2.3.1.4	Assemble, Bakeout, Test	8.3			
1.2.2.1.2.3.1.5	Installation	5.1			
1.2.2.1.2.3.1.6	Bellows	7.2			
1.2.2.1.2.3.1.7	Isolation Valves	22.3			
** *******					
1.2.2.1.2.3.2	Septum Magnets & Power Supplies		58.2		
** ******					
1.2.2.1.2.4	Beam Diagnostics & Instrumentation			520.8	
** *******					
1.2.2.1.2.4.1	Electron Beam Position Monitor		194.5		
1.2.2.1.2.4.2	Beamline Scintillator		109.2		
1.2.2.1.2.4.3	Undulator Scintillators		25.9		
1.2.2.1.2.4.4	Current Monitors		13.2		
1.2.2.1.2.4.5	Slow Deflector		25.0		
1.2.2.1.2.4.6	X-Ray Monitors		67.8		
1.2.2.1.2.4.7	Analyzer TV System		53.0		
1.2.2.1.2.4.8	Synchrotron Monitors		32.0		
** ******					
1.2.2.1.2.5	Stands and Supports			226.1	
1.2.2.1.2.6	Installation			497.5	
** *****					
1.2.2.1.3	Undulator and Optical Systems				2,130.3
** ******					
1.2.2.1.3.1	U5.0 - 2.1 Meter Undulator System			896.2	
** *******					
1.2.2.1.3.1.1	Magnetic Structure		471.2		
** ********					
1.2.2.1.3.1.1.1	Magnetic Material	95.2			
1.2.2.1.3.1.1.2	Model-Pole & Pole Assembly (not req'd)	0.0			

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Work Breakdown Structure #	Description				Material & Labor Total K$
1.2.2.1.3.1.1.3	Pole Assemblies	121.3			
1.2.2.1.3.1.1.4	End Pole Assemblies	54.9			
1.2.2.1.3.1.1.5	Backing Beams	104.9			
1.2.2.1.3.1.1.6	Magnet Structure Assembly	39.2			
1.2.2.1.3.1.1.7	Magnetic Measurements: Mechanical	20.4			
1.2.2.1.3.1.1.8	Magnetic Measurements: Electrical	35.2			
** *******					
1.2.2.1.3.1.2	Support & Drive Systems		274.3		
** ********					
1.2.2.1.3.1.2.1	Support System Fabrication	104.2			
1.2.2.1.3.1.2.2	Drive System Fabrication	148.8			
1.2.2.1.3.1.2.3	Local Temperature Control Fabrication	21.2			
** *******					
1.2.2.1.3.1.3	Vacuum System		86.9		
** ********					
1.2.2.1.3.1.3.1	Vacuum Chambers	33.4			
1.2.2.1.3.1.3.2	Pumping Systems & Instrumentation	14.3			
1.2.2.1.3.1.3.3	Support Structure	13.8			
1.2.2.1.3.1.3.4	Vacuum Diagnostics	25.3			
** *******					
1.2.2.1.3.1.4	Motor Control System		44.1		
1.2.2.1.3.1.5	Installation		19.6		
** ******					
1.2.2.1.3.2	Optical Systems			1,234.0	
** *******					
1.2.2.1.3.2.1	Lasing Mirror Systems		315.7		
1.2.2.1.3.2.2	Optical diagnostics		439.5		
1.2.2.1.3.2.3	IR Transport		438.7		
1.2.2.1.3.2.4	Installation		40.0		
** *****					
1.2.2.1.4	Electron Beam Dumping System				295.6
** ******					
1.2.2.1.4.1	Beam Spreading System			96.1	
1.2.2.1.4.2	Beam Dumps			63.4	
1.2.2.1.4.3	Dump Water Processing			136.0	
** *****					
1.2.2.1.5	Control System				823.1

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Work Breakdown Structure #	Description		Material & Labor Total K$
** ******			
1.2.2.1.5.1	Network and Workstations		75.8
** *******			
1.2.2.1.5.1.1	Network Resource Manager	14.4	
1.2.2.1.5.1.2	Work Stations	28.8	
1.2.2.1.5.1.3	Network Software & Documentation	26.9	
1.2.2.1.5.1.4	Installation	5.5	
** ******			
1.2.2.1.5.2	Consoles		129.4
** *******			
1.2.2.1.5.2.1	Color Monitors & Touch Panels	78.5	
1.2.2.1.5.2.2	Video Copier & Mux	17.6	
1.2.2.1.5.2.3	Portable Consoles	19.4	
1.2.2.1.5.2.4	Operator Interface	5.1	
1.2.2.1.5.2.5	Installation	8.6	
** ******			
1.2.2.1.5.3	Display & Collector Micro Modules		240.9
** *******			
1.2.2.1.5.3.1	Display Micro Modules	66.6	
1.2.2.1.5.3.2	Operating System	16.6	
1.2.2.1.5.3.3	Network Access Software	7.4	
1.2.2.1.5.3.4	Parameter Access & Modeling Software Int	42.7	
1.2.2.1.5.3.5	Error Monitoring Software	22.8	
1.2.2.1.5.3.6	Display Generation Software	21.3	
1.2.2.1.5.3.7	Display Micro Module Documentation	8.3	
1.2.2.1.5.3.8	Collector Micro Module	37.2	
1.2.2.1.5.3.9	Collector Micro Module Software	11.6	
1.2.2.1.5.3.10	Installation	6.1	
** ******			
1.2.2.1.5.4	Input/Output Controller Modules		352.7
** *******			
1.2.2.1.5.4.1	Intelligent Local Controller(ILC)	204.1	
1.2.2.1.5.4.2	ILC Software & Documentation	66.2	
1.2.2.1.5.4.3	I/O Micro Modules(IOMM's)	37.7	
1.2.2.1.5.4.4	IOMM Software & Documentation	17.8	
1.2.2.1.5.4.5	Data Base Generation for I/O Controllers	3.5	
1.2.2.1.5.4.6	Installation	23.2	

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Work Breakdown Structure #	Description					Material & Labor Total K$
** ********						
1.2.2.1.5.4.6.1	ILC Installation	20.0				
1.2.2.1.5.4.6.2	IOMM Installation	3.1				
** ******						
1.2.2.1.5.5	Computer Timing & Synchronization		24.0			
** *******						
1.2.2.1.5.5.1	Manchester Encoder & Timing Module	6.4				
1.2.2.1.5.5.2	Manchester Decoder & Fiber Optics	14.3				
1.2.2.1.5.5.3	Installation	3.2				
** *****						
1.2.2.1.6	Safety Systems			281.7		
** ******						
1.2.2.1.6.1	Access Control Fabrication		56.3			
1.2.2.1.6.2	Area Monitoring Fabrication		125.4			
1.2.2.1.6.3	Control Room Fabrication		4.1			
1.2.2.1.6.4	Beam Dump Interlocks		26.7			
1.2.2.1.6.5	Installation		69.1			
** *****						
1.2.2.1.7	Accelerator/FEL Physics			461.8		
** ****						
1.2.2.2	ALS Beamlines				5,306.9	
** *****						
1.2.2.2.1	CDRL: U10.0			1,411.2		
** ******						
1.2.2.2.1.1	Magnetic Structure		851.0			
** *******						
1.2.2.2.1.1.1	Magnetic Material	398.0				
1.2.2.2.1.1.2	Model-Pole & Pole Assembly (not req'd)	0.0				
1.2.2.2.1.1.3	Pole Assemblies	168.1				
1.2.2.2.1.1.4	End Pole Assemblies	57.9				
1.2.2.2.1.1.5	Backing Beams	110.2				
1.2.2.2.1.1.6	Magnet Structure Assembly	54.8				
1.2.2.2.1.1.7	Magnetic Measurements: Mechanical	23.1				
1.2.2.2.1.1.8	Magnetic Measurements: Electrical	38.6				
** ******						
1.2.2.2.1.2	Support & Drive Systems		245.0			

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Work Breakdown Structure #	Description				Material & Labor Total K$
** *******					
1.2.2.2.1.2.1	Support System Fabrication		104.1		
1.2.2.2.1.2.2	Drive System Fabrication		119.6		
1.2.2.2.1.2.3	Local Temperature Control Fabrication		21.2		
** ******					
1.2.2.2.1.3	Vacuum System			261.7	
** *******					
1.2.2.2.1.3.1	Vacuum Chamber		167.1		
1.2.2.2.1.3.2	Pumping Systems & Instrumentation		49.1		
1.2.2.2.1.3.3	Support Structure		14.8		
1.2.2.2.1.3.4	Vacuum Diagnostics		30.5		
** ******					
1.2.2.2.1.4	Motor Control System			33.7	
1.2.2.2.1.5	Installation			19.6	
** *****					
1.2.2.2.2	Undulator Beamline				2,337.8
** ******					
1.2.2.2.2.1	Front End			587.3	
** *******					
1.2.2.2.2.1.1	Fixed Aperture		57.7		
** ********					
1.2.2.2.2.1.1.1	Aperture Plate	4.3			
1.2.2.2.2.1.1.2	Bellows	3.1			
1.2.2.2.2.1.1.3	Collimating Spool	4.3			
1.2.2.2.2.1.1.4	Isolation Valve	24.1			
1.2.2.2.2.1.1.5	Support Stand	10.2			
1.2.2.2.2.1.1.6	Assemble, Bakeout, Test	4.3			
1.2.2.2.2.1.1.7	Installation	7.1			
** *******					
1.2.2.2.2.1.2	Photon BPM #1		74.2		
** ********					
1.2.2.2.2.1.2.1	Fab/Buy Mech Parts & Subassy's	14.3			
1.2.2.2.2.1.2.2	Fab/Buy Electrical and Controls	26.8			
1.2.2.2.2.1.2.3	Fab/Buy Support Stand	6.3			
1.2.2.2.2.1.2.4	Bellows	8.8			
1.2.2.2.2.1.2.5	Assemble, Bakeout, Test (Assembly Shop)	8.5			
1.2.2.2.2.1.2.6	Installation	9.3			

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Work Breakdown Structure #	Description		Material & Labor Total K$
** *******			
1.2.2.2.2.1.3	Photon Shutter		120.3
** ********			
1.2.2.2.2.1.3.1	Fab/Buy Mech Parts & Subassy's	23.9	
1.2.2.2.2.1.3.2	Fab/Buy Electrical and Controls	8.5	
1.2.2.2.2.1.3.3	Fab/Buy Vacuum Chamber & Supports	19.7	
1.2.2.2.2.1.3.4	Vacuum Pumping, Gauges, Controllers, P.S.	16.5	
1.2.2.2.2.1.3.5	Assemble, Bakeout, Test	14.7	
1.2.2.2.2.1.3.6	Installation	8.8	
1.2.2.2.2.1.3.7	Titanium Sublimation Pump	8.7	
1.2.2.2.2.1.3.8	Isolation Valve	19.2	
** *******			
1.2.2.2.2.1.4	Fast Valve		43.3
** ********			
1.2.2.2.2.1.4.1	Fast Valve	26.0	
1.2.2.2.2.1.4.2	Fab/Buy Electrical and Controls	2.8	
1.2.2.2.2.1.4.3	Bellows	3.6	
1.2.2.2.2.1.4.4	Aperture Plate	4.3	
1.2.2.2.2.1.4.5	Assemble, Bakeout, Test	3.9	
1.2.2.2.2.1.4.6	Installation	2.5	
** *******			
1.2.2.2.2.1.5	Personnel Safety Shutter		104.4
** ********			
1.2.2.2.2.1.5.1	Fab/Buy Mech Parts & Subassy's	21.3	
1.2.2.2.2.1.5.2	Fab/Buy Electrical and Controls	4.6	
1.2.2.2.2.1.5.3	Fab/Buy Vacuum Chamber & Supports	16.3	
1.2.2.2.2.1.5.4	Vacuum Pumping, Gauges, Controllers, P.S.	15.8	
1.2.2.2.2.1.5.5	Assemble, Bakeout, Test	14.2	
1.2.2.2.2.1.5.6	Installation	6.3	
1.2.2.2.2.1.5.7	Shield Wall Transition Spool	9.4	
1.2.2.2.2.1.5.8	Isolation Valve	16.2	
** *******			
1.2.2.2.2.1.6	Photon BPM #2		79.5
** ********			
1.2.2.2.2.1.6.1	Fab/Buy Mech Parts & Subassy's	16.0	
1.2.2.2.2.1.6.2	Fab/Buy Electrical and Controls	30.5	
1.2.2.2.2.1.6.3	Fab/Buy Support Stand	6.3	
1.2.2.2.2.1.6.4	Bellows	8.8	

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1.2.2.2.2.1.6.5	Assemble, Bakeout, Test	8.5			
1.2.2.2.2.1.6.6	Installation	9.2			
** *******					
1.2.2.2.2.1.7	Vacuum System, Utilities & Installation		85.1		
** ********					
1.2.2.2.2.1.7.1	Fab/Buy Mech Parts & Subassy's	7.8			
1.2.2.2.2.1.7.2	Fab/Buy Electical and Controls	19.0			
1.2.2.2.2.1.7.3	Fab/Buy Vacuum Chamber & Supports	6.8			
1.2.2.2.2.1.7.4	Vacuum Pumping, Gauges, Controllers, P.S.	14.2			
1.2.2.2.2.1.7.5	Assemble, Bakeout, Test	11.2			
1.2.2.2.2.1.7.6	Installation	25.8			
** *******					
1.2.2.2.2.1.8	Safety Systems		22.5		
** ******					
1.2.2.2.2.2	Branchline			1,750.5	
** *******					
1.2.2.2.2.2.1	Horiz. & Vert. Beam Defining Apertures		122.4		
1.2.2.2.2.2.2	M1 Mirror		145.3		
1.2.2.2.2.2.3	M2 Mirror		121.4		
1.2.2.2.2.2.4	M3 Mirror		84.0		
1.2.2.2.2.2.5	Monochromator (NIM)		464.2		
1.2.2.2.2.2.6	M4 Mirror		77.5		
1.2.2.2.2.2.7	M5 Mirror		72.7		
1.2.2.2.2.2.8	Branch Line Diagnostics		64.8		
1.2.2.2.2.2.9	Vacuum System: Controls & Installation		190.4		
1.2.2.2.2.2.10	Branch Line Safety Systems		12.1		
1.2.2.2.2.2.11	Harmonic Suppression & Optical Filters		145.3		
1.2.2.2.2.2.12	Secondary Branchline		250.0		
** *****					
1.2.2.2.3	Bend Magnet Beamline				1,557.8
** ******					
1.2.2.2.3.1	Front End			299.8	
** *******					
1.2.2.2.3.1.1	Aperture Assemblies 1 & 2		9.4		
1.2.2.2.3.1.2	Bellows 1 & 2		7.8		
1.2.2.2.3.1.3	Isolation Valves 1 & 2		35.9		
1.2.2.2.3.1.4	Photon Shutter		24.2		
1.2.2.2.3.1.5	Vacuum Systems		21.1		

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Work Breakdown Structure #	Description				Material & Labor Total K$
1.2.2.2.3.1.6	Photon Shutter Support System	17.5			
1.2.2.2.3.1.7	Fast Shutter	34.0			
1.2.2.2.3.1.8	Collimation Spool	5.6			
1.2.2.2.3.1.9	Cleaning, Assemble, Bakeout & Test	10.8			
1.2.2.2.3.1.10	Installation	16.7			
1.2.2.2.3.1.11	Misc. Mechanical, Electrical & Controls	53.1			
1.2.2.2.3.1.12	Safety Systems	16.8			
1.2.2.2.3.1.13	Shield Wall Transition Assembly	46.5			
** ******					
1.2.2.2.3.2	Branchline		1,257.9		
** *******					
1.2.2.2.3.2.1	M1 Mirror	100.4			
1.2.2.2.3.2.2	M2 Mirror	96.7			
1.2.2.2.3.2.3	M3 Mirror	64.8			
1.2.2.2.3.2.4	Monochromator (NIM)	417.2			
1.2.2.2.3.2.5	M4 Mirror	80.6			
1.2.2.2.3.2.6	M5 Mirror	80.6			
1.2.2.2.3.2.7	Branch Line Diagnostics	64.5			
1.2.2.2.3.2.8	Vacuum System: Controls & Installation	194.1			
1.2.2.2.3.2.9	Branch Line Safety Systems	12.6			
1.2.2.2.3.2.10	Differential Pumping Sys, Optical Filters	146.2			
** ****					
1.2.2.3	Experimental Systems				11,200.7
** *****					
1.2.2.3.1	Experimental Stations			8,213.6	
** ******					
1.2.2.3.1.1	System A		1,022.3		
** *******					
1.2.2.3.1.1.1	Vacuum Chamber	594.7			
1.2.2.3.1.1.2	Detector Systems	178.4			
1.2.2.3.1.1.3	Lasers	150.5			
1.2.2.3.1.1.4	Installation	98.5			
** ******					
1.2.2.3.1.2	System B		711.8		
** *******					
1.2.2.3.1.2.1	Vacuum Chamber	167.3			
1.2.2.3.1.2.2	Detector Systems	214.8			
1.2.2.3.1.2.3	Lasers	304.7			

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Work Breakdown Structure #	Description		Material & Labor Total K$
1.2.2.3.1.2.4	Installation	24.9	
** ******			
1.2.2.3.1.3	System C		609.3
** *******			
1.2.2.3.1.3.1	Vacuum Chamber	202.4	
1.2.2.3.1.3.2	Detector Systems	76.7	
1.2.2.3.1.3.3	Lasers	295.7	
1.2.2.3.1.3.4	Installation	34.4	
** ******			
1.2.2.3.1.4	System D		571.5
** *******			
1.2.2.3.1.4.1	Vacuum Chamber	271.9	
1.2.2.3.1.4.2	Detector Systems	174.7	
1.2.2.3.1.4.3	Lasers	77.9	
1.2.2.3.1.4.4	Installation	46.9	
** ******			
1.2.2.3.1.5	System E		930.3
** *******			
1.2.2.3.1.5.1	Vacuum Chamber	273.5	
1.2.2.3.1.5.2	Detector Systems	316.5	
1.2.2.3.1.5.3	Lasers	304.7	
1.2.2.3.1.5.4	Installation	35.5	
** ******			
1.2.2.3.1.6	Chemical Dynamics Experimental Station (SNL)		1,489.8
** *******			
1.2.2.3.1.6.1	Vacuum Chambers & Pumps	547.9	
1.2.2.3.1.6.2	Detector System	199.6	
1.2.2.3.1.6.3	Lasers	708.2	
1.2.2.3.1.6.4	Installation	33.9	
** ******			
1.2.2.3.1.7	Chemical Kinetics Experimental Station (SNL)		1,378.3
** *******			
1.2.2.3.1.7.1	Vacuum Chambers & Pumps	369.5	
1.2.2.3.1.7.2	Detector System	217.6	
1.2.2.3.1.7.3	Lasers	757.1	

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description				Material & Labor Total K$
1.2.2.3.1.7.4	Installation	33.9			
** ******					
1.2.2.3.1.8	Experimental Station Enhancements (SNL)	1,500.0			
** *****					
1.2.2.3.2	Advanced Lasers (3 systems)		2,690.9		
** ******					
1.2.2.3.2.1	Lasers	1,513.6			
1.2.2.3.2.2	Laser Accessories	426.1			
1.2.2.3.2.3	Optical Transport and Support	137.5			
1.2.2.3.2.4	Diagnostics and Control	334.2			
1.2.2.3.2.5	System Integration	279.4			
** *****					
1.2.2.3.3	Laser Safety & Controls		126.9		
** ******					
1.2.2.3.3.1	Laser Safety Covers	42.4			
1.2.2.3.3.2	Laser Timing / Synchronization	84.4			
** *****					
1.2.2.3.4	User Control Interface		169.2		
** **					
1.3	Conventional Facilities				23,768.3
** ***					
1.3.1	ED&I			2,430.0	
1.3.2	Construction			16,628.3	
** ****					
1.3.2.1	Phase I (Site Preparation)			2,396.0	
** *****					
1.3.2.1.1	Improvements to Land		156.0		
** ******					
1.3.2.1.1.1	Building 10 Demolition	156.0			
** *****					
1.3.2.1.2	Building		748.0		
** ******					
1.3.2.1.2.1	Shoring and Underpinning	438.0			
1.3.2.1.2.2	Excavation	310.0			

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description				Material & Labor Total K$
** *****					
1.3.2.1.3	Utilities			1,492.0	
** ******					
1.3.2.1.3.1	Mods to Existing Systems		1,492.0		
** ****					
1.3.2.2	Phase II (Building Construction)				14,232.3
** *****					
1.3.2.2.1	Improvements to Land			199.0	
** ******					
1.3.2.2.1.1	Paving and Surfacing		51.0		
1.3.2.2.1.2	Cyclotron Road Parking		94.0		
1.3.2.2.1.3	Site Improvements		47.0		
1.3.2.2.1.4	Landscaping		7.0		
** *****					
1.3.2.2.2	Building			11,018.0	
** ******					
1.3.2.2.2.1	Concrete		2,040.8		
1.3.2.2.2.2	Metals		1,197.6		
** *******					
1.3.2.2.2.2.1	Structural Steel	828.4			
1.3.2.2.2.2.2	Steel Deck	242.2			
1.3.2.2.2.2.3	Metal Fabrications	126.9			
** ******					
1.3.2.2.2.3	Wood and Plastic		59.2		
** *******					
1.3.2.2.2.3.1	Custom Casework	59.2			
** ******					
1.3.2.2.2.4	Thermal and Moisture Protection		730.0		
** *******					
1.3.2.2.2.4.1	Waterproofing	45.4			
1.3.2.2.2.4.2	Dampproofing	5.2			
1.3.2.2.2.4.3	Insulation	15.8			
1.3.2.2.2.4.4	Fireproofing	98.3			
1.3.2.2.2.4.5	Preformed Metal Siding	487.7			
1.3.2.2.2.4.6	Membrane Roofing	45.4			

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description		Material & Labor Total K$
1.3.2.2.2.4.7	Sheet Metal Flashing	13.7	
1.3.2.2.2.4.8	Sealants	17.9	
** ******			
1.3.2.2.2.5	Doors and Windows		375.5
** *******			
1.3.2.2.2.5.1	Metal Doors and Frames	38.0	
1.3.2.2.2.5.2	Wood Doors	42.3	
1.3.2.2.2.5.3	Overhead Coiling Doors	14.8	
1.3.2.2.2.5.4	Metal Windows	170.3	
1.3.2.2.2.5.5	Hardware	83.5	
1.3.2.2.2.5.6	Glazing	26.4	
** ******			
1.3.2.2.2.6	Finishes		1,280.1
** *******			
1.3.2.2.2.6.1	Metal Support Systems	478.2	
1.3.2.2.2.6.2	Gypsum Board Systems	357.6	
1.3.2.2.2.6.3	Tile	117.4	
1.3.2.2.2.6.4	Acoustical Ceilings	51.8	
1.3.2.2.2.6.5	Resilient Flooring	30.6	
1.3.2.2.2.6.6	Carpet	41.2	
1.3.2.2.2.6.7	Painting	203.1	
** ******			
1.3.2.2.2.7	Specialties		44.4
** *******			
1.3.2.2.2.7.1	Visual Display Boards	3.1	
1.3.2.2.2.7.2	Metal Toilet Compartments	5.2	
1.3.2.2.2.7.3	Metal Wall Louvers	33.8	
1.3.2.2.2.7.4	Toilet and Bath Accessories	2.1	
** ******			
1.3.2.2.2.8	Energy Monitoring and Control Systems		239.1
1.3.2.2.2.9	Conveying Systems		472.9
** *******			
1.3.2.2.2.9.1	Elevators	257.0	
1.3.2.2.2.9.2	Hoists and Cranes	215.8	
** ******			
1.3.2.2.2.10	Mechanical		2,784.6

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description			Material & Labor Total K$
** *******				
1.3.2.2.2.10.1	Basic Materials and Methods	420.0		
1.3.2.2.2.10.2	Mechanical Insulation	133.3		
1.3.2.2.2.10.3	Fire Protection	245.4		
1.3.2.2.2.10.4	Plumbing	142.8		
1.3.2.2.2.10.5	Compressed Air System	50.7		
1.3.2.2.2.10.6	Deionized Water System	62.4		
1.3.2.2.2.10.7	Low Conductivity Water System	34.9		
1.3.2.2.2.10.8	Heat Generation	100.5		
1.3.2.2.2.10.9	Refrigeration	471.8		
1.3.2.2.2.10.10	Air Handling	479.2		
1.3.2.2.2.10.11	Air Distribution	630.5		
1.3.2.2.2.10.12	Testing and Balancing	12.7		
** ******				
1.3.2.2.2.11	Electrical		1,793.3	
** *******				
1.3.2.2.2.11.1	12 kV Distributions	790.3		
1.3.2.2.2.11.2	Power Service and Distribution	249.6		
1.3.2.2.2.11.3	Emergency System	100.5		
1.3.2.2.2.11.4	Power and Motor Feeders	259.2		
1.3.2.2.2.11.5	Lighting	189.3		
1.3.2.2.2.11.6	Misc. Power Devices	55.0		
1.3.2.2.2.11.7	Communications	126.9		
1.3.2.2.2.11.8	Fire Alarm System	22.2		
** *****				
1.3.2.2.3	Special Building Facilities			1,502.6
** ******				
1.3.2.2.3.1	Laboratory Benches		210.3	
1.3.2.2.3.2	Chemical Storage Cabinets		9.8	
1.3.2.2.3.3	Fume Hoods		232.1	
1.3.2.2.3.4	Instrument Racks		52.7	
1.3.2.2.3.5	Vacuum Systems		105.5	
1.3.2.2.3.6	Liquid Nitrogen Distribution Systems		246.1	
1.3.2.2.3.7	Acid Drain Systems		62.8	
1.3.2.2.3.8	Laser Safety Contol Systems		32.0	
1.3.2.2.3.9	Vacuum Control Systems		37.6	
1.3.2.2.3.10	Chemical Detection Systems		232.3	
1.3.2.2.3.11	Data Acquisition System		281.4	
** *****				
1.3.2.2.4	Utilities			1,512.6

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description			Material & Labor Total K$	
** ******					
1.3.2.2.4.1	Mechanical Utilities		47.2		
** *******					
1.3.2.2.4.1.1	Water Distribution Systems	21.7			
1.3.2.2.4.1.2	Gas Distribution System	21.7			
1.3.2.2.4.1.3	Sewage and Drainage	3.7			
** ******					
1.3.2.2.4.2	Cooling Tower		1,398.2		
** *******					
1.3.2.2.4.2.1	Building 37 Extension	1,316.1			
1.3.2.2.4.2.2	Low Conductivity Water (LCW) Connection	41.0			
1.3.2.2.4.2.3	Treated Water Connection	41.0			
** ******					
1.3.2.2.4.3	Electrical Utilities		67.1		
** *******					
1.3.2.2.4.3.1	15 kV Power Service	67.1			
** ***					
1.3.3	Standard Equipment				4,709.9
** ****					
1.3.3.1	Standard Laser Systems			1,033.1	
1.3.3.2	Office Furniture & Equipment			111.0	
1.3.3.3	Personal Computers			161.0	
1.3.3.4	Computer Workstations			855.3	
1.3.3.5	Diagnostic and Detection Systems			493.2	
1.3.3.6	Electronic Balance			4.4	
1.3.3.7	Vacuum Leak Detector			20.0	
1.3.3.8	Casettometer			5.5	
1.3.3.9	Streak Camera System			149.9	
1.3.3.10	Equipment for SNL upstairs lab			1,876.0	
** **					
1.4	Contingency				16,154.0
** ***					
1.4.1	Project Management Contingency				700.0
1.4.2	Special Research Facilities Contingency				11,643.0
** ****					
1.4.2.1	IRFEL			5,443.0	
1.4.2.2	ALS Beamlines			1,795.0	

Cost Estimate Report
Summary of Material and Labor
by Rollup Levels

Work Breakdown Structure #	Description	Material & Labor Total K$
1.4.2.3	Experimental Systems	4,405.0
** ***		
1.4.3	Conventional Facilities Contingency	3,811.0

Chemical Dynamics Research Laboratory rev 2/6/92

Cost Breakdown for Special Research Facilities Construction by Craft

Craft Code	Craft Description	Craft Rate $/hr.	Total Labor Hrs	Person Years	Total Cost ($)	Percent
CP	Computer Programming	59.40	8,161	4.62	484,763	6.59%
EE	Electronic Engineering	59.40	2,446	1.38	145,292	1.97%
EI	Electronic Installation	33.00	17,147	9.70	565,851	7.69%
EM	Electronic Maintenance	33.00	1,952	1.10	64,416	0.88%
ES	Electronic Shops	33.00	6,923	3.92	228,459	3.11%
RG	Rigger	37.65	128	0.07	4,819	0.07%
IEL	Contract Electrician	62.85	4,339	2.46	272,706	3.71%
IPL	Contract Plumber	67.40	1,544	0.87	104,066	1.41%
ISM	Contract Sheet Metal	72.00	96	0.05	6,912	0.09%
MA	Mechanical Assembly Shop	38.60	43,814	24.80	1,691,220	22.99%
ME	Mechanical Engineering	59.40	7,420	4.20	440,748	5.99%
MM	Machine Shop	38.60	29,819	16.88	1,151,013	15.64%
MS	Mechanical Shops (misc.)	37.73	28,378	16.06	1,070,702	14.55%
MT	Mechanical Tech Trainee	27.85	8,541	4.83	237,867	3.23%
MU	Mechanical Technician	35.92	13,520	7.65	485,638	6.60%
NC	Mechanical Shops NC Tool	56.50	24	0.01	1,356	0.02%
AA	Physicist	42.75	9,400	5.32	401,850	5.46%
		Totals	**183,652**	**104**	**7,357,680**	**100%**

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *										
1	Chemical Dynamics Research Laboratory	1	260142	11197.33	75402.19	86599.52	260142	11197.33	75402.19	86599.52
** **										
1.1	Project Management and Administration	1	76490	3839.66	1050.20	4889.86	76490	3839.66	1050.20	4889.86
** ***										
1.1.1	Project Direction and Management	1	38530	2216.87	250.00	2466.87	38530	2216.87	250.00	2466.87
1.1.2	Project Office Services	1	37960	1622.79	100.20	1722.99	37960	1622.79	100.20	1722.99
1.1.3	Incremental Indirects	1	0	0.00	700.00	700.00	0	0.00	700.00	700.00
** **										
1.2	Special Research Facilities	1	183652	7357.68	34429.67	41787.35	183652	7357.68	34429.67	41787.35
** ***										
1.2.1	ED&I	1	0	0.00	9894.00	9894.00	0	0.00	9894.00	9894.00
** ****										
1.2.1.1	ED&I for IRFEL	1	0	0.00	4765.00	4765.00	0	0.00	4765.00	4765.00
** *****										
1.2.1.1.1	Accelerator Systems	1	0	0.00	2385.00	2385.00	0	0.00	2385.00	2385.00
1.2.1.1.2	Electron Beam Transport	1	0	0.00	1130.00	1130.00	0	0.00	1130.00	1130.00
1.2.1.1.3	Undulator and Optical System	1	0	0.00	675.00	675.00	0	0.00	675.00	675.00
1.2.1.1.4	Electron Beam Dumping System	1	0	0.00	105.00	105.00	0	0.00	105.00	105.00
1.2.1.1.5	Control System	1	0	0.00	245.00	245.00	0	0.00	245.00	245.00
1.2.1.1.6	Safety Systems	1	0	0.00	85.00	85.00	0	0.00	85.00	85.00
1.2.1.1.7	Accelerator/FEL Physics	1	0	0.00	140.00	140.00	0	0.00	140.00	140.00
** ****										
1.2.1.2	ED&I for ALS Beamlines	1	0	0.00	1655.00	1655.00	0	0.00	1655.00	1655.00
** *****										
1.2.1.2.1	U10 Undulator	1	0	0.00	420.00	420.00	0	0.00	420.00	420.00
1.2.1.2.2	Undulator Beamline	1	0	0.00	740.00	740.00	0	0.00	740.00	740.00
1.2.1.2.3	Bend Magnet Beamline	1	0	0.00	495.00	495.00	0	0.00	495.00	495.00
** ****										
1.2.1.3	ED&I for Experimental Systems	1	0	0.00	3474.00	3474.00	0	0.00	3474.00	3474.00
** *****										
1.2.1.3.1	Experimental Stations	1	0	0.00	2425.00	2425.00	0	0.00	2425.00	2425.00
1.2.1.3.2	Advanced Lasers	1	0	0.00	930.00	930.00	0	0.00	930.00	930.00
1.2.1.3.3	Laser Safety & Controls	1	0	0.00	51.00	51.00	0	0.00	51.00	51.00
1.2.1.3.4	User Control Interface	1	0	0.00	68.00	68.00	0	0.00	68.00	68.00
** ***										
1.2.2	Construction	1	183652	7357.68	24535.67	31893.35	183652	7357.68	24535.67	31893.35

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** ****										
1.2.2.1	IRFEL	1	117680	4623.31	10762.29	15385.60	117680	4623.31	10762.29	15385.60
** *****										
1.2.2.1.1	Accelerator Systems	1	22096	831.45	6736.24	7567.70	22096	831.45	6736.24	7567.70
** ******										
1.2.2.1.1.1	Electron Gun	1	1260	47.74	233.80	281.54	1260	47.74	233.80	281.54
1.2.2.1.1.2	GTL and Buncher Systems	1	6626	242.65	792.20	1034.85	6626	242.65	792.20	1034.85
** *******										
1.2.2.1.1.2.1	Magnets and Power Supplies	1	920	30.36	122.40	152.76	920	30.36	122.40	152.76
1.2.2.1.1.2.2	Subharmonic Bunchers	1	480	18.53	82.00	100.53	480	18.53	82.00	100.53
1.2.2.1.1.2.3	Buncher RF System	1	2280	81.65	396.60	478.25	2280	81.65	396.60	478.25
1.2.2.1.1.2.4	Vacuum System	1	302	10.05	140.10	150.15	302	10.05	140.10	150.15
** ********										
1.2.2.1.1.2.4.1	Vacuum Chambers	1	0	0.00	48.80	48.80	0	0.00	48.80	48.80
1.2.2.1.1.2.4.2	Pumping Systems	1	30	1.08	72.90	73.98	30	1.08	72.90	73.98
1.2.2.1.1.2.4.3	Monitoring and Control	1	272	8.98	18.40	27.38	272	8.98	18.40	27.38
** *******										
1.2.2.1.1.2.5	Cooling Systems	1	1384	49.57	41.10	90.67	1384	49.57	41.10	90.67
1.2.2.1.1.2.6	Stands and Supports	1	200	7.55	10.00	17.55	200	7.55	10.00	17.55
1.2.2.1.1.2.7	Installation	1	1060	44.94	0.00	44.94	1060	44.94	0.00	44.94
** ******										
1.2.2.1.1.3	500 MHz Systems	1	10872	423.89	4970.20	5394.10	10872	423.89	4970.20	5394.10
** *******										
1.2.2.1.1.3.1	Magnets and Power Supplies	1	464	17.19	224.30	241.49	464	17.19	224.30	241.49
1.2.2.1.1.3.2	S.C. Accelerator Modules	1	0	0.00	1800.00	1800.00	0	0.00	1800.00	1800.00
1.2.2.1.1.3.3	RF System	1	5110	189.84	1861.90	2051.74	5110	189.84	1861.90	2051.74
** ********										
1.2.2.1.1.3.3.1	High Power Systems	1	3080	113.30	1683.50	1796.80	3080	113.30	1683.50	1796.80
1.2.2.1.1.3.3.2	Low Power Systems	1	2030	76.54	178.40	254.94	2030	76.54	178.40	254.94
** *******										
1.2.2.1.1.3.4	Cryogenic System	1	1320	58.56	1054.00	1112.56	1320	58.56	1054.00	1112.56
** ********										
1.2.2.1.1.3.4.1	Cryostat Services	1	600	21.20	50.00	71.20	600	21.20	50.00	71.20
1.2.2.1.1.3.4.2	He Refrigeration	1	320	20.84	662.00	682.84	320	20.84	662.00	682.84
1.2.2.1.1.3.4.3	Transfer Line, Distribution Sys, Storage	1	400	16.52	342.00	358.52	400	16.52	342.00	358.52
** *******										
1.2.2.1.1.3.5	Stands and Supports	1	842	31.85	28.00	59.85	842	31.85	28.00	59.85

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *										
1	Chemical Dynamics Research Laboratory	1	260142	11197.33	75402.19	86599.52	260142	11197.33	75402.19	86599.52
** **										
1.1	Project Management and Administration	1	76490	3839.66	1050.20	4889.86	76490	3839.66	1050.20	4889.86
** ***										
1.1.1	Project Direction and Management	1	38530	2216.87	250.00	2466.87	38530	2216.87	250.00	2466.87
1.1.2	Project Office Services	1	37960	1622.79	100.20	1722.99	37960	1622.79	100.20	1722.99
1.1.3	Incremental Indirects	1	0	0.00	700.00	700.00	0	0.00	700.00	700.00
** **										
1.2	Special Research Facilities	1	183652	7357.68	34429.67	41787.35	183652	7357.68	34429.67	41787.35
** ***										
1.2.1	ED&I	1	0	0.00	9894.00	9894.00	0	0.00	9894.00	9894.00
** ****										
1.2.1.1	ED&I for IRFEL	1	0	0.00	4765.00	4765.00	0	0.00	4765.00	4765.00
** *****										
1.2.1.1.1	Accelerator Systems	1	0	0.00	2385.00	2385.00	0	0.00	2385.00	2385.00
1.2.1.1.2	Electron Beam Transport	1	0	0.00	1130.00	1130.00	0	0.00	1130.00	1130.00
1.2.1.1.3	Undulator and Optical System	1	0	0.00	675.00	675.00	0	0.00	675.00	675.00
1.2.1.1.4	Electron Beam Dumping System	1	0	0.00	105.00	105.00	0	0.00	105.00	105.00
1.2.1.1.5	Control System	1	0	0.00	245.00	245.00	0	0.00	245.00	245.00
1.2.1.1.6	Safety Systems	1	0	0.00	85.00	85.00	0	0.00	85.00	85.00
1.2.1.1.7	Accelerator/FEL Physics	1	0	0.00	140.00	140.00	0	0.00	140.00	140.00
** ****										
1.2.1.2	ED&I for ALS Beamlines	1	0	0.00	1655.00	1655.00	0	0.00	1655.00	1655.00
** *****										
1.2.1.2.1	U10 Undulator	1	0	0.00	420.00	420.00	0	0.00	420.00	420.00
1.2.1.2.2	Undulator Beamline	1	0	0.00	740.00	740.00	0	0.00	740.00	740.00
1.2.1.2.3	Bend Magnet Beamline	1	0	0.00	495.00	495.00	0	0.00	495.00	495.00
** ****										
1.2.1.3	ED&I for Experimental Systems	1	0	0.00	3474.00	3474.00	0	0.00	3474.00	3474.00
** *****										
1.2.1.3.1	Experimental Stations	1	0	0.00	2425.00	2425.00	0	0.00	2425.00	2425.00
1.2.1.3.2	Advanced Lasers	1	0	0.00	930.00	930.00	0	0.00	930.00	930.00
1.2.1.3.3	Laser Safety & Controls	1	0	0.00	51.00	51.00	0	0.00	51.00	51.00
1.2.1.3.4	User Control Interface	1	0	0.00	68.00	68.00	0	0.00	68.00	68.00
** ***										
1.2.2	Construction	1	183652	7357.68	24535.67	31893.35	183652	7357.68	24535.67	31893.35

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.2.2.1.1.3.6	Installation	1	3136	126.45	2.00	128.45	3136	126.45	2.00	128.45
** ******										
1.2.2.1.1.4	Timing System	1	302	9.97	57.00	66.97	302	9.97	57.00	66.97
1.2.2.1.1.5	Diagnostics and Instrumentation	1	3036	107.20	683.04	790.25	3036	107.20	683.04	790.25
** *******										
1.2.2.1.1.5.1	Electron Beam Position Monitor	12	44	1.66	5.05	6.71	528	19.92	60.60	80.52
1.2.2.1.1.5.2	Wall Current Monitor	4	23	0.78	3.43	4.20	92	3.11	13.70	16.82
1.2.2.1.1.5.3	Scintillators and TV Cameras	8	52	1.89	5.39	7.28	416	15.09	43.16	58.25
1.2.2.1.1.5.4	X-Ray Monitors	4	48	1.62	2.90	4.52	192	6.49	11.60	18.09
1.2.2.1.1.5.5	Scintillator Display and Analysis	2	32	1.48	21.00	22.48	64	2.96	42.00	44.96
1.2.2.1.1.5.6	Equipment Racks	10	88	2.90	2.70	5.60	880	29.04	27.00	56.04
1.2.2.1.1.5.7	6 MeV Bend Magnet	1	132	4.83	2.50	7.33	132	4.83	2.50	7.33
1.2.2.1.1.5.8	Pinhole Emittance Insert	2	108	3.98	11.39	15.37	216	7.96	22.78	30.74
1.2.2.1.1.5.9	Slow Deflector	1	0	0.00	25.00	25.00	0	0.00	25.00	25.00
1.2.2.1.1.5.10	Temporal Analysis	1	128	5.00	131.50	136.50	128	5.00	131.50	136.50
1.2.2.1.1.5.11	Control Room Instrumentation	1	388	12.80	188.20	201.00	388	12.80	188.20	201.00
1.2.2.1.1.5.12	Spectrometer Instrumentation	1	0	0.00	15.00	15.00	0	0.00	15.00	15.00
1.2.2.1.1.5.13	Hall Probe Field Analysis	1	0	0.00	20.00	20.00	0	0.00	20.00	20.00
1.2.2.1.1.5.14	Feedback Instrumentation	4	0	0.00	20.00	20.00	0	0.00	80.00	80.00
** *****										
1.2.2.1.2	Electron Beam Transport	1	62700	2380.03	1445.24	3825.27	62700	2380.03	1445.24	3825.27
** ******										
1.2.2.1.2.1	Transport Magnets and Power Supplies	1	37408	1455.40	543.20	1998.60	37408	1455.40	543.20	1998.60
** *******										
1.2.2.1.2.1.1	Dipole Magnets & Power Supplies	1	12440	484.68	140.90	625.58	12440	484.68	140.90	625.58
1.2.2.1.2.1.2	Quadrupole Magnets & Power Supplies	1	18412	717.39	298.00	1015.39	18412	717.39	298.00	1015.39
1.2.2.1.2.1.3	Sextupole Magnets & Power Supplies	1	2504	97.52	14.40	111.92	2504	97.52	14.40	111.92
1.2.2.1.2.1.4	Steering Magnets & Power Supplies	1	4052	155.80	89.90	245.70	4052	155.80	89.90	245.70
** ******										
1.2.2.1.2.2	Vacuum System	1	3740	142.16	262.05	404.21	3740	142.16	262.05	404.21
** *******										
1.2.2.1.2.2.1	Vacuum Chambers	1	3426	132.24	128.60	260.84	3426	132.24	128.60	260.84
1.2.2.1.2.2.2	Pumping Systems	1	284	9.08	104.90	113.98	284	9.08	104.90	113.98
1.2.2.1.2.2.3	Monitoring and Control	1	30	0.84	28.55	29.39	30	0.84	28.55	29.39
** ******										
1.2.2.1.2.3	Special Systems	1	2404	91.94	85.93	177.87	2404	91.94	85.93	177.87
** *******										
1.2.2.1.2.3.1	High Power Slit	1	1240	46.44	73.23	119.67	1240	46.44	73.23	119.67

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** ********										
1.2.2.1.2.3.1.1	Fab/Buy Machined Parts & Subassy's	1	756	28.45	9.80	38.25	756	28.45	9.80	38.25
1.2.2.1.2.3.1.2	Fab/Buy Vacuum Chamber & Supports	1	128	4.76	17.00	21.76	128	4.76	17.00	21.76
1.2.2.1.2.3.1.3	Vac Pumping,Gauges,Controllers,P.S.	1	24	0.82	15.73	16.54	24	0.82	15.73	16.54
1.2.2.1.2.3.1.4	Assemble, Bakeout, Test	1	176	6.32	2.00	8.32	176	6.32	2.00	8.32
1.2.2.1.2.3.1.5	Installation	1	112	4.51	0.60	5.11	112	4.51	0.60	5.11
1.2.2.1.2.3.1.6	Bellows	1	16	0.59	6.70	7.29	16	0.59	6.70	7.29
1.2.2.1.2.3.1.7	Isolation Valves	1	28	0.99	21.40	22.39	28	0.99	21.40	22.39
** *******										
1.2.2.1.2.3.2	Septum Magnets & Power Supplies	1	1164	45.51	12.70	58.21	1164	45.51	12.70	58.21
** ******										
1.2.2.1.2.4	Beam Diagnostics & Instrumentation	1	3254	118.77	402.06	520.83	3254	118.77	402.06	520.83
** *******										
1.2.2.1.2.4.1	Electron Beam Position Monitor	29	44	1.66	5.05	6.71	1276	48.14	146.45	194.59
1.2.2.1.2.4.2	Beamline Scintillator	15	52	1.89	5.39	7.28	780	28.29	80.92	109.22
1.2.2.1.2.4.3	Undulator Scintillators	3	90	3.32	5.33	8.65	270	9.96	15.99	25.95
1.2.2.1.2.4.4	Current Monitors	3	0	0.00	4.40	4.40	0	0.00	13.20	13.20
1.2.2.1.2.4.5	Slow Deflector	1	0	0.00	25.00	25.00	0	0.00	25.00	25.00
1.2.2.1.2.4.6	X-Ray Monitors	15	48	1.62	2.90	4.52	720	24.33	43.50	67.83
1.2.2.1.2.4.7	Analyzer TV System	2	104	4.02	22.50	26.52	208	8.04	45.00	53.04
1.2.2.1.2.4.8	Synchrotron Monitors	4	0	0.00	8.00	8.00	0	0.00	32.00	32.00
** ******										
1.2.2.1.2.5	Stands and Supports	1	4892	186.57	39.60	226.17	4892	186.57	39.60	226.17
1.2.2.1.2.6	Installation	1	11002	385.18	112.40	497.58	11002	385.18	112.40	497.58
** *****										
1.2.2.1.3	Undulator and Optical Systems	1	11811	456.41	1673.89	2130.30	11811	456.41	1673.89	2130.30
** ******										
1.2.2.1.3.1	U5.0 - 2.1 Meter Undulator System	1	10723	414.40	481.87	896.28	10723	414.40	481.87	896.28
** *******										
1.2.2.1.3.1.1	Magnetic Structure	1	5439	213.38	257.91	471.29	5439	213.38	257.91	471.29
** ********										
1.2.2.1.3.1.1.1	Magnetic Material	1	288	12.66	82.54	95.20	288	12.66	82.54	95.20
1.2.2.1.3.1.1.2	Model-Pole & Pole Assembly (not req'd)	1	0	0.00	0.00	0.00	0	0.00	0.00	0.00
1.2.2.1.3.1.1.3	Pole Assemblies	1	1562	60.27	61.10	121.37	1562	60.27	61.10	121.37
1.2.2.1.3.1.1.4	End Pole Assemblies	1	864	33.18	21.75	54.93	864	33.18	21.75	54.93
1.2.2.1.3.1.1.5	Backing Beams	1	416	16.06	88.85	104.91	416	16.06	88.85	104.91
1.2.2.1.3.1.1.6	Magnet Structure Assembly	1	936	36.13	3.15	39.27	936	36.13	3.15	39.27
1.2.2.1.3.1.1.7	Magnetic Measurements: Mechanical	1	536	19.87	0.53	20.40	536	19.87	0.53	20.40
1.2.2.1.3.1.1.8	Magnetic Measurements: Electrical	1	838	35.20	0.00	35.20	838	35.20	0.00	35.20

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *******										
1.2.2.1.3.1.2	Support & Drive Systems	1	3064	117.82	156.50	274.32	3064	117.82	156.50	274.32
** ********										
1.2.2.1.3.1.2.1	Support System Fabrication	1	1148	44.31	59.90	104.21	1148	44.31	59.90	104.21
1.2.2.1.3.1.2.2	Drive System Fabrication	1	1516	58.52	90.30	148.82	1516	58.52	90.30	148.82
1.2.2.1.3.1.2.3	Local Temperature Control Fabrication	1	400	14.99	6.30	21.29	400	14.99	6.30	21.29
** *******										
1.2.2.1.3.1.3	Vacuum System	1	1276	47.77	39.17	86.95	1276	47.77	39.17	86.95
** ********										
1.2.2.1.3.1.3.1	Vacuum Chambers	1	760	29.16	4.30	33.46	760	29.16	4.30	33.46
1.2.2.1.3.1.3.2	Pumping Systems & Instrumentation	1	0	0.00	14.32	14.32	0	0.00	14.32	14.32
1.2.2.1.3.1.3.3	Support Structure	1	280	10.81	3.00	13.81	280	10.81	3.00	13.81
1.2.2.1.3.1.3.4	Vacuum Diagnostics	1	236	7.80	17.55	25.36	236	7.80	17.55	25.36
** *******										
1.2.2.1.3.1.4	Motor Control System	1	490	17.96	26.15	44.11	490	17.96	26.15	44.11
1.2.2.1.3.1.5	Installation	1	454	17.46	2.15	19.61	454	17.46	2.15	19.61
** ******										
1.2.2.1.3.2	Optical Systems	1	1088	42.01	1192.02	1234.03	1088	42.01	1192.02	1234.0[illegible]
** *******										
1.2.2.1.3.2.1	Lasing Mirror Systems	1	216	8.11	307.61	315.72	216	8.11	307.61	315.72
1.2.2.1.3.2.2	Optical diagnostics	1	40	1.54	438.00	439.54	40	1.54	438.00	439.54
1.2.2.1.3.2.3	IR Transport	1	272	10.32	428.41	438.73	272	10.32	428.41	438.73
1.2.2.1.3.2.4	Installation	1	560	22.04	18.00	40.04	560	22.04	18.00	40.04
** *****										
1.2.2.1.4	Electron Beam Dumping System	1	1242	53.70	241.90	295.60	1242	53.70	241.90	295.60
** ******										
1.2.2.1.4.1	Beam Spreading System	1	1042	40.22	55.90	96.12	1042	40.22	55.90	96.12
1.2.2.1.4.2	Beam Dumps	1	200	13.48	50.00	63.48	200	13.48	50.00	63.48
1.2.2.1.4.3	Dump Water Processing	1	0	0.00	136.00	136.00	0	0.00	136.00	136.00
** *****										
1.2.2.1.5	Control System	1	7389	381.33	441.79	823.11	7389	381.33	441.79	823.11
** ******										
1.2.2.1.5.1	Network and Workstations	1	536	31.41	44.45	75.86	536	31.41	44.45	75.86
** *******										
1.2.2.1.5.1.1	Network Resource Manager	1	10	0.39	14.10	14.49	10	0.39	14.10	14.49
1.2.2.1.5.1.2	Work Stations	1	10	0.54	28.35	28.89	10	0.54	28.35	28.89
1.2.2.1.5.1.3	Network Software & Documentation	1	420	24.95	2.00	26.95	420	24.95	2.00	26.95
1.2.2.1.5.1.4	Installation	1	96	5.53	0.00	5.53	96	5.53	0.00	5.53

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** ******										
1.2.2.1.5.2	Consoles	1	690	31.12	98.36	129.48	690	31.12	98.36	129.48
** *******										
1.2.2.1.5.2.1	Color Monitors & Touch Panels	1	184	8.66	69.90	78.56	184	8.66	69.90	78.56
1.2.2.1.5.2.2	Video Copier & Mux	1	58	2.92	14.75	17.67	58	2.92	14.75	17.67
1.2.2.1.5.2.3	Portable Consoles	1	118	6.96	12.51	19.47	118	6.96	12.51	19.47
1.2.2.1.5.2.4	Operator Interface	1	98	3.97	1.20	5.17	98	3.97	1.20	5.17
1.2.2.1.5.2.5	Installation	1	232	8.61	0.00	8.61	232	8.61	0.00	8.61
** ******										
1.2.2.1.5.3	Display & Collector Micro Modules	1	2311	133.22	107.78	240.99	2311	133.22	107.78	240.99
** *******										
1.2.2.1.5.3.1	Display Micro Modules	1	48	2.32	64.30	66.62	48	2.32	64.30	66.62
1.2.2.1.5.3.2	Operating System	1	120	7.13	9.50	16.63	120	7.13	9.50	16.63
1.2.2.1.5.3.3	Network Access Software	1	125	7.42	0.00	7.42	125	7.42	0.00	7.42
1.2.2.1.5.3.4	Parameter Access & Modeling Software Int	1	720	42.77	0.00	42.77	720	42.77	0.00	42.77
1.2.2.1.5.3.5	Error Monitoring Software	1	384	22.81	0.00	22.81	384	22.81	0.00	22.81
1.2.2.1.5.3.6	Display Generation Software	1	360	21.38	0.00	21.38	360	21.38	0.00	21.38
1.2.2.1.5.3.7	Display Micro Module Documentation	1	140	8.32	0.00	8.32	140	8.32	0.00	8.32
1.2.2.1.5.3.8	Collector Micro Module	1	90	3.29	33.98	37.26	90	3.29	33.98	37.26
1.2.2.1.5.3.9	Collector Micro Module Software	1	196	11.64	0.00	11.64	196	11.64	0.00	11.64
1.2.2.1.5.3.10	Installation	1	128	6.13	0.00	6.13	128	6.13	0.00	6.13
** ******										
1.2.2.1.5.4	Input/Output Controller Modules	1	3428	170.78	181.99	352.77	3428	170.78	181.99	352.77
** *******										
1.2.2.1.5.4.1	Intelligent Local Controller(ILC)	90	10	0.45	1.82	2.27	864	40.39	163.71	204.10
1.2.2.1.5.4.2	ILC Software & Documentation	1	1116	66.29	0.00	66.29	1116	66.29	0.00	66.29
1.2.2.1.5.4.3	I/O Micro Modules(IOMM's)	1	460	21.99	15.78	37.77	460	21.99	15.78	37.77
1.2.2.1.5.4.4	IOMM Software & Documentation	1	300	17.82	0.00	17.82	300	17.82	0.00	17.82
1.2.2.1.5.4.5	Data Base Generation for I/O Controllers	1	60	3.56	0.00	3.56	60	3.56	0.00	3.56
1.2.2.1.5.4.6	Installation	1	628	20.72	2.50	23.22	628	20.72	2.50	23.22
** ********										
1.2.2.1.5.4.6.1	ILC Installation	90	6	0.20	0.03	0.22	540	17.82	2.25	20.07
1.2.2.1.5.4.6.2	IOMM Installation	1	88	2.90	0.25	3.15	88	2.90	0.25	3.15
** ******										
1.2.2.1.5.5	Computer Timing & Synchronization	1	424	14.80	9.21	24.01	424	14.80	9.21	24.01
** *******										
1.2.2.1.5.5.1	Manchester Encoder & Timing Module	1	120	4.17	2.25	6.42	120	4.17	2.25	6.42
1.2.2.1.5.5.2	Manchester Decoder & Fiber Optics	4	56	1.85	1.74	3.59	224	7.39	6.96	14.35

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.2.2.1.5.5.3	Installation	5	16	0.65	0.00	0.65	80	3.24	0.00	3.24
** *****										
1.2.2.1.6	Safety Systems	1	3042	118.54	163.22	281.76	3042	118.54	163.22	281.76
** ******										
1.2.2.1.6.1	Access Control Fabrication	1	888	29.87	26.43	56.30	888	29.87	26.43	56.30
1.2.2.1.6.2	Area Monitoring Fabrication	1	380	12.54	112.90	125.44	380	12.54	112.90	125.44
1.2.2.1.6.3	Control Room Fabrication	1	66	2.18	1.94	4.12	66	2.18	1.94	4.12
1.2.2.1.6.4	Beam Dump Interlocks	1	400	19.85	6.92	26.77	400	19.85	6.92	26.77
1.2.2.1.6.5	Installation	1	1308	54.11	15.03	69.14	1308	54.11	15.03	69.14
** *****										
1.2.2.1.7	Accelerator/FEL Physics	1	9400	401.85	60.00	461.85	9400	401.85	60.00	461.85
** ****										
1.2.2.2	ALS Beamlines	1	43258	1632.38	3674.58	5306.97	43258	1632.38	3674.58	5306.97
** *****										
1.2.2.2.1	CDRL: U10.0	1	12016	464.77	946.49	1411.26	12016	464.77	946.49	1411.26
** ******										
1.2.2.2.1.1	Magnetic Structure	1	6534	255.26	595.82	851.08	6534	255.26	595.82	851.0
** *******										
1.2.2.2.1.1.1	Magnetic Material	1	438	18.09	379.92	398.01	438	18.09	379.92	398.01
1.2.2.2.1.1.2	Model-Pole & Pole Assembly (not req'd)	1	0	0.00	0.00	0.00	0	0.00	0.00	0.00
1.2.2.2.1.1.3	Pole Assemblies	1	1936	74.75	93.42	168.17	1936	74.75	93.42	168.17
1.2.2.2.1.1.4	End Pole Assemblies	1	864	33.18	24.79	57.98	864	33.18	24.79	57.98
1.2.2.2.1.1.5	Backing Beams	1	456	17.60	92.66	110.26	456	17.60	92.66	110.26
1.2.2.2.1.1.6	Magnet Structure Assembly	1	1304	50.33	4.50	54.84	1304	50.33	4.50	54.84
1.2.2.2.1.1.7	Magnetic Measurements: Mechanical	1	608	22.65	0.53	23.18	608	22.65	0.53	23.18
1.2.2.2.1.1.8	Magnetic Measurements: Electrical	1	928	38.65	0.00	38.65	928	38.65	0.00	38.65
** ******										
1.2.2.2.1.2	Support & Drive Systems	1	2782	106.94	138.10	245.04	2782	106.94	138.10	245.04
** *******										
1.2.2.2.1.2.1	Support System Fabrication	1	1145	44.20	59.90	104.10	1145	44.20	59.90	104.10
1.2.2.2.1.2.2	Drive System Fabrication	1	1237	47.75	71.90	119.65	1237	47.75	71.90	119.65
1.2.2.2.1.2.3	Local Temperature Control Fabrication	1	400	14.99	6.30	21.29	400	14.99	6.30	21.29
** ******										
1.2.2.2.1.3	Vacuum System	1	1886	71.44	190.30	261.74	1886	71.44	190.30	261.74
** *******										
1.2.2.2.1.3.1	Vacuum Chamber	1	1140	44.00	123.11	167.12	1140	44.00	123.11	167.12
1.2.2.2.1.3.2	Pumping Systems & Instrumentation	1	200	7.72	41.47	49.19	200	7.72	41.47	49.19
1.2.2.2.1.3.3	Support Structure	1	300	11.58	3.25	14.84	300	11.58	3.25	14.84

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.2.2.2.1.3.4	Vacuum Diagnostics	1	246	8.13	22.46	30.59	246	8.13	22.46	30.59
** ******										
1.2.2.2.1.4	Motor Control System	1	360	13.67	20.12	33.79	360	13.67	20.12	33.79
1.2.2.2.1.5	Installation	1	454	17.46	2.15	19.61	454	17.46	2.15	19.61
** *****										
1.2.2.2.2	Undulator Beamline	1	19001	708.96	1628.92	2337.88	19001	708.96	1628.92	2337.88
** ******										
1.2.2.2.2.1	Front End	1	6463	240.29	347.08	587.37	6463	240.29	347.08	587.37
** *******										
1.2.2.2.2.1.1	Fixed Aperture	1	543	20.08	37.64	57.72	543	20.08	37.64	57.72
** ********										
1.2.2.2.2.1.1.1	Aperture Plate	1	80	2.96	1.40	4.36	80	2.96	1.40	4.36
1.2.2.2.2.1.1.2	Bellows	1	3	0.11	3.05	3.16	3	0.11	3.05	3.16
1.2.2.2.2.1.1.3	Collimating Spool	1	56	2.10	2.25	4.35	56	2.10	2.25	4.35
1.2.2.2.2.1.1.4	Isolation Valve	1	36	1.32	22.84	24.16	36	1.32	22.84	24.16
1.2.2.2.2.1.1.5	Support Stand	1	128	4.74	5.50	10.24	128	4.74	5.50	10.24
1.2.2.2.2.1.1.6	Assemble, Bakeout, Test	1	72	2.64	1.70	4.34	72	2.64	1.70	4.34
1.2.2.2.2.1.1.7	Installation	1	168	6.20	0.90	7.10	168	6.20	0.90	7.10
** *******										
1.2.2.2.2.1.2	Photon BPM #1	1	848	30.82	43.44	74.26	848	30.82	43.44	74.26
** ********										
1.2.2.2.2.1.2.1	Fab/Buy Mech Parts & Subassy's	1	208	7.80	6.55	14.35	208	7.80	6.55	14.35
1.2.2.2.2.1.2.2	Fab/Buy Electrical and Controls	1	188	6.20	20.69	26.89	188	6.20	20.69	26.89
1.2.2.2.2.1.2.3	Fab/Buy Support Stand	1	56	2.11	4.20	6.31	56	2.11	4.20	6.31
1.2.2.2.2.1.2.4	Bellows	1	4	0.14	8.70	8.84	4	0.14	8.70	8.84
1.2.2.2.2.1.2.5	Assemble, Bakeout, Test (Assembly Shop)	1	172	6.06	2.50	8.56	172	6.06	2.50	8.56
1.2.2.2.2.1.2.6	Installation	1	220	8.50	0.80	9.30	220	8.50	0.80	9.30
** *******										
1.2.2.2.2.1.3	Photon Shutter	1	1306	48.23	72.13	120.36	1306	48.23	72.13	120.36
** ********										
1.2.2.2.2.1.3.1	Fab/Buy Mech Parts & Subassy's	1	460	17.36	6.60	23.96	460	17.36	6.60	23.96
1.2.2.2.2.1.3.2	Fab/Buy Electrical and Controls	1	92	3.04	5.50	8.54	92	3.04	5.50	8.54
1.2.2.2.2.1.3.3	Fab/Buy Vacuum Chamber & Supports	1	128	4.76	15.00	19.76	128	4.76	15.00	19.76
1.2.2.2.2.1.3.4	Vacuum Pumping, Gauges, Controllers, P.S.	1	24	0.82	15.73	16.54	24	0.82	15.73	16.54
1.2.2.2.2.1.3.5	Assemble, Bakeout, Test	1	352	12.79	2.00	14.79	352	12.79	2.00	14.79
1.2.2.2.2.1.3.6	Installation	1	208	7.96	0.90	8.86	208	7.96	0.90	8.86
1.2.2.2.2.1.3.7	Titanium Sublimation Pump	1	28	1.02	7.70	8.72	28	1.02	7.70	8.72
1.2.2.2.2.1.3.8	Isolation Valve	1	14	0.50	18.70	19.20	14	0.50	18.70	19.20

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *******										
1.2.2.2.2.1.4	Fast Valve	1	256	9.65	33.70	43.35	256	9.65	33.70	43.35
** ********										
1.2.2.2.2.1.4.1	Fast Valve	1	0	0.00	26.00	26.00	0	0.00	26.00	26.00
1.2.2.2.2.1.4.2	Fab/Buy Electrical and Controls	1	24	0.79	2.10	2.89	24	0.79	2.10	2.89
1.2.2.2.2.1.4.3	Bellows	1	8	0.29	3.35	3.64	8	0.29	3.35	3.64
1.2.2.2.2.1.4.4	Aperture Plate	1	80	2.96	1.40	4.36	80	2.96	1.40	4.36
1.2.2.2.2.1.4.5	Assemble, Bakeout, Test	1	96	3.45	0.50	3.95	96	3.45	0.50	3.95
1.2.2.2.2.1.4.6	Installation	1	48	2.16	0.35	2.51	48	2.16	0.35	2.51
** *******										
1.2.2.2.2.1.5	Personnel Safety Shutter	1	1106	40.39	64.02	104.40	1106	40.39	64.02	104.40
** ********										
1.2.2.2.2.1.5.1	Fab/Buy Mech Parts & Subassy's	1	300	11.32	10.00	21.32	300	11.32	10.00	21.32
1.2.2.2.2.1.5.2	Fab/Buy Electrical and Controls	1	72	2.38	2.30	4.68	72	2.38	2.30	4.68
1.2.2.2.2.1.5.3	Fab/Buy Vacuum Chamber & Supports	1	108	4.04	12.30	16.34	108	4.04	12.30	16.34
1.2.2.2.2.1.5.4	Vacuum Pumping, Gauges, Controllers, P.S.	1	16	0.55	15.31	15.87	16	0.55	15.31	15.87
1.2.2.2.2.1.5.5	Assemble, Bakeout, Test	1	332	11.93	2.30	14.23	332	11.93	2.30	14.23
1.2.2.2.2.1.5.6	Installation	1	160	5.76	0.60	6.36	160	5.76	0.60	6.36
1.2.2.2.2.1.5.7	Shield Wall Transition Spool	1	104	3.92	5.50	9.42	104	3.92	5.50	9.42
1.2.2.2.2.1.5.8	Isolation Valve	1	14	0.50	15.70	16.20	14	0.50	15.70	16.20
** *******										
1.2.2.2.2.1.6	Photon BPM #2	1	896	32.53	47.03	79.56	896	32.53	47.03	79.56
** ********										
1.2.2.2.2.1.6.1	Fab/Buy Mech Parts & Subassy's	1	248	9.31	6.75	16.06	248	9.31	6.75	16.06
1.2.2.2.2.1.6.2	Fab/Buy Electrical and Controls	1	196	6.47	24.08	30.55	196	6.47	24.08	30.55
1.2.2.2.2.1.6.3	Fab/Buy Support Stand	1	56	2.11	4.20	6.31	56	2.11	4.20	6.31
1.2.2.2.2.1.6.4	Bellows	1	4	0.14	8.70	8.84	4	0.14	8.70	8.84
1.2.2.2.2.1.6.5	Assemble, Bakeout, Test	1	172	6.06	2.50	8.56	172	6.06	2.50	8.56
1.2.2.2.2.1.6.6	Installation	1	220	8.44	0.80	9.24	220	8.44	0.80	9.24
** *******										
1.2.2.2.2.1.7	Vacuum System, Utilities & Installation	1	1225	47.67	37.47	85.14	1225	47.67	37.47	85.14
** ********										
1.2.2.2.2.1.7.1	Fab/Buy Mech Parts & Subassy's	1	160	5.89	2.00	7.89	160	5.89	2.00	7.89
1.2.2.2.2.1.7.2	Fab/Buy Electical and Controls	1	301	12.32	6.77	19.09	301	12.32	6.77	19.09
1.2.2.2.2.1.7.3	Fab/Buy Vacuum Chamber & Supports	1	20	0.72	6.10	6.82	20	0.72	6.10	6.82
1.2.2.2.2.1.7.4	Vacuum Pumping, Gauges, Controllers, P.S.	1	48	1.70	12.55	14.25	48	1.70	12.55	14.25
1.2.2.2.2.1.7.5	Assemble, Bakeout, Test	1	256	9.20	2.00	11.20	256	9.20	2.00	11.20
1.2.2.2.2.1.7.6	Installation	1	440	17.84	8.05	25.89	440	17.84	8.05	25.89

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *******										
1.2.2.2.2.1.8	Safety Systems	1	283	10.91	11.66	22.57	283	10.91	11.66	22.57
** ******										
1.2.2.2.2.2	Branchline	1	12538	468.68	1281.84	1750.52	12538	468.68	1281.84	1750.52
** *******										
1.2.2.2.2.2.1	Horiz. & Vert. Beam Defining Apertures	1	1262	46.70	75.70	122.40	1262	46.70	75.70	122.40
1.2.2.2.2.2.2	M1 Mirror	1	1694	63.39	82.00	145.39	1694	63.39	82.00	145.39
1.2.2.2.2.2.3	M2 Mirror	1	1432	53.34	68.10	121.44	1432	53.34	68.10	121.44
1.2.2.2.2.2.4	M3 Mirror	1	1076	39.98	44.05	84.03	1076	39.98	44.05	84.03
1.2.2.2.2.2.5	Monochromator (NIM)	1	2436	91.65	372.60	464.25	2436	91.65	372.60	464.25
1.2.2.2.2.2.6	M4 Mirror	1	616	23.06	54.45	77.51	616	23.06	54.45	77.51
1.2.2.2.2.2.7	M5 Mirror	1	496	18.60	54.10	72.70	496	18.60	54.10	72.70
1.2.2.2.2.2.8	Branch Line Diagnostics	1	876	32.90	31.90	64.80	876	32.90	31.90	64.80
1.2.2.2.2.2.9	Vacuum System: Controls & Installation	1	1650	62.66	127.79	190.45	1650	62.66	127.79	190.45
1.2.2.2.2.2.10	Branch Line Safety Systems	1	160	5.28	6.90	12.18	160	5.28	6.90	12.18
1.2.2.2.2.2.11	Harmonic Suppression & Optical Filters	1	840	31.12	114.25	145.37	840	31.12	114.25	145.37
1.2.2.2.2.2.12	Secondary Branchline	1	0	0.00	250.00	250.00	0	0.00	250.00	250.00
** *****										
1.2.2.2.3	Bend Magnet Beamline	1	12241	458.65	1099.17	1557.82	12241	458.65	1099.17	1557.82
** ******										
1.2.2.2.3.1	Front End	1	3389	128.40	171.46	299.86	3389	128.40	171.46	299.86
** *******										
1.2.2.2.3.1.1	Aperture Assemblies 1 & 2	1	196	7.20	2.23	9.42	196	7.20	2.23	9.42
1.2.2.2.3.1.2	Bellows 1 & 2	1	40	1.45	6.35	7.80	40	1.45	6.35	7.80
1.2.2.2.3.1.3	Isolation Valves 1 & 2	1	40	1.43	34.55	35.98	40	1.43	34.55	35.98
1.2.2.2.3.1.4	Photon Shutter	1	322	12.22	11.99	24.21	322	12.22	11.99	24.21
1.2.2.2.3.1.5	Vacuum Systems	1	102	3.60	17.57	21.17	102	3.60	17.57	21.17
1.2.2.2.3.1.6	Photon Shutter Support System	1	314	11.77	5.80	17.57	314	11.77	5.80	17.57
1.2.2.2.3.1.7	Fast Shutter	1	56	2.40	31.62	34.03	56	2.40	31.62	34.03
1.2.2.2.3.1.8	Collimation Spool	1	64	2.31	3.30	5.61	64	2.31	3.30	5.61
1.2.2.2.3.1.9	Cleaning, Assemble, Bakeout & Test	1	256	9.20	1.60	10.80	256	9.20	1.60	10.80
1.2.2.2.3.1.10	Installation	1	296	11.69	5.05	16.74	296	11.69	5.05	16.74
1.2.2.2.3.1.11	Misc. Mechanical, Electrical & Controls	1	833	34.01	19.17	53.18	833	34.01	19.17	53.18
1.2.2.2.3.1.12	Safety Systems	1	212	7.00	9.82	16.82	212	7.00	9.82	16.82
1.2.2.2.3.1.13	Shield Wall Transition Assembly	1	658	24.14	22.40	46.54	658	24.14	22.40	46.54
** ******										
1.2.2.2.3.2	Branchline	1	8852	330.25	927.72	1257.97	8852	330.25	927.72	1257.97
** *******										
1.2.2.2.3.2.1	M1 Mirror	1	852	31.47	69.00	100.47	852	31.47	69.00	100.47
1.2.2.2.3.2.2	M2 Mirror	1	1052	39.02	57.70	96.72	1052	39.02	57.70	96.72
1.2.2.2.3.2.3	M3 Mirror	1	632	23.59	41.25	64.84	632	23.59	41.25	64.84
1.2.2.2.3.2.4	Monochromator (NIM)	1	1546	57.70	359.52	417.23	1546	57.70	359.52	417.23

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.2.2.2.3.2.5	M4 Mirror	1	632	23.59	57.02	80.61	632	23.59	57.02	80.61
1.2.2.2.3.2.6	M5 Mirror	1	632	23.59	57.02	80.61	632	23.59	57.02	80.61
1.2.2.2.3.2.7	Branch Line Diagnostics	1	876	32.90	31.60	64.50	876	32.90	31.60	64.50
1.2.2.2.3.2.8	Vacuum System: Controls & Installation	1	1650	62.66	131.44	194.10	1650	62.66	131.44	194.10
1.2.2.2.3.2.9	Branch Line Safety Systems	1	160	5.28	7.40	12.68	160	5.28	7.40	12.68
1.2.2.2.3.2.10	Differential Pumping Sys, Optical Filters	1	820	30.46	115.75	146.21	820	30.46	115.75	146.21
** ****										
1.2.2.3	Experimental Systems	1	22713	1101.98	10098.80	11200.78	22713	1101.98	10098.80	11200.78
** *****										
1.2.2.3.1	Experimental Stations	1	12932	583.08	7630.56	8213.64	12932	583.08	7630.56	8213.64
** ******										
1.2.2.3.1.1	System A	1	5327	248.66	773.70	1022.36	5327	248.66	773.70	1022.36
** *******										
1.2.2.3.1.1.1	Vacuum Chamber	1	3167	146.37	448.33	594.71	3167	146.37	448.33	594.71
1.2.2.3.1.1.2	Detector Systems	1	80	3.70	174.79	178.48	80	3.70	174.79	178.48
1.2.2.3.1.1.3	Lasers	1	0	0.00	150.58	150.58	0	0.00	150.58	150.58
1.2.2.3.1.1.4	Installation	1	2080	98.59	0.00	98.59	2080	98.59	0.00	98.59
** ******										
1.2.2.3.1.2	System B	1	1339	54.79	657.10	711.89	1339	54.79	657.10	711.89
** *******										
1.2.2.3.1.2.1	Vacuum Chamber	1	739	28.53	138.79	167.32	739	28.53	138.79	167.32
1.2.2.3.1.2.2	Detector Systems	1	40	1.32	213.55	214.87	40	1.32	213.55	214.87
1.2.2.3.1.2.3	Lasers	1	0	0.00	304.77	304.77	0	0.00	304.77	304.77
1.2.2.3.1.2.4	Installation	1	560	24.94	0.00	24.94	560	24.94	0.00	24.94
** ******										
1.2.2.3.1.3	System C	1	760	35.77	573.53	609.30	760	35.77	573.53	609.30
** *******										
1.2.2.3.1.3.1	Vacuum Chamber	1	0	0.00	202.40	202.40	0	0.00	202.40	202.40
1.2.2.3.1.3.2	Detector Systems	1	40	1.32	75.39	76.71	40	1.32	75.39	76.71
1.2.2.3.1.3.3	Lasers	1	0	0.00	295.74	295.74	0	0.00	295.74	295.74
1.2.2.3.1.3.4	Installation	1	720	34.45	0.00	34.45	720	34.45	0.00	34.45
** ******										
1.2.2.3.1.4	System D	1	4047	185.11	386.43	571.54	4047	185.11	386.43	571.54
** *******										
1.2.2.3.1.4.1	Vacuum Chamber	1	3007	136.87	135.07	271.94	3007	136.87	135.07	271.94
1.2.2.3.1.4.2	Detector Systems	1	40	1.32	173.41	174.73	40	1.32	173.41	174.73
1.2.2.3.1.4.3	Lasers	1	0	0.00	77.94	77.94	0	0.00	77.94	77.94
1.2.2.3.1.4.4	Installation	1	1000	46.92	0.00	46.92	1000	46.92	0.00	46.92

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** ******										
1.2.2.3.1.5	System E	1	1459	58.75	871.61	930.36	1459	58.75	871.61	930.36
** *******										
1.2.2.3.1.5.1	Vacuum Chamber	1	739	28.53	244.98	273.51	739	28.53	244.98	273.51
1.2.2.3.1.5.2	Detector Systems	1	160	5.28	311.24	316.52	160	5.28	311.24	316.52
1.2.2.3.1.5.3	Lasers	1	0	0.00	304.77	304.77	0	0.00	304.77	304.77
1.2.2.3.1.5.4	Installation	1	560	24.94	10.62	35.56	560	24.94	10.62	35.56
** ******										
1.2.2.3.1.6	Chemical Dynamics Experimental Station (SNL)	1	0	0.00	1489.85	1489.85	0	0.00	1489.85	1489.85
** *******										
1.2.2.3.1.6.1	Vacuum Chambers & Pumps	1	0	0.00	547.94	547.94	0	0.00	547.94	547.94
1.2.2.3.1.6.2	Detector System	1	0	0.00	199.64	199.64	0	0.00	199.64	199.64
1.2.2.3.1.6.3	Lasers	1	0	0.00	708.29	708.29	0	0.00	708.29	708.29
1.2.2.3.1.6.4	Installation	1	0	0.00	33.98	33.98	0	0.00	33.98	33.98
** ******										
1.2.2.3.1.7	Chemical Kinetics Experimental Station (SNL)	1	0	0.00	1378.35	1378.35	0	0.00	1378.35	1378.35
** *******										
1.2.2.3.1.7.1	Vacuum Chambers & Pumps	1	0	0.00	369.54	369.54	0	0.00	369.54	369.54
1.2.2.3.1.7.2	Detector System	1	0	0.00	217.69	217.69	0	0.00	217.69	217.69
1.2.2.3.1.7.3	Lasers	1	0	0.00	757.13	757.13	0	0.00	757.13	757.13
1.2.2.3.1.7.4	Installation	1	0	0.00	33.98	33.98	0	0.00	33.98	33.98
** ******										
1.2.2.3.1.8	Experimental Station Enhancements (SNL)	1	0	0.00	1500.00	1500.00	0	0.00	1500.00	1500.00
** *****										
1.2.2.3.2	Advanced Lasers (3 systems)	1	6508	335.66	2355.25	2690.91	6508	335.66	2355.25	2690.91
** ******										
1.2.2.3.2.1	Lasers	1	800	46.69	1466.94	1513.63	800	46.69	1466.94	1513.63
1.2.2.3.2.2	Laser Accessories	1	248	9.57	416.55	426.12	248	9.57	416.55	426.12
1.2.2.3.2.3	Optical Transport and Support	1	0	0.00	137.51	137.51	0	0.00	137.51	137.51
1.2.2.3.2.4	Diagnostics and Control	1	0	0.00	334.25	334.25	0	0.00	334.25	334.25
1.2.2.3.2.5	System Integration	1	5460	279.40	0.00	279.40	5460	279.40	0.00	279.40
** *****										
1.2.2.3.3	Laser Safety & Controls	1	423	13.96	112.99	126.95	423	13.96	112.99	126.95
** ******										
1.2.2.3.3.1	Laser Safety Covers	1	0	0.00	42.48	42.48	0	0.00	42.48	42.48
1.2.2.3.3.2	Laser Timing / Synchronization	1	423	13.96	70.51	84.47	423	13.96	70.51	84.47

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *****										
1.2.2.3.4	User Control Interface	1	2850	169.29	0.00	169.29	2850	169.29	0.00	169.29
** **										
1.3	Conventional Facilities	1	0	0.00	23768.31	23768.31	0	0.00	23768.31	23768.31
** ***										
1.3.1	ED&I	1	0	0.00	2430.00	2430.00	0	0.00	2430.00	2430.00
1.3.2	Construction	1	0	0.00	16628.38	16628.38	0	0.00	16628.38	16628.38
** ****										
1.3.2.1	Phase I (Site Preparation)	1	0	0.00	2396.00	2396.00	0	0.00	2396.00	2396.00
** *****										
1.3.2.1.1	Improvements to Land	1	0	0.00	156.00	156.00	0	0.00	156.00	156.00
** ******										
1.3.2.1.1.1	Building 10 Demolition	1	0	0.00	156.00	156.00	0	0.00	156.00	156.00
** *****										
1.3.2.1.2	Building	1	0	0.00	748.00	748.00	0	0.00	748.00	748.00
** ******										
1.3.2.1.2.1	Shoring and Underpinning	1	0	0.00	438.00	438.00	0	0.00	438.00	438.00
1.3.2.1.2.2	Excavation	1	0	0.00	310.00	310.00	0	0.00	310.00	310.00
** *****										
1.3.2.1.3	Utilities	1	0	0.00	1492.00	1492.00	0	0.00	1492.00	1492.00
** ******										
1.3.2.1.3.1	Mods to Existing Systems	1	0	0.00	1492.00	1492.00	0	0.00	1492.00	1492.00
** ****										
1.3.2.2	Phase II (Building Construction)	1	0	0.00	14232.38	14232.38	0	0.00	14232.38	14232.38
** *****										
1.3.2.2.1	Improvements to Land	1	0	0.00	199.00	199.00	0	0.00	199.00	199.00
** ******										
1.3.2.2.1.1	Paving and Surfacing	1	0	0.00	51.00	51.00	0	0.00	51.00	51.00
1.3.2.2.1.2	Cyclotron Road Parking	1	0	0.00	94.00	94.00	0	0.00	94.00	94.00
1.3.2.2.1.3	Site Improvements	1	0	0.00	47.00	47.00	0	0.00	47.00	47.00
1.3.2.2.1.4	Landscaping	1	0	0.00	7.00	7.00	0	0.00	7.00	7.00
** *****										
1.3.2.2.2	Building	1	0	0.00	11018.01	11018.01	0	0.00	11018.01	11018.01

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** ******										
1.3.2.2.2.1	Concrete	1	0	0.00	2040.88	2040.88	0	0.00	2040.88	2040.88
1.3.2.2.2.2	Metals	1	0	0.00	1197.66	1197.66	0	0.00	1197.66	1197.66
** *******										
1.3.2.2.2.2.1	Structural Steel	1	0	0.00	828.41	828.41	0	0.00	828.41	828.41
1.3.2.2.2.2.2	Steel Deck	1	0	0.00	242.28	242.28	0	0.00	242.28	242.28
1.3.2.2.2.2.3	Metal Fabrications	1	0	0.00	126.96	126.96	0	0.00	126.96	126.96
** ******										
1.3.2.2.2.3	Wood and Plastic	1	0	0.00	59.25	59.25	0	0.00	59.25	59.25
** *******										
1.3.2.2.2.3.1	Custom Casework	1	0	0.00	59.25	59.25	0	0.00	59.25	59.25
** ******										
1.3.2.2.2.4	Thermal and Moisture Protection	1	0	0.00	730.02	730.02	0	0.00	730.02	730.02
** *******										
1.3.2.2.2.4.1	Waterproofing	1	0	0.00	45.49	45.49	0	0.00	45.49	45.49
1.3.2.2.2.4.2	Dampproofing	1	0	0.00	5.29	5.29	0	0.00	5.29	5.29
1.3.2.2.2.4.3	Insulation	1	0	0.00	15.87	15.87	0	0.00	15.87	15.87
1.3.2.2.2.4.4	Fireproofing	1	0	0.00	98.39	98.39	0	0.00	98.39	98.39
1.3.2.2.2.4.5	Preformed Metal Siding	1	0	0.00	487.74	487.74	0	0.00	487.74	487.74
1.3.2.2.2.4.6	Membrane Roofing	1	0	0.00	45.49	45.49	0	0.00	45.49	45.49
1.3.2.2.2.4.7	Sheet Metal Flashing	1	0	0.00	13.75	13.75	0	0.00	13.75	13.75
1.3.2.2.2.4.8	Sealants	1	0	0.00	17.99	17.99	0	0.00	17.99	17.99
** ******										
1.3.2.2.2.5	Doors and Windows	1	0	0.00	375.59	375.59	0	0.00	375.59	375.59
** *******										
1.3.2.2.2.5.1	Metal Doors and Frames	1	0	0.00	38.09	38.09	0	0.00	38.09	38.09
1.3.2.2.2.5.2	Wood Doors	1	0	0.00	42.32	42.32	0	0.00	42.32	42.32
1.3.2.2.2.5.3	Overhead Coiling Doors	1	0	0.00	14.81	14.81	0	0.00	14.81	14.81
1.3.2.2.2.5.4	Metal Windows	1	0	0.00	170.34	170.34	0	0.00	170.34	170.34
1.3.2.2.2.5.5	Hardware	1	0	0.00	83.58	83.58	0	0.00	83.58	83.58
1.3.2.2.2.5.6	Glazing	1	0	0.00	26.45	26.45	0	0.00	26.45	26.45
** ******										
1.3.2.2.2.6	Finishes	1	0	0.00	1280.18	1280.18	0	0.00	1280.18	1280.18
** *******										
1.3.2.2.2.6.1	Metal Support Systems	1	0	0.00	478.22	478.22	0	0.00	478.22	478.22
1.3.2.2.2.6.2	Gypsum Board Systems	1	0	0.00	357.60	357.60	0	0.00	357.60	357.60
1.3.2.2.2.6.3	Tile	1	0	0.00	117.44	117.44	0	0.00	117.44	117.44
1.3.2.2.2.6.4	Acoustical Ceilings	1	0	0.00	51.84	51.84	0	0.00	51.84	51.84
1.3.2.2.2.6.5	Resilient Flooring	1	0	0.00	30.68	30.68	0	0.00	30.68	30.68
1.3.2.2.2.6.6	Carpet	1	0	0.00	41.26	41.26	0	0.00	41.26	41.26

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.3.2.2.2.6.7	Painting	1	0	0.00	203.14	203.14	0	0.00	203.14	203.14
** ******										
1.3.2.2.2.7	Specialties	1	0	0.00	44.44	44.44	0	0.00	44.44	44.44
** *******										
1.3.2.2.2.7.1	Visual Display Boards	1	0	0.00	3.17	3.17	0	0.00	3.17	3.17
1.3.2.2.2.7.2	Metal Toilet Compartments	1	0	0.00	5.29	5.29	0	0.00	5.29	5.29
1.3.2.2.2.7.3	Metal Wall Louvers	1	0	0.00	33.86	33.86	0	0.00	33.86	33.86
1.3.2.2.2.7.4	Toilet and Bath Accessories	1	0	0.00	2.12	2.12	0	0.00	2.12	2.12
** ******										
1.3.2.2.2.8	Energy Monitoring and Control Systems	1	0	0.00	239.11	239.11	0	0.00	239.11	239.11
1.3.2.2.2.9	Conveying Systems	1	0	0.00	472.93	472.93	0	0.00	472.93	472.93
** *******										
1.3.2.2.2.9.1	Elevators	1	0	0.00	257.09	257.09	0	0.00	257.09	257.09
1.3.2.2.2.9.2	Hoists and Cranes	1	0	0.00	215.83	215.83	0	0.00	215.83	215.83
** ******										
1.3.2.2.2.10	Mechanical	1	0	0.00	2784.66	2784.66	0	0.00	2784.66	2784.66
** *******										
1.3.2.2.2.10.1	Basic Materials and Methods	1	0	0.00	420.03	420.03	0	0.00	420.03	420.03
1.3.2.2.2.10.2	Mechanical Insulation	1	0	0.00	133.31	133.31	0	0.00	133.31	133.31
1.3.2.2.2.10.3	Fire Protection	1	0	0.00	245.46	245.46	0	0.00	245.46	245.46
1.3.2.2.2.10.4	Plumbing	1	0	0.00	142.83	142.83	0	0.00	142.83	142.83
1.3.2.2.2.10.5	Compressed Air System	1	0	0.00	50.78	50.78	0	0.00	50.78	50.78
1.3.2.2.2.10.6	Deionized Water System	1	0	0.00	62.42	62.42	0	0.00	62.42	62.42
1.3.2.2.2.10.7	Low Conductivity Water System	1	0	0.00	34.91	34.91	0	0.00	34.91	34.91
1.3.2.2.2.10.8	Heat Generation	1	0	0.00	100.51	100.51	0	0.00	100.51	100.51
1.3.2.2.2.10.9	Refrigeration	1	0	0.00	471.87	471.87	0	0.00	471.87	471.87
1.3.2.2.2.10.10	Air Handling	1	0	0.00	479.27	479.27	0	0.00	479.27	479.27
1.3.2.2.2.10.11	Air Distribution	1	0	0.00	630.57	630.57	0	0.00	630.57	630.57
1.3.2.2.2.10.12	Testing and Balancing	1	0	0.00	12.70	12.70	0	0.00	12.70	12.70
** ******										
1.3.2.2.2.11	Electrical	1	0	0.00	1793.31	1793.31	0	0.00	1793.31	1793.31
** *******										
1.3.2.2.2.11.1	12 kV Distributions	1	0	0.00	790.33	790.33	0	0.00	790.33	790.33
1.3.2.2.2.11.2	Power Service and Distribution	1	0	0.00	249.69	249.69	0	0.00	249.69	249.69
1.3.2.2.2.11.3	Emergency System	1	0	0.00	100.51	100.51	0	0.00	100.51	100.51
1.3.2.2.2.11.4	Power and Motor Feeders	1	0	0.00	259.21	259.21	0	0.00	259.21	259.21
1.3.2.2.2.11.5	Lighting	1	0	0.00	189.38	189.38	0	0.00	189.38	189.38
1.3.2.2.2.11.6	Misc. Power Devices	1	0	0.00	55.02	55.02	0	0.00	55.02	55.02
1.3.2.2.2.11.7	Communications	1	0	0.00	126.96	126.96	0	0.00	126.96	126.96
1.3.2.2.2.11.8	Fire Alarm System	1	0	0.00	22.22	22.22	0	0.00	22.22	22.22

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
** *****										
1.3.2.2.3	Special Building Facilities	1	0	0.00	1502.68	1502.68	0	0.00	1502.68	1502.68
** ******										
1.3.2.2.3.1	Laboratory Benches	1	0	0.00	210.30	210.30	0	0.00	210.30	210.30
1.3.2.2.3.2	Chemical Storage Cabinets	1	0	0.00	9.80	9.80	0	0.00	9.80	9.80
1.3.2.2.3.3	Fume Hoods	1	0	0.00	232.10	232.10	0	0.00	232.10	232.10
1.3.2.2.3.4	Instrument Racks	1	0	0.00	52.70	52.70	0	0.00	52.70	52.70
1.3.2.2.3.5	Vacuum Systems	1	0	0.00	105.50	105.50	0	0.00	105.50	105.50
1.3.2.2.3.6	Liquid Nitrogen Distribution Systems	1	0	0.00	246.18	246.18	0	0.00	246.18	246.18
1.3.2.2.3.7	Acid Drain Systems	1	0	0.00	62.80	62.80	0	0.00	62.80	62.80
1.3.2.2.3.8	Laser Safety Contol Systems	1	0	0.00	32.00	32.00	0	0.00	32.00	32.00
1.3.2.2.3.9	Vacuum Control Systems	1	0	0.00	37.60	37.60	0	0.00	37.60	37.60
1.3.2.2.3.10	Chemical Detection Systems	1	0	0.00	232.30	232.30	0	0.00	232.30	232.30
1.3.2.2.3.11	Data Acquisition System	1	0	0.00	281.40	281.40	0	0.00	281.40	281.40
** *****										
1.3.2.2.4	Utilities	1	0	0.00	1512.68	1512.68	0	0.00	1512.68	1512.68
** ******										
1.3.2.2.4.1	Mechanical Utilities	1	0	0.00	47.25	47.25	0	0.00	47.25	47.25
** *******										
1.3.2.2.4.1.1	Water Distribution Systems	1	0	0.00	21.74	21.74	0	0.00	21.74	21.74
1.3.2.2.4.1.2	Gas Distribution System	1	0	0.00	21.74	21.74	0	0.00	21.74	21.74
1.3.2.2.4.1.3	Sewage and Drainage	1	0	0.00	3.77	3.77	0	0.00	3.77	3.77
** ******										
1.3.2.2.4.2	Cooling Tower	1	0	0.00	1398.24	1398.24	0	0.00	1398.24	1398.24
** *******										
1.3.2.2.4.2.1	Building 37 Extension	1	0	0.00	1316.12	1316.12	0	0.00	1316.12	1316.12
1.3.2.2.4.2.2	Low Conductivity Water (LCW) Connection	1	0	0.00	41.06	41.06	0	0.00	41.06	41.06
1.3.2.2.4.2.3	Treated Water Connection	1	0	0.00	41.06	41.06	0	0.00	41.06	41.06
** ******										
1.3.2.2.4.3	Electrical Utilities	1	0	0.00	67.19	67.19	0	0.00	67.19	67.19
** *******										
1.3.2.2.4.3.1	15 kV Power Service	1	0	0.00	67.19	67.19	0	0.00	67.19	67.19
** ***										
1.3.3	Standard Equipment	1	0	0.00	4709.94	4709.94	0	0.00	4709.94	4709.94
** ****										
1.3.3.1	Standard Laser Systems	1	0	0.00	1033.17	1033.17	0	0.00	1033.17	1033.17
1.3.3.2	Office Furniture & Equipment	1	0	0.00	111.09	111.09	0	0.00	111.09	111.09
1.3.3.3	Personal Computers	1	0	0.00	161.08	161.08	0	0.00	161.08	161.08
1.3.3.4	Computer Workstations	1	0	0.00	855.39	855.39	0	0.00	855.39	855.39

Cost Estimate Summary Report

Work Breakdown Structure #	Description	Qty Reqd	Labor Hours	Labor K$	ISC K$	Cost K$	Total Labor Hours	TOTAL Labor K$	TOTAL ISC K$	TOTAL COST K$
1.3.3.5	Diagnostic and Detection Systems	1	0	0.00	493.24	493.24	0	0.00	493.24	493.24
1.3.3.6	Electronic Balance	1	0	0.00	4.44	4.44	0	0.00	4.44	4.44
1.3.3.7	Vacuum Leak Detector	1	0	0.00	20.00	20.00	0	0.00	20.00	20.00
1.3.3.8	Casettometer	1	0	0.00	5.55	5.55	0	0.00	5.55	5.55
1.3.3.9	Streak Camera System	1	0	0.00	149.97	149.97	0	0.00	149.97	149.97
1.3.3.10	Equipment for SNL upstairs lab	1	0	0.00	1876.00	1876.00	0	0.00	1876.00	1876.00
** **										
1.4	Contingency	1	0	0.00	16154.00	16154.00	0	0.00	16154.00	16154.00
** ***										
1.4.1	Project Management Contingency	1	0	0.00	700.00	700.00	0	0.00	700.00	700.00
1.4.2	Special Research Facilities Contingency	1	0	0.00	11643.00	11643.00	0	0.00	11643.00	11643.00
** ****										
1.4.2.1	IRFEL	1	0	0.00	5443.00	5443.00	0	0.00	5443.00	5443.00
1.4.2.2	ALS Beamlines	1	0	0.00	1795.00	1795.00	0	0.00	1795.00	1795.00
1.4.2.3	Experimental Systems	1	0	0.00	4405.00	4405.00	0	0.00	4405.00	4405.00
** ***										
1.4.3	Conventional Facilities Contingency	1	0	0.00	3811.00	3811.00	0	0.00	3811.00	3811.00

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.1.1	Project Direction and Management												
1	Project Manager		0	0.00		0.0	1	8390.0	8390	ME	59.40	498.4	498.4
2	Deputy Project Manager		0	0.00		0.0	1	8390.0	8390	EE	59.40	498.4	498.4
3	Conventionl Facilits Mgr		0	0.00		0.0	1	4970.0	4970	PEN	44.95	223.4	223.4
4	QA Officer		0	0.00		0.0	1	8390.0	8390	ME	59.40	498.4	498.4
5	Safety Officer		0	0.00		0.0	1	8390.0	8390	ME	59.40	498.4	498.4
6	Supplies & Expenses		1	250000.00	eu	250.0	0	0.0	0		0.00	0.0	250.0
** Subtotal **						250.0			38530			2216.9	2466.9
** WBS: 1.1.2	Project Office Services												
1	Clerical Support		0	0.00		0.0	2	8390.0	16780	AA	42.75	717.3	717.3
2	C/SCS Support		0	0.00		0.0	3	7060.0	21180	AA	42.75	905.4	905.4
3	Supplies & Expenses	lot	1	100200.00	eu	100.2	0	0.0	0		0.00	0.0	100.2
** Subtotal **						100.2			37960			1622.8	1723.0
** WBS: 1.1.3	Incremental Indirects												
1	Incremental Indirects		1	700000.00		700.0	0	0.0	0		0.00	0.0	700.0
** Subtotal **						700.0			0			0.0	700.0
** WBS: 1.2.1.1.1	Accelerator Systems												
1	Accelerator Systems EDI		1	2385000.00		2385.0	0	0.0	0		0.00	0.0	2385.0
** Subtotal **						2385.0			0			0.0	2385.0
** WBS: 1.2.1.1.2	Electron Beam Transport												
1	Electrn transprt etc, EDI		1	1130000.00		1130.0	0	0.0	0		0.00	0.0	1130.0
** Subtotal **						1130.0			0			0.0	1130.0
** WBS: 1.2.1.1.3	Undulator and Optical System												
1	Undultr&Optical Sys EDI		1	675000.00		675.0	0	0.0	0		0.00	0.0	675.0
** Subtotal **						675.0			0			0.0	675.0
** WBS: 1.2.1.1.4	Electron Beam Dumping System												
1	Electron Beam Dump EDI		1	105000.00		105.0	0	0.0	0		0.00	0.0	105.0
** Subtotal **						105.0			0			0.0	105.0
** WBS: 1.2.1.1.5	Control System												
1	Control System EDI		1	245000.00		245.0	0	0.0	0		0.00	0.0	245.0
** Subtotal **						245.0			0			0.0	245.0
** WBS: 1.2.1.1.6	Safety Systems												
1	Safety Systems EDI		1	85000.00		85.0	0	0.0	0		0.00	0.0	85.0
** Subtotal **						85.0			0			0.0	85.0
** WBS: 1.2.1.1.7	Accelerator/FEL Physics												
1	Accelrtr/FEL Physics EDI		1	140000.00		140.0	0	0.0	0		0.00	0.0	140.0
** Subtotal **						140.0			0			0.0	140.0
** WBS: 1.2.1.2.1	U10 Undulator												
1	U10 Undulator EDI		1	420000.00		420.0	0	0.0	0		0.00	0.0	420.0
** Subtotal **						420.0			0			0.0	420.0
** WBS: 1.2.1.2.2	Undulator Beamline												
1	Undulator Beamline EDI		1	740000.00		740.0	0	0.0	0		0.00	0.0	740.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC LABOR K
** Subtotal **					740.0			0			0.0	740.0
** WBS: 1.2.1.2.3	Bend Magnet Beamline											
1	Bend Magnet Beamline EDI		1	495000.00	495.0	0	0.0	0		0.00	0.0	495.0
** Subtotal **					495.0			0			0.0	495.0
** WBS: 1.2.1.3.1	Experimental Stations											
1	Experimental Stations EDI		1	2425000.00	2425.0	0	0.0	0		0.00	0.0	2425.0
** Subtotal **					2425.0			0			0.0	2425.0
** WBS: 1.2.1.3.2	Advanced Lasers											
1	Advanced Lasers EDI		1	930000.00	930.0	0	0.0	0		0.00	0.0	930.0
** Subtotal **					930.0			0			0.0	930.0
** WBS: 1.2.1.3.3	Laser Safety & Controls											
1	Laser Safety/Controls EDI		1	51000.00	51.0	0	0.0	0		0.00	0.0	51.0
** Subtotal **					51.0			0			0.0	51.0
** WBS: 1.2.1.3.4	User Control Interface											
1	User Control Intrfce EDI		1	68000.00	68.0	0	0.0	0		0.00	0.0	68.0
** Subtotal **					68.0			0			0.0	68.0
** WBS: 1.2.2.1.1.1	Electron Gun											
1	Gun body & cathodes	ea	1	100000.00 eu	100.0	1	60.0	60	MS	37.73	2.3	102.3
2	Gun body cooling	ea	1	3000.00 eu	3.0	1	40.0	40	MS	37.73	1.5	4.5
3	Isolated gun deck	ea	1	35000.00 eu	35.0	1	160.0	160	MA	38.60	6.2	41.2
4	300 kv power supply	ea	1	29000.00 cp	29.0	1	60.0	60	EI	33.00	2.0	31.0
5	Gun & PS enclosure	ea	1	12000.00 eu	12.0	1	160.0	160	MS	37.73	6.0	18.
6	Enclosure air conditning	ea	1	7000.00 eu	7.0	1	60.0	60	IPL	67.40	4.0	11.[illegible]
7	Gun electronics	lot	1	15000.00 eu	15.0	1	240.0	240	EI	33.00	7.9	22.9
8	Gun tank gas system	ea	1	12000.00 eu	12.0	1	60.0	60	MU	35.92	2.2	14.2
9	Control modules	ea	1	6000.00 eu	6.0	1	240.0	240	EI	33.00	7.9	13.9
10	Equipment Racks	ea	1	2800.00 eu	2.8	1	60.0	60	IEL	62.85	3.8	6.6
11	Optos/ILCs/X-conn	lot	3	4000.00 eu	12.0	3	40.0	120	EI	33.00	4.0	16.0
** Subtotal **					233.8			1260			47.7	281.5
** WBS: 1.2.2.1.1.2.1	Magnets and Power Supplies											
1	Gun focus coils	ea	2	300.00 eu	0.6	2	50.0	100	EI	33.00	3.3	3.9
2	Steering coils	ea	12	400.00 eu	4.8	12	20.0	240	EI	33.00	7.9	12.7
3	Focus/steering PS	ea	14	1300.00 eu	18.2	14	30.0	420	ES	33.00	13.9	32.1
4	Solenoid coils and mounts	ea	16	4000.00 eu	64.0	0	0.0	0		0.00	0.0	64.0
5	Solenoid PS	ea	8	3200.00 cp	25.6	0	0.0	0		0.00	0.0	25.6
6	Rack/AC/x-connect	ea	4	2300.00 cp	9.2	4	40.0	160	EI	33.00	5.3	14.5
** Subtotal **					122.4			920			30.4	152.8
** WBS: 1.2.2.1.1.2.2	Subharmonic Bunchers											
1	60 MHz cavity	ea	1	40000.00 eu	40.0	1	240.0	240	MM	38.60	9.3	49.3
2	170 MHz cavity	ea	1	42000.00 eu	42.0	1	240.0	240	MM	38.60	9.3	51.3
** Subtotal **					82.0			480			18.5	100.5
** WBS: 1.2.2.1.1.2.3	Buncher RF System											
1	60 MHz 25kw cw pwr source	ea	1	120000.00 eu	120.0	1	240.0	240	EI	33.00	7.9	127.9
2	60 MHz L.P. RF	ea	1	8000.00 eu	8.0	1	240.0	240	EI	33.00	7.9	15.9
3	Amplifier control modules	set	1	8000.00 eu	8.0	1	260.0	260	EI	33.00	8.6	16.6
4	ILCs/Opto-isolators	lot	1	7200.00 eu	7.2	1	40.0	40	EI	33.00	1.3	8.5
5	Racks/AC/x-connects	lot	2	2300.00 cp	4.6	2	40.0	80	IEL	62.85	5.0	9.6
6	RF feeder	lot	1	5000.00 eu	5.0	1	120.0	120	MU	35.92	4.3	9.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
7	60 MHz Cavity cooling	ea	1	40000.00	eu	40.0	1	160.0	160	MU	35.92	5.7	45.7
8	170 MHz 25kw cw pwr sourc	ea	1	130000.00	eu	130.0	1	240.0	240	EI	33.00	7.9	137.9
9	170 MHz L.P. RF	ea	1	9000.00	eu	9.0	1	240.0	240	EI	33.00	7.9	16.9
10	Amplifier control modules	lot	1	8000.00	eu	8.0	1	260.0	260	EI	33.00	8.6	16.6
11	ILCs/Opto-isolators	lot	1	7200.00	eu	7.2	1	40.0	40	EI	33.00	1.3	8.5
12	Racks/AC/x-connects	ea	2	2300.00	cp	4.6	2	40.0	80	IEL	62.85	5.0	9.6
13	RF feeder	lot	1	5000.00	eu	5.0	1	120.0	120	MU	35.92	4.3	9.3
14	170 MHz Cavity cooling	ea	1	40000.00	eu	40.0	1	160.0	160	MU	35.92	5.7	45.7
** Subtotal **						396.6			2280			81.7	478.3
** WBS: 1.2.2.1.1.2.4.1	Vacuum Chambers												
1	GTL components/mounts	lot	1	15400.00	eu	15.4	0	0.0	0		0.00	0.0	15.4
2	Buncher componts/mounts	lot	1	3000.00	eu	3.0	0	0.0	0		0.00	0.0	3.0
3	All metal valves	ea	3	7200.00	cp	21.6	0	0.0	0		0.00	0.0	21.6
4	Roughing valves	ea	3	2100.00	cp	6.3	0	0.0	0		0.00	0.0	6.3
5	Installation materials	lot	1	2500.00	eu	2.5	0	0.0	0		0.00	0.0	2.5
** Subtotal **						48.8			0			0.0	48.8
** WBS: 1.2.2.1.1.2.4.2	Pumping Systems												
1	20L ion pump	ea	1	1300.00	cp	1.3	0	0.0	0		0.00	0.0	1.3
2	120L ion pump	ea	5	4500.00	cp	22.5	0	0.0	0		0.00	0.0	22.5
3	Pump controllers	ea	6	2600.00	cp	15.6	0	0.0	0		0.00	0.0	15.6
4	Roughing trolley	ea	1	31500.00	cp	31.5	1	30.0	30	MU	35.92	1.1	32.6
5	Installation materials	lot	1	2000.00	eu	2.0	0	0.0	0		0.00	0.0	2.0
** Subtotal **						72.9			30			1.1	74.0
** WBS: 1.2.2.1.1.2.4.3	Monitoring and Control												
1	Ion gauge systems	ea	4	2900.00	cp	11.6	4	16.0	64	EI	33.00	2.1	13.7
2	Control modules	set	1	800.00	eu	0.8	1	40.0	40	ES	33.00	1.3	2.1
3	Racks/AC/x-connects	ea	2	2300.00	cp	4.6	2	40.0	80	EI	33.00	2.6	7.2
4	Opto-isolators	ea	2	400.00	eu	0.8	2	44.0	88	EI	33.00	2.9	3.7
5	Installation materials	lot	1	600.00	eu	0.6	0	0.0	0		0.00	0.0	0.6
** Subtotal **						18.4			272			9.0	27.4
** WBS: 1.2.2.1.1.2.5	Cooling Systems												
1	Gun air system	lot	1	500.00	eu	0.5	1	32.0	32	MU	35.92	1.1	1.6
2	GTL water system	lot	1	800.00	eu	0.8	1	40.0	40	MU	35.92	1.4	2.2
3	Buncher water manifold	ea	2	400.00	eu	0.8	2	32.0	64	MU	35.92	2.3	3.1
4	Klystron systems	ea	10	3000.00	eu	30.0	10	80.0	800	MU	35.92	28.7	58.7
5	Waveguide systems	ea	5	1000.00	eu	5.0	5	80.0	400	MU	35.92	14.4	19.4
6	Buncher control systems	ea	2	2000.00	eu	4.0	2	24.0	48	EI	33.00	1.6	5.6
** Subtotal **						41.1			1384			49.6	90.7
** WBS: 1.2.2.1.1.2.6	Stands and Supports												
1	GTL stand/supports	ea	1	10000.00	eu	10.0	1	200.0	200	MS	37.73	7.5	17.5
** Subtotal **						10.0			200			7.5	17.5
** WBS: 1.2.2.1.1.2.7	Installation												
1	GTL stand mechanical		0	0.00		0.0	1	120.0	120	MU	35.92	4.3	4.3
2	GTL stand electrical		0	0.00		0.0	1	240.0	240	EI	33.00	7.9	7.9
3	Gun enclosure mechanical		0	0.00		0.0	1	20.0	20	MU	35.92	0.7	0.7
4	Gun electronics		0	0.00		0.0	1	40.0	40	EI	33.00	1.3	1.3
5	Rack installation		0	0.00		0.0	8	40.0	320	EI	33.00	10.6	10.6
6	" "		0	0.00		0.0	8	40.0	320	IEL	62.85	20.1	20.1
** Subtotal **						0.0			1060			44.9	44.9
** WBS: 1.2.2.1.1.3.1	Magnets and Power Supplies												
1	Dipole magnets	ea	8	11900.00	eu	95.2	0	0.0	0		0.00	0.0	95.2
2	Dipole mag power supplies	ea	2	12000.00	eu	24.0	0	0.0	0		0.00	0.0	24.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC LABOR K
3	Quad magnets	ea	2	12000.00	eu	24.0	0	0.0	0		0.00	0.0	24.0
4	Quad power supplies	ea	2	6000.00	eu	12.0	0	0.0	0		0.00	0.0	12.0
5	Septum mag & power supply	ea	2	29100.00	eu	58.2	0	0.0	0		0.00	0.0	58.2
6	Racks/AC/x-connects	ea	1	2300.00	cp	2.3	1	40.0	40	EI	33.00	1.3	3.6
7	Opto-isolators	ea	2	400.00	eu	0.8	2	44.0	88	EI	33.00	2.9	3.7
8	Installation materials	lot	1	600.00	eu	0.6	0	0.0	0		0.00	0.0	0.6
9	Toroids	ea	6	200.00	eu	1.2	6	56.0	336	MA	38.60	13.0	14.2
10	PS:	ea	6	1000.00	eu	6.0	0	0.0	0		0.00	0.0	6.0
** Subtotal **						224.3			464			17.2	241.5
** WBS: 1.2.2.1.1.3.2	S.C. Accelerator Modules												
1	0.5 GHz S.C. Cavities	meter	6	300000.00	eu	1800.0	0	0.0	0		0.00	0.0	1800.0
** Subtotal **						1800.0			0			0.0	1800.0
** WBS: 1.2.2.1.1.3.3.1	High Power Systems												
1	6o kw klystron modules	ea	10	63000.00	cp	630.0	10	30.0	300	MU	35.92	10.8	640.8
2	Power combiners	ea	5	19000.00	eu	95.0	5	60.0	300	MU	35.92	10.8	105.8
3	Circulators & loads	ea	5	102000.00	eu	510.0	5	48.0	240	MU	35.92	8.6	518.6
4	Waveguide systems	ea	5	15000.00	eu	75.0	5	80.0	400	MU	35.92	14.4	89.4
5	Klystron HV dist. unit	ea	1	65000.00	eu	65.0	1	240.0	240	EI	33.00	7.9	72.9
6	27kv 1.3 MV xfmr/rect	ea	1	105000.00	eu	105.0	1	240.0	240	IEL	62.85	15.1	120.1
7	Klystron cooling panel	ea	1	60000.00	eu	60.0	1	300.0	300	MU	35.92	10.8	70.8
8	Klystron auxiliaries	lot	5	10000.00	eu	50.0	5	48.0	240	EI	33.00	7.9	57.9
9	Klystron drivers	ea	10	4000.00	eu	40.0	10	12.0	120	EI	33.00	4.0	44.0
10	Auxiliary racks	ea	15	2300.00	eu	34.5	15	40.0	600	EI	33.00	19.8	54.3
11	ILCs/Optos	lot	5	3800.00	eu	19.0	5	20.0	100	EI	33.00	3.3	22.3
** Subtotal **						1683.5			3080			113.3	1796.8
** WBS: 1.2.2.1.1.3.3.2	Low Power Systems												
1	Master oscillator system	ea	1	7000.00	eu	7.0	1	120.0	120	EI	33.00	4.0	11.0
2	Distribution system	ea	1	6000.00	eu	6.0	1	120.0	120	EI	33.00	4.0	10.
3	Servos & controls	set	1	30000.00	eu	30.0	1	400.0	400	EI	33.00	13.2	43..
4	Special rf cables	set	1	45000.00	eu	45.0	1	300.0	300	EI	33.00	9.9	54.9
5	RF safety systems	ea	1	25000.00	eu	25.0	1	250.0	250	EI	33.00	8.2	33.2
6	Interlocks sys/patch pnls	lot	1	20000.00	eu	20.0	1	400.0	400	EI	33.00	13.2	33.2
7	RF diagnostics	ea	1	27000.00	eu	27.0	1	120.0	120	EI	33.00	4.0	31.0
8	Racks/x-connects	lot	8	2300.00	eu	18.4	8	40.0	320	IEL	62.85	20.1	38.5
** Subtotal **						178.4			2030			76.5	254.9
** WBS: 1.2.2.1.1.3.4.1	Cryostat Services												
1	Technicians		0	0.00		0.0	2	240.0	480	MU	35.92	17.2	17.2
2	Insulating Vac System	lot	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
3	Instrumentation	lot	1	35000.00	eu	35.0	1	120.0	120	EI	33.00	4.0	39.0
** Subtotal **						50.0			600			21.2	71.2
** WBS: 1.2.2.1.1.3.4.2	He Refrigeration												
1	Cold Box/Compressors/600w	ea	1	600000.00	eu	600.0	0	0.0	0		0.00	0.0	600.0
2	Plumbing/Piping	lot	1	12000.00	eu	12.0	2	80.0	160	IPL	67.40	10.8	22.8
3	Motor switchgear,H20 Pump	lot	1	50000.00	eu	50.0	2	80.0	160	IEL	62.85	10.1	60.1
** Subtotal **						662.0			320			20.8	682.8
** WBS: 1.2.2.1.1.3.4.3	Transfer Line, Distribution Sys, Storage												
1	Propane tanks,1000gal	ea	6	2000.00	eu	12.0	0	0.0	0		0.00	0.0	12.0
2	Transfer line,He @ 4K	ft	100	350.00	eu	35.0	2	160.0	320	MU	35.92	11.5	46.5
3	Transfer line,N2 @80K	ft	300	150.00	eu	45.0	0	0.0	0		0.00	0.0	45.0
4	Valve box,subcooler,cntrl	lot	1	250000.00	eu	250.0	2	40.0	80	IEL	62.85	5.0	255.0
** Subtotal **						342.0			400			16.5	358.5

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.1.1.3.5	Stands and Supports												
1	Waveguide supports	ea	5	2000.00	eu	10.0	5	60.0	300	MS	37.73	11.3	21.3
2	Circulator Supports	ea	5	2000.00	eu	10.0	5	60.0	300	MS	37.73	11.3	21.3
3	Magnet supports/mounts	ea	6	1000.00	eu	6.0	12	16.0	192	MM	38.60	7.4	13.4
4	Installation/earthquake	lot	1	2000.00	eu	2.0	1	50.0	50	MU	35.92	1.8	3.8
** Subtotal **						28.0			842			31.8	59.8
** WBS: 1.2.2.1.1.3.6	Installation												
1	Klystrons		0	0.00		0.0	10	70.0	700	EI	33.00	23.1	23.1
2	Klystron racks		0	0.00		0.0	15	40.0	600	EI	33.00	19.8	19.8
3	" "		0	0.00		0.0	15	20.0	300	IEL	62.85	18.9	18.9
4	Low power RF		0	0.00		0.0	5	80.0	400	EI	33.00	13.2	13.2
5	Klystron HV distribution		0	0.00		0.0	1	240.0	240	IEL	62.85	15.1	15.1
6	HV power supply		0	0.00		0.0	1	80.0	80	IEL	62.85	5.0	5.0
7	Controlled water systems		0	0.00		0.0	2	120.0	240	MU	35.92	8.6	8.6
8	Magnets		0	0.00		0.0	12	24.0	288	MT	27.85	8.0	8.0
9	Magnet cabling	lot	1	2000.00	eu	2.0	12	16.0	192	IEL	62.85	12.1	14.1
10	Magnet alignment		0	0.00		0.0	12	8.0	96	MT	27.85	2.7	2.7
** Subtotal **						2.0			3136			126.4	128.4
** WBS: 1.2.2.1.1.4	Timing System												
1	500MHZ LINK TO ALS	EA	1	3000.00	EU	3.0	1	80.0	80	ES	33.00	2.6	5.6
2	GUN TIMER	EA	1	5000.00	EU	5.0	1	80.0	80	ES	33.00	2.6	7.6
3	MODULATION TIMER	EA	1	2000.00	EU	2.0	1	40.0	40	ES	33.00	1.3	3.3
4	PROGRAMMABLE DELAYS	EA	10	3300.00	CP	33.0	10	2.0	20	ES	33.00	0.7	33.7
5	CABLES	LOT	1	10000.00	EU	10.0	1	80.0	80	ES	33.00	2.6	12.6
6	JITTER ANALYZER	EA	1	4000.00	EU	4.0	1	2.0	2	ES	33.00	0.1	4.1
** Subtotal **						57.0			302			10.0	67.0
** WBS: 1.2.2.1.1.5.1	Electron Beam Position Monitor												
1	ELECTRONICS	SET	1	3200.00	eu	3.2	0	0.0	0		0.00	0.0	3.2
2	BEAM PICKUP	SET	1	800.00	EU	0.8	1	40.0	40	MS	37.73	1.5	2.3
3	CABLES	SET	1	1000.00	EU	1.0	0	0.0	0		0.00	0.0	1.0
4	INSTALL PICKUP ASSY	EA	1	50.00	EU	0.1	1	4.0	4	MS	37.73	0.2	0.2
** Subtotal **						5.0			44			1.7	6.7
** WBS: 1.2.2.1.1.5.2	Wall Current Monitor												
1	CERAMIC BREAK	EA	1	1000.00	CP	1.0	1	4.0	4	MS	37.73	0.2	1.2
2	RESISTOR BELT	EA	1	100.00	EU	0.1	1	8.0	8	ES	33.00	0.3	0.4
3	POWER COMBINER	EA	3	442.00	CP	1.3	3	1.0	3	ES	33.00	0.1	1.4
4	CABLES	LOT	1	1000.00	EU	1.0	1	8.0	8	ES	33.00	0.3	1.3
** Subtotal **						3.4			23			0.8	4.2
** WBS: 1.2.2.1.1.5.3	Scintillators and TV Cameras												
1	5-WAY CROSS	EA	1	565.00	CP	0.6	1	2.0	2	MS	37.73	0.1	0.6
2	ACTUATOR	EA	1	1500.00	EU	1.5	1	8.0	8	MS	37.73	0.3	1.8
3	VIEW PORT	EA	2	315.00	CP	0.6	3	1.0	3	MS	37.73	0.1	0.7
4	SCINTILLATOR	EA	1	600.00	EU	0.6	1	4.0	4	MS	37.73	0.2	0.8
5	TV CAMERA	EA	1	1000.00	EU	1.0	1	2.0	2	MS	37.73	0.1	1.1
6	LENS	EA	1	300.00	CP	0.3	1	1.0	1	MS	37.73	0.0	0.3
7	CAMERA MOUNT	EA	1	100.00	EU	0.1	1	8.0	8	MS	37.73	0.3	0.4
8	ADJUSTABLE FILTER	EA	1	200.00	EU	0.2	1	8.0	8	MS	37.73	0.3	0.5
9	CABLES	LOT	1	500.00	EU	0.5	1	16.0	16	ES	33.00	0.5	1.0
** Subtotal **						5.4			52			1.9	7.3
** WBS: 1.2.2.1.1.5.4	X-Ray Monitors												
1	X-ray ionization chamber	EA	1	1000.00	eu	1.0	1	8.0	8	MS	37.73	0.3	1.3
2	Cables	SET	1	700.00	EU	0.7	1	16.0	16	EI	33.00	0.5	1.2
3	Sample and Hold	EA	1	600.00	eu	0.6	1	8.0	8	EI	33.00	0.3	0.9
4	Log meter	EA	1	500.00	EU	0.5	1	8.0	8	EI	33.00	0.3	0.8

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
5	Interlock	EA	1	100.00	EU	0.1	1	8.0	8	EI	33.00	0.3	0.4
** Subtotal **						2.9			48			1.6	4.5
** WBS: 1.2.2.1.1.5.5	Scintillator Display and Analysis												
1	TV MONITOR	EA	2	1000.00	EU	2.0	2	4.0	8	ES	33.00	0.3	2.3
2	FRAME GRABBER	EA	1	6000.00	EU	6.0	1	8.0	8	EE	59.40	0.5	6.5
3	PC	EA	1	8000.00	EU	8.0	1	8.0	8	EE	59.40	0.5	8.5
4	VIDEO MUX	EA	1	5000.00	EU	5.0	1	8.0	8	ES	33.00	0.3	5.3
** Subtotal **						21.0			32			1.5	22.5
** WBS: 1.2.2.1.1.5.6	Equipment Racks												
1	DOUBLE RACK	1	1	1200.00	ACT89	1.2	1	8.0	8	ES	33.00	0.3	1.5
2	POWER DISTRIBUTION	LOT	1	1500.00	EU	1.5	1	80.0	80	ES	33.00	2.6	4.1
** Subtotal **						2.7			88			2.9	5.6
** WBS: 1.2.2.1.1.5.7	6 MeV Bend Magnet												
1	6MeV BEND MAGNET	EA	1	1000.00	EU	1.0	1	100.0	100	MS	37.73	3.8	4.8
2	MAGNET POWER SUPPLY	EA	1	1000.00	EU	1.0	1	16.0	16	ES	33.00	0.5	1.5
3	CABLES	LOT	1	500.00	EU	0.5	1	16.0	16	ES	33.00	0.5	1.0
** Subtotal **						2.5			132			4.8	7.3
** WBS: 1.2.2.1.1.5.8	Pinhole Emittance Insert												
1	5-way cross	EA	2	565.00	cp	1.1	1	4.0	4	MS	37.73	0.2	1.3
2	Actuator	EA	2	1500.00	eu	3.0	1	16.0	16	MS	37.73	0.6	3.6
3	View port	EA	4	315.00	cp	1.3	1	6.0	6	MS	37.73	0.2	1.5
4	Hole array	EA	2	600.00	EU	1.2	1	16.0	16	MS	37.73	0.6	1.8
5	Scintillator	ea	1	600.00	eu	0.6	1	8.0	8	MS	37.73	0.3	0.9
6	TV camera	ea	2	1000.00	eu	2.0	1	4.0	4	MS	37.73	0.2	2.2
7	Lens	ea	2	300.00	cp	0.6	1	2.0	2	MS	37.73	0.1	0.7
8	Camera mounts	ea	2	100.00	eu	0.2	1	16.0	16	MS	37.73	0.6	0.[illegible]
9	Adjustable filter	ea	2	200.00	eu	0.4	1	16.0	16	MS	37.73	0.6	1.[illegible]
10	Cables	lot	1	1000.00	eu	1.0	1	20.0	20	EI	33.00	0.7	1.7
** Subtotal **						11.4			108			4.0	15.4
** WBS: 1.2.2.1.1.5.9	Slow Deflector												
1	Slow magnet	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
2	Power supply	ea	1	10000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
** Subtotal **						25.0			0			0.0	25.0
** WBS: 1.2.2.1.1.5.10	Temporal Analysis												
1	STREAK CAMERA	EA	1	120000.00	EU	120.0	1	40.0	40	MS	37.73	1.5	121.5
2	MOUNTING APPARATUS	EA	1	500.00	EU	0.5	1	40.0	40	MS	37.73	1.5	2.0
3	QUARTZ DETECTOR	EA	1	1000.00	EU	1.0	1	40.0	40	MS	37.73	1.5	2.5
4	TV CAMERA W/ INTENSIFIER	EA	2	5000.00	EU	10.0	2	4.0	8	EE	59.40	0.5	10.5
** Subtotal **						131.5			128			5.0	136.5
** WBS: 1.2.2.1.1.5.11	Control Room Instrumentation												
1	CUSTOM EQUIPMENT RACKS	EA	1	15000.00	EU	15.0	1	80.0	80	ES	33.00	2.6	17.6
2	STANDARD DUAL RACKS	EA	6	1200.00	ACT89	7.2	6	16.0	96	ES	33.00	3.2	10.4
3	DIGITIZING SCOPE 500MS/S	EA	6	8000.00	CP	48.0	6	4.0	24	ES	33.00	0.8	48.8
4	SPECTRUM ANALYZER	EA	1	78000.00	CP	78.0	1	4.0	4	ES	33.00	0.1	78.1
5	VIDEO MULTIPLEXER	EA	1	5000.00	EU	5.0	1	8.0	8	ES	33.00	0.3	5.3
6	RF MULTIPLEXER	EA	1	10000.00	EU	10.0	1	8.0	8	ES	33.00	0.3	10.3
7	MICROWAVE MULTIPLEXER	EA	1	15000.00	EU	15.0	1	8.0	8	ES	33.00	0.3	15.3
8	CABLES	LOT	1	10000.00	EU	10.0	1	160.0	160	ES	33.00	5.3	15.3
** Subtotal **						188.2			388			12.8	201.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.1.1.5.12	Spectrometer Instrumentation												
1	Spectrometer Instrumntatn	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
** Subtotal **						15.0			0			0.0	15.0
** WBS: 1.2.2.1.1.5.13	Hall Probe Field Analysis												
1	Hall Probe Field Analysis	ea	1	20000.00	eu	20.0	0	0.0	0		0.00	0.0	20.0
** Subtotal **						20.0			0			0.0	20.0
** WBS: 1.2.2.1.1.5.14	Feedback Instrumentation												
1	Feedback instrumentation	ea	1	20000.00	eu	20.0	0	0.0	0		0.00	0.0	20.0
** Subtotal **						20.0			0			0.0	20.0
** WBS: 1.2.2.1.2.1.1	Dipole Magnets & Power Supplies												
1	Coils (H2O)	ea	37	400.00	eu	14.8	37	80.0	2960	MA	38.60	114.3	129.1
2	Cores (H2O)	ea	37	600.00	eu	22.2	37	128.0	4736	MM	38.60	182.8	205.0
3	Assembly (H2O)	ea	37	800.00	eu	29.6	37	96.0	3552	MA	38.60	137.1	166.7
4	Tooling (H2O)	lot	1	2200.00	eu	2.2	1	600.0	600	MM	38.60	23.2	25.4
5	PS: 7.3V-408A, +/-.005%	ea	6	12000.00	CP	72.0	0	0.0	0		0.00	0.0	72.0
10	Magnetic Measurement	lot	1	100.00	eu	0.1	37	8.0	296	EM	33.00	9.8	9.9
11			0	0.00		0.0	37	8.0	296	EE	59.40	17.6	17.6
** Subtotal **						140.9			12440			484.7	625.6
** WBS: 1.2.2.1.2.1.2	Quadrupole Magnets & Power Supplies												
1	Coils (H2O)	ea	22	500.00	eu	11.0	22	120.0	2640	MA	38.60	101.9	112.9
2	Cores (H2O)	ea	22	300.00	eu	6.6	22	152.0	3344	MM	38.60	129.1	135.7
3	Assembly (H2O)	ea	22	1000.00	eu	22.0	22	116.0	2552	MA	38.60	98.5	120.5
4	Tooling (H2O)	ea	1	2400.00	eu	2.4	1	600.0	600	MM	38.60	23.2	25.6
5	Coils (Air)	ea	33	500.00	eu	16.5	33	64.0	2112	MA	38.60	81.5	98.0
6	Cores (Air)	ea	33	700.00	eu	23.1	33	136.0	4488	MM	38.60	173.2	196.3
7	Assembly (Air)	ea	33	300.00	eu	9.9	33	48.0	1584	MA	38.60	61.1	71.0
8	Tooling (Air)	lot	1	2300.00	eu	2.3	1	212.0	212	MA	38.60	8.2	10.5
9	PS: 4.6v-410A +/-0.1%	ea	34	6000.00	eu	204.0	0	0.0	0		0.00	0.0	204.0
10	Magnetic Measurement	lot	1	200.00	eu	0.2	55	8.0	440	EM	33.00	14.5	14.7
11			0	0.00		0.0	55	8.0	440	EE	59.40	26.1	26.1
** Subtotal **						298.0			18412			717.4	1015.4
** WBS: 1.2.2.1.2.1.3	Sextupole Magnets & Power Supplies												
1	Coils	ea	6	400.00	eu	2.4	6	94.0	564	MA	38.60	21.8	24.2
2	Cores	ea	6	500.00	eu	3.0	6	228.0	1368	MM	38.60	52.8	55.8
3	Assembly	ea	6	300.00	eu	1.8	6	48.0	288	MA	38.60	11.1	12.9
4	Tooling	ea	1	1200.00	eu	1.2	1	212.0	212	MM	38.60	8.2	9.4
5	PS: 3.8V - 11.8A +/-0.1%	ea	3	2000.00	eu	6.0	0	0.0	0		0.00	0.0	6.0
6	Magnetic Measurement		0	0.00		0.0	6	4.0	24	EM	33.00	0.8	0.8
7			0	0.00		0.0	6	8.0	48	EE	59.40	2.9	2.9
** Subtotal **						14.4			2504			97.5	111.9
** WBS: 1.2.2.1.2.1.4	Steering Magnets & Power Supplies												
1	Coils	ea	27	300.00	eu	8.1	27	64.0	1728	MA	38.60	66.7	74.8
2	Cores	ea	27	200.00	eu	5.4	27	44.0	1188	MM	38.60	45.9	51.3
3	Assembly	ea	27	300.00	EU	8.1	27	28.0	756	MA	38.60	29.2	37.3
4	Tooling	ea	1	700.00	EU	0.7	1	272.0	272	MM	38.60	10.5	11.2
5	PS: 0.6V-12A +/-0.1%	ea	45	1500.00	EU	67.5	0	0.0	0		0.00	0.0	67.5
6	Magnetic Measurement	lot	1	100.00	eu	0.1	27	4.0	108	EM	33.00	3.6	3.7
** Subtotal **						89.9			4052			155.8	245.7
** WBS: 1.2.2.1.2.2.1	Vacuum Chambers												
1	Quad - drift spools	ea	17	1000.00	eu	17.0	17	50.0	850	MA	38.60	32.8	49.8
2	Bend Chambers	ea	28	1000.00	eu	28.0	28	74.0	2072	MA	38.60	80.0	108.0
3	Bellows sections	ea	28	1200.00	eu	33.6	28	18.0	504	MA	38.60	19.5	53.1

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
4	Fast Valves	ea	5	10000.00	CP	50.0	0	0.0	0		0.00	0.0	50.0
** Subtotal **						128.6			3426			132.2	260.8
** WBS: 1.2.2.1.2.2.2	Pumping Systems												
1	Ion Pumps 60l/sec	ea	19	2636.00	A92	50.1	19	4.0	76	MU	35.92	2.7	52.8
2	Ion Pumps 400 l/sec	ea	2	10510.00	CP	21.0	2	4.0	8	MU	35.92	0.3	21.3
3	Roughing Cart	ea	1	5000.00	eu	5.0	1	80.0	80	MT	27.85	2.2	7.2
4	Ion pump power supplies	ea	6	1478.00	A92	8.9	6	4.0	24	MT	27.85	0.7	9.5
5	Cables	ea	21	530.00	CP	11.1	0	0.0	0		0.00	0.0	11.1
6	Interconnecting boxes	ea	4	1000.00	eu	4.0	0	0.0	0		0.00	0.0	4.0
7	Equipment racks	ea	4	1200.00	eu	4.8	4	24.0	96	EI	33.00	3.2	8.0
** Subtotal **						104.9			284			9.1	114.0
** WBS: 1.2.2.1.2.2.3	Monitoring and Control												
1	IG Controller	ea	5	1750.00	CP	8.8	5	4.0	20	MT	27.85	0.6	9.3
2	Ion Gauges	ea	10	400.00	CP	4.0	10	1.0	10	MT	27.85	0.3	4.3
3	Ion Gauge cabling	ea	10	200.00	CP	2.0	0	0.0	0		0.00	0.0	2.0
4	Convectron gauges	ea	3	200.00	CP	0.6	0	0.0	0		0.00	0.0	0.6
5	Convectron cables	ea	3	200.00	CP	0.6	0	0.0	0		0.00	0.0	0.6
6	IEEE interface	ea	8	500.00	CP	4.0	0	0.0	0		0.00	0.0	4.0
7	ILC crates	ea	2	1000.00	eu	2.0	0	0.0	0		0.00	0.0	2.0
8	ILCs	ea	6	1100.00	eu	6.6	0	0.0	0		0.00	0.0	6.6
** Subtotal **						28.5			30			0.8	29.4
** WBS: 1.2.2.1.2.3.1.1	Fab/Buy Machined Parts & Subassy's												
1	Machine absorber blades	ea	4	1000.00	A91	4.0	4	40.0	160	MS	37.73	6.0	10.0
2	Braze absorber blades	ea	4	100.00	A91	0.4	4	20.0	80	MS	37.73	3.0	3.4
3	Brazing tooling/fixtures	ea	1	200.00	A91	0.2	1	20.0	20	MS	37.73	0.8	1.0
4	Blade/pivot mounting	ea	4	500.00	A91	2.0	4	60.0	240	MS	37.73	9.1	11.1
5	Actuator mechanism	ea	4	100.00	eu	0.4	4	20.0	80	MS	37.73	3.0	3.4
6	Bellws/conflat ass'y/weld	ea	4	500.00	eu	2.0	4	40.0	160	MS	37.73	6.0	8.0
7	Flow switch & interlocks	ea	2	400.00	eu	0.8	2	8.0	16	EI	33.00	0.5	1.3
** Subtotal **						9.8			756			28.4	38.2
** WBS: 1.2.2.1.2.3.1.2	Fab/Buy Vacuum Chamber & Supports												
1	Custom vacuum chamber	ea	1	10000.00	eu	10.0	1	40.0	40	MU	35.92	1.4	11.4
2	Misc flanges/UHV hardware	lot	1	2500.00	eu	2.5	0	0.0	0		0.00	0.0	2.5
3	Mounting struts/hardware	ea	6	500.00	A91	3.0	6	8.0	48	MS	37.73	1.8	4.8
4	Support posts,frame,hrdwr	lot	1	1500.00	A91	1.5	1	40.0	40	MS	37.73	1.5	3.0
** Subtotal **						17.0			128			4.8	21.8
** WBS: 1.2.2.1.2.3.1.3	Vac Pumping,Gauges,Controllers,P.S.												
1	Ion pump, 400 l/s	ea	1	7527.00	A92	7.5	1	4.0	4	MU	35.92	0.1	7.7
2	Ion pump controller	ea	1	2180.00	A92	2.2	1	4.0	4	EI	33.00	0.1	2.3
3	Ion pump cable,bakeable	ea	1	250.00	A92	0.2	1	4.0	4	EI	33.00	0.1	0.4
4	IEEE-48 cable,3m cntrller	ea	1	421.00	A92	0.4	0	0.0	0		0.00	0.0	0.4
5	Roughing valve	ea	2	650.00	A91	1.3	0	0.0	0		0.00	0.0	1.3
6	Ion gauge & controls	ea	1	3500.00	A91	3.5	1	4.0	4	MU	35.92	0.1	3.6
7	Ion gauge cable, bakeable	ea	1	250.00	cp	0.2	1	4.0	4	EI	33.00	0.1	0.4
8	Junction box,IG cable	ea	1	200.00	eu	0.2	1	4.0	4	EI	33.00	0.1	0.3
9	Interlock cable	ea	1	100.00	eu	0.1	0	0.0	0		0.00	0.0	0.1
** Subtotal **						15.7			24			0.8	16.5
** WBS: 1.2.2.1.2.3.1.4	Assemble, Bakeout, Test												
1	Assemble & test	ea	1	500.00	eu	0.5	2	40.0	80	MU	35.92	2.9	3.4
2	Bakeout & UHV qualify	lot	1	500.00	eu	0.5	2	20.0	40	MU	35.92	1.4	1.9
3	Survey/calibration		0	0.00		0.0	2	8.0	16	MU	35.92	0.6	0.6
4	Misc tools,fixtures,cart	lot	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						2.0			176			6.3	8.3
** WBS: 1.2.2.1.2.3.1.5	Installation												
1	LCW hardware/connections	lot	1	300.00	eu	0.3	2	8.0	16	MU	35.92	0.6	0.9
2	Transport/on-site setup	lot	1	200.00	eu	0.2	2	8.0	16	MU	35.92	0.6	0.8
3	Vac assemble & leak check	lot	1	50.00	eu	0.1	2	8.0	16	MU	35.92	0.6	0.6
4	Installation alignment		0	0.00		0.0	2	16.0	32	MS	37.73	1.2	1.2
5	Mech install/test/debug	lot	1	50.00	eu	0.1	2	8.0	16	MU	35.92	0.6	0.6
6	Elec installation		0	0.00		0.0	1	16.0	16	IEL	62.85	1.0	1.0
** Subtotal **						0.6			112			4.5	5.1
** WBS: 1.2.2.1.2.3.1.6	Bellows												
1	Welded bellows assy	ea	2	3000.00	A91	6.0	2	4.0	8	MS	37.73	0.3	6.3
2	Blank flanges,gaskets,etc	lot	2	300.00	cp	0.6	0	0.0	0		0.00	0.0	0.6
3	Inspection,cleaning,bake	ea	2	50.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.4
** Subtotal **						6.7			16			0.6	7.3
** WBS: 1.2.2.1.2.3.1.7	Isolation Valves												
1	Valve & contrllr proc.	ea	2	10000.00	vq	20.0	0	0.0	0		0.00	0.0	20.0
2	Prelim assembl & test	ea	2	50.00	eu	0.1	2	8.0	16	MU	35.92	0.6	0.7
3	Inspection,cleaning,etc.	lot	2	50.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.4
4	Cables & connectors	lot	2	200.00	eu	0.4	2	2.0	4	EI	33.00	0.1	0.5
5	Blank flanges & hardware	lot	4	200.00	eu	0.8	0	0.0	0		0.00	0.0	0.8
** Subtotal **						21.4			28			1.0	22.4
** WBS: 1.2.2.1.2.3.2	Septum Magnets & Power Supplies												
1	Coils	ea	2	600.00	eu	1.2	2	124.0	248	MA	38.60	9.6	10.8
2	Cores	ea	2	600.00	eu	1.2	2	114.0	228	MM	38.60	8.8	10.0
3	Assembly	ea	2	800.00	eu	1.6	2	115.0	230	MA	38.60	8.9	10.5
4	Tooling	ea	1	700.00	eu	0.7	1	410.0	410	MM	38.60	15.8	16.5
5	PS	ea	2	4000.00	eu	8.0	0	0.0	0		0.00	0.0	8.0
6	Magnetic Measurement		0	0.00		0.0	2	8.0	16	EM	33.00	0.5	0.5
6			0	0.00		0.0	2	16.0	32	EE	59.40	1.9	1.9
** Subtotal **						12.7			1164			45.5	58.2
** WBS: 1.2.2.1.2.4.1	Electron Beam Position Monitor												
1	ELECTRONICS	SET	1	3200.00	eu	3.2	0	0.0	0		0.00	0.0	3.2
2	BEAM PICKUP	SET	1	800.00	EU	0.8	1	40.0	40	MS	37.73	1.5	2.3
3	CABLES	SET	1	1000.00	EU	1.0	0	0.0	0		0.00	0.0	1.0
4	INSTALL PICKUP ASSY	EA	1	50.00	EU	0.1	1	4.0	4	MS	37.73	0.2	0.2
** Subtotal **						5.0			44			1.7	6.7
** WBS: 1.2.2.1.2.4.2	Beamline Scintillator												
1	5-WAY CROSS	EA	1	565.00	CP	0.6	1	2.0	2	MS	37.73	0.1	0.6
2	ACTUATOR	EA	1	1500.00	EU	1.5	1	8.0	8	MS	37.73	0.3	1.8
3	VIEW PORT	EA	2	315.00	CP	0.6	3	1.0	3	MS	37.73	0.1	0.7
4	SCINTILLATOR	EA	1	600.00	EU	0.6	1	4.0	4	MS	37.73	0.2	0.8
5	TV CAMERA	EA	1	1000.00	EU	1.0	1	2.0	2	MS	37.73	0.1	1.1
6	LENS	EA	1	300.00	CP	0.3	1	1.0	1	MS	37.73	0.0	0.3
7	CAMERA MOUNT	EA	1	100.00	EU	0.1	1	8.0	8	MS	37.73	0.3	0.4
8	ADJUSTABLE FILTER	EA	1	200.00	EU	0.2	1	8.0	8	MS	37.73	0.3	0.5
9	CABLES	LOT	1	500.00	EU	0.5	1	16.0	16	ES	33.00	0.5	1.0
** Subtotal **						5.4			52			1.9	7.3
** WBS: 1.2.2.1.2.4.3	Undulator Scintillators												
1	VACUUM BOX	EA	1	500.00	EU	0.5	1	40.0	40	MS	37.73	1.5	2.0
2	ACTUATOR	EA	1	1500.00	EU	1.5	1	8.0	8	MS	37.73	0.3	1.8
3	VIEW PORT	EA	2	315.00	CP	0.6	3	1.0	3	MS	37.73	0.1	0.7
4	SCINTILLATOR	EA	1	600.00	EU	0.6	1	4.0	4	MS	37.73	0.2	0.8

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC LABOR
5	TV CAMERA	EA	1	1000.00	EU	1.0	1	2.0	2	MS	37.73	0.1	1.1
6	LENS	EA	1	300.00	CP	0.3	1	1.0	1	MS	37.73	0.0	0.3
7	CAMERA MOUNT	EA	1	100.00	EU	0.1	1	8.0	8	MS	37.73	0.3	0.4
8	ADJUSTABLE FILTER	EA	1	200.00	EU	0.2	1	8.0	8	MS	37.73	0.3	0.5
9	CABLES	LOT	1	500.00	EU	0.5	1	16.0	16	ES	33.00	0.5	1.0
** Subtotal **						5.3			90			3.3	8.7
** WBS: 1.2.2.1.2.4.4	Current Monitors												
1	Currents monitors	EA	1	4400.00	EU	4.4	0	0.0	0		0.00	0.0	4.4
** Subtotal **						4.4			0			0.0	4.4
** WBS: 1.2.2.1.2.4.5	Slow Deflector												
1	Slow magnet	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
2	Power supply	ea	1	10000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
** Subtotal **						25.0			0			0.0	25.0
** WBS: 1.2.2.1.2.4.6	X-Ray Monitors												
1	X-ray ionization chamber	EA	1	1000.00	EU	1.0	1	8.0	8	MS	37.73	0.3	1.3
2	Cables	set	1	700.00	EU	0.7	1	16.0	16	EI	33.00	0.5	1.2
3	Sample and Hold	ea	1	600.00	eu	0.6	1	8.0	8	EI	33.00	0.3	0.9
4	Log meter	EA	1	500.00	EU	0.5	1	8.0	8	EI	33.00	0.3	0.8
5	Interlock	ea	1	100.00	eu	0.1	1	8.0	8	EI	33.00	0.3	0.4
** Subtotal **						2.9			48			1.6	4.5
** WBS: 1.2.2.1.2.4.7	Analyzer TV System												
1	QUARTZ DETECTOR	EA	1	1000.00	EU	1.0	1	40.0	40	MS	37.73	1.5	2.5
2	MOUNTING APPARATUS	EA	1	500.00	EU	0.5	1	40.0	40	MS	37.73	1.5	2.0
3	TV CAMERA W/ INTENSIFIER	EA	2	10000.00	EU	20.0	2	4.0	8	EE	59.40	0.5	20.5
4	PULSED LIGHT SYSTEM	EA	1	1000.00	EU	1.0	1	16.0	16	ES	33.00	0.5	1.5
** Subtotal **						22.5			104			4.0	26.
** WBS: 1.2.2.1.2.4.8	Synchrotron Monitors												
1	Synchrotron monitors	ea	1	8000.00	eu	8.0	0	0.0	0		0.00	0.0	8.0
** Subtotal **						8.0			0			0.0	8.0
** WBS: 1.2.2.1.2.5	Stands and Supports												
1	Arc stands	ea	3	1000.00	eu	3.0	3	144.0	432	MS	37.73	16.3	19.3
2			0	0.00		0.0	3	120.0	360	MM	38.60	13.9	13.9
3	Arc stand translators	ea	1	15000.00	eu	15.0	2	320.0	640	MS	37.73	24.1	39.1
4	Switchyard stands	ea	4	1000.00	eu	4.0	4	96.0	384	MS	37.73	14.5	18.5
5			0	0.00		0.0	4	80.0	320	MM	38.60	12.4	12.4
6	Triplet stands	ea	15	750.00	eu	11.2	15	76.0	1140	MS	37.73	43.0	54.3
7			0	0.00		0.0	15	40.0	600	MM	38.60	23.2	23.2
8	Magnet mounts	ea	127	50.00	eu	6.3	127	8.0	1016	MM	38.60	39.2	45.6
** Subtotal **						39.6			4892			186.6	226.2
** WBS: 1.2.2.1.2.6	Installation												
1	Monuments and survey	lot	1	41000.00	eu	41.0	10	16.0	160	MA	38.60	6.2	47.2
2	Manifolds	lot	1	13300.00	eu	13.3	1	480.0	480	IPL	67.40	32.4	45.7
3	Cooling water sys	lot	23	500.00	eu	11.5	23	28.0	644	IPL	67.40	43.4	54.9
3	Supports installation	ea	23	200.00	eu	4.6	23	24.0	552	MT	27.85	15.4	20.0
4	Magnet install h20 cooled		0	0.00		0.0	61	24.0	1464	MT	27.85	40.8	40.8
5			0	0.00		0.0	61	6.0	366	EI	33.00	12.1	12.1
6	Magnet install air cooled		0	0.00		0.0	66	12.0	792	MT	27.85	22.1	22.1
7			0	0.00		0.0	66	8.0	528	EI	33.00	17.4	17.4
8	PS install/trays/cables	lot	1	10000.00	eu	10.0	4	200.0	800	IEL	62.85	50.3	60.3
9	Vac system installation	lot	1	32000.00	eu	32.0	4	1050.0	4200	MT	27.85	117.0	149.0
10	Magnet alignment		0	0.00		0.0	127	8.0	1016	MT	27.85	28.3	28.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						112.4			11002			385.2	497.6
** WBS: 1.2.2.1.3.1.1.1	Magnetic Material												
1	Samarium cobalt blocks	ea	1230	67.02	A89	82.4	0	0.0	0		0.00	0.0	82.4
2	Measurement Prep		0	0.00		0.0	1	20.0	20	EM	33.00	0.7	0.7
3			0	0.00		0.0	1	20.0	20	EE	59.40	1.2	1.2
4	Measurements	LOT	1	105.00	EU	0.1	0	0.0	0		0.00	0.0	0.1
5	3-Axis H.C. Meas		0	0.00		0.0	1230	0.1	148	EM	33.00	4.9	4.9
6	Supervision		0	0.00		0.0	1	100.0	100	EE	59.40	5.9	5.9
** Subtotal **						82.5			288			12.7	95.2
** WBS: 1.2.2.1.3.1.1.3	Pole Assemblies												
1	Vanadium Permendur	ea	210	30.05	A91	6.3	0	0.0	0		0.00	0.0	6.3
2	Keepers	ea	210	205.00	A91	43.0	0	0.0	0		0.00	0.0	43.0
3	Keeper Inspection	lot	1	1050.00	EU	1.1	210	0.8	158	MM	38.60	6.1	7.1
4	Assembly	ea	210	10.50	A82	2.2	210	6.0	1260	MM	38.60	48.6	50.8
7	Pole Assembly Mounts	ea	6	1414.00	A91	8.5	6	24.0	144	MM	38.60	5.6	14.0
** Subtotal **						61.1			1562			60.3	121.4
** WBS: 1.2.2.1.3.1.1.4	End Pole Assemblies												
1	End Pole Keepers	LOT	1	12157.00	A91	12.2	0	0.0	0		0.00	0.0	12.2
2	NdFe Block Cutting		0	0.00		0.0	24	4.0	96	MS	37.73	3.6	3.6
3	Assembly - Keepers		0	0.00		0.0	8	24.0	192	MA	38.60	7.4	7.4
4	Rotator		0	0.00		0.0	8	32.0	256	MM	38.60	9.9	9.9
5	Rotator Block Cutting		0	0.00		0.0	24	4.0	96	MS	37.73	3.6	3.6
6	Assemble - Rotator		0	0.00		0.0	8	4.0	32	MA	38.60	1.2	1.2
7	Rotator Linkage	ea	8	105.00	EU	0.8	8	4.0	32	MM	38.60	1.2	2.1
8	Manual Rotatr Drv	ea	8	525.00	CP	4.2	8	16.0	128	MM	38.60	4.9	9.1
9			0	0.00		0.0	8	4.0	32	MA	38.60	1.2	1.2
10	End pole mounts/levelers	lot	1	4550.00	A91	4.5	0	0.0	0		0.00	0.0	4.5
** Subtotal **						21.7			864			33.2	54.9
** WBS: 1.2.2.1.3.1.1.5	Backing Beams												
1	Backing Beams (2)	lot	1	74900.00	A91	74.9	1	50.0	50	MM	38.60	1.9	76.8
2	Flux Shunts	ea	1	6500.00	Act 91	6.5	1	206.0	206	MA	38.60	8.0	14.5
3	Adjusters/guides	lot	1	5553.00	A91	5.6	0	0.0	0		0.00	0.0	5.6
4	Rigging Hardware	lot	1	900.00	EU	0.9	1	80.0	80	MM	38.60	3.1	4.0
5	Misc.	lot	1	1000.00	eu	1.0	1	80.0	80	MA	38.60	3.1	4.1
** Subtotal **						88.9			416			16.1	104.9
** WBS: 1.2.2.1.3.1.1.6	Magnet Structure Assembly												
1	Keeper Pole Mount Assembl	ea	6	235.00	EU	1.4	6	60.0	360	MA	38.60	13.9	15.3
2	End Pole Assembly		0	0.00		0.0	4	16.0	64	MM	38.60	2.5	2.5
3	Pole Mount/Bckg Bm Assy	ea	6	105.00	EU	0.6	6	48.0	288	MA	38.60	11.1	11.7
6	Fiducializing	lot	1	105.00	EU	0.1	6	24.0	144	MA	38.60	5.6	5.7
7	Interferometer Hardware	lot	1	1000.00	eu	1.0	1	80.0	80	MA	38.60	3.1	4.1
** Subtotal **						3.1			936			36.1	39.3
** WBS: 1.2.2.1.3.1.1.7	Magnetic Measurements: Mechanical												
1	Coil & Probe Mounts		0	0.00		0.0	1	40.0	40	MU	35.92	1.4	1.4
2	Assembly Section Setup		0	0.00		0.0	6	12.0	72	MA	38.60	2.8	2.8
3	Coils	ea	2	105.00	eu	0.2	2	120.0	240	MU	35.92	8.6	8.8
4	Gap Spacers		0	0.00		0.0	1	24.0	24	MU	35.92	0.9	0.9
5	ID Setup	lot	1	315.00	eu	0.3	1	160.0	160	MA	38.60	6.2	6.5
** Subtotal **						0.5			536			19.9	20.4
** WBS: 1.2.2.1.3.1.1.8	Magnetic Measurements: Electrical												
1	Setup Assembly Sections		0	0.00		0.0	1	16.0	16	EE	59.40	1.0	1.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
2			0	0.00		0.0	6	4.0	24	ES	33.00	0.8	0.8
3	Data Acquire: Assy Sectns		0	0.00		0.0	6	3.0	18	EE	59.40	1.1	1.1
4			0	0.00		0.0	6	8.0	48	ES	33.00	1.6	1.6
5	Data Analysis:Assy Sectns		0	0.00		0.0	1	80.0	80	EE	59.40	4.8	4.8
6	Calibrate Null Coil		0	0.00		0.0	1	20.0	20	EE	59.40	1.2	1.2
7			0	0.00		0.0	1	20.0	20	ES	33.00	0.7	0.7
8	Code Software Coil Paramt		0	0.00		0.0	1	8.0	8	CP	59.40	0.5	0.5
9			0	0.00		0.0	1	8.0	8	EE	59.40	0.5	0.5
10	ID Setup: Electronic		0	0.00		0.0	1	16.0	16	EE	59.40	1.0	1.0
11			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
12	ID Setup: Electrical		0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
13	ID: Data Acquisition		0	0.00		0.0	1	40.0	40	EE	59.40	2.4	2.4
14			0	0.00		0.0	1	240.0	240	ES	33.00	7.9	7.9
15	ID: Data Analysis		0	0.00		0.0	1	40.0	40	EE	59.40	2.4	2.4
16	Data Preparation		0	0.00		0.0	1	80.0	80	ES	33.00	2.6	2.6
17	Q/C Verification		0	0.00		0.0	1	20.0	20	EE	59.40	1.2	1.2
18			0	0.00		0.0	1	20.0	20	ES	33.00	0.7	0.7
19	Shutdown/Storage		0	0.00		0.0	1	20.0	20	EE	59.40	1.2	1.2
20			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						0.0			838			35.2	35.2
** WBS: 1.2.2.1.3.1.2.1	Support System Fabrication												
1	Support System Assembly	ea	1	55200.00	A91	55.2	1	18.0	18	MA	38.60	0.7	55.9
2	Associated Parts	lot	1	1000.00	EU	1.0	1	80.0	80	MM	38.60	3.1	4.1
3	Miscellaneous	lot	1	1900.00	A91	1.9	1	210.0	210	MM	38.60	8.1	10.0
4	Assembly	lot	1	1800.00	A91	1.8	1	840.0	840	MA	38.60	32.4	34.2
** Subtotal **						59.9			1148			44.3	104.2
** WBS: 1.2.2.1.3.1.2.2	Drive System Fabrication												
1	Roller Screw Assembly	ea	8	6700.00	A91	53.6	1	32.0	32	MA	38.60	1.2	54.8
2	Spring System	ea	1	1000.00	A91	1.0	1	130.0	130	MM	38.60	5.0	6.0
3	Bearing System	lot	1	900.00	A91	0.9	1	105.0	105	MM	38.60	4.1	5.0
4	Sprocket/Chain System	lot	1	700.00	A91	0.7	1	50.0	50	MM	38.60	1.9	2.6
5	Gear Box & Mtg.	ea	1	1700.00	A91	1.7	1	20.0	20	MM	38.60	0.8	2.5
6	Encoder Systems (2)	ea	1	1000.00	A91	1.0	1	104.0	104	MM	38.60	4.0	5.0
7	Motor Mounting Bracket	ea	1	400.00	A91	0.4	1	40.0	40	MM	38.60	1.5	1.9
8	Fan System	lot	1	200.00	A91	0.2	1	40.0	40	MM	38.60	1.5	1.7
9	Miscellaneous	lot	1	1200.00	A91	1.2	1	240.0	240	MM	38.60	9.3	10.5
10	Assembly	lot	1	900.00	A91	0.9	1	365.0	365	MA	38.60	14.1	15.0
11	Roller Screw Kinematc Mnt	ea	8	1400.00	A91	11.2	1	170.0	170	MM	38.60	6.6	17.8
12	Gap interferometer	ea	1	15000.00	eu	15.0	1	120.0	120	MA	38.60	4.6	19.6
13	Taper drive	ea	1	2500.00	eu	2.5	1	100.0	100	MA	38.60	3.9	6.4
** Subtotal **						90.3			1516			58.5	148.8
** WBS: 1.2.2.1.3.1.2.3	Local Temperature Control Fabrication												
1	Frame & Curtain	lot	1	3000.00	EU	3.0	1	200.0	200	MA	38.60	7.7	10.7
2	Blower & Dryer System	lot	1	1100.00	EU	1.1	1	80.0	80	MA	38.60	3.1	4.2
3	Miscellaneous	lot	1	2000.00	EU	2.0	1	40.0	40	MA	38.60	1.5	3.5
4	Electrical Installation	lot	1	200.00	eu	0.2	1	80.0	80	EI	33.00	2.6	2.8
** Subtotal **						6.3			400			15.0	21.3
** WBS: 1.2.2.1.3.1.3.1	Vacuum Chambers												
1	Vacuum Chamber	ea	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
2	Flanges	lot	1	500.00	eu	0.5	0	0.0	0		0.00	0.0	0.5
3	Fabrication		0	0.00		0.0	1	80.0	80	MM	38.60	3.1	3.1
4			0	0.00		0.0	1	120.0	120	MS	37.73	4.5	4.5
5	Assembly/Test		0	0.00		0.0	1	40.0	40	MA	38.60	1.5	1.5
6	System assembly		0	0.00		0.0	1	120.0	120	MA	38.60	4.6	4.6
7	Trans: Bellows	ea	2	1200.00	eu	2.4	0	0.0	0		0.00	0.0	2.4
8	Trans.: Flanges	ea	8	50.00	eu	0.4	0	0.0	0		0.00	0.0	0.4
9	Trans.: Fab		0	0.00		0.0	2	80.0	160	MM	38.60	6.2	6.2
10			0	0.00		0.0	2	40.0	80	MS	37.73	3.0	3.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
11			0	0.00		0.0	2	40.0	80	MA	38.60	3.1	3.1
12	Trans: Assembly/Test		0	0.00		0.0	2	40.0	80	MA	38.60	3.1	3.1
** Subtotal **						4.3			760			29.2	33.5
** WBS: 1.2.2.1.3.1.3.2	Pumping Systems & Instrumentation												
1	Ion Pump/TSP Combination	ea	2	4200.00	A91	8.4	0	0.0	0		0.00	0.0	8.4
2	Right Angle Valve	ea	1	919.80	CP	0.9	0	0.0	0		0.00	0.0	0.9
3	Roughing cart	ea	1	5000.00	eu	5.0	0	0.0	0		0.00	0.0	5.0
** Subtotal **						14.3			0			0.0	14.3
** WBS: 1.2.2.1.3.1.3.3	Support Structure												
1	Vacuum Chamber Support	lot	1	2100.00	EU	2.1	1	160.0	160	MM	38.60	6.2	8.3
2	Ion Pump Supports	ea	2	200.00	EU	0.4	2	20.0	40	MM	38.60	1.5	1.9
3	Installation Fixture	ea	1	500.00	EU	0.5	1	80.0	80	MM	38.60	3.1	3.6
** Subtotal **						3.0			280			10.8	13.8
** WBS: 1.2.2.1.3.1.3.4	Vacuum Diagnostics												
1	IG Controller	ea	1	895.00	A91	0.9	1	2.0	2	ES	33.00	0.1	1.0
2	Degas Module	ea	1	157.50	CP	0.2	0	0.0	0		0.00	0.0	0.2
3	Second IG Module	ea	1	78.75	CP	0.1	0	0.0	0		0.00	0.0	0.1
4	Process Control Module	ea	1	367.50	CP	0.4	0	0.0	0		0.00	0.0	0.4
5	Rack Mount	ea	1	52.50	CP	0.1	1	1.0	1	ES	33.00	0.0	0.1
6	Remote I/O Module	ea	1	85.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
7	Dual Convectron Module	ea	1	420.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
8	UHV Electrometer Module	ea	1	420.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
9	IEEE-488 Interface	ea	1	378.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
10	Nude Ion Gauge	ea	1	326.55	CP	0.3	1	1.0	1	MS	37.73	0.0	0.4
11	IG Cable: 50 feet	ea	1	204.75	CP	0.2	1	1.0	1	ES	33.00	0.0	0.2
12	Convectron Gauge	ea	1	145.95	CP	0.1	1	1.0	1	MS	37.73	0.0	0.2
13	Convectron Cable: 50 feet	ea	1	220.50	CP	0.2	1	1.0	1	ES	33.00	0.0	0.3
14	IG Connector	ea	1	10.50	EU	0.0	1	1.0	1	MS	37.73	0.0	0.0
15	IG Cable Interface	ea	1	52.50	EU	0.1	1	4.0	4	ES	33.00	0.1	0.2
16	Ion Pump Controller	ea	2	2045.40	CP	4.1	2	2.0	4	ES	33.00	0.1	4.2
17	Ion Pump Cable	ea	2	234.15	CP	0.5	2	4.0	8	ES	33.00	0.3	0.7
18	Ion Pump Cable Interface	ea	2	105.00	EU	0.2	2	4.0	8	ES	33.00	0.3	0.5
19	IEEE-488 Interface	ea	2	522.90	CP	1.0	0	0.0	0		0.00	0.0	1.0
20	ILC Crate	ea	1	1000.00	EU	1.0	1	40.0	40	ES	33.00	1.3	2.3
21	ILC	ea	2	1100.00	EU	2.2	1	40.0	40	ES	33.00	1.3	3.5
22	Sublimation Controller	ea	1	2100.00	CP	2.1	1	4.0	4	ES	33.00	0.1	2.2
23	Sublimation Mux	ea	1	2100.00	eu	2.1	1	80.0	80	EI	33.00	2.6	4.7
24	Filament Cables	set	1	525.00	eu	0.5	1	40.0	40	EI	33.00	1.3	1.8
** Subtotal **						17.6			236			7.8	25.4
** WBS: 1.2.2.1.3.1.4	Motor Control System												
1	Controller 500 Indexer	ea	2	1515.00	CP	3.0	0	0.0	0		0.00	0.0	3.0
2	Motor Package PK130M-T	ea	2	4703.00	CP	9.4	0	0.0	0		0.00	0.0	9.4
3	Abosolute Encoder	ea	2	1805.00	CP	3.6	0	0.0	0		0.00	0.0	3.6
4	100 ft Cables	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
5	ILC	ea	1	1100.00	eu	1.1	0	0.0	0		0.00	0.0	1.1
6	ILC Crate (holds 6 ILCs)	ea	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
7	Final Installation	lot	1	4000.00	EU	4.0	1	270.0	270	EI	33.00	8.9	12.9
8			0	0.00		0.0	1	60.0	60	IEL	62.85	3.8	3.8
9	Shop Installation	lot	1	3000.00	EU	3.0	1	160.0	160	EI	33.00	5.3	8.3
** Subtotal **						26.1			490			18.0	44.1
** WBS: 1.2.2.1.3.1.5	Installation												
1	Prepare & Truck to Site	lot	1	525.00	eu	0.5	1	80.0	80	MA	38.60	3.1	3.6
2	Rigger's Work	lot	1	1200.00	eu	1.2	1	64.0	64	RG	37.65	2.4	3.6
3	Survey & Alignment		0	0.00		0.0	1	80.0	80	MA	38.60	3.1	3.1
4	Installation	lot	1	315.00	eu	0.3	1	100.0	100	MA	38.60	3.9	4.2
5	Vacuum Hookup/Pumpdown	lot	1	105.00	eu	0.1	1	40.0	40	MA	38.60	1.5	1.6

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
6	Reinstall Temp Ctrl Housg		0	0.00		0.0	1	40.0	40	MA	38.60	1.5	1.5
7	Miscellaneous		0	0.00		0.0	1	50.0	50	MA	38.60	1.9	1.9
** Subtotal **						2.1			454			17.5	19.6
** WBS: 1.2.2.1.3.2.1	Lasing Mirror Systems												
1	Custom lasing mirrors	ea	10	7500.00	cp	75.0	0	0.0	0		0.00	0.0	75.0
2	Water cooling unit	ea	2	5000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
3	Custom mirror mount	ea	2	11270.00	cp	22.5	0	0.0	0		0.00	0.0	22.5
4	Lasing mirror drivers	ea	2	525.00	cp	1.1	0	0.0	0		0.00	0.0	1.1
5	Drive Controller	ea	1	26400.00	cp	26.4	0	0.0	0		0.00	0.0	26.4
6	XYZ transl stage +drives	ea	2	22260.00	cp	44.5	0	0.0	0		0.00	0.0	44.5
7	Vacuum preparation	ea	1	11956.00	cp	12.0	0	0.0	0		0.00	0.0	12.0
8	Iris diaphrgm w/rem chang	ea	1	5000.00	eu	5.0	0	0.0	0		0.00	0.0	5.0
9	Vibration isolation systm	ea	2	15000.00	eu	30.0	0	0.0	0		0.00	0.0	30.0
10	Mirror/pedstl vac housing	ea	2	5000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
11	Support structure	ea	2	500.00	eu	1.0	5	8.0	40	MM	38.60	1.5	2.5
12	Precision positioning sys	ea	1	28530.00	cp	28.5	0	0.0	0		0.00	0.0	28.5
13	Vac ion pump, 400l/s	ea	2	7527.00	A92	15.1	0	0.0	0		0.00	0.0	15.1
14	Vac ion pump power supply	ea	2	2180.00	A92	4.4	0	0.0	0		0.00	0.0	4.4
15	Pump cntrl/intrfc/cables	ea	2	700.00	cp	1.4	2	8.0	16	EI	33.00	0.5	1.9
16	Metal seal roughing valve	ea	2	900.00	cp	1.8	0	0.0	0		0.00	0.0	1.8
17	Ionization gage/controllr	ea	2	3000.00	cp	6.0	0	0.0	0		0.00	0.0	6.0
18	X-ray shield for gage	ea	2	500.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
19	Misc. UHV items	lot	1	3000.00	eu	3.0	0	0.0	0		0.00	0.0	3.0
20	Misc. lasing cavity parts	lot	1	4000.00	eu	4.0	20	8.0	160	MS	37.73	6.0	10.0
21	Misc. interlocks, etc.	lot	1	5000.00	eu	5.0	0	0.0	0		0.00	0.0	5.0
** Subtotal **						307.6			216			8.1	315.7
** WBS: 1.2.2.1.3.2.2	Optical diagnostics												
1	Optical table	ea	2	6000.00	cp	12.0	0	0.0	0		0.00	0.0	12.0
2	He-Ne laser	ea	5	1200.00	eu	6.0	0	0.0	0		0.00	0.0	6.0
3	CW CO2 laser	ea	1	13500.00	cp	13.5	0	0.0	0		0.00	0.0	13.5
4	IR monochromator	ea	1	35000.00	eu	35.0	0	0.0	0		0.00	0.0	35.0
5	1D linear array	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
6	Autocorrelator	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
7	Misc. vac line components	lot	1	1500.00	eu	1.5	5	8.0	40	MA	38.60	1.5	3.0
8	Power/Energy meter	ea	1	7500.00	eu	7.5	0	0.0	0		0.00	0.0	7.5
9	Misc optical mounts,lense	lot	1	20000.00	eu	20.0	0	0.0	0		0.00	0.0	20.0
10	IR detector (cooled)	ea	2	7500.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
11	IR detector (room temp)	ea	5	2000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
12	Oscilloscope	ea	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
13	Delay generator	ea	1	3500.00	eu	3.5	0	0.0	0		0.00	0.0	3.5
14	CO2 laser spctrm analyzer	ea	1	2000.00	eu	2.0	0	0.0	0		0.00	0.0	2.0
15	2D beam analyzer	ea	1	32000.00	cp	32.0	0	0.0	0		0.00	0.0	32.0
16	Semiconductor materials	lot	1	5000.00	eu	5.0	0	0.0	0		0.00	0.0	5.0
17	Short pulse laser system	ea	1	140000.00	eu	140.0	0	0.0	0		0.00	0.0	140.0
18	Windows/Atten/Beamsplittr	lot	1	15000.00	eu	15.0	0	0.0	0		0.00	0.0	15.0
19	Elect instru for feedback	lot	1	75000.00	eu	75.0	0	0.0	0		0.00	0.0	75.0
** Subtotal **						438.0			40			1.5	439.5
** WBS: 1.2.2.1.3.2.3	IR Transport												
1	Custom transport mirror	ea	14	7500.00	eu	105.0	0	0.0	0		0.00	0.0	105.0
2	Mirror mounts (manual)	ea	9	7200.00	eu	64.8	0	0.0	0		0.00	0.0	64.8
3	Mirror mounts (remote)	ea	5	10270.00	cp	51.4	0	0.0	0		0.00	0.0	51.4
4	Lasing mirror drivers	ea	10	525.00		5.2	0	0.0	0		0.00	0.0	5.2
5	Motion controller	ea	1	18400.00	cp	18.4	0	0.0	0		0.00	0.0	18.4
6	Kinematic beam splitter	ea	5	10000.00	eu	50.0	0	0.0	0		0.00	0.0	50.0
7	Pyro quad detctr assy	ea	5	5000.00	eu	25.0	0	0.0	0		0.00	0.0	25.0
8	Vac can for tuning mirror	ea	5	5000.00	eu	25.0	8	15.0	120	MM	38.60	4.6	29.6
9	11" beam tube/flanges	lot	1	20000.00	eu	20.0	8	15.0	120	MM	38.60	4.6	24.6
10	Can support/pedestals	ea	14	1000.00	eu	14.0	0	0.0	0		0.00	0.0	14.0
11	Vac ion pump,400l/s	ea	4	7527.00	A92	30.1	0	0.0	0		0.00	0.0	30.1
12	Gauges/controller/PS	ea	4	3000.00	eu	12.0	4	8.0	32	EI	33.00	1.1	13.1

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
13	Interlocks	lot	1	7500.00	eu	7.5	0	0.0	0		0.00	0.0	7.5
** Subtotal **						428.4			272			10.3	438.7
** WBS: 1.2.2.1.3.2.4	Installation												
1	Mechanical Installation	lot	1	3000.00	eu	3.0	50	8.0	400	MU	35.92	14.4	17.4
2	Electrical Installation	lot	1	10000.00	eu	10.0	10	8.0	80	IEL	62.85	5.0	15.0
3	Electronics Installation	lot	1	5000.00	eu	5.0	1	80.0	80	EI	33.00	2.6	7.6
** Subtotal **						18.0			560			22.0	40.0
** WBS: 1.2.2.1.4.1	Beam Spreading System												
1	Tooling	lot	1	700.00	eu	0.7	1	270.0	270	MM	38.60	10.4	11.1
2	Coils	ea	2	300.00	eu	0.6	2	74.0	148	MA	38.60	5.7	6.3
3	Cores	ea	2	8700.00	eu	17.4	2	192.0	384	MM	38.60	14.8	32.2
4	Assembly	ea	2	600.00	eu	1.2	2	120.0	240	MA	38.60	9.3	10.5
5	Ceramic vacuum chambers	ea	2	15000.00	eu	30.0	0	0.0	0		0.00	0.0	30.0
6	Power supply (Crown)	ea	2	3000.00	eu	6.0	0	0.0	0		0.00	0.0	6.0
** Subtotal **						55.9			1042			40.2	96.1
** WBS: 1.2.2.1.4.2	Beam Dumps												
1	Dumps(75 gal)fab/assy/tst	ea	2	25000.00	eu	50.0	0	0.0	0		0.00	0.0	50.0
2	Installation		0	0.00		0.0	1	200.0	200	IPL	67.40	13.5	13.5
** Subtotal **						50.0			200			13.5	63.5
** WBS: 1.2.2.1.4.3	Dump Water Processing												
1	Surge tank(100gal)S.Steel	ea	1	10000.00	eu	10.0	0	0.0	0		0.00	0.0	10.0
2	H2 recombiner	ea	1	18000.00	eu	18.0	0	0.0	0		0.00	0.0	18.0
3	Recombiner instrumentatn	lot	1	8000.00	eu	8.0	0	0.0	0		0.00	0.0	8.0
4	HX,IX,plumbing,valvs,etc	lot	1	100000.00	eu	100.0	0	0.0	0		0.00	0.0	100.0
** Subtotal **						136.0			0			0.0	136.0
** WBS: 1.2.2.1.5.1.1	Network Resource Manager												
1	NETWORK RESOURCE		1	12500.00	CP	12.5	1	4.0	4	EI	33.00	0.1	12.6
2	MANAGER		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	LINE PRINTER		1	1250.00	CP	1.2	1	4.0	4	EI	33.00	0.1	1.4
4	LINE PRINTER ENCLOSURE		0	0.00	A84	0.0	0	0.0	0	ES	33.00	0.0	0.0
5	ETHERNET TRANSCEIVER		1	350.00	CP	0.3	1	2.0	2	IEL	62.85	0.1	0.5
** Subtotal **						14.1			10			0.4	14.5
** WBS: 1.2.2.1.5.1.2	Work Stations												
1	MULTIBUS II SYSTEM		1	10000.00	CP	10.0	1	4.0	4	CP	59.40	0.2	10.2
2	PC WORKSTATIONS		1	12000.00	CP	12.0	1	4.0	4	CP	59.40	0.2	12.2
3	PC SOFTWARE		6	500.00	EU	3.0	0	0.0	0		0.00	0.0	3.0
4	ETHERNET INTERFACES		1	350.00	CP	0.3	0	0.0	0		0.00	0.0	0.3
5	ETHERNET CABLE	METERS	500	2.00	CP	1.0	0	0.0	0		0.00	0.0	1.0
6	PLM COMPILER		1	750.00	CP	0.8	0	0.0	0		0.00	0.0	0.8
7	FORTRAN COMPILER		1	750.00	CP	0.8	0	0.0	0		0.00	0.0	0.8
9	PC PRINTERS		1	500.00	CP	0.5	1	2.0	2	EI	33.00	0.1	0.6
** Subtotal **						28.4			10			0.5	28.9
** WBS: 1.2.2.1.5.1.3	Network Software & Documentation												
1	RMX NETWORKING SOFT.		1	2000.00	CP	2.0	0	0.0	0		0.00	0.0	2.0
2	SOFTWARE FOR ETHERNET		0	0.00		0.0	0	0.0	0	CP	59.40	0.0	0.0
3	ACCESS INTO NRM PART 1		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
4	RMX NETWORK SOFT PART 2		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
5	RMX NETWORK SOFT PART 3		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
6	DOCUMENTATION		0	0.00		0.0	1	120.0	120	CP	59.40	7.1	7.1
** Subtotal **						2.0			420			24.9	26.9

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.1.5.1.4		Installation										
1	INSTALL ETHERNET		0	0.00	0.0	1	40.0	40	IEL	62.85	2.5	2.5
2	COAX CABLE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	INSTALL ETHERNET		0	0.00	0.0	8	4.0	32	IEL	62.85	2.0	2.0
4	TRANSCEIVERS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
5	INSTALL WORKSTATIONS		0	0.00	0.0	2	6.0	12	EI	33.00	0.4	0.4
6	INSTALL NRM		0	0.00	0.0	1	8.0	8	CP	59.40	0.5	0.5
7	INSTALL PRINTERS		0	0.00	0.0	1	4.0	4	EI	33.00	0.1	0.1
** Subtotal **					0.0			96			5.5	5.5
** WBS: 1.2.2.1.5.2.1		Color Monitors & Touch Panels										
1	HIGH RESOLUTION		4	2500.00 CP	10.0	4	8.0	32	EI	33.00	1.1	11.1
2	MONITORS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	TOUCH-PANELS		0	0.00 CP	0.0	0	0.0	0	ES	33.00	0.0	0.0
4	IBM PC (486)		4	11000.00 CP	44.0	4	8.0	32	ES	33.00	1.1	45.1
5	VIDEO BOARD		4	2000.00 CP	8.0	4	4.0	16	EI	33.00	0.5	8.5
6	SERIAL CONNECTION		4	1200.00 EU	4.8	4	4.0	16	IEL	62.85	1.0	5.8
7	TO DMM		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
8	SERIAL CONNECTION		4	25.00 EU	0.1	4	2.0	8	EI	33.00	0.3	0.4
9	TO INTERFACE CHASSIS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
10	VIDEO AND GRAPHICS		1	3000.00 EU	3.0	1	40.0	40	CP	59.40	2.4	5.4
11	SOFTWARE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
12	SOFTWARE FOR TOUCH		0	0.00 CP	0.0	0	0.0	0	CP	59.40	0.0	0.0
13	PANEL		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
14	DOCUMENTATION		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **					69.9			184			8.7	78.6
** WBS: 1.2.2.1.5.2.2		Video Copier & Mux										
1	VIDEO MUX		1	2750.00 EU	2.8	1	20.0	20	EI	33.00	0.7	3.4
2	COLOR COPIER		1	12000.00 CP	12.0	1	10.0	10	CP	59.40	0.6	12.6
3	SOFTWARE FOR MUX		0	0.00	0.0	1	8.0	8	CP	59.40	0.5	0.5
4	AND COPIER		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
5	DOCUMENTATION		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
** Subtotal **					14.8			58			2.9	17.7
** WBS: 1.2.2.1.5.2.3		Portable Consoles										
1	PORTABLE/386 COMPUTER	ea	1	12500.00 CP	12.5	1	16.0	16	CP	59.40	1.0	13.5
2	HIGH RESOLUTION		0	0.00 CP	0.0	0	0.0	0	EI	33.00	0.0	0.0
3	MONITORS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
4	TOUCH PANELS		0	0.00 CP	0.0	0	0.0	0	ES	33.00	0.0	0.0
5	VIDEO BOARD		0	0.00 CP	0.0	0	0.0	0	EI	33.00	0.0	0.0
6	SERIAL CONNECTION		1	12.00 EU	0.0	1	2.0	2	EI	33.00	0.1	0.1
7	TO IOMM/ILC		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
8	SOFTWARE FOR PORTABLE		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
9	CONSOLE PART 1		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
10	SOFT. FOR PORTABLE PART 2		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
11	DOCUMENTATION		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
** Subtotal **					12.5			118			7.0	19.5
** WBS: 1.2.2.1.5.2.4		Operator Interface										
1	INTELLIGENT TOUCH		0	0.00 CP	0.0	0	0.0	0	EI	33.00	0.0	0.0
2	PANEL		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	INTELLIGENT KNOB		2	400.00 CP	0.8	2	20.0	40	ES	33.00	1.3	2.1
4	PANEL		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
5	INTELLIGENT KEYBOARD		1	400.00 CP	0.4	1	30.0	30	ES	33.00	1.0	1.4
6	SOFTWARE FOR INPUT		0	0.00	0.0	1	8.0	8	CP	59.40	0.5	0.5
7	DEVICES		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
8	DOCUMENTATION		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
** Subtotal **					1.2			98			4.0	5.2

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.1.5.2.5	Installation											
1	INSTALL TV'S		0	0.00	0.0	4	12.0	48	EI	33.00	1.6	1.6
2	INSTALL CHASSIS		0	0.00	0.0	4	12.0	48	EI	33.00	1.6	1.6
3	INSTALL LINKS		0	0.00	0.0	4	8.0	32	IEL	62.85	2.0	2.0
4	INSTALL MUX/COPIER		0	0.00	0.0	4	8.0	32	EI	33.00	1.1	1.1
5	INSTALL OPERATOR		0	0.00	0.0	6	12.0	72	EI	33.00	2.4	2.4
6	INTERFACE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
** Subtotal **					0.0			232			8.6	8.6
** WBS: 1.2.2.1.5.3.1	Display Micro Modules											
1	MULTIBUS II SYSTEM		1	30000.00 CP	30.0	1	8.0	8	CP	59.40	0.5	30.5
2	LINK TO MULTIBUS I		1	1000.00 CP	1.0	1	4.0	4	CP	59.40	0.2	1.2
3	CPU BOARDS		3	9000.00 CP	27.0	3	4.0	12	CP	59.40	0.7	27.7
4	NETWORK BOARD		1	2000.00 CP	2.0	1	4.0	4	CP	59.40	0.2	2.2
5	TRANSCEIVER		1	300.00 CP	0.3	1	4.0	4	EI	33.00	0.1	0.4
6	SBX SERIAL CONNECTION		4	1000.00 EU	4.0	4	4.0	16	EI	33.00	0.5	4.5
7	TO CONSOLES		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
** Subtotal **					64.3			48			2.3	66.6
** WBS: 1.2.2.1.5.3.2	Operating System											
1	RMX-386		1	9500.00 CP	9.5	0	0.0	0		0.00	0.0	9.5
2	SOFTWARE FOR OPERATING		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
3	SYSTEM FOR 386 BOARDS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
4	PARALLEL PROCESSING		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
5	SOFTWARE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
6	DOCUMENTATION		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **					9.5			120			7.1	16.6
** WBS: 1.2.2.1.5.3.3	Network Access Software											
1	SOFTWARE FOR DMM/		0	0.00	0.0	1	100.0	100	CP	59.40	5.9	5.9
2	MULTIBUS II ACCESS		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	INTO NETWORK (PLM)		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
4	DOCUMENTATION		0	0.00	0.0	1	25.0	25	CP	59.40	1.5	1.5
** Subtotal **					0.0			125			7.4	7.4
** WBS: 1.2.2.1.5.3.4	Parameter Access & Modeling Software Int											
1	PROTECTED PARAMETER		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
2	ACCESS INTO DATABASE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	MODELING/DIAGNOSTICS		0	0.00	0.0	1	500.0	500	CP	59.40	29.7	29.7
4	SOFTWARE		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
5	DOCUMENTATION		0	0.00	0.0	2	100.0	200	CP	59.40	11.9	11.9
** Subtotal **					0.0			720			42.8	42.8
** WBS: 1.2.2.1.5.3.5	Error Monitoring Software											
1	ERROR MONITORING Part 1		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
2	Error Monitoring Part 2		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
3	ACCELERATOR ON/OFF		0	0.00	0.0	1	100.0	100	CP	59.40	5.9	5.9
4	DEF. CONDITIONS, PART 1		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
5	ACCEL. ON/OFF ETC, PART 2		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
6	Accel. DB Save\Rest Prt 1		0	0.00	0.0	1	20.0	20	CP	59.40	1.2	1.2
7	Accel. DB Save/Rest Prt 2		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
8	ERROR MONITORING PART 3		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
9	DOCUMENTATION		0	0.00	0.0	4	16.0	64	CP	59.40	3.8	3.8
** Subtotal **					0.0			384			22.8	22.8
** WBS: 1.2.2.1.5.3.6	Display Generation Software											
1	PROGRAM FOR INTERACTIVE		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
2	DISPLAY GENERATION		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
3	Display Programs Part 1		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4
4	Display Programs Part 2		0	0.00	0.0	1	40.0	40	CP	59.40	2.4	2.4

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
5	SUBSYS SCAN Prog Part 1		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
6	Subsys Scan Prog Part 2		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
7	DISPLAY PROGRAMS PART 3		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
8	DISPLAY PROGRAMS PART 4		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
9	SUBSYS SCAN PROG PART 3		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
10	SUBSYS SCAN PROG PART 4		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **						0.0			360			21.4	21.4
** WBS: 1.2.2.1.5.3.7	Display Micro Module Documentation												
1	DOCUMENTATION FOR DMM AND		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
2	CONTROL SYSTEM ARCHITECTU		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	MODE OF OPERATION,		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
4	MAINTENANCE, etc. Part 1		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
5	DOCUMENTATION, PART 2		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **						0.0			140			8.3	8.3
** WBS: 1.2.2.1.5.3.8	Collector Micro Module												
1	20 SLOT CARDCAGE	ea	1	6000.00	CP	6.0	1	30.0	30	EI	33.00	1.0	7.0
2	CPU BOARDS	ea	2	5000.00	CP	10.0	1	6.0	6	CP	59.40	0.4	10.4
3	COMMUNICATION SBX MODULE		2	1000.00	EU	2.0	2	4.0	8	EI	33.00	0.3	2.3
4	MANAGER CPU BOARD	ea	1	5000.00	CP	5.0	1	6.0	6	CP	59.40	0.4	5.4
5	FIBER OPTIC INTERFACE		10	400.00	CP	4.0	10	4.0	40	ES	33.00	1.3	5.3
6	FIBER OPTIC TRANSCEIVERS		15	315.00	CP	4.7	0	0.0	0		0.00	0.0	4.7
7	FIBER OPTIC CABLE		500	4.50	CP	2.2	0	0.0	0		0.00	0.0	2.2
** Subtotal **						34.0			90			3.3	37.3
** WBS: 1.2.2.1.5.3.9	Collector Micro Module Software												
1	SOFTWARE FOR COLLECTOR		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
2	MANAGER		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	LINK MANAGER SOFTWARE		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
4	FOR THE CPU BOARDS		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
5	LINK MANAGER SOFTWARE		0	0.00		0.0	1	16.0	16	CP	59.40	1.0	1.0
6	FOR THE SBX MODULES		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
7	DOCUMENTATION		0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **						0.0			196			11.6	11.6
** WBS: 1.2.2.1.5.3.10	Installation												
1	INSTALL DMM-S		0	0.00		0.0	1	24.0	24	EI	33.00	0.8	0.8
2	INSTALL CMM		0	0.00		0.0	1	40.0	40	EI	33.00	1.3	1.3
3	INSTALL CMM LINKS, PART 1		0	0.00		0.0	4	8.0	32	IEL	62.85	2.0	2.0
4	INSTALL CMM LINKS, PART 2		0	0.00		0.0	4	8.0	32	IEL	62.85	2.0	2.0
** Subtotal **						0.0			128			6.1	6.1
** WBS: 1.2.2.1.5.4.1	Intelligent Local Controller(ILC)												
1	CHASSIS & POWER SUPPLY		0	700.00	CP	0.3	0	8.0	3	ES	33.00	0.1	0.4
2	APPROX. 2.5 ILC-S/CHASSIS		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	POWER/BACKPLANE/CABLING		1	120.00	EU	0.1	0	1.0	0	EI	33.00	0.0	0.1
4	OPTO 22 MOTHER BOARDS		1	25.00	CP	0.0	1	1.0	1	ES	33.00	0.0	0.1
5	ILC OPTO 22 MODULES		1	40.00	CP	0.0	0	0.0	0		0.00	0.0	0.0
6	ILC CICUIT BOARD		1	75.00	EU	0.1	0	0.0	0		0.00	0.0	0.1
7	ILC PROCESSOR (80C186EB)		1	38.00	CP	0.0	0	0.0	0		0.00	0.0	0.0
8	ILC SERIAL IFCE (83C152)		1	50.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
9	ILC DACS (NOMINAL 16 BIT)		4	30.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
10	ILC ADC (NOMINAL 16 BIT)		2	70.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
11	ILC CMOS BATT-BACKED RAM		2	70.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
12	ILC PAL-S, FPGA		1	310.00	CP	0.3	0	0.0	0		0.00	0.0	0.3
13	ILC CRYSTALS/OSCILLATORS		2	25.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
14	ILC CONNECTORS		1	26.00	CP	0.0	0	0.0	0		0.00	0.0	0.0
15	ILC FRONT PANEL		1	12.00	CP	0.0	0	0.0	0		0.00	0.0	0.0
16	ILC CAPS/RESISTORS/SWITCH		40	2.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
17	ILC PARALLEL I/O CHIP		1	8.00	CP	0.0	0	0.0	0		0.00	0.0	0.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
18	ILC SOCKETS/MISCELLANEOUS		20	5.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
19	LOAD ILC WITH CHIPS ETC.		1	45.00	EU	0.0	0	0.0	0		0.00	0.0	0.0
20	SOFTWARE AND TEST		0	0.00		0.0	1	3.0	3	CP	59.40	0.2	0.2
21	DATABASE GENERATION		0	0.00		0.0	1	2.0	2	CP	59.40	0.1	0.1
22	ILC MATH PROC. (80C187)		1	160.00	CP	0.2	0	0.0	0		0.00	0.0	0.2
** Subtotal **						1.8			10			0.4	2.3
** WBS: 1.2.2.1.5.4.2	ILC Software & Documentation												
1	GENERAL ILC SFTWRE Part 1		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
2	General ILC Sftwr Part 2		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
3	ILC DB SPCFC Sftwr Part 1		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
4	ILC DB Spcfc Sftwr Part 2		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
5	ILC Multdrp Lnk Sftwr 1		0	0.00		0.0	1	8.0	8	CP	59.40	0.5	0.5
6	ILC Mltidrp Lnk Sftwr 2		0	0.00		0.0	1	8.0	8	CP	59.40	0.5	0.5
7	DOCUMENTATION		0	0.00		0.0	1	300.0	300	CP	59.40	17.8	17.8
** Subtotal **						0.0			1116			66.3	66.3
** WBS: 1.2.2.1.5.4.3	I/O Micro Modules(IOMM's)												
1	CARD CAGE AND		1	2500.00	CP	2.5	1	20.0	20	ES	33.00	0.7	3.2
2	AND POWER SUPPLY		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	COMMUNICATION SBX MODULE		1	1000.00	EU	1.0	1	12.0	12	ES	33.00	0.4	1.4
4	MAIN CPU BOARD		1	3500.00	CP	3.5	1	2.0	2	EI	33.00	0.1	3.6
5	DAC BOARD		1	1200.00	CP	1.2	1	2.0	2	EI	33.00	0.1	1.3
6	ADC BOARD		1	1400.00	CP	1.4	1	2.0	2	EI	33.00	0.1	1.5
7	BOOLEAN BOARD		2	700.00	CP	1.4	1	2.0	2	EI	33.00	0.1	1.5
8	SPECIAL FUNCTION		1	1500.00	EU	1.5	1	2.0	2	EI	33.00	0.1	1.6
9	BOARD		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
10	OPTO-22 P.C. BOARD		4	120.00	CP	0.5	4	2.0	8	ES	33.00	0.3	0.7
11	OPTO 22 MODULES		150	10.00	CP	1.5	0	0.0	0		0.00	0.0	1.5
12	ADC PASSIVE INTERFACE		1	400.00	A83	0.4	1	32.0	32	ES	33.00	1.1	1.5
13	DAC PASSIVE INTERFACE		1	400.00	A83	0.4	1	32.0	32	ES	33.00	1.1	1.5
14	CROSS CONNECT		1	250.00	A83	0.2	1	64.0	64	EI	33.00	2.1	2.4
15	BLOCKS AND RACK		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
16	5/24 VOLT D.C. POWER		1	250.00	CP	0.2	1	24.0	24	EI	33.00	0.8	1.0
17	SUPPLY AND DISTRIBUTION		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
18	IOMM SPECIFIC SOFTWARE		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
19	IOMM DATA BASE		0	0.00		0.0	1	8.0	8	CP	59.40	0.5	0.5
20	DOCUMENTATION		0	0.00		0.0	1	50.0	50	CP	59.40	3.0	3.0
** Subtotal **						15.8			460			22.0	37.8
** WBS: 1.2.2.1.5.4.4	IOMM Software & Documentation												
1	IOMM GENERAL SOFTWARE		0	0.00		0.0	1	200.0	200	CP	59.40	11.9	11.9
2	DOCUMENTATION		0	0.00		0.0	1	100.0	100	CP	59.40	5.9	5.9
** Subtotal **						0.0			300			17.8	17.8
** WBS: 1.2.2.1.5.4.5	Data Base Generation for I/O Controllers												
1	GENERAL DATA-BASE		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
2	GENERATION SOFTWARE		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	DOCUMENTATION		0	0.00		0.0	1	60.0	60	CP	59.40	3.6	3.6
** Subtotal **						0.0			60			3.6	3.6
** WBS: 1.2.2.1.5.4.6.1	ILC Installation												
1	INSTALL ILC		1	25.00	EU	0.0	1	6.0	6	EI	33.00	0.2	0.2
** Subtotal **						0.0			6			0.2	0.2
** WBS: 1.2.2.1.5.4.6.2	IOMM Installation												
1	INSTALL IOMM		1	250.00	EU	0.2	1	88.0	88	EI	33.00	2.9	3.2
** Subtotal **						0.2			88			2.9	3.2

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.1.5.5.1	Manchester Encoder & Timing Module												
1	MANCHESTER ENCODER		1	350.00	A83	0.3	1	48.0	48	ES	33.00	1.6	1.9
2	NIM MODULE		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	TIMING NIM MODULE		1	700.00	A83	0.7	1	64.0	64	ES	33.00	2.1	2.8
4	NIM BIN WITH		1	1200.00	A83	1.2	0	0.0	0		0.00	0.0	1.2
5	POWER SUPPLY		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
6	TIMING MODULE SOFTWARE		0	0.00		0.0	1	8.0	8	CP	59.40	0.5	0.5
7	AND DOCUMENTATION		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
** Subtotal **						2.2			120			4.2	6.4
** WBS: 1.2.2.1.5.5.2	Manchester Decoder & Fiber Optics												
1	MANCHESTER DECODER		1	300.00	A83	0.3	1	48.0	48	ES	33.00	1.6	1.9
2	FIBER OPTIC TRANSMITTER		1	75.00	CP	0.1	1	4.0	4	ES	33.00	0.1	0.2
3	FIBER OPTIC RECEIVER		1	75.00	CP	0.1	1	4.0	4	ES	33.00	0.1	0.2
4	NIM BIN WITH		1	1200.00	A83	1.2	0	0.0	0		0.00	0.0	1.2
5	POWER SUPPLY		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
6	FIBER OPTIC CABLE	METERS	30	3.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
** Subtotal **						1.7			56			1.8	3.6
** WBS: 1.2.2.1.5.5.3	Installation												
1	INSTALL MANCHESTER		0	0.00		0.0	1	12.0	12	EI	33.00	0.4	0.4
2	ENCODER OR DECODER		0	0.00		0.0	0	0.0	0		0.00	0.0	0.0
3	INSTALL F.O. CABLING		0	0.00		0.0	1	4.0	4	IEL	62.85	0.3	0.3
** Subtotal **						0.0			16			0.6	0.6
** WBS: 1.2.2.1.6.1	Access Control Fabrication												
1	GATE, FAB	EA	2	637.70	A84	1.3	2	26.0	52	MS	37.73	2.0	3.2
2	JUNCTION BOX	EA	2	117.66	EU	0.2	2	5.0	10	EI	33.00	0.3	0.6
3	KEY CACHE, FAB	EA	4	1100.00	EU	4.4	4	24.0	96	EI	33.00	3.2	7.6
4	KEY CACHE - EM WIRE CK	EA	0	0.00		0.0	4	2.0	8	EM	33.00	0.3	0.3
5	CHAIN LITE PNL, FAB	EA	4	525.00	CP	2.1	4	16.0	64	EI	33.00	2.1	4.2
6	CHAIN LITE PNL - EM CHECK		0	0.00		0.0	4	2.0	8	EM	33.00	0.3	0.3
7	CRASH-OFF/RESET BOX, FAB	EA	6	729.00	CP	4.4	6	8.0	48	EI	33.00	1.6	6.0
8	CRASH-OFF BX - EM CHECK		0	0.00		0.0	6	2.0	12	EM	33.00	0.4	0.4
9	CRASH-IN/OUT GATE RELEASE	EA	2	450.00	EU	0.9	2	32.0	64	MS	37.73	2.4	3.3
10	DOUBLE RACKS	EA	2	1535.00	A89	3.1	2	12.0	24	EI	33.00	0.8	3.9
11	P 2 PNL WITH 20 BREAKERS	EA	2	148.40	CP	0.3	2	8.0	16	EI	33.00	0.5	0.8
12	24VDC CONTROL POWER P.S.	EA	2	250.00	EU	0.5	2	32.0	64	EI	33.00	2.1	2.6
13	24VDC PS - EM WIRE CHECK	EA	0	0.00		0.0	2	4.0	8	EM	33.00	0.3	0.3
14	BA4 PANEL (3 PH AC PWR)	EA	2	97.44	CP	0.2	2	4.0	8	EI	33.00	0.3	0.5
15	BA2 PANEL (NEUT & GND)	EA	4	63.95	CP	0.3	4	4.0	16	EI	33.00	0.5	0.8
16	X CONNECT BLOCKS	EA	2	183.68	CP	0.4	2	8.0	16	EI	33.00	0.5	0.9
17	X CONNECT RELAY BLOCKS	EA	4	1017.68	CP	4.1	4	8.0	32	EI	33.00	1.1	5.1
18	RELAYS, KRP14DG	EA	120	11.88	CP	1.4	4	4.0	16	EI	33.00	0.5	2.0
19	X CONNECT TERMINATIONS	EA	1200	0.05	CP	0.1	1200	0.0	50	EI	33.00	1.7	1.7
20	MISC RACK WIRING	LOT	2	117.66	EU	0.2	2	16.0	32	EI	33.00	1.1	1.3
21	MODIFY ACCESS WARNING BOX	EA	2	646.73	CP	1.3	2	16.0	32	EI	33.00	1.1	2.3
22	ACCESS WRN BX - EM CHECK		0	0.00		0.0	2	2.0	4	EM	33.00	0.1	0.1
23	24VDC DIST PNL	EA	2	300.00	CP	0.6	2	40.0	80	EI	33.00	2.6	3.2
24	24 VDC DIST PNL-EM CHECK		0	0.00		0.0	2	4.0	8	EM	33.00	0.3	0.3
25	OPTO-22 CHASSIS	EA	2	390.00	CP	0.8	2	40.0	80	EI	33.00	2.6	3.4
26	OPTO-22 CHASS - EM CHECK		0	0.00		0.0	2	4.0	8	EM	33.00	0.3	0.3
27	MISC RACK WIRING EM CHECK	EA	0	0.00		0.0	4	8.0	32	EM	33.00	1.1	1.1
** Subtotal **						26.4			888			29.9	56.3
** WBS: 1.2.2.1.6.2	Area Monitoring Fabrication												
1	X-RAY DET W/RMTE READOUT	EA	10	5000.00	CP	50.0	10	2.0	20	EI	33.00	0.7	50.7
2	NEUTRON DET W/RMTE READ	EA	10	6250.00	CP	62.5	10	4.0	40	EI	33.00	1.3	63.8
3	WIRE X-RAY DET TO X-CONN	EA	10	20.00	EU	0.2	10	8.0	80	EI	33.00	2.6	2.8
4	WIRE NEUT DET TO X-CONN	EA	10	20.00	EU	0.2	10	8.0	80	EI	33.00	2.6	2.8
5	EM WIRE CHECK	EA	0	0.00		0.0	20	8.0	160	EM	33.00	5.3	5.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						112.9			380			12.5	125.4
** WBS: 1.2.2.1.6.3	Control Room Fabrication												
1	CONTROL ROOM KEY PNL -FAB	EA	2	419.89	CP	0.8	2	8.0	16	EI	33.00	0.5	1.4
2	KEY PANEL - EM WIRE CHECK	EA	0	0.00		0.0	2	1.0	2	EM	33.00	0.1	0.1
3	VIDEO MONITOR	EA	1	200.00	CP	0.2	0	0.0	0		0.00	0.0	0.2
4	VIDEO MULTIPLEXER	EA	1	500.00	EU	0.5	0	0.0	0		0.00	0.0	0.5
5	GATE COMMUNICATIONS PNL	EA	1	400.00	EA	0.4	1	40.0	40	EI	33.00	1.3	1.7
6	COMM PNL -EM WIRE CHECK	EA	0	0.00		0.0	1	8.0	8	EM	33.00	0.3	0.3
** Subtotal **						1.9			66			2.2	4.1
** WBS: 1.2.2.1.6.4	Beam Dump Interlocks												
1	Install Gate	ea	2	235.00	eu	0.5	2	24.0	48	ISM	72.00	3.5	3.9
2	Door Switches	ea	4	100.00	eu	0.4	4	4.0	16	EI	33.00	0.5	0.9
3	Crash-In/Out Switches	ea	2	12.00	eu	0.0	2	4.0	8	EI	33.00	0.3	0.3
4	Crash-Off/Reset boxes	ea	2	12.00	eu	0.0	2	4.0	8	EI	33.00	0.3	0.3
5	Installation	lot	2	2000.00	eu	4.0	2	80.0	160	IEL	62.85	10.1	14.1
6	" "	lot	2	1000.00	eu	2.0	2	80.0	160	EI	33.00	5.3	7.3
** Subtotal **						6.9			400			19.8	26.8
** WBS: 1.2.2.1.6.5	Installation												
1	INSTALL GATE	EA	2	235.31	EU	0.5	2	24.0	48	ISM	72.00	3.5	3.9
2	INSTALL RACK (DOUBLE)	EA	2	11.76	EU	0.0	2	16.0	32	EI	33.00	1.1	1.1
3	JUNCTION BOX	EA	2	11.76	EU	0.0	2	4.0	8	EI	33.00	0.3	0.3
4	DOOR SWITCHES	EA	4	98.35	A80	0.4	4	4.0	16	EI	33.00	0.5	0.9
5	CRASH-IN/OUT SWITCHES	EA	4	11.76	EU	0.0	4	4.0	16	EI	33.00	0.5	0.6
6	EMT 1/2" 10'LGS (AC PWR)	LG	8	1.35	CP	0.0	2	8.0	16	IEL	62.85	1.0	1.0
7	#12 THHN (5 COND)	CL	5	29.05	CP	0.1	2	8.0	16	IEL	62.85	1.0	1.2
8	RACK AC PWR - EM CHECK	EA	0	0.00		0.0	2	2.0	4	EM	33.00	0.1	0.1
9	EMT 1/2" TO TRAY (#18 TC)	LG	8	1.35	CP	0.0	2	4.0	8	IEL	62.85	0.5	0.5
10	4C #18 TC 4 X 50 FT	FT	200	0.60	A89	0.1	8	4.0	32	IEL	62.85	2.0	2.1
11	CRASH-OFF/RESET BOXES	EA	6	11.76	EU	0.1	6	4.0	24	EI	33.00	0.8	0.9
12	EMT 1" - CRASH-OFF BOXES	LG	72	2.70	CP	0.2	6	16.0	96	IEL	62.85	6.0	6.2
13	21C #18 TC CRASH-OFF BOX	FT	720	2.50	EU	1.8	6	8.0	48	IEL	62.85	3.0	4.8
14	CRASH-OFF BX - EM CHECK	EA	0	0.00		0.0	6	2.0	12	EM	33.00	0.4	0.4
15	KEY CACHE - INSTALL	EA	4	11.76	EU	0.0	4	4.0	16	EI	33.00	0.5	0.6
16	MISC FITTINGS ($1/FT)	LOT	1	89.64	EU	0.1	1	8.0	8	IEL	62.85	0.5	0.6
17	EMT 3/4" TO TRAY (KEYS)	LG	8	1.70	CP	0.0	2	8.0	16	IEL	62.85	1.0	1.0
18	5 COND #18 TC (KEY CACHE)	FT	160	0.75	A89	0.1	2	16.0	32	IEL	62.85	2.0	2.1
19	KEY CACHE - EM WIRE CHECK		0	0.00		0.0	4	2.0	8	EM	33.00	0.3	0.3
20	TELEVISION CAMERA INSTALL	EA	2	300.00	CP	0.6	2	8.0	16	EI	33.00	0.5	1.1
21	RG-59 T.V. COAX PULL-IN	FT	1000	0.26	CP	0.3	2	16.0	32	EI	33.00	1.1	1.3
22	T.V. CAMERA - EM CHECK		0	0.00		0.0	2	2.0	4	EM	33.00	0.1	0.1
23	ACCESS SIGN/COMM -INSTALL	EA	2	11.76	EU	0.0	2	8.0	16	EI	33.00	0.5	0.6
24	EMT 1/2" -ACCESS SIGN	LG	8	1.35	CP	0.0	2	8.0	16	IEL	62.85	1.0	1.0
25	26 COND #18 TC -ACCESS BX	FT	100	1.00	EU	0.1	2	16.0	32	EI	33.00	1.1	1.2
26	ACCESS SIGN -EM CHECK		0	0.00		0.0	2	4.0	8	EM	33.00	0.3	0.3
27	X-CONN WIRING -EM CHECK		0	0.00		0.0	2	16.0	32	EM	33.00	1.1	1.1
28	MOUNT XRAY & NEUT DETECT	EA	20	20.00	EU	0.4	10	8.0	80	EI	33.00	2.6	3.0
29	X-RAY DET CABLE -INSTALL	FT	1000	4.50	EU	4.5	10	40.0	400	EI	33.00	13.2	17.7
30	NEUT DET CABLE - INSTALL	FT	1000	4.50	EU	4.5	4	40.0	160	EI	33.00	5.3	9.8
31	INSTALL KEY PANEL	EA	1	0.00	EU	0.0	1	2.0	2	EI	33.00	0.1	0.1
32	INSTALL VIDEO MONITOR	EA	1	50.00	EU	0.1	1	8.0	8	EI	33.00	0.3	0.3
33	INSTALL VIDEO MUX	EA	1	0.00		0.0	1	4.0	4	EI	33.00	0.1	0.1
34	INSTALL COMM PANEL	EA	1	0.00		0.0	1	2.0	2	EI	33.00	0.1	0.1
35	PULL IN 26C # 18 TC	FT	500	2.00	EU	1.0	1	16.0	16	IEL	62.85	1.0	2.0
36	TERMINATE 26C #18 TC	EA	52	0.05	EU	0.0	1	8.0	8	EI	33.00	0.3	0.3
37	EM WIRE CHECK CONTROL RM	LOT	1	0.00		0.0	1	16.0	16	EM	33.00	0.5	0.5
** Subtotal **						15.0			1308			54.1	69.1
** WBS: 1.2.2.1.7	Accelerator/FEL Physics												
1	Physics		0	0.00		0.0	1	9400.0	9400	AA	42.75	401.9	401.9

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
3	S&E (@15%)	lot	1	60000.00	eu	60.0	0	0.0	0		0.00	0.0	60.0
** Subtotal **						60.0			9400			401.9	461.9
** WBS: 1.2.2.2.1.1.1	Magnetic Material												
1	NDFE Blocks	ea	1150	330.00	VQ	379.5	0	0.0	0		0.00	0.0	379.5
2	Gauges/Field Coils/Holdrs	lot	1	315.00	EU	0.3	1	160.0	160	MU	35.92	5.7	6.1
3	Measurement Prep		0	0.00		0.0	1	20.0	20	EM	33.00	0.7	0.7
4			0	0.00		0.0	1	20.0	20	EE	59.40	1.2	1.2
5	Measurements	LOT	1	105.00	EU	0.1	0	0.0	0		0.00	0.0	0.1
6	3-Axis H.C. Meas		0	0.00		0.0	1150	0.1	138	EM	33.00	4.6	4.6
7	Supervision		0	0.00		0.0	1	100.0	100	EE	59.40	5.9	5.9
** Subtotal **						379.9			438			18.1	398.0
** WBS: 1.2.2.2.1.1.3	Pole Assemblies												
1	Vanadium Permendur	ea	198	120.20	A91	23.8	0	0.0	0		0.00	0.0	23.8
2	Keepers	ea	198	246.00	A91	48.7	0	0.0	0		0.00	0.0	48.7
3	Keeper Inspection	lot	1	1050.00	EU	1.1	198	0.8	148	MM	38.60	5.7	6.8
4	Containers	ea	198	15.75	EU	3.1	0	0.0	0		0.00	0.0	3.1
5	Assy Fixtures	ea	10	52.50	A82	0.5	12	30.0	360	MM	38.60	13.9	14.4
6	Assembly	ea	198	10.50	A82	2.1	198	6.0	1188	MM	38.60	45.9	47.9
7	Pole Assembly Mounts	ea	10	1414.00	A91	14.1	10	24.0	240	MM	38.60	9.3	23.4
** Subtotal **						93.4			1936			74.7	168.2
** WBS: 1.2.2.2.1.1.4	End Pole Assemblies												
1	End Pole Keepers	LOT	1	12157.00	A91	12.2	0	0.0	0		0.00	0.0	12.2
2	NdFe Block Cutting		0	0.00		0.0	24	4.0	96	MS	37.73	3.6	3.6
3	Assembly - Keepers		0	0.00		0.0	8	24.0	192	MA	38.60	7.4	7.4
4	Rotator		0	0.00		0.0	8	32.0	256	MM	38.60	9.9	9.9
5	Rotator Block Cutting		0	0.00		0.0	24	4.0	96	MS	37.73	3.6	3.6
6	Assemble - Rotator		0	0.00		0.0	8	4.0	32	MA	38.60	1.2	1.2
7	Rotator Linkage	ea	8	105.00	EU	0.8	8	4.0	32	MM	38.60	1.2	2.1
8	Manual Rotatr Drv	ea	8	525.00	CP	4.2	8	16.0	128	MM	38.60	4.9	9.1
9			0	0.00		0.0	8	4.0	32	MA	38.60	1.2	1.2
10	End pole mounts/levelers	lot	1	7595.00	A91	7.6	0	0.0	0		0.00	0.0	7.6
** Subtotal **						24.8			864			33.2	58.0
** WBS: 1.2.2.2.1.1.5	Backing Beams												
1	Backing Beams (2)	lot	1	74900.00	A91	74.9	1	50.0	50	MM	38.60	1.9	76.8
2	Flux Shunt	ea	1	6500.00	eu	6.5	1	206.0	206	MA	38.60	8.0	14.5
3	Rigging Hardware	lot	1	900.00	EU	0.9	1	80.0	80	MM	38.60	3.1	4.0
4	Misc.	lot	1	1000.00	eu	1.0	1	80.0	80	MA	38.60	3.1	4.1
5	Shimes	lot	1	100.00	eu	0.1	1	40.0	40	MM	38.60	1.5	1.6
6	Adjusters/guides	lot	1	9257.00	A91	9.3	0	0.0	0		0.00	0.0	9.3
** Subtotal **						92.7			456			17.6	110.3
** WBS: 1.2.2.2.1.1.6	Magnet Structure Assembly												
1	Keeper Pole Mount Assembl	ea	10	235.00	A91	2.4	10	60.0	600	MA	38.60	23.2	25.5
2	End Pole Assembly		0	0.00		0.0	4	16.0	64	MM	38.60	2.5	2.5
3	Pole Mount/Bckg Bm Assy	ea	10	105.00	EU	1.1	10	48.0	480	MA	38.60	18.5	19.6
4	Fiducializing	lot	1	105.00	EU	0.1	2	40.0	80	MA	38.60	3.1	3.2
5	Interferometer Hardware	lot	1	1000.00	eu	1.0	1	80.0	80	MM	38.60	3.1	4.1
** Subtotal **						4.5			1304			50.3	54.8
** WBS: 1.2.2.2.1.1.7	Magnetic Measurements: Mechanical												
1	Coil & Probe Mounts		0	0.00		0.0	1	40.0	40	MU	35.92	1.4	1.4
2	Assembly Section Setup		0	0.00		0.0	12	12.0	144	MA	38.60	5.6	5.6
3	Coils	ea	2	105.00	eu	0.2	2	120.0	240	MU	35.92	8.6	8.8
4	Gap Spacers		0	0.00		0.0	1	24.0	24	MU	35.92	0.9	0.9
5	ID Setup	lot	1	315.00	eu	0.3	1	160.0	160	MA	38.60	6.2	6.5

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **					0.5			608			22.7	23.2
** WBS: 1.2.2.2.1.1.8	Magnetic Measurements: Electrical											
1	Setup Assembly Sections		0	0.00	0.0	1	16.0	16	EE	59.40	1.0	1.0
2			0	0.00	0.0	12	4.0	48	ES	33.00	1.6	1.6
3	Data Acquire: Assy Sectns		0	0.00	0.0	12	3.0	36	EE	59.40	2.1	2.1
4			0	0.00	0.0	12	8.0	96	ES	33.00	3.2	3.2
5	Data Analysis:Assy Sectns		0	0.00	0.0	1	80.0	80	EE	59.40	4.8	4.8
6	Calibrate Null Coil		0	0.00	0.0	1	20.0	20	EE	59.40	1.2	1.2
7			0	0.00	0.0	1	20.0	20	ES	33.00	0.7	0.7
8	Code Software Coil Paramt		0	0.00	0.0	1	8.0	8	CP	59.40	0.5	0.5
9			0	0.00	0.0	1	8.0	8	EE	59.40	0.5	0.5
10	ID Setup: Electronic		0	0.00	0.0	1	16.0	16	EE	59.40	1.0	1.0
11			0	0.00	0.0	1	40.0	40	ES	33.00	1.3	1.3
12	ID Setup: Electrical		0	0.00	0.0	1	40.0	40	ES	33.00	1.3	1.3
13	ID: Data Acquisition		0	0.00	0.0	1	40.0	40	EE	59.40	2.4	2.4
14			0	0.00	0.0	1	240.0	240	ES	33.00	7.9	7.9
15	ID: Data Analysis		0	0.00	0.0	1	40.0	40	EE	59.40	2.4	2.4
16	Data Preparation		0	0.00	0.0	1	80.0	80	ES	33.00	2.6	2.6
17	Q/C Verification		0	0.00	0.0	1	20.0	20	EE	59.40	1.2	1.2
18			0	0.00	0.0	1	20.0	20	ES	33.00	0.7	0.7
19	Shutdown/Storage		0	0.00	0.0	1	20.0	20	EE	59.40	1.2	1.2
20			0	0.00	0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **					0.0			928			38.6	38.6
** WBS: 1.2.2.2.1.2.1	Support System Fabrication											
1	Support System Assembly	ea	1	55200.00 EU	55.2	1	20.0	20	MA	38.60	0.8	56.0
2	Associated Parts	lot	1	1000.00 EU	1.0	1	80.0	80	MM	38.60	3.1	4.1
3	Miscellaneous	lot	1	1900.00 EU	1.9	1	210.0	210	MM	38.60	8.1	10.0
4	Assembly	lot	1	1800.00 EU	1.8	1	835.0	835	MA	38.60	32.2	34.0
** Subtotal **					59.9			1145			44.2	104.1
** WBS: 1.2.2.2.1.2.2	Drive System Fabrication											
1	Roller Screw Assembly	ea	1	53200.00 A91	53.2	1	32.0	32	MM	38.60	1.2	54.4
2	Spring System	ea	1	1000.00 eu	1.0	1	130.0	130	MM	38.60	5.0	6.0
3	Bearing System	lot	1	900.00 EU	0.9	1	105.0	105	MM	38.60	4.1	5.0
4	Sprocket/Chain System	lot	1	700.00 eu	0.7	1	50.0	50	MM	38.60	1.9	2.6
5	Gear Box & Mtg.	ea	1	1700.00 EU	1.7	1	20.0	20	MM	38.60	0.8	2.5
6	Encoder System	lot	1	500.00 eu	0.5	1	50.0	50	MM	38.60	1.9	2.4
7	Motor Mounting Bracket	ea	1	400.00 eu	0.4	1	40.0	40	MM	38.60	1.5	1.9
8	Fan System	lot	1	200.00 eu	0.2	1	40.0	40	MM	38.60	1.5	1.7
9	Miscellaneous	lot	1	1200.00 EU	1.2	1	235.0	235	MM	38.60	9.1	10.3
10	Assembly	lot	1	900.00 EU	0.9	1	365.0	365	MA	38.60	14.1	15.0
11	Roller Screw Kinematc Mnt	ea	8	1400.00 eu	11.2	1	170.0	170	MM	38.60	6.6	17.8
** Subtotal **					71.9			1237			47.7	119.6
** WBS: 1.2.2.2.1.2.3	Local Temperature Control Fabrication											
1	Frame & Curtain	lot	1	3000.00 EU	3.0	1	200.0	200	MA	38.60	7.7	10.7
2	Blower & Dryer System	lot	1	1100.00 EU	1.1	1	80.0	80	MA	38.60	3.1	4.2
3	Miscellaneous	lot	1	2000.00 EU	2.0	1	40.0	40	MA	38.60	1.5	3.5
4	Electrical Installation	ea	1	200.00 eu	0.2	1	80.0	80	EI	33.00	2.6	2.8
** Subtotal **					6.3			400			15.0	21.3
** WBS: 1.2.2.2.1.3.1	Vacuum Chamber											
1	Vacuum Chamber (1 cm)		0	0.00	0.0	0	0.0	0		0.00	0.0	0.0
2	Material	lbs	2275	2.32 VQ	5.3	0	0.0	0		0.00	0.0	5.3
3	Fabrication	ea	1	58810.00 A91	58.8	0	0.0	0		0.00	0.0	58.8
4		ea	1	55260.00 A91	55.3	0	0.0	0		0.00	0.0	55.3
5	Fabricate Flanges	lot	1	2620.00 A91	2.6	1	120.0	120	MM	38.60	4.6	7.3
6	Fab Flange Transitions	lot	1	1144.00 A91	1.1	6	30.0	180	MM	38.60	6.9	8.1
7	Assemble/Test		0	0.00	0.0	1	320.0	320	MA	38.60	12.4	12.4

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
8	System Assembly		0	0.00		0.0	1	80.0	80	MA	38.60	3.1	3.1
9	UHV Bakeout		0	0.00		0.0	1	160.0	160	MA	38.60	6.2	6.2
10	Trial Installation		0	0.00		0.0	1	80.0	80	MA	38.60	3.1	3.1
11	Final Installation		0	0.00		0.0	1	120.0	120	MA	38.60	4.6	4.6
12	Vacuum Chamber Inspection		0	0.00		0.0	1	80.0	80	MM	38.60	3.1	3.1
** Subtotal **						123.1			1140			44.0	167.1
** WBS: 1.2.2.2.1.3.2	Pumping Systems & Instrumentation												
1	Photon Stop/TSP Pump	ea	1	21000.00	EU	21.0	0	0.0	0		0.00	0.0	21.0
2	Ion Pump/TSP Combination	ea	3	4200.00	CP	12.6	0	0.0	0		0.00	0.0	12.6
3	90 deg Elbow to Pump	ea	3	610.00	CP	1.8	0	0.0	0		0.00	0.0	1.8
4	Right Angle Valve	ea	2	880.00	CP	1.8	0	0.0	0		0.00	0.0	1.8
5	Aluminum Conflats	ea	5	95.00	CP	0.5	0	0.0	0		0.00	0.0	0.5
6	NEG Electrical Feedthru	ea	2	200.00	eu	0.4	0	0.0	0		0.00	0.0	0.4
7	NEG Strip	ea	2	1340.00	CP	2.7	0	0.0	0		0.00	0.0	2.7
8	NEG Strip Mountng Hardwre	ea	2	312.00	eu	0.6	2	60.0	120	MM	38.60	4.6	5.3
9	NEG Strip Assembly	ea	1	104.00	eu	0.1	2	40.0	80	MA	38.60	3.1	3.2
** Subtotal **						41.5			200			7.7	49.2
** WBS: 1.2.2.2.1.3.3	Support Structure												
1	Vacuum Chamber Support	lot	1	2100.00	EU	2.1	1	160.0	160	MM	38.60	6.2	8.3
2	Ion Pump Supports	ea	3	210.00	EU	0.6	3	20.0	60	MM	38.60	2.3	2.9
3	Installation Fixture	ea	1	525.00	EU	0.5	1	80.0	80	MM	38.60	3.1	3.6
** Subtotal **						3.3			300			11.6	14.8
** WBS: 1.2.2.2.1.3.4	Vacuum Diagnostics												
1	IG Controller	eaa	1	895.00	CP	0.9	1	2.0	2	ES	33.00	0.1	1.0
2	Degas Module	ea	1	157.50	CP	0.2	0	0.0	0		0.00	0.0	0.2
3	Second IG Module	ea	1	78.75	CP	0.1	0	0.0	0		0.00	0.0	0.1
4	Process Control Module	ea	1	367.50	CP	0.4	0	0.0	0		0.00	0.0	0.4
5	Rack Mount	ea	1	52.50	CP	0.1	1	1.0	1	ES	33.00	0.0	0.1
6	Remote I/O Module	ea	1	85.00	CP	0.1	0	0.0	0		0.00	0.0	0.1
7	Dual Convectron Module	ea	1	420.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
8	UHV Electrometer Module	ea	1	420.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
9	IEEE-488 Interface	ea	1	378.00	CP	0.4	0	0.0	0		0.00	0.0	0.4
10	Nude Ion Gauge	ea	1	326.55	CP	0.3	1	1.0	1	MS	37.73	0.0	0.4
11	IG Cable: 50 feet	ea	1	204.75	CP	0.2	1	1.0	1	ES	33.00	0.0	0.2
12	Convectron Gauge	ea	1	145.95	CP	0.1	1	1.0	1	MS	37.73	0.0	0.2
13	Convectron Cable: 50 feet	ea	1	220.50	CP	0.2	1	1.0	1	ES	33.00	0.0	0.3
14	IG Connector	ea	1	10.50	EU	0.0	1	1.0	1	MS	37.73	0.0	0.0
15	IG Cable Interface	ea	1	52.50	EU	0.1	1	4.0	4	ES	33.00	0.1	0.2
16	Ion Pump Controller	ea	3	2045.40	CP	6.1	3	2.0	6	ES	33.00	0.2	6.3
17	Ion Pump Cable	ea	3	234.15	CP	0.7	3	4.0	12	ES	33.00	0.4	1.1
18	Ion Pump Cable Interface	ea	3	105.00	EU	0.3	3	4.0	12	ES	33.00	0.4	0.7
19	IEEE-488 Interface	ea	3	522.90	CP	1.6	0	0.0	0		0.00	0.0	1.6
20	ILC Crate	ea	1	1000.00	EU	1.0	1	40.0	40	ES	33.00	1.3	2.3
21	ILC	ea	2	1100.00	EU	2.2	1	40.0	40	ES	33.00	1.3	3.5
22	Sublimation Controller	ea	1	2100.00	CP	2.1	1	4.0	4	ES	33.00	0.1	2.2
23	Sublimation Mux	ea	1	2100.00	EU	2.1	1	80.0	80	ES	33.00	2.6	4.7
24	Filament Cables	set	1	525.00	EU	0.5	1	40.0	40	ES	33.00	1.3	1.8
25	NEG Power Supply	ea	1	2000.00	eu	2.0	0	0.0	0		0.00	0.0	2.0
** Subtotal **						22.5			246			8.1	30.6
** WBS: 1.2.2.2.1.4	Motor Control System												
1	Controller 500 Indexer	ea	1	1515.00	CP	1.5	0	0.0	0		0.00	0.0	1.5
2	Motor Package PK130M-T	ea	1	4703.00	CP	4.7	0	0.0	0		0.00	0.0	4.7
3	Absolute Encoder	ea	1	1805.00	CP	1.8	0	0.0	0		0.00	0.0	1.8
4	100 Ft cables	set	1	1000.00	CP	1.0	0	0.0	0		0.00	0.0	1.0
5	ILC	ea	1	1100.00	eu	1.1	0	0.0	0		0.00	0.0	1.1
6	ILC Crate (holds 6 ILCs)	ea	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
7	Final Installation	lot	1	4000.00	eu	4.0	1	180.0	180	EI	33.00	5.9	9.9
8	Indexer/Cont.	lot	1	2000.00	eu	2.0	1	60.0	60	IEL	62.85	3.8	5.8

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
9	Shop Installation	lot	1	3000.00	eu	3.0	1	120.0	120	EI	33.00	4.0	7.0
** Subtotal **						20.1			360			13.7	33.8
** WBS: 1.2.2.2.1.5	Installation												
1	Prepare & Truck to Site	lot	1	525.00	eu	0.5	1	80.0	80	MA	38.60	3.1	3.6
2	Rigger's Work	lot	1	1200.00	eu	1.2	1	64.0	64	RG	37.65	2.4	3.6
3	Survey & Alignment		0	0.00		0.0	1	80.0	80	MA	38.60	3.1	3.1
4	Installation	lot	1	315.00	eu	0.3	1	100.0	100	MA	38.60	3.9	4.2
5	Vacuum Hookup/Pumpdown	lot	1	105.00	eu	0.1	1	40.0	40	MA	38.60	1.5	1.6
6	Reinstall Temp Ctrl Housg		0	0.00		0.0	1	40.0	40	MA	38.60	1.5	1.5
7	Miscellaneous		0	0.00		0.0	1	50.0	50	MA	38.60	1.9	1.9
** Subtotal **						2.1			454			17.5	19.6
** WBS: 1.2.2.2.2.1.1.1	Aperture Plate												
1	Water Cooled Absorber	ea	1	800.00	A91	0.8	1	40.0	40	MS	37.73	1.5	2.3
2	Brazing Fixtures/Tooling	LOT	1	200.00	EU	0.2	1	30.0	30	MU	35.92	1.1	1.3
3	Flange Gaskets & Hardware	lot	2	200.00	eu	0.4	1	10.0	10	MS	37.73	0.4	0.8
** Subtotal **						1.4			80			3.0	4.4
** WBS: 1.2.2.2.2.1.1.2	Bellows												
1	Welded Bellows Assy	ea	1	3000.00	A91	3.0	1	1.0	1	MS	37.73	0.0	3.0
2	Inspect,Clean,Bake	ea	1	50.00	eu	0.1	1	2.0	2	MU	35.92	0.1	0.1
** Subtotal **						3.0			3			0.1	3.2
** WBS: 1.2.2.2.2.1.1.3	Collimating Spool												
1	Spool Piece	ea	1	1250.00	A91	1.2	1	8.0	8	MU	35.92	0.3	1.5
2	Misc. Flanges/UHV Hardwre	lot	1	500.00	eu	0.5	1	8.0	8	MS	37.73	0.3	0.8
3	Lead Shielding & Mounting	lot	1	500.00	eu	0.5	1	40.0	40	MS	37.73	1.5	2.0
** Subtotal **						2.2			56			2.1	4.3
** WBS: 1.2.2.2.2.1.1.4	Isolation Valve												
1	Valve & Controller Proc.	ea	1	22140.00	A91	22.1	0	0.0	0		0.00	0.0	22.1
2	Prelim Assemble & Test	lot	1	50.00	ea	0.1	1	8.0	8	MU	35.92	0.3	0.3
3	Inspect/Clean/Etc.	lot	1	50.00	eu	0.1	1	4.0	4	MU	35.92	0.1	0.2
4	Cables & connectors	lot	1	200.00	eu	0.2	1	4.0	4	EI	33.00	0.1	0.3
5	Blank flngs & mntng hrdwr	lot	2	200.00	eu	0.4	1	20.0	20	MS	37.73	0.8	1.2
** Subtotal **						22.8			36			1.3	24.2
** WBS: 1.2.2.2.2.1.1.5	Support Stand												
1	Support stand, misc. hrdw	ea	1	1500.00	eu	1.5	1	40.0	40	MS	37.73	1.5	3.0
2	Struts & hardware	ea	6	500.00	A91	3.0	6	8.0	48	MU	35.92	1.7	4.7
3	Misc.	lot	1	1000.00	eu	1.0	1	40.0	40	MS	37.73	1.5	2.5
** Subtotal **						5.5			128			4.7	10.2
** WBS: 1.2.2.2.2.1.1.6	Assemble, Bakeout, Test												
1	Clean parts	lot	1	100.00	eu	0.1	1	16.0	16	MU	35.92	0.6	0.7
2	Final vac assy,leak check	lot	1	100.00	eu	0.1	1	16.0	16	MU	35.92	0.6	0.7
3	Bakeout jackets	ea	1	1500.00	A91	1.5	1	8.0	8	MU	35.92	0.3	1.8
3	Fiducialize		0	0.00		0.0	2	8.0	16	MS	37.73	0.6	0.6
4	RGA scans, UHV pre-qualfy		0	0.00		0.0	1	16.0	16	MS	37.73	0.6	0.6
** Subtotal **						1.7			72			2.6	4.3
** WBS: 1.2.2.2.2.1.1.7	Installation												
1	Install/check valvs/cntrl	lot	1	200.00	eu	0.2	1	16.0	16	EI	33.00	0.5	0.7
2	Install utilities	lot	1	500.00	eu	0.5	1	16.0	16	MU	35.92	0.6	1.1
3	Install/align supprt stnd	lot	1	200.00	eu	0.2	2	16.0	32	MU	35.92	1.1	1.3
4	Instll/align vac hardware		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1
5	Vac cnnctns, leak check		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
6	Bakeout		0	0.00	0.0	2	16.0	32	MU	35.92	1.1	1.1
7	Elec. installation		0	0.00	0.0	1	8.0	8	IEL	62.85	0.5	0.5
** Subtotal **					0.9			168			6.2	7.1
** WBS: 1.2.2.2.2.1.2.1	Fab/Buy Mech Parts & Subassy's											
1	Flange/mntng plate fab	ea	1	600.00 eu	0.6	1	40.0	40	MS	37.73	1.5	2.1
2	CF feed-thrus for electrn	ea	8	200.00 eu	1.6	0	0.0	0		0.00	0.0	1.6
3	Brazing & fixtures	lot	1	100.00 eu	0.1	1	20.0	20	MU	35.92	0.7	0.8
4	Feedthrus welding	lot	1	50.00 eu	0.1	1	20.0	20	MS	37.73	0.8	0.8
5	Blades fab	ea	2	100.00 eu	0.2	2	20.0	40	MS	37.73	1.5	1.7
6	In-vac parts & elec fab	lot	1	200.00 eu	0.2	1	40.0	40	MS	37.73	1.5	1.7
7	LCW hardware	lot	1	100.00 eu	0.1	1	8.0	8	MU	35.92	0.3	0.4
8	2-axis translation mech	ea	1	3000.00 eu	3.0	0	0.0	0		0.00	0.0	3.0
9	Outside vac mntng hardwre	lot	1	500.00 eu	0.5	1	20.0	20	MS	37.73	0.8	1.3
10	Blade alignment fixtures	lot	1	200.00 eu	0.2	1	20.0	20	MS	37.73	0.8	1.0
** Subtotal **					6.6			208			7.8	14.3
** WBS: 1.2.2.2.2.1.2.2	Fab/Buy Electrical and Controls											
1	Bias power supply	ea	2	3000.00 eu	6.0	2	8.0	16	EI	33.00	0.5	6.5
2	ILC & SBX	ea	3	1500.00 eu	4.5	3	20.0	60	EI	33.00	2.0	6.5
3	Electrometer	ea	2	1695.00 cp	3.4	2	8.0	16	EI	33.00	0.5	3.9
4	Eurocard crate	ea	1	1000.00 eu	1.0	1	16.0	16	EI	33.00	0.5	1.5
5	Thermocouples & controls	ea	2	500.00 eu	1.0	2	8.0	16	EI	33.00	0.5	1.5
6	Stepper motor controller	ea	1	3000.00 eu	3.0	1	16.0	16	EI	33.00	0.5	3.5
7	Cables	lot	1	1000.00 eu	1.0	1	40.0	40	EI	33.00	1.3	2.3
8	Flow switch	ea	2	400.00 eu	0.8	2	4.0	8	EI	33.00	0.3	1.1
** Subtotal **					20.7			188			6.2	26.9
** WBS: 1.2.2.2.2.1.2.3	Fab/Buy Support Stand											
1	Slides mounting hardwre	ea	1	200.00 eu	0.2	1	8.0	8	MS	37.73	0.3	0.5
2	Support post & hardware	lot	1	3000.00 eu	3.0	1	8.0	8	MS	37.73	0.3	3.3
3	Misc hardwre & fixtures	lot	1	1000.00 eu	1.0	1	40.0	40	MS	37.73	1.5	2.5
** Subtotal **					4.2			56			2.1	6.3
** WBS: 1.2.2.2.2.1.2.4	Bellows											
1	Welded bellows assy	ea	2	4000.00 A91	8.0	0	0.0	0		0.00	0.0	8.0
2	Blank flanges,gaskets,etc	lot	2	300.00 cp	0.6	0	0.0	0		0.00	0.0	0.6
3	Inspect,clean,bake	lot	2	50.00 eu	0.1	2	2.0	4	MU	35.92	0.1	0.2
** Subtotal **					8.7			4			0.1	8.8
** WBS: 1.2.2.2.2.1.2.5	Assemble, Bakeout, Test (Assembly Shop)											
1	Assemble/test PBPM mech	ea	1	500.00 eu	0.5	2	20.0	40	MU	35.92	1.4	1.9
2	Assemble/test PBPM elec	ea	1	500.00 eu	0.5	1	40.0	40	EI	33.00	1.3	1.8
3	Bakeout/UHV pre-qualify	ea	1	500.00 eu	0.5	1	40.0	40	MU	35.92	1.4	1.9
4	Fiducialization		0	0.00	0.0	2	16.0	32	MU	35.92	1.1	1.1
5	Misc assy equip,jackets,	lot	1	1000.00 eu	1.0	1	20.0	20	MU	35.92	0.7	1.7
** Subtotal **					2.5			172			6.1	8.6
** WBS: 1.2.2.2.2.1.2.6	Installation											
1	LCW Hardware & connection	lot	1	300.00 eu	0.3	2	20.0	40	MU	35.92	1.4	1.7
2	Transport & on-site setup	lot	1	200.00 eu	0.2	2	8.0	16	MU	35.92	0.6	0.8
3	Vac assemble & leak check	lot	1	100.00 eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
4	Installation alignment		0	0.00	0.0	2	16.0	32	MS	37.73	1.2	1.2
5	Mech install,test,debug	lot	1	100.00 eu	0.1	2	20.0	40	MU	35.92	1.4	1.5
6	ELec. installation	lot	1	100.00 eu	0.1	1	20.0	20	IEL	62.85	1.3	1.4
7	Final bake & UHV qualify		0	0.00	0.0	2	20.0	40	MU	35.92	1.4	1.4
** Subtotal **					0.8			220			8.5	9.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.2.2.1.3.1	Fab/Buy Mech Parts & Subassy's												
1	Machine absorber blades	ea	2	1000.00	A91	2.0	2	40.0	80	MS	37.73	3.0	5.0
2	Braze absorber blades	ea	2	100.00	eu	0.2	2	20.0	40	MS	37.73	1.5	1.7
3	Brazing tooling/fixtures	ea	1	200.00	eu	0.2	1	20.0	20	MS	37.73	0.8	1.0
4	Blade/pivot mounting	ea	2	500.00	A91	1.0	2	60.0	120	MS	37.73	4.5	5.5
5	Pneumatic actuator mechan	ea	2	500.00	eu	1.0	2	40.0	80	MS	37.73	3.0	4.0
6	Limit stops & switches	ea	2	100.00	eu	0.2	2	20.0	40	MS	37.73	1.5	1.7
7	Bellws/conflat ass'y/weld	ea	2	1000.00	A91	2.0	2	40.0	80	MS	37.73	3.0	5.0
** Subtotal **						6.6			460			17.4	24.0
** WBS: 1.2.2.2.2.1.3.2	Fab/Buy Electrical and Controls												
1	ILC & SBX	ea	1	1500.00	eu	1.5	1	20.0	20	EI	33.00	0.7	2.2
2	Cables	lot	1	200.00	eu	0.2	1	8.0	8	EI	33.00	0.3	0.5
3	Flow switch & interlocks	ea	2	400.00	eu	0.8	2	4.0	8	EI	33.00	0.3	1.1
4	Position indicators	set	1	500.00	eu	0.5	1	8.0	8	EI	33.00	0.3	0.8
5	Air solenoids	ea	4	500.00	eu	2.0	4	8.0	32	EI	33.00	1.1	3.1
6	Air pressure interlocks	ea	1	500.00	eu	0.5	1	16.0	16	EI	33.00	0.5	1.0
** Subtotal **						5.5			92			3.0	8.5
** WBS: 1.2.2.2.2.1.3.3	Fab/Buy Vacuum Chamber & Supports												
1	Custom vacuum chamber	ea	1	8000.00	A91	8.0	1	40.0	40	MU	35.92	1.4	9.4
2	Misc flanges & UHV hardwr	lot	1	2500.00	eu	2.5	0	0.0	0		0.00	0.0	2.5
3	Mounting struts/hardware	ea	6	500.00	A91	3.0	6	8.0	48	MS	37.73	1.8	4.8
4	Support posts,frame,hrdwr	lot	1	1500.00	A91	1.5	1	40.0	40	MS	37.73	1.5	3.0
** Subtotal **						15.0			128			4.8	19.8
** WBS: 1.2.2.2.2.1.3.4	Vacuum Pumping, Gauges, Controllers, P.S.												
1	Ion pump, 400 l/s	ea	1	7527.00	A92	7.5	1	4.0	4	MU	35.92	0.1	7.7
2	Ion pump controller	ea	1	2180.00	A92	2.2	1	4.0	4	EI	33.00	0.1	2.3
3	Ion pump cable,bakeable	ea	1	250.00	A91	0.2	1	4.0	4	EI	33.00	0.1	0.4
4	IEEE-48 cable,3m cntrller	ea	1	421.00	A92	0.4	0	0.0	0		0.00	0.0	0.4
5	Roughing valve	ea	2	650.00	A91	1.3	0	0.0	0		0.00	0.0	1.3
6	Ion gauge & controls	ea	1	3500.00	A91	3.5	1	4.0	4	MU	35.92	0.1	3.6
7	Ion gauge cable, bakeable	ea	1	250.00	cp	0.2	1	4.0	4	EI	33.00	0.1	0.4
8	Junction box,IG cable	ea	1	200.00	eu	0.2	1	4.0	4	EI	33.00	0.1	0.3
9	Interlock cable	ea	1	100.00	eu	0.1	0	0.0	0		0.00	0.0	0.1
** Subtotal **						15.7			24			0.8	16.5
** WBS: 1.2.2.2.2.1.3.5	Assemble, Bakeout, Test												
1	Assemble & test	ea	1	500.00	eu	0.5	2	80.0	160	MU	35.92	5.7	6.2
2	Bakeout & UHV qualify	lot	1	500.00	eu	0.5	2	40.0	80	MS	37.73	3.0	3.5
3	Survey/calibration		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1
4	Misc tools,fixtures,cart,	lot	1	1000.00	eu	1.0	1	80.0	80	MU	35.92	2.9	3.9
** Subtotal **						2.0			352			12.8	14.8
** WBS: 1.2.2.2.2.1.3.6	Installation												
1	LCW hardware/connections	lot	1	300.00	eu	0.3	2	16.0	32	MU	35.92	1.1	1.4
2	Transport/on-site setup	lot	1	200.00	eu	0.2	2	16.0	32	MU	35.92	1.1	1.3
3	Vac assemble & leak check	lot	1	50.00	eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
4	Installation alignment		0	0.00		0.0	2	16.0	32	MS	37.73	1.2	1.2
5	Pneumatic hardware/cnnctn	lot	1	300.00	eu	0.3	2	16.0	32	MU	35.92	1.1	1.4
6	Mech install/test/debug	lot	1	50.00	eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
7	Elec installation		0	0.00		0.0	1	16.0	16	IEL	62.85	1.0	1.0
** Subtotal **						0.9			208			8.0	8.9
** WBS: 1.2.2.2.2.1.3.7	Titanium Sublimation Pump												
1	TSP pump spool piece	ea	1	2700.00	A91	2.7	0	0.0	0		0.00	0.0	2.7
2	TSP filaments & controllr	ea	1	3500.00	eu	3.5	1	8.0	8	EI	33.00	0.3	3.8
3	Flanges & UHV hardware	lot	1	500.00	eu	0.5	0	0.0	0		0.00	0.0	0.5
4	Misc (extrusions, etc.)	lot	1	1000.00	eu	1.0	1	20.0	20	MS	37.73	0.8	1.8

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						7.7			28			1.0	8.7
** WBS: 1.2.2.2.2.1.3.8	Isolation Valve												
1	Valve & controllr proc.	ea	1	18000.00	A91	18.0	0	0.0	0		0.00	0.0	18.0
2	Prelim assemble & test	lot	1	50.00	eu	0.1	1	8.0	8	MU	35.92	0.3	0.3
3	Inspection, cleaning, etc	lot	1	50.00	eu	0.1	1	4.0	4	MU	35.92	0.1	0.2
4	Cables & connectors	lot	1	200.00	eu	0.2	1	2.0	2	EI	33.00	0.1	0.3
5	Blank flanges & hardware	lot	2	200.00	eu	0.4	0	0.0	0		0.00	0.0	0.4
** Subtotal **						18.7			14			0.5	19.2
** WBS: 1.2.2.2.2.1.4.1	Fast Valve												
1	Modified VAT fast shutter	ea	1	26000.00	A91	26.0	0	0.0	0		0.00	0.0	26.0
** Subtotal **						26.0			0			0.0	26.0
** WBS: 1.2.2.2.2.1.4.2	Fab/Buy Electrical and Controls												
1	Cables & connectors	lot	1	500.00	A91	0.5	1	8.0	8	EI	33.00	0.3	0.8
2	Air pressure interlocks	ea	1	500.00	eu	0.5	1	16.0	16	EI	33.00	0.5	1.0
3	Junction box,IG cable	ea	3	200.00	eu	0.6	0	0.0	0		0.00	0.0	0.6
4	Interlock cable	ea	1	500.00	eu	0.5	0	0.0	0		0.00	0.0	0.5
** Subtotal **						2.1			24			0.8	2.9
** WBS: 1.2.2.2.2.1.4.3	Bellows												
1	Welded bellows assy	ea	1	3000.00	A91	3.0	1	4.0	4	MS	37.73	0.2	3.2
2	Blank flanges,gaskets,etc	lot	1	300.00	cp	0.3	0	0.0	0		0.00	0.0	0.3
3	Inspect,clean,bake	lot	1	50.00	eu	0.1	1	4.0	4	MU	35.92	0.1	0.2
** Subtotal **						3.3			8			0.3	3.6
** WBS: 1.2.2.2.2.1.4.4	Aperture Plate												
1	Water-cooled absorber	ea	1	800.00	A91	0.8	1	40.0	40	MS	37.73	1.5	2.3
2	Brazing,fixtures,tooling	lot	1	200.00	eu	0.2	1	30.0	30	MU	35.92	1.1	1.3
3	Flange gaskets & hardware	lot	2	200.00	eu	0.4	1	10.0	10	MS	37.73	0.4	0.8
** Subtotal **						1.4			80			3.0	4.4
** WBS: 1.2.2.2.2.1.4.5	Assemble, Bakeout, Test												
1	Assemble & test	ea	1	500.00	eu	0.5	1	80.0	80	MU	35.92	2.9	3.4
2	Survey/calibration		0	0.00		0.0	1	16.0	16	MU	35.92	0.6	0.6
** Subtotal **						0.5			96			3.4	3.9
** WBS: 1.2.2.2.2.1.4.6	Installation												
1	Pneumatic hardwar/cnnctns	lot	1	300.00	eu	0.3	1	16.0	16	MU	35.92	0.6	0.9
2	Mech install/test/debug	lot	1	50.00	eu	0.1	1	16.0	16	MU	35.92	0.6	0.6
3	Elec installation		0	0.00		0.0	1	16.0	16	IEL	62.85	1.0	1.0
** Subtotal **						0.3			48			2.2	2.5
** WBS: 1.2.2.2.2.1.5.1	Fab/Buy Mech Parts & Subassy's												
1	Sintered tungsten shutter	ea	1	4000.00	eu	4.0	1	40.0	40	MS	37.73	1.5	5.5
2	Shutter flange-mounting	ea	1	500.00	eu	0.5	1	40.0	40	MS	37.73	1.5	2.0
3	In-vac position stops/mon	ea	1	1500.00	eu	1.5	1	80.0	80	MS	37.73	3.0	4.5
4	Bellows/cnflat ass'y/weld	ea	1	2000.00	eu	2.0	1	20.0	20	MS	37.73	0.8	2.8
5	Pneumatic actuatr/mountng	ea	1	2000.00	eu	2.0	1	120.0	120	MS	37.73	4.5	6.5
** Subtotal **						10.0			300			11.3	21.3
** WBS: 1.2.2.2.2.1.5.2	Fab/Buy Electrical and Controls												
1	ILC & SBX	ea	1	1500.00	eu	1.5	1	16.0	16	EI	33.00	0.5	2.0
2	Cables	lot	1	200.00	eu	0.2	1	16.0	16	EI	33.00	0.5	0.7
3	Position indicators	set	1	200.00	eu	0.2	1	16.0	16	EI	33.00	0.5	0.7
4	Air solenoids	ea	1	200.00	eu	0.2	1	8.0	8	EI	33.00	0.3	0.5

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
5	Air pressure interlocks	ea	1	200.00	eu	0.2	1	16.0	16	EI	33.00	0.5	0.7
** Subtotal **						2.3			72			2.4	4.7
** WBS: 1.2.2.2.2.1.5.3	Fab/Buy Vacuum Chamber & Supports												
1	Custom vacuum chamber	ea	1	5000.00	A91	5.0	1	20.0	20	MU	35.92	0.7	5.7
2	Misc flanges & UHV hardwr	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Roughing valve	ea	2	650.00	A91	1.3	0	0.0	0		0.00	0.0	1.3
4	Mounting struts/hardware	ea	6	500.00	A91	3.0	6	8.0	48	MS	37.73	1.8	4.8
5	Support posts	ea	2	1000.00	eu	2.0	2	20.0	40	MS	37.73	1.5	3.5
** Subtotal **						12.3			108			4.0	16.3
** WBS: 1.2.2.2.2.1.5.4	Vacuum Pumping, Gauges, Controllers, P.S.												
1	Ion pump, 220 l/s	ea	1	4865.00	A91	4.9	1	4.0	4	MU	35.92	0.1	5.0
2	Ion pump controller	ea	1	2500.00	A91	2.5	1	4.0	4	EI	33.00	0.1	2.6
3	Ion pump cable, bakeable	ea	1	250.00	A91	0.2	0	0.0	0		0.00	0.0	0.2
4	IEEE-488 cable,3m cntller	ea	1	150.00	cp	0.1	0	0.0	0		0.00	0.0	0.1
5	Ion gauge & controls	ea	1	3500.00	A91	3.5	1	4.0	4	MU	35.92	0.1	3.6
6	Ion gauge cable, bakeable	ea	1	250.00	cp	0.2	1	4.0	4	EI	33.00	0.1	0.4
7	Junction box, IG cable	ea	1	200.00	eu	0.2	0	0.0	0		0.00	0.0	0.2
8	Ion gauge controller	ea	1	3500.00	cp	3.5	0	0.0	0		0.00	0.0	3.5
9	Interlock cable	ea	1	100.00	eu	0.1	0	0.0	0		0.00	0.0	0.1
** Subtotal **						15.3			16			0.6	15.9
** WBS: 1.2.2.2.2.1.5.5	Assemble, Bakeout, Test												
1	Assemble & test	lot	1	500.00	eu	0.5	2	80.0	160	MU	35.92	5.7	6.2
2	Pre-bakeout tungstn block	ea	1	300.00	eu	0.3	1	20.0	20	MU	35.92	0.7	1.0
3	Bakeout & UHV qualify	ea	1	500.00	eu	0.5	2	40.0	80	MU	35.92	2.9	3.4
3	Survey/calibration		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1
4	Misc tools,fixtures,cart,	lot	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4
** Subtotal **						2.3			332			11.9	14.2
** WBS: 1.2.2.2.2.1.5.6	Installation												
1	Transport & on-site setup	lot	1	200.00	eu	0.2	2	16.0	32	MU	35.92	1.1	1.3
2	Vac assemble & leak check	lot	1	50.00	eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
3	Instlltn algnmnt (stnd)		0	0.00		0.0	2	16.0	32	MS	37.73	1.2	1.2
4	Pneumatic hardwar/cnnctns	lot	1	300.00	eu	0.3	1	16.0	16	MU	35.92	0.6	0.9
5	Mech install,test,debug	lot	1	50.00	eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
6	Elec installation		0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
** Subtotal **						0.6			160			5.8	6.4
** WBS: 1.2.2.2.2.1.5.7	Shield Wall Transition Spool												
1	SWT spool piece	ea	1	2500.00	A91	2.5	1	4.0	4	MS	37.73	0.2	2.7
2	Misc. flanges & UHV hrdwr	lot	1	500.00	eu	0.5	1	4.0	4	MS	37.73	0.2	0.7
3	Lead shielding & supports	lot	1	500.00	eu	0.5	1	40.0	40	MS	37.73	1.5	2.0
4	Struts and hardware	lot	2	500.00	A91	1.0	2	8.0	16	MS	37.73	0.6	1.6
5	Misc extrusions, etc.	lot	1	1000.00	eu	1.0	1	40.0	40	MS	37.73	1.5	2.5
** Subtotal **						5.5			104			3.9	9.4
** WBS: 1.2.2.2.2.1.5.8	Isolation Valve												
1	Valve & controller proc	ea	1	15000.00	vq	15.0	0	0.0	0		0.00	0.0	15.0
2	Prelim assy & test	lot	1	50.00	eu	0.1	1	8.0	8	MU	35.92	0.3	0.3
3	Inspection,cleaning,etc.	lot	1	50.00	eu	0.1	1	4.0	4	MU	35.92	0.1	0.2
4	Cables & connectors	ea	1	200.00	eu	0.2	1	2.0	2	EI	33.00	0.1	0.3
5	Blank flanges & hardware	lot	2	200.00	eu	0.4	0	0.0	0		0.00	0.0	0.4
** Subtotal **						15.7			14			0.5	16.2
** WBS: 1.2.2.2.2.1.6.1	Fab/Buy Mech Parts & Subassy's												
1	Flange & mntng plate fab	ea	1	600.00	eu	0.6	1	40.0	40	MS	37.73	1.5	2.1
2	Cf feedthru for electrncs	ea	8	200.00	eu	1.6	0	0.0	0		0.00	0.0	1.6

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
3	Brazing & fixtures	ea	1	100.00	eu	0.1	1	20.0	20	MU	35.92	0.7	0.8
4	Feedthrus - welding	ea	1	50.00	eu	0.1	1	20.0	20	MS	37.73	0.8	0.8
5	Blades fab	ea	4	100.00	eu	0.4	4	20.0	80	MS	37.73	3.0	3.4
6	In-vac parts & elec fab	lot	1	200.00	eu	0.2	1	40.0	40	MS	37.73	1.5	1.7
7	LCW Hardware	lot	1	100.00	eu	0.1	1	8.0	8	MU	35.92	0.3	0.4
8	2-axis transltn mechanism	ea	1	3000.00	eu	3.0	0	0.0	0		0.00	0.0	3.0
9	Outside-vac mntng hardwre	lot	1	500.00	eu	0.5	1	20.0	20	MS	37.73	0.8	1.3
10	Blade alignment fixtures	ea	1	200.00	eu	0.2	1	20.0	20	MS	37.73	0.8	1.0
** Subtotal **						6.8			248			9.3	16.1
** WBS: 1.2.2.2.2.1.6.2	Fab/Buy Electrical and Controls												
1	Bias power supply	ea	2	3000.00	eu	6.0	2	8.0	16	EI	33.00	0.5	6.5
2	ILC & SBX	ea	3	1500.00	eu	4.5	3	20.0	60	EI	33.00	2.0	6.5
3	Electrometer	ea	4	1695.00	cp	6.8	4	8.0	32	EI	33.00	1.1	7.8
4	Eurocard crate	ea	1	1000.00	eu	1.0	1	16.0	16	EI	33.00	0.5	1.5
5	Thermocouples & controls	ea	2	500.00	eu	1.0	2	8.0	16	EI	33.00	0.5	1.5
6	Stepper motor controller	ea	1	3000.00	eu	3.0	1	16.0	16	EI	33.00	0.5	3.5
7	Cables	lot	1	1000.00	eu	1.0	1	32.0	32	EI	33.00	1.1	2.1
8	Flow switch	ea	2	400.00	eu	0.8	2	4.0	8	EI	33.00	0.3	1.1
** Subtotal **						24.1			196			6.5	30.5
** WBS: 1.2.2.2.2.1.6.3	Fab/Buy Support Stand												
1	Slides mounting hardwr	ea	1	200.00	EU	0.2	1	8.0	8	MS	37.73	0.3	0.5
2	Support post & hardware	ea	1	3000.00	eu	3.0	1	8.0	8	MS	37.73	0.3	3.3
3	Misc hardware & fixtures	ea	1	1000.00	eu	1.0	1	40.0	40	MS	37.73	1.5	2.5
** Subtotal **						4.2			56			2.1	6.3
** WBS: 1.2.2.2.2.1.6.4	Bellows												
1	Welded bellows assy	ea	2	4000.00	A91	8.0	0	0.0	0		0.00	0.0	8.0
2	Blank flanges, gaskets,	lot	2	300.00	cp	0.6	0	0.0	0		0.00	0.0	0.6
3	Inspection,cleaning,bake	lot	2	50.00	eu	0.1	2	2.0	4	MU	35.92	0.1	0.2
** Subtotal **						8.7			4			0.1	8.8
** WBS: 1.2.2.2.2.1.6.5	Assemble, Bakeout, Test												
1	Assemble/test PBPM mech	ea	1	500.00	eu	0.5	2	20.0	40	MU	35.92	1.4	1.9
2	Assemble/test PBPM elec	ea	1	500.00	eu	0.5	1	40.0	40	EI	33.00	1.3	1.8
3	Bakeout/UHV pre-qualify	ea	1	500.00	eu	0.5	1	40.0	40	MU	35.92	1.4	1.9
4	Fiducialization		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1
5	Misc assy equip,jackets,	lot	1	1000.00	eu	1.0	1	20.0	20	MU	35.92	0.7	1.7
** Subtotal **						2.5			172			6.1	8.6
** WBS: 1.2.2.2.2.1.6.6	Installation												
1	LCW Hardware & connection	lot	1	300.00	eu	0.3	2	20.0	40	MU	35.92	1.4	1.7
2	Transport & on-site setup	lot	1	200.00	eu	0.2	2	8.0	16	MU	35.92	0.6	0.8
3	Vac assemble & leak check	lot	1	100.00	eu	0.1	2	16.0	32	MU	35.92	1.1	1.2
4	Installation alignment		0	0.00		0.0	2	16.0	32	MU	35.92	1.1	1.1
5	Mech install,test,debug	lot	1	100.00	eu	0.1	2	20.0	40	MU	35.92	1.4	1.5
6	ELec. installation	lot	1	100.00	eu	0.1	1	20.0	20	IEL	62.85	1.3	1.4
7	Final bake & UHV qualify		0	0.00		0.0	2	20.0	40	MU	35.92	1.4	1.4
** Subtotal **						0.8			220			8.4	9.2
** WBS: 1.2.2.2.2.1.7.1	Fab/Buy Mech Parts & Subassy's												
1	Misc machine shop effort	lot	1	1000.00	eu	1.0	1	80.0	80	MS	37.73	3.0	4.0
2	Misc mech tech & tools	lot	1	1000.00	eu	1.0	1	80.0	80	MU	35.92	2.9	3.9
** Subtotal **						2.0			160			5.9	7.9
** WBS: 1.2.2.2.2.1.7.2	Fab/Buy Electical and Controls												
1	Cables,valve actuation &	lot	3	100.00	eu	0.3	3	8.0	24	EI	33.00	0.8	1.1
2	X-connect blocks & frame	ea	1	500.00	eu	0.5	1	40.0	40	EI	33.00	1.3	1.8

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
3	Relays blocks & frame	ea	1	580.00	cp	0.6	1	40.0	40	EI	33.00	1.3	1.9
4	48 Ch. opto-isolator	ea	1	700.00	cp	0.7	1	40.0	40	EI	33.00	1.3	2.0
5	Cable trays, conduit, etc	lot	1	2000.00	eu	2.0	1	80.0	80	IEL	62.85	5.0	7.0
6	Double elec. rack	ea	1	1300.00	eu	1.3	1	40.0	40	EI	33.00	1.3	2.6
7	BA panel 3 ph 30A	ea	1	50.00	cp	0.1	1	1.0	1	EI	33.00	0.0	0.1
8	Breaker panel	ea	2	200.00	cp	0.4	2	4.0	8	EI	33.00	0.3	0.7
9	Plug strip	ea	2	20.00	eu	0.0	2	4.0	8	EI	33.00	0.3	0.3
10	Rack fans	ea	2	50.00	eu	0.1	2	2.0	4	EI	33.00	0.1	0.2
11	Flow switches/interlocks	ea	2	400.00	eu	0.8	2	8.0	16	EI	33.00	0.5	1.3
** Subtotal **						6.8			301			12.3	19.1
** WBS: 1.2.2.2.2.1.7.3	Fab/Buy Vacuum Chamber & Supports												
1	Misc flanges,viewprts,etc	lot	1	3000.00	eu	3.0	0	0.0	0		0.00	0.0	3.0
2	Roughing valves	ea	4	650.00	cp	2.6	0	0.0	0		0.00	0.0	2.6
3	Misc. unistrut/hardware	lot	1	500.00	eu	0.5	1	20.0	20	MU	35.92	0.7	1.2
** Subtotal **						6.1			20			0.7	6.8
** WBS: 1.2.2.2.2.1.7.4	Vacuum Pumping, Gauges, Controllers, P.S.												
1	RGA system	ea	1	12000.00	cp	12.0	1	40.0	40	MU	35.92	1.4	13.4
2	RGA cable, bakeable	ea	1	250.00	cp	0.2	1	8.0	8	EI	33.00	0.3	0.5
3	Junction box, RGA cable	ea	1	200.00	eu	0.2	0	0.0	0		0.00	0.0	0.2
4	Interlock cable	ea	1	100.00	eu	0.1	0	0.0	0		0.00	0.0	0.1
** Subtotal **						12.5			48			1.7	14.3
** WBS: 1.2.2.2.2.1.7.5	Assemble, Bakeout, Test												
1	Misc assemble & test	ea	1	1000.00	eu	1.0	2	40.0	80	MU	35.92	2.9	3.9
2	Misc bakeout/UHV qualify	lot	1	1000.00	eu	1.0	2	40.0	80	MU	35.92	2.9	3.9
3	Survey/calibration		0	0.00		0.0	3	32.0	96	MU	35.92	3.4	3.4
** Subtotal **						2.0			256			9.2	11.2
** WBS: 1.2.2.2.2.1.7.6	Installation												
1	Shielding wall modify	lot	1	500.00	eu	0.5	2	40.0	80	MU	35.92	2.9	3.4
2	Lead shielding installatn	lot	1	500.00	eu	0.5	1	40.0	40	MU	35.92	1.4	1.9
3	Installatn final alignment		0	0.00		0.0	2	40.0	80	MU	35.92	2.9	2.9
4	F.E. pneumatic service	ea	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4
5	F.E. LCW service	lot	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4
6	Mech install/test/debug	lot	1	50.00	eu	0.1	1	40.0	40	MU	35.92	1.4	1.5
7	Elec installation		0	0.00		0.0	1	80.0	80	IEL	62.85	5.0	5.0
8	LCW temp control system	ea	1	5000.00	A90	5.0	1	40.0	40	EI	33.00	1.3	6.3
** Subtotal **						8.1			440			17.8	25.9
** WBS: 1.2.2.2.2.1.8	Safety Systems												
1	ILC & SBX	ea	2	1500.00	eu	3.0	2	20.0	40	EI	33.00	1.3	4.3
2	Eurocard crate	ea	2	800.00	eu	1.6	0	0.0	0		0.00	0.0	1.6
3	Key panel	ea	1	400.00	cp	0.4	0	0.0	0		0.00	0.0	0.4
4	Monitor lights panel	ea	6	500.00	cp	3.0	0	0.0	0		0.00	0.0	3.0
5	Push button panel	ea	1	500.00	cp	0.5	0	0.0	0		0.00	0.0	0.5
6	Breaker panel	ea	1	500.00	cp	0.5	0	0.0	0		0.00	0.0	0.5
7	Cables	lot	1	500.00	eu	0.5	0	0.0	0		0.00	0.0	0.5
8	Wiring assembly		0	0.00		0.0	1	120.0	120	EI	33.00	4.0	4.0
9	Video camera & lens	ea	1	800.00	cp	0.8	0	0.0	0		0.00	0.0	0.8
10	Video monitor	ea	1	300.00	cp	0.3	0	0.0	0		0.00	0.0	0.3
11	RG59 coax,camera/monitor	ea	1	50.00	eu	0.1	1	2.0	2	EI	33.00	0.1	0.1
12	Video connectors	ea	2	5.00	eu	0.0	2	0.5	1	EI	33.00	0.0	0.0
13	Misc hardware	lot	1	1000.00	eu	1.0	1	80.0	80	MS	37.73	3.0	4.0
14	Elec. installation		0	0.00		0.0	1	40.0	40	IEL	62.85	2.5	2.5
** Subtotal **						11.7			283			10.9	22.6
** WBS: 1.2.2.2.2.2.1	Horiz. & Vert. Beam Defining Apertures												
1	Fab/procure mech parts	lot	1	30000.00	eu	30.0	1	460.0	460	MS	37.73	17.4	47.4

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
2	Fab/procure elec & cntrls	lot	1	12300.00	eu	12.3	1	40.0	40	MS	37.73	1.5	13.8
3			0	0.00		0.0	1	72.0	72	EI	33.00	2.4	2.4
4	Fab/procure vac chamber	lot	1	15000.00	eu	15.0	1	128.0	128	MS	37.73	4.8	19.8
5	Vac pumpng,gages,ps,etc.	lot	1	15800.00	eu	15.8	1	16.0	16	MU	35.92	0.6	16.4
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	2000.00	eu	2.0	1	352.0	352	MU	35.92	12.6	14.6
8	Installation	lot	1	600.00	eu	0.6	1	130.0	130	MU	35.92	4.7	5.3
9			0	0.00		0.0	1	32.0	32	MS	37.73	1.2	1.2
10			0	0.00		0.0	1	16.0	16	IEL	62.85	1.0	1.0
** Subtotal **						75.7			1262			46.7	122.4
** WBS: 1.2.2.2.2.2.2	M1 Mirror												
1	Fab/procure	lot	1	32200.00	eu	32.2	1	1116.0	1116	MS	37.73	42.1	74.3
2	Fab/procure	lot	1	16700.00	eu	16.7	1	40.0	40	MS	37.73	1.5	18.2
3			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
4	Fab/procure vac chamber	lot	1	15150.00	eu	15.2	1	100.0	100	MS	37.73	3.8	18.9
5	Vac pumpng,gages,ps,etc.	lot	1	16850.00	eu	16.9	1	16.0	16	MS	37.73	0.6	17.5
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	500.00	eu	0.5	1	230.0	230	MS	37.73	8.7	9.2
8	Installation	lot	1	600.00	eu	0.6	1	100.0	100	MU	35.92	3.6	4.2
9			0	0.00		0.0	1	20.0	20	MS	37.73	0.8	0.8
10			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						82.0			1694			63.4	145.4
** WBS: 1.2.2.2.2.2.3	M2 Mirror												
1	Fab/procure mech parts	lot	1	31200.00	eu	31.2	1	816.0	816	MS	37.73	30.8	62.0
2	Fab/procure elec & cntrls	lot	1	7700.00	eu	7.7	1	40.0	40	MS	37.73	1.5	9.2
3			0	0.00		0.0	1	52.0	52	ES	33.00	1.7	1.7
4	Fab/procure vac chamber	lot	1	15350.00	eu	15.3	1	100.0	100	MS	37.73	3.8	19.1
5	Vac pumpng,gages,ps,etc.	lot	1	12750.00	eu	12.8	1	16.0	16	MS	37.73	0.6	13.4
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	500.00	eu	0.5	1	232.0	232	MS	37.73	8.8	9.3
8	Installation	lot	1	600.00	eu	0.6	1	100.0	100	MU	35.92	3.6	4.2
9			0	0.00		0.0	1	20.0	20	MS	37.73	0.8	0.8
10			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						68.1			1432			53.3	121.4
** WBS: 1.2.2.2.2.2.4	M3 Mirror												
1	Fab/procure mech parts	lot	1	15900.00	eu	15.9	1	536.0	536	MS	37.73	20.2	36.1
2	Fab/procure elect & cntrl	lot	1	4950.00	eu	5.0	1	20.0	20	MS	37.73	0.8	5.7
3			0	0.00		0.0	1	36.0	36	ES	33.00	1.2	1.2
4	Fab/procure vac chamber	lot	1	9350.00	eu	9.3	1	100.0	100	MS	37.73	3.8	13.1
5	Vac pumpng,gages,ps,etc.	lot	1	12750.00	eu	12.8	1	16.0	16	MS	37.73	0.6	13.4
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	500.00	eu	0.5	1	192.0	192	MS	37.73	7.2	7.7
8	Installation	lot	1	600.00	eu	0.6	1	100.0	100	MU	35.92	3.6	4.2
9			0	0.00		0.0	1	20.0	20	MS	37.73	0.8	0.8
10			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						44.1			1076			40.0	84.0
** WBS: 1.2.2.2.2.2.5	Monochromator (NIM)												
1	Fab/procure mech parts	lot	1	323600.00	eu	323.6	1	932.0	932	MS	37.73	35.2	358.8
2	Fab/procure elec & cntrls	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	12800.00	eu	12.8	1	480.0	480	MS	37.73	18.1	30.9
4	Vac pumpng,gages,ps,etc.	lot	1	34200.00	eu	34.2	1	32.0	32	MS	37.73	1.2	35.4
5			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	400.00	eu	0.4	1	616.0	616	MS	37.73	23.2	23.6
7	Installation	lot	1	600.00	eu	0.6	1	240.0	240	MS	37.73	9.1	9.7
8			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
9			0	0.00		0.0	1	80.0	80	MS	37.73	3.0	3.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						372.6			2436			91.6	464.2
** WBS: 1.2.2.2.2.2.6	M4 Mirror												
1	Fab/procure mech parts	lot	1	30000.00	eu	30.0	1	256.0	256	MS	37.73	9.7	39.7
2	Fab/procure	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	11350.00	eu	11.3	1	100.0	100	MS	37.73	3.8	15.1
4	Vac pumpng,gages,ps,etc.	lot	1	11600.00	eu	11.6	1	16.0	16	MS	37.73	0.6	12.2
5			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	200.00	eu	0.2	1	152.0	152	MS	37.73	5.7	5.9
7	Installation	lot	1	300.00	eu	0.3	1	60.0	60	MU	35.92	2.2	2.5
8			0	0.00		0.0	1	16.0	16	MS	37.73	0.6	0.6
** Subtotal **						54.5			616			23.1	77.5
** WBS: 1.2.2.2.2.2.7	M5 Mirror												
1	Fab/procure	lot	1	30000.00	eu	30.0	1	256.0	256	MS	37.73	9.7	39.7
2	Fab/procure	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	11350.00	eu	11.3	1	100.0	100	MS	37.73	3.8	15.1
4	Vac pumpng,gages,ps,etc.	lot	1	11600.00	eu	11.6	1	16.0	16	MS	37.73	0.6	12.2
5			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	100.00	eu	0.1	1	72.0	72	MS	37.73	2.7	2.8
7	Installation	lot	1	50.00	eu	0.1	1	16.0	16	MS	37.73	0.6	0.7
8			0	0.00		0.0	1	20.0	20	MU	35.92	0.7	0.7
** Subtotal **						54.1			496			18.6	72.7
** WBS: 1.2.2.2.2.2.8	Branch Line Diagnostics												
1	Fab/procure mech parts	lot	1	18000.00	eu	18.0	1	480.0	480	MS	37.73	18.1	36.1
2	Fab/procure vac chamber	lot	1	13200.00	eu	13.2	1	84.0	84	MS	37.73	3.2	16.4
3	Assemble,bakeout,test	lot	1	600.00	eu	0.6	1	228.0	228	MS	37.73	8.6	9.2
4	Installation	lot	1	100.00	eu	0.1	1	84.0	84	MU	35.92	3.0	3.1
** Subtotal **						31.9			876			32.9	64.8
** WBS: 1.2.2.2.2.2.9	Vacuum System: Controls & Installation												
1	Fab/procure mech parts	lot	1	17500.00	eu	17.5	1	100.0	100	MU	35.92	3.6	21.1
2			0	0.00		0.0	1	52.0	52	MS	37.73	2.0	2.0
3	Fab/procure elec & cntrls	lot	1	48790.00	eu	48.8	1	120.0	120	EM	33.00	4.0	52.8
4			0	0.00		0.0	1	162.0	162	ES	33.00	5.3	5.3
5			0	0.00		0.0	1	120.0	120	CP	59.40	7.1	7.1
6			0	0.00		0.0	1	60.0	60	EI	33.00	2.0	2.0
7	Fab/procure vac chamber	lot	1	45150.00	eu	45.1	1	288.0	288	MS	37.73	10.9	56.0
8	Vac pumpng,gages,ps,etc.	lot	1	11850.00	eu	11.8	1	16.0	16	MS	37.73	0.6	12.5
9			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
10	Assemble,bakeout,test	lot	1	300.00	eu	0.3	1	168.0	168	MS	37.73	6.3	6.6
11	Installation	lot	1	4200.00	eu	4.2	1	340.0	340	MU	35.92	12.2	16.4
12			0	0.00		0.0	1	48.0	48	MS	37.73	1.8	1.8
13			0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
14			0	0.00		0.0	1	120.0	120	ES	33.00	4.0	4.0
** Subtotal **						127.8			1650			62.7	190.5
** WBS: 1.2.2.2.2.2.10	Branch Line Safety Systems												
1	Branch Line Safety System	lot	1	6900.00	eu	6.9	1	80.0	80	ES	33.00	2.6	9.5
2			0	0.00		0.0	1	80.0	80	EM	33.00	2.6	2.6
** Subtotal **						6.9			160			5.3	12.2
** WBS: 1.2.2.2.2.2.11	Harmonic Suppression & Optical Filters												
1	Fab/procure mech parts	lot	1	23000.00	eu	23.0	1	160.0	160	MS	37.73	6.0	29.0
2	Fab/procure vac chamber	lot	1	26850.00	lot	26.9	1	100.0	100	MS	37.73	3.8	30.6
3	Vac pumpng,gages,ps,etc.	lot	1	63700.00	eu	63.7	1	56.0	56	MS	37.73	2.1	65.8
4			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
5	Assemble,bakeout,test	lot	1	400.00	eu	0.4	1	288.0	288	MS	37.73	10.9	11.3
6	Installation	lot	1	300.00	eu	0.3	1	120.0	120	MU	35.92	4.3	4.6

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST	BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
7			0	0.00		0.0	1	40.0	40	MS	37.73	1.5	1.5
8			0	0.00		0.0	1	60.0	60	ES	33.00	2.0	2.0
** Subtotal **						114.3			840			31.1	145.4
** WBS: 1.2.2.2.2.2.12	Secondary Branchline												
1	Sec. Branchline Allowance	lot	1	250000.00		250.0	0	0.0	0		0.00	0.0	250.0
** Subtotal **						250.0			0			0.0	250.0
** WBS: 1.2.2.2.3.1.1	Aperture Assemblies 1 & 2												
1	Parts fabrication	ea	2	350.00	eu	0.7	2	40.0	80	MS	37.73	3.0	3.7
2	Inspection	LOT	2	25.00	EU	0.1	2	4.0	8	MS	37.73	0.3	0.4
3	Cleaning	lot	2	25.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.3
4	Brazing,fixturing,tooling	ea	2	200.00	eu	0.4	2	40.0	80	MU	35.92	2.9	3.3
5	Vac & water leak check	ea	1	25.00	eu	0.0	2	6.0	12	MU	35.92	0.4	0.5
6	Misc flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3
** Subtotal **						2.2			196			7.2	9.4
** WBS: 1.2.2.2.3.1.2	Bellows 1 & 2												
1	Welded capsule & flanges	ea	2	2500.00	cp	5.0	0	0.0	0		0.00	0.0	5.0
2	Inspection	ea	2	25.00	eu	0.1	2	4.0	8	MS	37.73	0.3	0.4
3	Cleaninig	ea	2	25.00	eu	0.1	2	2.0	4	MU	35.92	0.1	0.2
4	Vac furnace bakeout	ea	2	100.00	eu	0.2	2	6.0	12	MU	35.92	0.4	0.6
5	Leak check	ea	2	25.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.3
6	Misc flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3
** Subtotal **						6.3			40			1.5	7.8
** WBS: 1.2.2.2.3.1.3	Isolation Valves 1 & 2												
1	DN160, 24 volt,w/solenoid	ea	2	16450.00	A91	32.9	0	0.0	0		0.00	0.0	32.9
2	Leak check	ea	2	25.00	eu	0.1	2	4.0	8	MS	37.73	0.3	0.4
3	Inspection & cleaning	ea	2	50.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.4
4	Test & qualify	ea	2	50.00	eu	0.1	2	4.0	8	MU	35.92	0.3	0.4
5	Cables & connectors	ea	2	200.00	eu	0.4	2	4.0	8	EI	33.00	0.3	0.7
6	Misc. flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3
** Subtotal **						34.5			40			1.4	36.0
** WBS: 1.2.2.2.3.1.4	Photon Shutter												
1	Vacuum vessel	ea	1	3300.00	A91	3.3	0	0.0	0		0.00	0.0	3.3
2	Vessel inspection	ea	1	25.00	eu	0.0	1	6.0	6	MS	37.73	0.2	0.3
3	Vessel leak check	ea	1	25.00	eu	0.0	1	4.0	4	MU	35.92	0.1	0.2
4	Bellows	ea	1	2535.00	A91	2.5	0	0.0	0		0.00	0.0	2.5
5	Bellows inspection	ea	1	25.00	eu	0.0	1	2.0	2	MS	37.73	0.1	0.1
6	Bellows cleaning	ea	1	25.00	eu	0.0	1	2.0	2	MU	35.92	0.1	0.1
7	Bellows furnace bakeout	ea	1	25.00	eu	0.0	1	6.0	6	MU	35.92	0.2	0.2
8	Bellows leak check	ea	1	25.00	eu	0.0	1	3.0	3	MU	35.92	0.1	0.1
9	Linear actuator	ea	1	1860.00	A91	1.9	0	0.0	0		0.00	0.0	1.9
10	Actuator Inspection	ea	1	25.00	eu	0.0	1	1.0	1	MS	37.73	0.0	0.1
11	Electro-pneumatic solenoi	ea	1	53.00	A91	0.1	0	0.0	0		0.00	0.0	0.1
12	Thermal absorber fab	ea	1	1724.00	A91	1.7	0	0.0	0		0.00	0.0	1.7
13	Absorber inspection	ea	1	25.00	eu	0.0	1	2.0	2	MS	37.73	0.1	0.1
14	Absorber cleaning &brazng	ea	1	200.00	eu	0.2	1	32.0	32	MU	35.92	1.1	1.3
15	Absorber welding	ea	1	25.00	eu	0.0	1	12.0	12	MU	35.92	0.4	0.5
16	Vac & water leak check	ea	1	25.00	eu	0.0	1	6.0	6	MU	35.92	0.2	0.2
17	Bellows drive plate	ea	1	120.00	A91	0.1	1	24.0	24	NC	56.50	1.4	1.5
18	Misc part fab	lot	1	400.00	eu	0.4	1	60.0	60	MS	37.73	2.3	2.7
19	Actuator support fab	ea	2	200.00	eu	0.4	1	18.0	18	MS	37.73	0.7	1.1
20	Actuator assy & alignment	ea	1	24.00	eu	0.0	1	16.0	16	MU	35.92	0.6	0.6
21	Bakeout & UHV qualify	ea	1	100.00	eu	0.1	1	80.0	80	MU	35.92	2.9	3.0
22	Photon shutter leak check	ea	1	25.00	eu	0.0	1	8.0	8	MU	35.92	0.3	0.3
23	Misc.	lot	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						12.0			322			12.2	24.2
** WBS: 1.2.2.2.3.1.5	Vacuum Systems												
1	TSP-vacuum vessel	ea	1	2620.00	A91	2.6	0	0.0	0		0.00	0.0	2.6
2	Vessel inspection	ea	1	25.00	eu	0.0	1	6.0	6	MS	37.73	0.2	0.3
3	Vessel leak check	ea	1	25.00	eu1	0.0	1	8.0	8	MU	35.92	0.3	0.3
4	TSP filament	ea	1	650.00	A91	0.7	0	0.0	0		0.00	0.0	0.7
5	TSP power supply	ea	1	1950.00	cp	1.9	0	0.0	0		0.00	0.0	1.9
6	TSP cartridge cable	ea	1	500.00	eu	0.5	0	0.0	0		0.00	0.0	0.5
7	TSP Extr. fab,clean,instl	ea	1	585.00	eu	0.6	1	40.0	40	MU	35.92	1.4	2.0
8	Ion pumps, 220 l/s	ea	1	4865.00	A91	4.9	1	8.0	8	MS	37.73	0.3	5.2
9	Ion pump controller	ea	1	2500.00	A91	2.5	1	8.0	8	EI	33.00	0.3	2.8
10	Ion pump cable, bakeable	ea	1	250.00	cp	0.2	1	8.0	8	EI	33.00	0.3	0.5
11	IEEE-488 cable, pump ctrl	ea	1	100.00	A91	0.1	0	0.0	0		0.00	0.0	0.1
12	Ion gauge	ea	1	400.00	cp	0.4	1	8.0	8	MU	35.92	0.3	0.7
13	Ion gauge cable, bakeable	ea	1	100.00	A91	0.1	1	8.0	8	EI	33.00	0.3	0.4
14	Junction box, IG cable	ea	1	200.00	eu	0.2	0	0.0	0		0.00	0.0	0.2
15	Ion gauge controller	ea	1	2700.00	A91	2.7	1	4.0	4	EI	33.00	0.1	2.8
16	Interlock cable	ea	1	100.00	eu	0.1	1	4.0	4	EI	33.00	0.1	0.2
** Subtotal **						17.6			102			3.6	21.2
** WBS: 1.2.2.2.3.1.6	Photon Shutter Support System												
1	Tri-frame weldment	ea	1	700.00	eu	0.7	1	60.0	60	MS	37.73	2.3	3.0
2	Assy frame weldment	ea	1	700.00	eu	0.7	1	60.0	60	MS	37.73	2.3	3.0
3	Inspection & painting	ea	2	150.00	eu	0.3	2	8.0	16	MS	37.73	0.6	0.9
4	Parker clevises	ea	6	25.00	cp	0.1	0	0.0	0		0.00	0.0	0.1
5	Hex stand-offs	ea	6	10.00	eu	0.1	6	2.0	12	MU	35.92	0.4	0.5
6	Strut assemblies	ea	6	500.00	eu	3.0	6	9.0	54	MS	37.73	2.0	5.0
7	Hilti stud assemblies	ea	6	25.00	eu	0.1	6	2.0	12	MS	37.73	0.5	0.6
8	Support table	ea	1	150.00	eu	0.1	1	8.0	8	MS	37.73	0.3	0.5
9	Ion pump supports	ea	2	15.00	eu	0.0	2	8.0	16	MS	37.73	0.6	0.6
10	IV #2 supports	ea	2	15.00	eu	0.0	2	8.0	16	MS	37.73	0.6	0.6
11	Fast shutter supports	ea	2	15.00	eu	0.0	2	8.0	16	MS	37.73	0.6	0.6
12	Installation & grouting	ea	6	25.00	eu	0.1	6	2.0	12	MS	37.73	0.5	0.6
13	Onsite floor prep	ea	6	25.00	eu	0.1	6	2.0	12	MU	35.92	0.4	0.6
14	Transport & onsite setup	ea	1	200.00	eu	0.2	1	20.0	20	MU	35.92	0.7	0.9
** Subtotal **						5.8			314			11.8	17.6
** WBS: 1.2.2.2.3.1.7	Fast Shutter												
1	DN160, 25x150 aperture	ea	1	16540.00	A91	16.5	0	0.0	0		0.00	0.0	16.5
2	High vacuum sensors	ea	2	1050.00	A91	2.1	0	0.0	0		0.00	0.0	2.1
3	HV sensor modules	ea	2	2607.00	A91	5.2	0	0.0	0		0.00	0.0	5.2
4	Controller rack unit	ea	1	2552.00	A91	2.6	0	0.0	0		0.00	0.0	2.6
5	Control module	ea	1	588.00	A91	0.6	0	0.0	0		0.00	0.0	0.6
7	Remote module	ea	1	1229.00	A91	1.2	0	0.0	0		0.00	0.0	1.2
8	Sense to control cable	ea	2	703.00	A91	1.4	0	0.0	0		0.00	0.0	1.4
9	Control to shutter cable	ea	1	447.00	A91	0.4	0	0.0	0		0.00	0.0	0.4
10	Shutter inspection	ea	1	25.00	eu	0.0	1	4.0	4	MS	37.73	0.2	0.2
11	Shutter leak check	ea	1	24.00	eu	0.0	1	12.0	12	MU	35.92	0.4	0.5
12	Misc flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3
14	Cables install	lot	1	500.00	eu	0.5	1	16.0	16	IEL	62.85	1.0	1.5
14	Cables terminate		0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
** Subtotal **						31.6			56			2.4	34.0
** WBS: 1.2.2.2.3.1.8	Collimation Spool												
1	Vacuum vessel	ea	1	1250.00	A91	1.2	0	0.0	0		0.00	0.0	1.2
2	Vessel inspection	ea	1	25.00	eu	0.0	1	4.0	4	MS	37.73	0.2	0.2
3	Vessel leak check	ea	1	25.00	eu	0.0	1	12.0	12	MU	35.92	0.4	0.5
4	Lead shielding assy	lot	1	1000.00	eu	1.0	1	40.0	40	MU	35.92	1.4	2.4
5	Misc flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						3.3			64			2.3	5.6
** WBS: 1.2.2.2.3.1.9	Cleaning, Assemble, Bakeout & Test												
1	Cleaning, assemble, &test	ea	1	200.00	eu	0.2	1	80.0	80	MU	35.92	2.9	3.1
2	Bakeout & UHV qualify	ea	1	200.00	eu	0.2	1	120.0	120	MU	35.92	4.3	4.5
3	Survey/calibration	ea	1	200.00	eu	0.2	1	32.0	32	MU	35.92	1.1	1.3
4	Misc. flanges & hardware	lot	1	500.00	eu	0.5	1	4.0	4	MU	35.92	0.1	0.6
5	Misc. fixtures & tools	lot	1	500.00	eu	0.5	1	20.0	20	MU	35.92	0.7	1.2
** Subtotal **						1.6			256			9.2	10.8
** WBS: 1.2.2.2.3.1.10	Installation												
1	Pneumatic service	ea	1	2000.00	eu	2.0	1	40.0	40	MU	35.92	1.4	3.4
2	LCW service	ea	1	2000.00	eu	2.0	1	40.0	40	MU	35.92	1.4	3.4
3	Transport & onsite setup	ea	1	200.00	eu	0.2	1	20.0	20	MU	35.92	0.7	0.9
4	Vac assemble & leak check	ea	1	50.00	eu	0.1	1	20.0	20	MU	35.92	0.7	0.8
5	Installation alignment	ea	1	100.00	eu	0.1	1	20.0	20	MS	37.73	0.8	0.9
6	Pneumatic hardware&connec	ea	1	300.00	eu	0.3	1	16.0	16	MU	35.92	0.6	0.9
7	Mech instll,test	lot	1	200.00	eu	0.2	1	80.0	80	MU	35.92	2.9	3.1
8	Elec install,test	lot	1	200.00	eu	0.2	1	40.0	40	IEL	62.85	2.5	2.7
9	" "		0	0.00		0.0	1	20.0	20	EI	33.00	0.7	0.7
** Subtotal **						5.0			296			11.7	16.7
** WBS: 1.2.2.2.3.1.11	Misc. Mechanical, Electrical & Controls												
1	Cables,valve actuation &	lot	3	100.00	eu	0.3	3	4.0	12	EI	33.00	0.4	0.7
2	X-connect blocks & frame	ea	1	500.00	eu	0.5	1	24.0	24	EI	33.00	0.8	1.3
3	Relays blocks & frame	ea	1	580.00	cp	0.6	1	24.0	24	EI	33.00	0.8	1.4
4	48 channel opto-isolator	ea	1	700.00	cp	0.7	1	24.0	24	EI	33.00	0.8	1.5
5	Cable trays, conduit, etc	lot	1	1000.00	eu	1.0	1	120.0	120	IEL	62.85	7.5	8.5
6	Double elec. rack	ea	1	1300.00	cp	1.3	1	16.0	16	EI	33.00	0.5	1.8
7	BA panel 3 ph 30A	ea	1	50.00	cp	0.1	1	1.0	1	EI	33.00	0.0	0.1
8	Breaker panel	ea	2	200.00	cp	0.4	2	2.0	4	EI	33.00	0.1	0.5
9	Plug strip	ea	2	20.00	eu	0.0	2	2.0	4	EI	33.00	0.1	0.2
10	Rack fans	ea	2	50.00	cp	0.1	2	2.0	4	EI	33.00	0.1	0.2
11	Flow switches/interlocks	ea	2	400.00	eu	0.8	4	8.0	32	EI	33.00	1.1	1.9
12	Custom bakeout jackets	ea	6	1200.00	EU	7.2	6	4.0	24	MU	35.92	0.9	8.1
13	Other bakeout heaters	ea	6	200.00	eu	1.2	6	4.0	24	MU	35.92	0.9	2.1
14	Misc electrical	lot	1	1000.00	eu	1.0	1	80.0	80	EI	33.00	2.6	3.6
15	Misc. hardware & locks	lot	1	1000.00	eu	1.0	1	80.0	80	MS	37.73	3.0	4.0
16	Electrical installation		0	0.00		0.0	1	40.0	40	IEL	62.85	2.5	2.5
17	Misc. machine shop effort	lot	1	1000.00	eu	1.0	1	160.0	160	MS	37.73	6.0	7.0
18	Misc mech tech & tools	lot	1	2000.00	eu	2.0	1	160.0	160	MU	35.92	5.7	7.7
** Subtotal **						19.2			833			34.0	53.2
** WBS: 1.2.2.2.3.1.12	Safety Systems												
1	ILC & SBX	ea	3	1500.00	eu	4.5	3	20.0	60	EI	33.00	2.0	6.5
2	Air pressure interlocks	ea	2	500.00	eu	1.0	2	16.0	32	EI	33.00	1.1	2.1
3	Eurocard crate	ea	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
4	Key panel	ea	1	300.00	eu	0.3	0	0.0	0		0.00	0.0	0.3
5	Monitor lights panel	ea	6	250.00	cp	1.5	0	0.0	0		0.00	0.0	1.5
6	Push button panel	ea	1	250.00	cp	0.2	0	0.0	0		0.00	0.0	0.2
7	Breaker panel	ea	1	250.00	eu	0.2	0	0.0	0		0.00	0.0	0.2
8	Fast shutter cable assy	ea	1	1000.00	eu	1.0	1	40.0	40	EI	33.00	1.3	2.3
9	Wiring assembly	ea	1	25.00	eu	0.0	1	80.0	80	EI	33.00	2.6	2.7
** Subtotal **						9.8			212			7.0	16.8
** WBS: 1.2.2.2.3.1.13	Shield Wall Transition Assembly												
1	SWT vessel fab	ea	1	1200.00	eu	1.2	1	32.0	32	MS	37.73	1.2	2.4
2	SWT inspection	ea	1	25.00	eu	0.0	1	4.0	4	MS	37.73	0.2	0.2
3	SWT leak check	ea	1	25.00	eu	0.0	1	4.0	4	MU	35.92	0.1	0.2
4	SWT supports	ea	2	500.00	eu	1.0	2	8.0	16	MU	35.92	0.6	1.6
5	Shield wall mods	lot	1	250.00	eu	0.2	1	40.0	40	MU	35.92	1.4	1.7

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
6	Lead shielding	lot	1	100.00	eu	0.1	1	10.0	10	MU	35.92	0.4	0.5
7	Misc flanges & hardware	lot	1	1000.00	eu	1.0	1	8.0	8	MU	35.92	0.3	1.3
8	Isolation Valve	ea	1	12100.00	eu	12.1	1	44.0	44	MU	35.92	1.6	13.7
9	Valve supports	ea	1	5100.00	eu	5.1	1	244.0	244	MS	37.73	9.2	14.3
10	Assemble & Install	lot	1	1600.00	eu	1.6	1	256.0	256	MU	35.92	9.2	10.8
** Subtotal **						22.4			658			24.1	46.5
** WBS: 1.2.2.2.3.2.1	M1 Mirror												
1	Fab/procure mech parts	lot	1	30000.00	eu	30.0	1	256.0	256	MS	37.73	9.7	39.7
2	Fab/procure elec & cntrls	lot	1	7300.00	eu	7.3	1	40.0	40	MS	37.73	1.5	8.8
3			0	0.00		0.0	1	48.0	48	ES	33.00	1.6	1.6
4	Fab/procure vac chamber	lot	1	16250.00	eu	16.2	1	100.0	100	MS	37.73	3.8	20.0
5	Vac pumpng,gages,ps,etc.	lot	1	13850.00	eu	13.8	1	16.0	16	MS	37.73	0.6	14.5
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	216.0	216	MS	37.73	8.1	9.1
8	Installation	lot	1	600.00	eu	0.6	1	100.0	100	MU	35.92	3.6	4.2
9			0	0.00		0.0	1	20.0	20	MS	37.73	0.8	0.8
10			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						69.0			852			31.5	100.5
** WBS: 1.2.2.2.3.2.2	M2 Mirror												
1	Fab/procure mech parts	lot	1	18700.00	eu	18.7	1	456.0	456	MS	37.73	17.2	35.9
2	Fab/procure elec & cntrls	lot	1	7300.00	eu	7.3	1	40.0	40	MS	37.73	1.5	8.8
3			0	0.00		0.0	1	48.0	48	ES	33.00	1.6	1.6
4	Fab/procure vac chamber	lot	1	16250.00	eu	16.2	1	100.0	100	MS	37.73	3.8	20.0
5	Vac pumpng,gages,ps,etc.	lot	1	13850.00	eu	13.8	1	16.0	16	MS	37.73	0.6	14.5
6			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
7	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	216.0	216	MS	37.73	8.1	9.1
8	Installation	lot	1	600.00	eu	0.6	1	100.0	100	MU	35.92	3.6	4.2
9			0	0.00		0.0	1	20.0	20	MS	37.73	0.8	0.8
10			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						57.7			1052			39.0	96.7
** WBS: 1.2.2.2.3.2.3	M3 Mirror												
1	Fab/procure mech parts	lot	1	15100.00	eu	15.1	1	256.0	256	MS	37.73	9.7	24.8
2	Fab/procure	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	11350.00	eu	11.3	1	100.0	100	MS	37.73	3.8	15.1
4	Vac pumpng,gages,ps,etc.	lot	1	11600.00	eu	11.6	1	16.0	16	MS	37.73	0.6	12.2
5			0	0.00		0.0	1	16.0	16	EI	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	152.0	152	MS	37.73	5.7	6.7
7	Installation	lot	1	1200.00	eu	1.2	1	60.0	60	MU	35.92	2.2	3.4
8			0	0.00		0.0	1	16.0	16	MS	37.73	0.6	0.6
9			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
** Subtotal **						41.3			632			23.6	64.8
** WBS: 1.2.2.2.3.2.4	Monochromator (NIM)												
1	Fab/procure mech parts	lot	1	314500.00	vq	314.5	1	240.0	240	MS	37.73	9.1	323.6
2	Fab/procure elec & cntrls	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	13000.00	eu	13.0	1	330.0	330	MS	37.73	12.5	25.5
4	Vac pumpng,gages,ps,etc.	lot	1	28950.00	eu	28.9	1	24.0	24	MS	37.73	0.9	29.9
5			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	2000.00	eu	2.0	1	616.0	616	MS	37.73	23.2	25.2
7	Installation	lot	1	75.00	eu	0.1	1	200.0	200	MU	35.92	7.2	7.3
8			0	0.00		0.0	1	80.0	80	MS	37.73	3.0	3.0
9			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						359.5			1546			57.7	417.2
** WBS: 1.2.2.2.3.2.5	M4 Mirror												
1	Fab/procure mech parts	lot	1	30000.00	eu	30.0	1	256.0	256	MS	37.73	9.7	39.7
2	Fab/procure elec & cntrls	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	13350.00	eu	13.3	1	100.0	100	MS	37.73	3.8	17.1

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
4	Vac pumpng,gages,ps,etc.	lot	1	11600.00	eu	11.6	1	16.0	16	MS	37.73	0.6	12.2
5			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	152.0	152	MS	37.73	5.7	6.7
7	Installation	lot	1	75.00	eu	0.1	1	60.0	60	MU	35.92	2.2	2.2
8			0	0.00		0.0	1	16.0	16	MS	37.73	0.6	0.6
9			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
** Subtotal **						57.0			632			23.6	80.6
** WBS: 1.2.2.2.3.2.6	M5 Mirror												
1	Fab/procure mech parts	lot	1	30000.00	eu	30.0	1	256.0	256	MS	37.73	9.7	39.7
2	Fab/procure elec & cntrls	lot	1	1000.00	eu	1.0	0	0.0	0		0.00	0.0	1.0
3	Fab/procure vac chamber	lot	1	13350.00	eu	13.3	1	100.0	100	MS	37.73	3.8	17.1
4	Vac pumpng,gages,ps,etc.	lot	1	11600.00	eu	11.6	1	16.0	16	MS	37.73	0.6	12.2
5			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
6	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	152.0	152	MS	37.73	5.7	6.7
7	Installation	lot	1	75.00	eu	0.1	1	60.0	60	MU	35.92	2.2	2.2
8			0	0.00		0.0	1	16.0	16	MS	37.73	0.6	0.6
9			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
** Subtotal **						57.0			632			23.6	80.6
** WBS: 1.2.2.2.3.2.7	Branch Line Diagnostics												
1	Fab/procure mech parts	lot	1	15000.00	eu	15.0	1	480.0	480	MS	37.73	18.1	33.1
2	Fab/procure vac chamber	lot	1	13500.00	eu	13.5	1	84.0	84	MS	37.73	3.2	16.7
3	Assemble,bakeout,test	lot	1	3000.00	eu	3.0	1	228.0	228	MS	37.73	8.6	11.6
4	Installation	lot	1	100.00	eu	0.1	1	84.0	84	MU	35.92	3.0	3.1
** Subtotal **						31.6			876			32.9	64.5
** WBS: 1.2.2.2.3.2.8	Vacuum System: Controls & Installation												
1	Fab/procure mech parts	lot	1	20000.00	eu	20.0	1	52.0	52	MS	37.73	2.0	22.0
2			0	0.00		0.0	1	100.0	100	MU	35.92	3.6	3.6
3	Fab/procure elec & cntrls	lot	1	48790.00	eu	48.8	1	120.0	120	EM	33.00	4.0	52.8
4			0	0.00		0.0	1	162.0	162	ES	33.00	5.3	5.3
5			0	0.00		0.0	1	120.0	120	CP	59.40	7.1	7.1
6			0	0.00		0.0	1	60.0	60	EI	33.00	2.0	2.0
7	Fab/procure vac chamber	lot	1	45150.00	eu	45.1	1	288.0	288	MS	37.73	10.9	56.0
8	Vac pumpng,gages,ps,etc.	lot	1	11850.00	eu	11.8	1	16.0	16	MS	37.73	0.6	12.5
9			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
10	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	168.0	168	MS	37.73	6.3	7.3
11	Installation	lot	1	4650.00	eu	4.7	1	340.0	340	MU	35.92	12.2	16.9
12			0	0.00		0.0	1	48.0	48	MS	37.73	1.8	1.8
13			0	0.00		0.0	1	120.0	120	ES	33.00	4.0	4.0
14			0	0.00		0.0	1	40.0	40	CP	59.40	2.4	2.4
** Subtotal **						131.4			1650			62.7	194.1
** WBS: 1.2.2.2.3.2.9	Branch Line Safety Systems												
1	Branch Line Safety System	lot	1	7400.00	eu	7.4	1	80.0	80	ES	33.00	2.6	10.0
2			0	0.00		0.0	1	80.0	80	EM	33.00	2.6	2.6
** Subtotal **						7.4			160			5.3	12.7
** WBS: 1.2.2.2.3.2.10	Differential Pumping Sys, Optical Filters												
1	Fab/procure mech parts	lot	1	23000.00	eu	23.0	1	160.0	160	MS	37.73	6.0	29.0
2	Fab/procure vac chamber	lot	1	26850.00	eu	26.9	1	100.0	100	MS	37.73	3.8	30.6
3	Vac pumpng,gages,ps,etc.	lot	1	63700.00	eu	63.7	1	56.0	56	MS	37.73	2.1	65.8
4			0	0.00		0.0	1	16.0	16	ES	33.00	0.5	0.5
5	Assemble,bakeout,test	lot	1	1000.00	eu	1.0	1	288.0	288	MS	37.73	10.9	11.9
6	Installation	lot	1	1200.00	eu	1.2	1	120.0	120	MU	35.92	4.3	5.5
7			0	0.00		0.0	1	40.0	40	MS	37.73	1.5	1.5
8			0	0.00		0.0	1	40.0	40	ES	33.00	1.3	1.3
** Subtotal **						115.8			820			30.5	146.2

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.3.1.1.1	Vacuum Chamber												
1	Main scattering chamber	ea	1	21238.00	eu	21.2	25	40.0	1000	ME	59.40	59.4	80.6
2	Differential pumpng stage	ea	1	2123.80	eu	2.1	1	208.0	208	MA	38.60	8.0	10.2
3	Source tee	ea	2	212.38	eu	0.4	1	302.0	302	MA	38.60	11.7	12.1
4	Source reducer	ea	2	106.19	eu	0.2	1	98.0	98	MA	38.60	3.8	4.0
5	Cold shield	ea	1	212.38	eu	0.2	1	74.0	74	MA	38.60	2.9	3.1
6	10" spools	ea	2	106.19	eu	0.2	1	74.0	74	MA	38.60	2.9	3.1
7	4" spools	ea	2	106.19	eu	0.2	1	46.0	46	MA	38.60	1.8	2.0
8	Chamber stand	ea	1	318.57	eu	0.3	1	70.0	70	MA	38.60	2.7	3.0
9	Foreline manifold	ea	1	3185.70	eu	3.2	1	40.0	40	MA	38.60	1.5	4.7
10	Rotating chmbr & bearing	ea	1	10619.00	eu	10.6	1	780.0	780	MA	38.60	30.1	40.7
11	Rotating chamber insert	ea	1	1061.90	eu	1.1	1	235.0	235	MA	38.60	9.1	10.1
12	Gas handling manifold	ea	1	2123.80	eu	2.1	1	40.0	40	MA	38.60	1.5	3.7
13	Water cooling manifold	ea	1	1592.85	eu	1.6	1	40.0	40	MA	38.60	1.5	3.1
14	Pneumatic 10" gate valve	ea	4	5309.50	cp	21.2	0	0.0	0		0.00	0.0	21.2
15	Cryogenic refrigerator	ea	1	302641.50	cp	302.6	0	0.0	0		0.00	0.0	302.6
16	Cryogenic manifold	ea	1	10619.00	eu	10.6	4	40.0	160	ME	59.40	9.5	20.1
17	10" diffusion pump	ea	4	3504.27	cp	14.0	0	0.0	0		0.00	0.0	14.0
18	4" diffusion pump	ea	2	1699.04	cp	3.4	0	0.0	0		0.00	0.0	3.4
19	Diffusion pump controllrs	ea	6	2123.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
20	Roughing valve, bellows	ea	12	318.57	cp	3.8	0	0.0	0		0.00	0.0	3.8
21	Misc. hardware	lot	1	21238.00	eu	21.2	0	0.0	0		0.00	0.0	21.2
22	4" gate valve	ea	2	1274.28	cp	2.5	0	0.0	0		0.00	0.0	2.5
23	Liquid nitrogen feeder	ea	3	1061.90	cp	3.2	0	0.0	0		0.00	0.0	3.2
24	LN sensing unit	ea	3	318.57	eu	1.0	0	0.0	0		0.00	0.0	1.0
25	PUlsed beam source/driver	ea	2	3716.65	cp	7.4	0	0.0	0		0.00	0.0	7.4
26	Skimmer	ea	3	318.57	cp	1.0	0	0.0	0		0.00	0.0	1.0
** Subtotal **						448.3			3167			146.4	594.7
** WBS: 1.2.2.3.1.1.2	Detector Systems												
1	Turbo pump, 400 l/s	ea	3	16140.88	cp	48.4	0	0.0	0		0.00	0.0	48.4
2	2" diffstak pump	ea	1	1592.85	cp	1.6	0	0.0	0		0.00	0.0	1.6
3	Pneumatic gate valve	ea	3	1061.90	cp	3.2	0	0.0	0		0.00	0.0	3.2
4	Cryogenic panel	ea	1	530.95	eu	0.5	1	40.0	40	ME	59.40	2.4	2.9
5	Filament power supply	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
6	High voltage power supply	ea	4	1061.90	cp	4.2	0	0.0	0		0.00	0.0	4.2
7	40 kV power supply	ea	1	1592.85	eu	1.6	0	0.0	0		0.00	0.0	1.6
9	PM power supply	ea	1	1061.90	cp	1.1	0	0.0	0		0.00	0.0	1.1
9	Quadrupole mass analyzer	ea	1	33980.80	cp	34.0	0	0.0	0		0.00	0.0	34.0
10	CAMAC crate	ea	1	3929.03	cp	3.9	0	0.0	0		0.00	0.0	3.9
11	Multi-channel scalar	ea	1	8495.20	cp	8.5	0	0.0	0		0.00	0.0	8.5
12	Count rate meter	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
13	Low noise amplifier	ea	1	2336.18	cp	2.3	0	0.0	0		0.00	0.0	2.3
14	Discriminator	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
15	100 MHz oscilloscope	ea	1	2336.18	cp	2.3	0	0.0	0		0.00	0.0	2.3
16	Pulse delay generator	ea	4	4778.55	cp	19.1	0	0.0	0		0.00	0.0	19.1
17	Computer work station	ea	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
18	CAMAC crate controller	ea	1	6052.83	cp	6.1	0	0.0	0		0.00	0.0	6.1
19	Programmable A/D convrter	ea	1	1805.23	cp	1.8	0	0.0	0		0.00	0.0	1.8
20	D/A converter	ea	1	743.33	cp	0.7	0	0.0	0		0.00	0.0	0.7
21	Computer interface/CAMAC	ea	1	637.14	cp	0.6	0	0.0	0		0.00	0.0	0.6
22	Stepping motor cntrllr/ps	ea	1	3716.65	cp	3.7	0	0.0	0		0.00	0.0	3.7
23	NIM to CAMAC adaptor	ea	1	424.76	cp	0.4	0	0.0	0		0.00	0.0	0.4
24	Misc. hardware	lot	1	6371.40	eu	6.4	0	0.0	0		0.00	0.0	6.4
25	Equipment racks	ea	4	1274.28	eu	5.1	1	40.0	40	EI	33.00	1.3	6.4
** Subtotal **						174.8			80			3.7	178.5
** WBS: 1.2.2.3.1.1.3	Lasers												
1	Excimer laser	ea	1	61590.20	cp	61.6	0	0.0	0		0.00	0.0	61.6
2	CO2 laser, TEA	ea	1	63714.00	cp	63.7	0	0.0	0		0.00	0.0	63.7
3	Laser table	ea	2	8919.96	cp	17.8	0	0.0	0		0.00	0.0	17.8
4	Optics and mounts	lot	1	4247.60	eu	4.2	0	0.0	0		0.00	0.0	4.2
5	Power meter & read out	ea	1	3185.70	cp	3.2	0	0.0	0		0.00	0.0	3.2

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **						150.6			0			0.0	150.6
** WBS: 1.2.2.3.1.1.4	Installation												
1	Installation engineer		0	0.00		0.0	22	40.0	880	ME	59.40	52.3	52.3
2	Installation technician		0	0.00		0.0	30	40.0	1200	MA	38.60	46.3	46.3
** Subtotal **						0.0			2080			98.6	98.6
** WBS: 1.2.2.3.1.2.1	Vacuum Chamber												
1	ISO - 200 gate valve	ea	1	3716.65	eu	3.7	0	0.0	0		0.00	0.0	3.7
2	ISO - 100 gate valve	ea	1	1274.28	eu	1.3	0	0.0	0		0.00	0.0	1.3
3	Turbo pump 400 l/s	ea	1	16247.07	cp	16.2	0	0.0	0		0.00	0.0	16.2
4	Turbo pump 1000 l/s	ea	1	32175.57	cp	32.2	0	0.0	0		0.00	0.0	32.2
5	High vac gauge	ea	2	2123.80	cp	4.2	0	0.0	0		0.00	0.0	4.2
6	Ion gauge	ea	1	424.76	cp	0.4	0	0.0	0		0.00	0.0	0.4
7	T.C. gauge	ea	2	265.48	eu	0.5	0	0.0	0		0.00	0.0	0.5
8	Main chamber	ea	1	8495.20	eu	8.5	1	570.0	570	MA	38.60	22.0	30.5
9	Valves w/RF flanges	ea	5	637.14	eu	3.2	0	0.0	0		0.00	0.0	3.2
10	10" diffstak pump	ea	2	9981.86	cp	20.0	0	0.0	0		0.00	0.0	20.0
11	2" diffstak pump	ea	1	1592.85	cp	1.6	0	0.0	0		0.00	0.0	1.6
12	Foreline trap	ea	4	318.57	cp	1.3	0	0.0	0		0.00	0.0	1.3
13	Foreline pressure gauge	ea	3	159.28	cp	0.5	0	0.0	0		0.00	0.0	0.5
14	Parani gauge head	ea	3	159.28	cp	0.5	0	0.0	0		0.00	0.0	0.5
15	Skimmer	ea	3	318.57	cp	1.0	0	0.0	0		0.00	0.0	1.0
16	Pulsed valve & driver	ea	1	1380.47	cp	1.4	0	0.0	0		0.00	0.0	1.4
17	Source chamber	ea	1	12742.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
18	Stand	ea	1	530.95	eu	0.5	1	65.0	65	MA	38.60	2.5	3.0
19	Misc. tubing,flanges,valv	lot	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
20	Diffusion pump controller	ea	3	318.57	eu	1.0	0	0.0	0		0.00	0.0	1.0
21	10" gate valve	ea	2	5309.50	cp	10.6	0	0.0	0		0.00	0.0	10.6
22	Detector chamber	ea	1	1592.85	cu	1.6	1	104.0	104	MA	38.60	4.0	5.6
** Subtotal **						138.8			739			28.5	167.3
** WBS: 1.2.2.3.1.2.2	Detector Systems												
1	Quadrupole mass filter	ea	1	33980.80	cp	34.0	0	0.0	0		0.00	0.0	34.0
2	100 psec rise time detect	ea	5	6371.40	eu	31.9	0	0.0	0		0.00	0.0	31.9
3	100 psec risetime preamp	ea	4	2123.80	eu	8.5	0	0.0	0		0.00	0.0	8.5
4	Multichannel scaler	ea	2	21238.00	eu	42.5	0	0.0	0		0.00	0.0	42.5
5	Fast risetime pulse genrt	ea	2	5309.50	eu	10.6	0	0.0	0		0.00	0.0	10.6
6	DC HV power supply	ea	3	1061.90	eu	3.2	0	0.0	0		0.00	0.0	3.2
7	400 MHz oscilloscope	ea	1	13804.70	eu	13.8	0	0.0	0		0.00	0.0	13.8
8	Digital delay generator	ea	1	4778.55	cp	4.8	0	0.0	0		0.00	0.0	4.8
9	Programmable dual p.s.	ea	1	1592.85	eu	1.6	0	0.0	0		0.00	0.0	1.6
10	CAMAC crate & controller	ea	1	6052.83	cp	6.1	0	0.0	0		0.00	0.0	6.1
11	CAMAC based modules	lot	1	12742.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
12	Box-car averager	ea	2	3185.70	cp	6.4	0	0.0	0		0.00	0.0	6.4
13	Signal processor	ea	1	1486.66	cp	1.5	0	0.0	0		0.00	0.0	1.5
14	Converter interface	ea	1	2123.80	cp	2.1	0	0.0	0		0.00	0.0	2.1
15	NIM crate & display modul	ea	1	1699.04	cp	1.7	0	0.0	0		0.00	0.0	1.7
16	Dual lock-in amplifier	ea	1	4247.60	cp	4.2	0	0.0	0		0.00	0.0	4.2
17	Low noise preamp	ea	2	530.95	cp	1.1	0	0.0	0		0.00	0.0	1.1
18	Dual ch gated photon cntr	ea	1	5734.26	cp	5.7	0	0.0	0		0.00	0.0	5.7
19	Fast preamp	ea	1	1061.90	cp	1.1	0	0.0	0		0.00	0.0	1.1
20	Computer work station	ea	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
21	Equipment rack	ea	4	1061.90	eu	4.2	1	40.0	40	EI	33.00	1.3	5.6
** Subtotal **						213.5			40			1.3	214.9
** WBS: 1.2.2.3.1.2.3	Lasers												
1	Excimer laser	ea	1	87075.80	cp	87.1	0	0.0	0		0.00	0.0	87.1
2	Ar ion laser	ea	1	36316.98	cp	36.3	0	0.0	0		0.00	0.0	36.3
3	Kr ion laser	ea	1	63183.05	cp	63.2	0	0.0	0		0.00	0.0	63.2
4	F-center lasr	ea	1	56280.70	cp	56.3	0	0.0	0		0.00	0.0	56.3
5	IR wavemeter	ea	1	15185.17	cp	15.2	0	0.0	0		0.00	0.0	15.2

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
6	IR spectrum analyzer	ea	1	5309.50	cp	5.3	0	0.0	0		0.00	0.0	5.3
7	IEEE 488 interface	ea	1	1911.42	cp	1.9	0	0.0	0		0.00	0.0	1.9
8	Spectrum analyzer contrlr	ea	1	1699.04	cp	1.7	0	0.0	0		0.00	0.0	1.7
9	Vac ion pump	ea	1	3185.70	eu	3.2	0	0.0	0		0.00	0.0	3.2
10	Ramp generator	ea	2	2548.56	cp	5.1	0	0.0	0		0.00	0.0	5.1
11	Laser tables	ea	2	8919.96	cp	17.8	0	0.0	0		0.00	0.0	17.8
12	Power meter & readout	ea	2	3185.70	cp	6.4	0	0.0	0		0.00	0.0	6.4
13	Optics,mounts, filters	lot	1	5309.50	eu	5.3	0	0.0	0		0.00	0.0	5.3
** Subtotal **						304.8			0			0.0	304.8
** WBS: 1.2.2.3.1.2.4	Installation												
1	Installation engineer		0	0.00		0.0	4	40.0	160	ME	59.40	9.5	9.5
2	Installation technician		0	0.00		0.0	10	40.0	400	MA	38.60	15.4	15.4
** Subtotal **						0.0			560			24.9	24.9
** WBS: 1.2.2.3.1.3.1	Vacuum Chamber												
1	UHV detector chamber	ea	1	30795.10	eu	30.8	0	0.0	0		0.00	0.0	30.8
2	Rotatable TOF detector	ea	1	4247.60	eu	4.2	0	0.0	0		0.00	0.0	4.2
3	10" rotatable platform	ea	1	7220.92	cp	7.2	0	0.0	0		0.00	0.0	7.2
4	Turbo pump	ea	1	16247.07	cp	16.2	0	0.0	0		0.00	0.0	16.2
5	2" diffstak pump	ea	1	1592.85	cp	1.6	0	0.0	0		0.00	0.0	1.6
6	Oil free mechanical pump	ea	1	5415.69	cp	5.4	0	0.0	0		0.00	0.0	5.4
7	Ion pump,220 l/s & ps	ea	1	8176.63	cp	8.2	0	0.0	0		0.00	0.0	8.2
8	Preparation chamber	ea	1	4778.55	cp	4.8	0	0.0	0		0.00	0.0	4.8
9	LEED diagnostics	ea	1	16034.69	cp	16.0	0	0.0	0		0.00	0.0	16.0
10	Sputter etching system	ea	1	17521.35	cp	17.5	0	0.0	0		0.00	0.0	17.5
11	Auger electron analyzer	ea	1	15291.36	cp	15.3	0	0.0	0		0.00	0.0	15.3
12	Auger control electronics	ea	1	7433.30	cp	7.4	0	0.0	0		0.00	0.0	7.4
13	Auger gun control	ea	1	7008.54	cp	7.0	0	0.0	0		0.00	0.0	7.0
14	Sample manipulator	ea	1	19432.77	cp	19.4	0	0.0	0		0.00	0.0	19.4
15	UHV ion gauge controller	ea	1	2123.80	cp	2.1	0	0.0	0		0.00	0.0	2.1
16	Ion gauge	ea	1	371.66	cp	0.4	0	0.0	0		0.00	0.0	0.4
17	LN2 shroud	ea	1	796.42	cp	0.8	0	0.0	0		0.00	0.0	0.8
18	Sublimation cartridge	ea	1	530.95	cp	0.5	0	0.0	0		0.00	0.0	0.5
19	Sublimation control unit	ea	1	2017.61	cp	2.0	0	0.0	0		0.00	0.0	2.0
20	UHV feedthroughs	lot	1	2654.75	eu	2.7	0	0.0	0		0.00	0.0	2.7
21	Mating flanges, conflat	lot	1	3716.65	cp	3.7	0	0.0	0		0.00	0.0	3.7
22	Bakable valves	ea	2	955.71	cp	1.9	0	0.0	0		0.00	0.0	1.9
23	Window flange	ea	2	1061.90	cp	2.1	0	0.0	0		0.00	0.0	2.1
24	View port	ea	2	530.95	cp	1.1	0	0.0	0		0.00	0.0	1.1
25	Chamber lamp heater	ea	1	2760.94	cp	2.8	0	0.0	0		0.00	0.0	2.8
26	Residual gas analyzer	ea	1	10619.00	cp	10.6	0	0.0	0		0.00	0.0	10.6
27	Gas flow monitor & cntrlr	ea	1	2867.13	cp	2.9	0	0.0	0		0.00	0.0	2.9
28	UHV right angle valve	ea	2	743.33	cp	1.5	0	0.0	0		0.00	0.0	1.5
29	UHV leak valve	ea	1	849.52	cp	0.8	0	0.0	0		0.00	0.0	0.8
30	Misc. parts	lot	1	5309.50	eu	5.3	0	0.0	0		0.00	0.0	5.3
** Subtotal **						202.4			0			0.0	202.4
** WBS: 1.2.2.3.1.3.2	Detector Systems												
1	Transient digitizer	ea	1	21238.00	cp	21.2	0	0.0	0		0.00	0.0	21.2
2	Multichnnl plate detector	ea	1	2123.80	cp	2.1	0	0.0	0		0.00	0.0	2.1
2	Pulse amplifier	ea	1	1061.90	cp	1.1	0	0.0	0		0.00	0.0	1.1
4	Programmabl delay genertr	ea	1	2548.56	cp	2.5	0	0.0	0		0.00	0.0	2.5
5	CAMAC crate	ea	1	3929.03	cp	3.9	0	0.0	0		0.00	0.0	3.9
6	CAMAC crate controller	ea	1	2123.80	cp	2.1	0	0.0	0		0.00	0.0	2.1
7	Digital delay generator	ea	1	4778.55	cp	4.8	0	0.0	0		0.00	0.0	4.8
8	Boxcar averager	ea	1	3185.70	cp	3.2	0	0.0	0		0.00	0.0	3.2
9	Signal processor	ea	1	1486.66	cp	1.5	0	0.0	0		0.00	0.0	1.5
10	Triggerable ADC	ea	1	1911.42	cp	1.9	0	0.0	0		0.00	0.0	1.9
11	DAC/pulse generator	ea	1	743.33	cp	0.7	0	0.0	0		0.00	0.0	0.7
12	HV power supply	ea	3	1592.85	cp	4.8	0	0.0	0		0.00	0.0	4.8
13	GPIB interface	ea	1	1168.09	cp	1.2	0	0.0	0		0.00	0.0	1.2
14	Stepping motor controller	ea	1	3716.65	cp	3.7	0	0.0	0		0.00	0.0	3.7

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
15	PC workstation	ea	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
16	NIM CAMAC adaptor	ea	1	424.76	cp	0.4	0	0.0	0		0.00	0.0	0.4
17	Equipment racks	ea	4	1061.90	eu	4.2	1	40.0	40	E1	33.00	1.3	5.6
** Subtotal **						75.4			40			1.3	76.7
** WBS: 1.2.2.3.1.3.3	Lasers												
1	Q-Switch Nd-YAG laser	ea	1	79961.07	cp	80.0	0	0.0	0		0.00	0.0	80.0
2	Pulsed dye laser	ea	2	41201.72	cp	82.4	0	0.0	0		0.00	0.0	82.4
3	Harmonic generator	ea	1	9875.67	cp	9.9	0	0.0	0		0.00	0.0	9.9
4	Wavelength separation pkg	ea	1	4459.98	cp	4.5	0	0.0	0		0.00	0.0	4.5
5	UV wavelength extender	ea	2	33980.80	cp	68.0	0	0.0	0		0.00	0.0	68.0
6	Laser table	ea	2	8919.96	cp	17.8	0	0.0	0		0.00	0.0	17.8
7	Optics and mounts	lot	1	10619.00	eu	10.6	0	0.0	0		0.00	0.0	10.6
8	Power meters	ea	2	3185.70	cp	6.4	0	0.0	0		0.00	0.0	6.4
9	Wavemeter	ea	1	16247.07	cp	16.2	0	0.0	0		0.00	0.0	16.2
** Subtotal **						295.7			0			0.0	295.7
** WBS: 1.2.2.3.1.3.4	Installation												
1	Installation engineer		0	0.00		0.0	8	40.0	320	ME	59.40	19.0	19.0
2	Installation technician		0	0.00		0.0	10	40.0	400	MA	38.60	15.4	15.4
** Subtotal **						0.0			720			34.4	34.4
** WBS: 1.2.2.3.1.4.1	Vacuum Chamber												
1	Main scattering chamber	ea	1	21238.00	eu	21.2	25	40.0	1000	ME	59.40	59.4	80.6
2	Differential pumpng stage	ea	1	2123.80	eu	2.1	1	208.0	208	MA	38.60	8.0	10.2
3	Source tee	ea	2	212.38	eu	0.4	1	302.0	302	MA	38.60	11.7	12.1
4	Source reducer	ea	2	106.19	eu	0.2	1	98.0	98	MA	38.60	3.8	4.0
5	Cold shield	ea	1	212.38	eu	0.2	1	74.0	74	MA	38.60	2.9	3.1
6	10" spools	ea	2	106.19	eu	0.2	1	74.0	74	MA	38.60	2.9	3.1
7	4" spools	ea	2	106.19	eu	0.2	1	46.0	46	MA	38.60	1.8	2.0
8	Chamber stand	ea	1	318.57	eu	0.3	1	70.0	70	MA	38.60	2.7	3.0
9	Foreline manifold	ea	1	3185.70	eu	3.2	1	40.0	40	MA	38.60	1.5	4.7
10	Rotating chmbr & bearing	ea	1	10619.00	eu	10.6	1	780.0	780	MA	38.60	30.1	40.7
11	Rotating chamber insert	ea	1	1061.90	eu	1.1	1	235.0	235	MA	38.60	9.1	10.1
12	Gas handling manifold	ea	1	2123.80	eu	2.1	1	40.0	40	MA	38.60	1.5	3.7
13	Water cooling manifold	ea	1	1592.85	eu	1.6	1	40.0	40	MA	38.60	1.5	3.1
14	Pneumatic 10" gate valve	ea	4	5309.50	cp	21.2	0	0.0	0		0.00	0.0	21.2
15	10" diffusion pump	ea	4	3504.27	cp	14.0	0	0.0	0		0.00	0.0	14.0
16	4" diffusion pump	ea	2	1699.04	cp	3.4	0	0.0	0		0.00	0.0	3.4
17	Diffusion pump controllrs	ea	6	2123.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
18	Roughing valve, bellows	ea	12	318.57	cp	3.8	0	0.0	0		0.00	0.0	3.8
19	Misc. hardware	lot	1	21238.00	eu	21.2	0	0.0	0		0.00	0.0	21.2
20	4" gate valve	ea	2	1274.28	cp	2.5	0	0.0	0		0.00	0.0	2.5
21	Liquid nitrogen feeder	ea	3	1061.90	cp	3.2	0	0.0	0		0.00	0.0	3.2
22	LN sensing unit	ea	3	318.57	eu	1.0	0	0.0	0		0.00	0.0	1.0
23	PUlsed beam source/driver	ea	2	3716.65	cp	7.4	0	0.0	0		0.00	0.0	7.4
24	Skimmer	ea	3	318.57	cp	1.0	0	0.0	0		0.00	0.0	1.0
** Subtotal **						135.1			3007			136.9	271.9
** WBS: 1.2.2.3.1.4.2	Detector Systems												
1	Turbo pump, 400 l/s	ea	3	16140.88	cp	48.4	0	0.0	0		0.00	0.0	48.4
2	2" diffstak pump	ea	1	1592.85	cp	1.6	0	0.0	0		0.00	0.0	1.6
3	Pneumatic gate valve	ea	3	1061.90	cp	3.2	0	0.0	0		0.00	0.0	3.2
4	Filament power supply	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
5	High voltage power supply	ea	4	1061.90	cp	4.2	0	0.0	0		0.00	0.0	4.2
6	40 kV power supply	ea	1	1592.85	eu	1.6	0	0.0	0		0.00	0.0	1.6
7	PM power supply	ea	1	1061.90	cp	1.1	0	0.0	0		0.00	0.0	1.1
8	Quadrupole mass analyzer	ea	1	33980.80	cp	34.0	0	0.0	0		0.00	0.0	34.0
9	CAMAC crate	ea	1	3929.03	cp	3.9	0	0.0	0		0.00	0.0	3.9
10	Multi-channel scalar	ea	1	8495.20	cp	8.5	0	0.0	0		0.00	0.0	8.5
11	Count rate meter	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
12	Low noise amplifier	ea	1	2336.18	cp	2.3	0	0.0	0		0.00	0.0	2.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
13	Discriminator	ea	1	1061.90	eu	1.1	0	0.0	0		0.00	0.0	1.1
14	100 MHz oscilloscope	ea	1	2336.18	cp	2.3	0	0.0	0		0.00	0.0	2.3
15	Pulse delay generator	ea	4	4778.55	cp	19.1	0	0.0	0		0.00	0.0	19.1
16	Computer work station	ea	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
17	CAMAC crate controller	ea	1	6052.83	cp	6.1	0	0.0	0		0.00	0.0	6.1
18	Programmable A/D convrter	ea	1	1805.23	cp	1.8	0	0.0	0		0.00	0.0	1.8
19	D/A converter	ea	1	743.33	cp	0.7	0	0.0	0		0.00	0.0	0.7
20	Computer interface/CAMAC	ea	1	637.14	cp	0.6	0	0.0	0		0.00	0.0	0.6
21	Stepping motor cntrllr/ps	ea	1	3716.65	cp	3.7	0	0.0	0		0.00	0.0	3.7
22	NIM to CAMAC adaptor	ea	1	424.76	cp	0.4	0	0.0	0		0.00	0.0	0.4
23	Misc. hardware	lot	1	6371.40	eu	6.4	0	0.0	0		0.00	0.0	6.4
24	Equipment racks	ea	4	1061.90	eu	4.2	1	40.0	40	EI	33.00	1.3	5.6
** Subtotal **						173.4			40			1.3	174.7
** WBS: 1.2.2.3.1.4.3	Lasers												
1	Excimer laser	ea	1	61590.20	cp	61.6	0	0.0	0		0.00	0.0	61.6
3	Laser table	ea	1	8919.96	cp	8.9	0	0.0	0		0.00	0.0	8.9
4	Optics and mounts	lot	1	4247.60	eu	4.2	0	0.0	0		0.00	0.0	4.2
5	Power meter & read out	ea	1	3185.70	cp	3.2	0	0.0	0		0.00	0.0	3.2
** Subtotal **						77.9			0			0.0	77.9
** WBS: 1.2.2.3.1.4.4	Installation												
1	Installation engineer		0	0.00		0.0	10	40.0	400	ME	59.40	23.8	23.8
2	Installation technician		0	0.00		0.0	15	40.0	600	MA	38.60	23.2	23.2
** Subtotal **						0.0			1000			46.9	46.9
** WBS: 1.2.2.3.1.5.1	Vacuum Chamber												
1	ISO - 200 gate valve	ea	1	3716.65	eu	3.7	0	0.0	0		0.00	0.0	3.7
2	ISO - 100 gate valve	ea	1	1274.28	eu	1.3	0	0.0	0		0.00	0.0	1.3
3	Turbo pump 400 l/s	ea	1	16247.07	cp	16.2	0	0.0	0		0.00	0.0	16.2
4	Turbo pump 1000 l/s	ea	1	32175.57	cp	32.2	0	0.0	0		0.00	0.0	32.2
5	High vac gauge	ea	2	2123.80	cp	4.2	0	0.0	0		0.00	0.0	4.2
6	Ion gauge	ea	1	424.76	cp	0.4	0	0.0	0		0.00	0.0	0.4
7	T.C. gauge	ea	2	265.48	eu	0.5	0	0.0	0		0.00	0.0	0.5
8	Main chamber	ea	1	8495.20	eu	8.5	1	570.0	570	MA	38.60	22.0	30.5
9	Valves w/RF flanges	ea	5	637.14	eu	3.2	0	0.0	0		0.00	0.0	3.2
10	10" diffstak pump	ea	2	9981.86	cp	20.0	0	0.0	0		0.00	0.0	20.0
11	2" diffstak pump	ea	1	1592.85	cp	1.6	0	0.0	0		0.00	0.0	1.6
12	Foreline trap	ea	4	318.57	cp	1.3	0	0.0	0		0.00	0.0	1.3
13	Foreline pressure gauge	ea	3	159.28	cp	0.5	0	0.0	0		0.00	0.0	0.5
14	Parani gauge head	ea	3	159.28	cp	0.5	0	0.0	0		0.00	0.0	0.5
15	Skimmer	ea	3	318.57	cp	1.0	0	0.0	0		0.00	0.0	1.0
16	Pulsed valve & driver	ea	1	1380.47	cp	1.4	0	0.0	0		0.00	0.0	1.4
17	Source chamber	ea	1	12742.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
18	Stand	ea	1	530.95	eu	0.5	1	65.0	65	MA	38.60	2.5	3.0
19	Misc. tubing,flanges,valv	lot	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
20	Diffusion pump controller	ea	3	318.57	eu	1.0	0	0.0	0		0.00	0.0	1.0
21	10" gate valve	ea	2	5309.50	cp	10.6	0	0.0	0		0.00	0.0	10.6
22	Detector chamber	ea	1	1592.85	cu	1.6	1	104.0	104	MA	38.60	4.0	5.6
23	Test Chambers	lot	1	106190.00	eu	106.2	0	0.0	0		0.00	0.0	106.2
** Subtotal **						245.0			739			28.5	273.5
** WBS: 1.2.2.3.1.5.2	Detector Systems												
1	Quadrupole mass filter	ea	1	33980.80	cp	34.0	0	0.0	0		0.00	0.0	34.0
2	100 psec rise time detect	ea	5	6371.40	eu	31.9	0	0.0	0		0.00	0.0	31.9
3	100 psec risetime preamp	ea	4	2123.80	eu	8.5	0	0.0	0		0.00	0.0	8.5
4	Multichannel scaler	ea	2	21238.00	eu	42.5	0	0.0	0		0.00	0.0	42.5
5	Fast risetime pulse genrt	ea	2	5309.50	eu	10.6	0	0.0	0		0.00	0.0	10.6
6	DC HV power supply	ea	3	1061.90	eu	3.2	0	0.0	0		0.00	0.0	3.2
7	400 MHz oscilloscope	ea	1	13804.70	eu	13.8	0	0.0	0		0.00	0.0	13.8
8	Digital delay generator	ea	1	4778.55	cp	4.8	0	0.0	0		0.00	0.0	4.8
9	Programmable dual p.s.	ea	1	1592.85	eu	1.6	0	0.0	0		0.00	0.0	1.6

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
10	CAMAC crate & controller	ea	1	6052.83	cp	6.1	0	0.0	0		0.00	0.0	6.1
11	CAMAC based modules	lot	1	12742.80	eu	12.7	0	0.0	0		0.00	0.0	12.7
12	Box-car averager	ea	2	3185.70	cp	6.4	0	0.0	0		0.00	0.0	6.4
13	Signal processor	ea	1	1486.66	cp	1.5	0	0.0	0		0.00	0.0	1.5
14	Converter interface	ea	1	2123.80	cp	2.1	0	0.0	0		0.00	0.0	2.1
15	NIM crate & display modul	ea	1	1699.04	cp	1.7	0	0.0	0		0.00	0.0	1.7
16	Dual lock-in amplifier	ea	1	4247.60	cp	4.2	0	0.0	0		0.00	0.0	4.2
17	Low noise preamp	ea	2	530.95	cp	1.1	0	0.0	0		0.00	0.0	1.1
18	Dual ch gated photon cntr	ea	1	5734.26	cp	5.7	0	0.0	0		0.00	0.0	5.7
19	Fast preamp	ea	1	1061.90	cp	1.1	0	0.0	0		0.00	0.0	1.1
20	Computer work station	ea	1	15928.50	eu	15.9	0	0.0	0		0.00	0.0	15.9
21	Equipment rack	ea	4	1061.90	eu	4.2	4	40.0	160	EI	33.00	5.3	9.5
22	Test Detectors	lot	1	97694.80	eu	97.7	0	0.0	0		0.00	0.0	97.7
** Subtotal **						311.2			160			5.3	316.5
** WBS: 1.2.2.3.1.5.3	Lasers												
1	Excimer laser	ea	1	87075.80	cp	87.1	0	0.0	0		0.00	0.0	87.1
2	Ar ion laser	ea	1	36316.98	cp	36.3	0	0.0	0		0.00	0.0	36.3
3	Kr ion laser	ea	1	63183.05	cp	63.2	0	0.0	0		0.00	0.0	63.2
4	F-center lasr	ea	1	56280.70	cp	56.3	0	0.0	0		0.00	0.0	56.3
5	IR wavemeter	ea	1	15185.17	cp	15.2	0	0.0	0		0.00	0.0	15.2
6	IR spectrum analyzer	ea	1	5309.50	cp	5.3	0	0.0	0		0.00	0.0	5.3
7	IEEE 488 interface	ea	1	1911.42	cp	1.9	0	0.0	0		0.00	0.0	1.9
8	Spectrum analyzer contrlr	ea	1	1699.04	cp	1.7	0	0.0	0		0.00	0.0	1.7
9	Vac ion pump	ea	1	3185.70	eu	3.2	0	0.0	0		0.00	0.0	3.2
10	Ramp generator	ea	2	2548.56	cp	5.1	0	0.0	0		0.00	0.0	5.1
11	Laser tables	ea	2	8919.96	cp	17.8	0	0.0	0		0.00	0.0	17.8
12	Power meter & readout	ea	2	3185.70	cp	6.4	0	0.0	0		0.00	0.0	6.4
13	Optics,mounts, filters	lot	1	5309.50	eu	5.3	0	0.0	0		0.00	0.0	5.3
** Subtotal **						304.8			0			0.0	304.8
** WBS: 1.2.2.3.1.5.4	Installation												
1	Installation engineer		0	0.00		0.0	4	40.0	160	ME	59.40	9.5	9.5
2	Installation technician		0	0.00		0.0	10	40.0	400	MA	38.60	15.4	15.4
3	Misc. Material	lot	1	10619.00	eu	10.6	0	0.0	0		0.00	0.0	10.6
** Subtotal **						10.6			560			24.9	35.6
** WBS: 1.2.2.3.1.6.1	Vacuum Chambers & Pumps												
1	Vacuum chambers & pumps	lot	1	547940.40	eu	547.9	0	0.0	0		0.00	0.0	547.9
** Subtotal **						547.9			0			0.0	547.9
** WBS: 1.2.2.3.1.6.2	Detector System												
1	Detector System	lot	1	199637.20	eu	199.6	0	0.0	0		0.00	0.0	199.6
** Subtotal **						199.6			0			0.0	199.6
** WBS: 1.2.2.3.1.6.3	Lasers												
1	Lasers	lot	1	708287.30	eu	708.3	0	0.0	0		0.00	0.0	708.3
** Subtotal **						708.3			0			0.0	708.3
** WBS: 1.2.2.3.1.6.4	Installation												
1	Installation	lot	1	33980.80	eu	34.0	0	0.0	0		0.00	0.0	34.0
** Subtotal **						34.0			0			0.0	34.0
** WBS: 1.2.2.3.1.7.1	Vacuum Chambers & Pumps												
1	Vacuum Chambers & pumps	lot	1	369541.20	eu	369.5	0	0.0	0		0.00	0.0	369.5
** Subtotal **						369.5			0			0.0	369.5

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.3.1.7.2	Detector System												
1	Detector System	lot	1	217689.50	eu	217.7	0	0.0	0		0.00	0.0	217.7
** Subtotal **						217.7			0			0.0	217.7
** WBS: 1.2.2.3.1.7.3	Lasers												
1	Lasers	lot	1	757134.70	eu	757.1	0	0.0	0		0.00	0.0	757.1
** Subtotal **						757.1			0			0.0	757.1
** WBS: 1.2.2.3.1.7.4	Installation												
1	Installation	lot	1	33980.80	eu	34.0	0	0.0	0		0.00	0.0	34.0
** Subtotal **						34.0			0			0.0	34.0
** WBS: 1.2.2.3.1.8	Experimental Station Enhancements (SNL)												
1	Allowance	lot	1	1500000.00	eu	1500.0	0	0.0	0		0.00	0.0	1500.0
** Subtotal **						1500.0			0			0.0	1500.0
** WBS: 1.2.2.3.2.1	Lasers												
1	Single-frequncy dye laser	ea	2	112763.16	cp	225.5	0	0.0	0		0.00	0.0	225.5
2	Argon ion laser	ea	2	76116.99	cp	152.2	2	8.0	16	MA	38.60	0.6	152.9
3	Seeded Nd-YAG laser	ea	2	124040.54	cp	248.1	1	8.0	8	MA	38.60	0.3	248.4
4	Pulsed dye nsec amplifier	ea	2	33041.02	cp	66.1	0	0.0	0		0.00	0.0	66.1
5	CW mode locked YAG laser	ea	2	85700.64	cp	171.4	1	8.0	8	MA	38.60	0.3	171.7
6	Modification to custom RF	ea	2	11277.38	eu	22.6	12	40.0	480	EE	59.40	28.5	51.1
7	Sub-picosecond dye laser	ea	1	75554.18		75.6	0	0.0	0		0.00	0.0	75.6
8	Modification to custom RF	ea	1	3382.15	eu	3.4	2	40.0	80	EE	59.40	4.8	8.1
9	Regenerative amp, 1kHz	ea	1	130242.03	cp	130.2	1	8.0	8	MA	38.60	0.3	130.6
10	Pulsed dye amplifier,1kHz	ea	1	39805.32	cp	39.8	0	0.0	0		0.00	0.0	39.8
11	SHG assembly for ML laser	ea	2	15785.14	cp	31.6	0	0.0	0		0.00	0.0	31.6
12	Picosecond dye laser	ea	2	31007.48	cp	62.0	0	0.0	0		0.00	0.0	62.0
13	Modification to custom RF	ea	2	3382.15	eu	6.8	3	40.0	120	EE	59.40	7.1	13.9
14	Regenerative amp, 50pps	ea	1	76116.99	cp	76.1	0	0.0	0		0.00	0.0	76.1
15	Pulsed dye amp, 50pps	ea	2	26499.71	cp	53.0	0	0.0	0		0.00	0.0	53.0
16	Final amp for dye, nsec	ea	2	5638.69	eu	11.3	10	8.0	80	EE	59.40	4.8	16.0
17	Cavity dumper	ea	3	30444.67	cp	91.3	0	0.0	0		0.00	0.0	91.3
** Subtotal **						1466.9			800			46.7	1513.6
** WBS: 1.2.2.3.2.2	Laser Accessories												
1	UV wavelength extender	ea	5	36083.36	cp	180.4	0	0.0	0		0.00	0.0	180.4
2	IR wavelength extender	ea	1	32701.21	cp	32.7	0	0.0	0		0.00	0.0	32.7
3	Doublrs for regenrtv amps	ea	2	11277.38	cp	22.6	0	0.0	0		0.00	0.0	22.6
4	Optical isolators	ea	6	6764.30	cp	40.6	0	0.0	0		0.00	0.0	40.6
5	Single pulse selector	ea	2	16916.07	cp	33.8	0	0.0	0		0.00	0.0	33.8
6	Pulsed nozzle powr supply	ea	1	3382.15	cp	3.4	0	0.0	0		0.00	0.0	3.4
7	Nozzle chamber	ea	1	3382.15	eu	3.4	3	40.0	120	MA	38.60	4.6	8.0
8	Cryopump	ea	1	13533.92	cp	13.5	0	0.0	0		0.00	0.0	13.5
9	Roughing pump	ea	2	2256.54	cp	4.5	0	0.0	0		0.00	0.0	4.5
10	Ion gauge & controller	ea	1	1693.73	eu	1.7	0	0.0	0		0.00	0.0	1.7
11	Vac line manifold	ea	2	1693.73	eu	3.4	1	40.0	40	MA	38.60	1.5	4.9
12	VUV monochromator	ea	1	31575.60	cp	31.6	2	8.0	16	MA	38.60	0.6	32.2
13	Grating	ea	1	2819.34	cp	2.8	0	0.0	0		0.00	0.0	2.8
14	Grating holder	ea	1	1125.61	cp	1.1	0	0.0	0		0.00	0.0	1.1
15	Monochromator pumping sys	ea	1	27965.14	cp	28.0	4	8.0	32	MA	38.60	1.2	29.2
16	Cold trap	ea	1	1805.23	cp	1.8	0	0.0	0		0.00	0.0	1.8
17	Support table	ea	1	5410.38	cp	5.4	0	0.0	0		0.00	0.0	5.4
18	Gas manifold	ea	1	2256.54	eu	2.3	1	40.0	40	MA	38.60	1.5	3.8
19	Pressure transducer	ea	2	902.61	cp	1.8	0	0.0	0		0.00	0.0	1.8
20	Transducer power supply	ea	2	902.61	cp	1.8	0	0.0	0		0.00	0.0	1.8
** Subtotal **						416.6			248			9.6	426.1

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST	COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** WBS: 1.2.2.3.2.3	Optical Transport and Support												
1	Optical Table tops	ea	7	8458.03	cp	59.2	0	0.0	0		0.00	0.0	59.2
2	Table support systems	ea	7	1014.11	cp	7.1	0	0.0	0		0.00	0.0	7.1
3	Optical support posts	lot	60	169.90	eu	10.2	0	0.0	0		0.00	0.0	10.2
4	Lenses and mirrors	lot	1	28193.44	eu	28.2	0	0.0	0		0.00	0.0	28.2
5	Translation stages	ea	20	791.12	cp	15.8	0	0.0	0		0.00	0.0	15.8
6	Optical mounts	ea	50	339.81	cp	17.0	0	0.0	0		0.00	0.0	17.0
** Subtotal **						137.5			0			0.0	137.5
** WBS: 1.2.2.3.2.4	Diagnostics and Control												
1	CW wavemeter	ea	2	14999.34	cp	30.0	0	0.0	0		0.00	0.0	30.0
2	Spectrum analyzer	ea	2	8681.03	cp	17.4	0	0.0	0		0.00	0.0	17.4
3	Spectrum analyzer cntrllr	ea	2	1693.73	cp	3.4	0	0.0	0		0.00	0.0	3.4
4	400 MHz oscilloscope	ea	4	14717.93	cp	58.9	0	0.0	0		0.00	0.0	58.9
5	50 MHz oscilloscope	ea	4	1242.42	cp	5.0	0	0.0	0		0.00	0.0	5.0
6	Sampling scope & plug-in	ea	2	37325.79	cp	74.7	0	0.0	0		0.00	0.0	74.7
7	Digital delay generator	ea	6	5075.88	cp	30.5	0	0.0	0		0.00	0.0	30.5
8	Fast scan autocorrelator	ea	2	14096.72	cp	28.2	0	0.0	0		0.00	0.0	28.2
9	Single pulse autocorreltr	ea	2	17250.57	cp	34.5	0	0.0	0		0.00	0.0	34.5
10	Translation stage	ea	2	3944.96	cp	7.9	0	0.0	0		0.00	0.0	7.9
11	Translation stage cntrllr	ea	2	1693.73	cp	3.4	0	0.0	0		0.00	0.0	3.4
12	Power meter & readout	ea	12	3382.15	cp	40.6	0	0.0	0		0.00	0.0	40.6
** Subtotal **						334.3			0			0.0	334.3
** WBS: 1.2.2.3.2.5	System Integration												
1	Integration chemist		0	0.00		0.0	1	3300.0	3300	ME	59.40	196.0	196.0
2	Integration technician		0	0.00		0.0	1	2160.0	2160	MA	38.60	83.4	83.4
** Subtotal **						0.0			5460			279.4	279.4
** WBS: 1.2.2.3.3.1	Laser Safety Covers												
1	Advanced laser systems	lot	1	21238.00	eu	21.2	0	0.0	0		0.00	0.0	21.2
2	Exp statn appartus lasers	lot	1	21238.00	eu	21.2	0	0.0	0		0.00	0.0	21.2
** Subtotal **						42.5			0			0.0	42.5
** WBS: 1.2.2.3.3.2	Laser Timing / Synchronization												
1	500MHZ LINK TO ALS	EA	1	5309.50	EU	5.3	1	80.0	80	ES	33.00	2.6	7.9
2	GUN TIMER	EA	1	10619.00	EU	10.6	1	80.0	80	ES	33.00	2.6	13.3
3	MODULATION TIMER	EA	1	7433.30	EU	7.4	1	80.0	80	ES	33.00	2.6	10.1
4	PROGRAMMABLE DELAYS	EA	8	4035.22	eu	32.3	8	2.0	16	ES	33.00	0.5	32.8
5	CABLES	LOT	1	10619.00	EU	10.6	1	80.0	80	ES	33.00	2.6	13.3
6	JITTER ANALYZER	EA	1	4247.60	EU	4.2	1	2.0	2	ES	33.00	0.1	4.3
7	SYSTEM TEST	EA	1	0.00	EU	0.0	1	85.0	85	ES	33.00	2.8	2.8
** Subtotal **						70.5			423			14.0	84.5
** WBS: 1.2.2.3.4	User Control Interface												
1	Computer Programming		0	0.00		0.0	1	2850.0	2850	CP	59.40	169.3	169.3
** Subtotal **						0.0			2850			169.3	169.3
** WBS: 1.3.1	ED&I												
1	ED&I (15% of constrction)		1	2430000.00	eu	2430.0	0	0.0	0		0.00	0.0	2430.0
** Subtotal **						2430.0			0			0.0	2430.0
** WBS: 1.3.2.1.1.1	Building 10 Demolition												
1	Building demolition	lot	1	156000.00	eu	156.0	0	0.0	0		0.00	0.0	156.0
** Subtotal **						156.0			0			0.0	156.0
** WBS: 1.3.2.1.2.1	Shoring and Underpinning												
1	Shoring & underpinning		1	438000.00	eu	438.0	0	0.0	0		0.00	0.0	438.0

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **				438.0			0			0.0	438.0
** WBS: 1.3.2.1.2.2	Excavation										
1 Excavation		1	310000.00 eu	310.0	0	0.0	0		0.00	0.0	310.0
** Subtotal **				310.0			0			0.0	310.0
** WBS: 1.3.2.1.3.1	Mods to Existing Systems										
1 Mods to existing systems		1	1492000.00 eu	1492.0	0	0.0	0		0.00	0.0	1492.0
** Subtotal **				1492.0			0			0.0	1492.0
** WBS: 1.3.2.2.1.1	Paving and Surfacing										
1 Paving and surfacing		1	51000.00 eu	51.0	0	0.0	0		0.00	0.0	51.0
** Subtotal **				51.0			0			0.0	51.0
** WBS: 1.3.2.2.1.2	Cyclotron Road Parking										
1 Cyclotron Road Parking	lot	1	94000.00 eu	94.0	0	0.0	0		0.00	0.0	94.0
** Subtotal **				94.0			0			0.0	94.0
** WBS: 1.3.2.2.1.3	Site Improvements										
1 Site improvements		1	47000.00 eu	47.0	0	0.0	0		0.00	0.0	47.0
** Subtotal **				47.0			0			0.0	47.0
** WBS: 1.3.2.2.1.4	Landscaping										
1 Landscaping		1	7000.00 eu	7.0	0	0.0	0		0.00	0.0	7.0
** Subtotal **				7.0			0			0.0	7.0
** WBS: 1.3.2.2.2.1	Concrete										
1 Concrete		1	2040882.00 eu	2040.9	0	0.0	0		0.00	0.0	2040.9
** Subtotal **				2040.9			0			0.0	2040.9
** WBS: 1.3.2.2.2.2.1	Structural Steel										
1 Structural steel		1	828414.00 eu	828.4	0	0.0	0		0.00	0.0	828.4
** Subtotal **				828.4			0			0.0	828.4
** WBS: 1.3.2.2.2.2.2	Steel Deck										
1 Steel deck		1	242282.00 eu	242.3	0	0.0	0		0.00	0.0	242.3
** Subtotal **				242.3			0			0.0	242.3
** WBS: 1.3.2.2.2.2.3	Metal Fabrications										
1 Metal fabrications		1	126960.00 eu	127.0	0	0.0	0		0.00	0.0	127.0
** Subtotal **				127.0			0			0.0	127.0
** WBS: 1.3.2.2.2.3.1	Custom Casework										
1 Custom casework		1	59248.00 eu	59.2	0	0.0	0		0.00	0.0	59.2
** Subtotal **				59.2			0			0.0	59.2
** WBS: 1.3.2.2.2.4.1	Waterproofing										
1 Waterproofing		1	45494.00 eu	45.5	0	0.0	0		0.00	0.0	45.5
** Subtotal **				45.5			0			0.0	45.5
** WBS: 1.3.2.2.2.4.2	Dampproofing										
1 Dampproofing		1	5290.00 eu	5.3	0	0.0	0		0.00	0.0	5.3

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **				5.3			0			0.0	5.3
** WBS: 1.3.2.2.2.4.3	Insulation										
1 Insulation		1	15870.00 eu	15.9	0	0.0	0		0.00	0.0	15.9
** Subtotal **				15.9			0			0.0	15.9
** WBS: 1.3.2.2.2.4.4	Fireproofing										
1 Fireproofing		1	98394.00 eu	98.4	0	0.0	0		0.00	0.0	98.4
** Subtotal **				98.4			0			0.0	98.4
** WBS: 1.3.2.2.2.4.5	Preformed Metal Siding										
1 Preformed metal siding		1	487738.00 eu	487.7	0	0.0	0		0.00	0.0	487.7
** Subtotal **				487.7			0			0.0	487.7
** WBS: 1.3.2.2.2.4.6	Membrane Roofing										
1 Membrane roofing		1	45494.00 eu	45.5	0	0.0	0		0.00	0.0	45.5
** Subtotal **				45.5			0			0.0	45.5
** WBS: 1.3.2.2.2.4.7	Sheet Metal Flashing										
1 Sheet metal flashing		1	13754.00 eu	13.8	0	0.0	0		0.00	0.0	13.8
** Subtotal **				13.8			0			0.0	13.8
** WBS: 1.3.2.2.2.4.8	Sealants										
1 Sealants		1	17986.00 eu	18.0	0	0.0	0		0.00	0.0	18.0
** Subtotal **				18.0			0			0.0	18.0
** WBS: 1.3.2.2.2.5.1	Metal Doors and Frames										
1 Metal doors and frames		1	38088.00 eu	38.1	0	0.0	0		0.00	0.0	38.1
** Subtotal **				38.1			0			0.0	38.1
** WBS: 1.3.2.2.2.5.2	Wood Doors										
1 Wood doors		1	42320.00 eu	42.3	0	0.0	0		0.00	0.0	42.3
** Subtotal **				42.3			0			0.0	42.3
** WBS: 1.3.2.2.2.5.3	Overhead Coiling Doors										
3 Overhead coiling doors		1	14812.00 eu	14.8	0	0.0	0		0.00	0.0	14.8
** Subtotal **				14.8			0			0.0	14.8
** WBS: 1.3.2.2.2.5.4	Metal Windows										
1 Metal windows		1	170338.00 eu	170.3	0	0.0	0		0.00	0.0	170.3
** Subtotal **				170.3			0			0.0	170.3
** WBS: 1.3.2.2.2.5.5	Hardware										
1 Hardware		1	83582.00 eu	83.6	0	0.0	0		0.00	0.0	83.6
** Subtotal **				83.6			0			0.0	83.6
** WBS: 1.3.2.2.2.5.6	Glazing										
1 Glazing		1	26450.00 eu	26.4	0	0.0	0		0.00	0.0	26.4
** Subtotal **				26.4			0			0.0	26.4
** WBS: 1.3.2.2.2.6.1	Metal Support Systems										
1 Metal support systems		1	478216.00 eu	478.2	0	0.0	0		0.00	0.0	478.2

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **				478.2			0			0.0	478.2
** WBS: 1.3.2.2.2.6.2	Gypsum Board Systems										
1 Gypsum board systems		1	357604.00 eu	357.6	0	0.0	0		0.00	0.0	357.6
** Subtotal **				357.6			0			0.0	357.6
** WBS: 1.3.2.2.2.6.3	Tile										
1 Tile		1	117438.00 eu	117.4	0	0.0	0		0.00	0.0	117.4
** Subtotal **				117.4			0			0.0	117.4
** WBS: 1.3.2.2.2.6.4	Acoustical Ceilings										
1 Acoustical Ceilings		1	51842.00 eu	51.8	0	0.0	0		0.00	0.0	51.8
** Subtotal **				51.8			0			0.0	51.8
** WBS: 1.3.2.2.2.6.5	Resilient Flooring										
1 Resilient flooring		1	30682.00 eu	30.7	0	0.0	0		0.00	0.0	30.7
** Subtotal **				30.7			0			0.0	30.7
** WBS: 1.3.2.2.2.6.6	Carpet										
1 Carpet		1	41262.00 eu	41.3	0	0.0	0		0.00	0.0	41.3
** Subtotal **				41.3			0			0.0	41.3
** WBS: 1.3.2.2.2.6.7	Painting										
1 Painting		1	203136.00 eu	203.1	0	0.0	0		0.00	0.0	203.1
** Subtotal **				203.1			0			0.0	203.1
** WBS: 1.3.2.2.2.7.1	Visual Display Boards										
1 Visual display boards		1	3174.00 eu	3.2	0	0.0	0		0.00	0.0	3.2
** Subtotal **				3.2			0			0.0	3.2
** WBS: 1.3.2.2.2.7.2	Metal Toilet Compartments										
1 Metal toilet compartments		1	5290.00 eu	5.3	0	0.0	0		0.00	0.0	5.3
** Subtotal **				5.3			0			0.0	5.3
** WBS: 1.3.2.2.2.7.3	Metal Wall Louvers										
1 Metal wall louvers		1	33856.00 eu	33.9	0	0.0	0		0.00	0.0	33.9
** Subtotal **				33.9			0			0.0	33.9
** WBS: 1.3.2.2.2.7.4	Toilet and Bath Accessories										
1 Toilet & bath accessories		1	2116.00 eu	2.1	0	0.0	0		0.00	0.0	2.1
** Subtotal **				2.1			0			0.0	2.1
** WBS: 1.3.2.2.2.8	Energy Monitoring and Control Systems										
1 Energy monitoring & cntrl		1	239108.00 eu	239.1	0	0.0	0		0.00	0.0	239.1
** Subtotal **				239.1			0			0.0	239.1
** WBS: 1.3.2.2.2.9.1	Elevators										
1 Elevators		1	257094.00 eu	257.1	0	0.0	0		0.00	0.0	257.1
** Subtotal **				257.1			0			0.0	257.1
** WBS: 1.3.2.2.2.9.2	Hoists and Cranes										
1 Hoists & cranes		1	215832.00 eu	215.8	0	0.0	0		0.00	0.0	215.8

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **				215.8			0			0.0	215.8
** WBS: 1.3.2.2.2.10.1 Basic Materials and Methods											
1 Basic materials/methods		1	420026.00 eu	420.0	0	0.0	0		0.00	0.0	420.0
** Subtotal **				420.0			0			0.0	420.0
** WBS: 1.3.2.2.2.10.2 Mechanical Insulation											
1 Mechanical insulation		1	133308.00 eu	133.3	0	0.0	0		0.00	0.0	133.3
** Subtotal **				133.3			0			0.0	133.3
** WBS: 1.3.2.2.2.10.3 Fire Protection											
1 Fire protection		1	245456.00 eu	245.5	0	0.0	0		0.00	0.0	245.5
** Subtotal **				245.5			0			0.0	245.5
** WBS: 1.3.2.2.2.10.4 Plumbing											
1 Plumbing		1	142830.00 eu	142.8	0	0.0	0		0.00	0.0	142.8
** Subtotal **				142.8			0			0.0	142.8
** WBS: 1.3.2.2.2.10.5 Compressed Air System											
1 Compressed air system		1	50784.00 eu	50.8	0	0.0	0		0.00	0.0	50.8
** Subtotal **				50.8			0			0.0	50.8
** WBS: 1.3.2.2.2.10.6 Deionized Water System											
1 Deionized water		1	62422.00 eu	62.4	0	0.0	0		0.00	0.0	62.4
** Subtotal **				62.4			0			0.0	62.4
** WBS: 1.3.2.2.2.10.7 Low Conductivity Water System											
1 Low conductivity water		1	34914.00 eu	34.9	0	0.0	0		0.00	0.0	34.9
** Subtotal **				34.9			0			0.0	34.9
** WBS: 1.3.2.2.2.10.8 Heat Generation											
1 Heat generation		1	100510.00 eu	100.5	0	0.0	0		0.00	0.0	100.5
** Subtotal **				100.5			0			0.0	100.5
** WBS: 1.3.2.2.2.10.9 Refrigeration											
1 Refrigeration		1	471868.00 eu	471.9	0	0.0	0		0.00	0.0	471.9
** Subtotal **				471.9			0			0.0	471.9
** WBS: 1.3.2.2.2.10.10 Air Handling											
1 Air handling		1	479274.00 eu	479.3	0	0.0	0		0.00	0.0	479.3
** Subtotal **				479.3			0			0.0	479.3
** WBS: 1.3.2.2.2.10.11 Air Distribution											
1 Air distribution		1	630568.00 eu	630.6	0	0.0	0		0.00	0.0	630.6
** Subtotal **				630.6			0			0.0	630.6
** WBS: 1.3.2.2.2.10.12 Testing and Balancing											
1 Testing and balancing		1	12696.00 eu	12.7	0	0.0	0		0.00	0.0	12.7
** Subtotal **				12.7			0			0.0	12.7
** WBS: 1.3.2.2.2.11.1 12 kV Distributions											
1 12 kV distribution		1	790326.00 eu	790.3	0	0.0	0		0.00	0.0	790.3

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **					790.3			0			0.0	790.3
** WBS: 1.3.2.2.2.11.2	Power Service and Distribution											
1	Power service & distribtn		1	249688.00 eu	249.7	0	0.0	0		0.00	0.0	249.7
** Subtotal **					249.7			0			0.0	249.7
** WBS: 1.3.2.2.2.11.3	Emergency System											
1	Emergency system		1	100510.00 eu	100.5	0	0.0	0		0.00	0.0	100.5
** Subtotal **					100.5			0			0.0	100.5
** WBS: 1.3.2.2.2.11.4	Power and Motor Feeders											
1	Power & motor feeders		1	259210.00 eu	259.2	0	0.0	0		0.00	0.0	259.2
** Subtotal **					259.2			0			0.0	259.2
** WBS: 1.3.2.2.2.11.5	Lighting											
1	Lighting		1	189382.00 eu	189.4	0	0.0	0		0.00	0.0	189.4
** Subtotal **					189.4			0			0.0	189.4
** WBS: 1.3.2.2.2.11.6	Misc. Power Devices											
1	Misc. power devices		1	55016.00 eu	55.0	0	0.0	0		0.00	0.0	55.0
** Subtotal **					55.0			0			0.0	55.0
** WBS: 1.3.2.2.2.11.7	Communications											
1	Communications		1	126960.00 eu	127.0	0	0.0	0		0.00	0.0	127.0
** Subtotal **					127.0			0			0.0	127.0
** WBS: 1.3.2.2.2.11.8	Fire Alarm System											
1	Fire alarm system		1	22218.00 eu	22.2	0	0.0	0		0.00	0.0	22.2
** Subtotal **					22.2			0			0.0	22.2
** WBS: 1.3.2.2.3.1	Laboratory Benches											
1	Laboratory benches		1	210300.00 eu	210.3	0	0.0	0		0.00	0.0	210.3
** Subtotal **					210.3			0			0.0	210.3
** WBS: 1.3.2.2.3.2	Chemical Storage Cabinets											
1	Chemical storage cabinets		1	9800.00 eu	9.8	0	0.0	0		0.00	0.0	9.8
** Subtotal **					9.8			0			0.0	9.8
** WBS: 1.3.2.2.3.3	Fume Hoods											
1	Fume hoods		1	232100.00 eu	232.1	0	0.0	0		0.00	0.0	232.1
** Subtotal **					232.1			0			0.0	232.1
** WBS: 1.3.2.2.3.4	Instrument Racks											
1	Instrument racks		1	52700.00 eu	52.7	0	0.0	0		0.00	0.0	52.7
** Subtotal **					52.7			0			0.0	52.7
** WBS: 1.3.2.2.3.5	Vacuum Systems											
1	Vacuum systems		1	105500.00 eu	105.5	0	0.0	0		0.00	0.0	105.5
** Subtotal **					105.5			0			0.0	105.5
** WBS: 1.3.2.2.3.6	Liquid Nitrogen Distribution Systems											
1	LN distribution systems		1	246180.00 eu	246.2	0	0.0	0		0.00	0.0	246.2

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **				246.2			0			0.0	246.2
** WBS: 1.3.2.2.3.7	Acid Drain Systems										
1 Acid drain systems		1	62800.00 eu	62.8	0	0.0	0		0.00	0.0	62.8
** Subtotal **				62.8			0			0.0	62.8
** WBS: 1.3.2.2.3.8	Laser Safety Contol Systems										
1 Laser safety control sys		1	32000.00 eu	32.0	0	0.0	0		0.00	0.0	32.0
** Subtotal **				32.0			0			0.0	32.0
** WBS: 1.3.2.2.3.9	Vacuum Control Systems										
1 Vacuum control systems		1	37600.00 eu	37.6	0	0.0	0		0.00	0.0	37.6
** Subtotal **				37.6			0			0.0	37.6
** WBS: 1.3.2.2.3.10	Chemical Detection Systems										
1 Chemical detection system		1	232300.00 eu	232.3	0	0.0	0		0.00	0.0	232.3
** Subtotal **				232.3			0			0.0	232.3
** WBS: 1.3.2.2.3.11	Data Acquisition System										
1 Data acquisitn sys (link)		1	281400.00 eu	281.4	0	0.0	0		0.00	0.0	281.4
** Subtotal **				281.4			0			0.0	281.4
** WBS: 1.3.2.2.4.1.1	Water Distribution Systems										
1 Water distribution system		1	21741.00 eu	21.7	0	0.0	0		0.00	0.0	21.7
** Subtotal **				21.7			0			0.0	21.7
** WBS: 1.3.2.2.4.1.2	Gas Distribution System										
1 Gas distribution system		1	21741.00 eu	21.7	0	0.0	0		0.00	0.0	21.7
** Subtotal **				21.7			0			0.0	21.7
** WBS: 1.3.2.2.4.1.3	Sewage and Drainage										
1 Sewage and drainage		1	3766.00 eu	3.8	0	0.0	0		0.00	0.0	3.8
** Subtotal **				3.8			0			0.0	3.8
** WBS: 1.3.2.2.4.2.1	Building 37 Extension										
1 Building 37 extension		1	1316120.26 eu	1316.1	0	0.0	0		0.00	0.0	1316.1
** Subtotal **				1316.1			0			0.0	1316.1
** WBS: 1.3.2.2.4.2.2	Low Conductivity Water (LCW) Connection										
1 LCW connection		1	41060.98 eu	41.1	0	0.0	0		0.00	0.0	41.1
** Subtotal **				41.1			0			0.0	41.1
** WBS: 1.3.2.2.4.2.3	Treated Water Connection										
1 Treated water connection		1	41060.98 eu	41.1	0	0.0	0		0.00	0.0	41.1
** Subtotal **				41.1			0			0.0	41.1
** WBS: 1.3.2.2.4.3.1	15 kV Power Service										
1 15 kV power service		1	67193.58 eu	67.2	0	0.0	0		0.00	0.0	67.2
** Subtotal **				67.2			0			0.0	67.2
** WBS: 1.3.3.1	Standard Laser Systems										
1 Standard laser systems		1	1033170.00 eu	1033.2	0	0.0	0		0.00	0.0	1033.2

Technical Components Cost Estimate

ITM ITM NBR DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **											
				1033.2			0			0.0	1033.2
** WBS: 1.3.3.2	Office Furniture & Equipment										
1 Office furn & equipment		1	111090.00 eu	111.1	0	0.0	0		0.00	0.0	111.1
** Subtotal **											
				111.1			0			0.0	111.1
** WBS: 1.3.3.3	Personal Computers										
1 Personal computers		1	161080.50 eu	161.1	0	0.0	0		0.00	0.0	161.1
** Subtotal **											
				161.1			0			0.0	161.1
** WBS: 1.3.3.4	Computer Workstations										
1 Computer workstations		1	855393.00 eu	855.4	0	0.0	0		0.00	0.0	855.4
** Subtotal **											
				855.4			0			0.0	855.4
** WBS: 1.3.3.5	Diagnostic and Detection Systems										
1 Diagnostic/detection sys		1	493239.60 eu	493.2	0	0.0	0		0.00	0.0	493.2
** Subtotal **											
				493.2			0			0.0	493.2
** WBS: 1.3.3.6	Electronic Balance										
1 Electronic balance		1	4443.60 eu	4.4	0	0.0	0		0.00	0.0	4.4
** Subtotal **											
				4.4			0			0.0	4.4
** WBS: 1.3.3.7	Vacuum Leak Detector										
1 Vacuum leak detector		1	19996.20 eu	20.0	0	0.0	0		0.00	0.0	20.0
** Subtotal **											
				20.0			0			0.0	20.0
** WBS: 1.3.3.8	Casettometer										
1 Casettometer		1	5554.50 eu	5.6	0	0.0	0		0.00	0.0	5.6
** Subtotal **											
				5.6			0			0.0	5.6
** WBS: 1.3.3.9	Streak Camera System										
1 Streak Camera System	lot	1	149971.50 eu	150.0	0	0.0	0		0.00	0.0	150.0
** Subtotal **											
				150.0			0			0.0	150.0
** WBS: 1.3.3.10	Equipment for SNL upstairs lab										
1 Equip for SNL lab	lot	1	1876000.00 fu	1876.0	0	0.0	0		0.00	0.0	1876.0
** Subtotal **											
				1876.0			0			0.0	1876.0
** WBS: 1.4.1	Project Management Contingency										
1 Project Mgmt Contingency		1	700000.00	700.0	0	0.0	0		0.00	0.0	700.0
** Subtotal **											
				700.0			0			0.0	700.0
** WBS: 1.4.2.1	IRFEL										
1 IRFEL Contingency		1	5443000.00	5443.0	0	0.0	0		0.00	0.0	5443.0
** Subtotal **											
				5443.0			0			0.0	5443.0
** WBS: 1.4.2.2	ALS Beamlines										
1 ALS Beamlines Contingency		1	1795000.00	1795.0	0	0.0	0		0.00	0.0	1795.0
** Subtotal **											
				1795.0			0			0.0	1795.0
** WBS: 1.4.2.3	Experimental Systems										
1 Exper Systems Contingency		1	4405000.00	4405.0	0	0.0	0		0.00	0.0	4405.0

Technical Components Cost Estimate

ITM NBR	ITM DESCRIPTION	UNIT MEAS	NBR UNITS	UNIT COST COST BASIS	TOTAL ISC K$	LBR UNTS	HRS/ UNIT	TOTAL HRS	CRAFT CODE	CRAFT RATE	TOTAL LABOR K$	ISC + LABOR K$
** Subtotal **					4405.0			0			0.0	4405.0
** WBS: 1.4.3	Conventional Facilities Contingency											
1	Convtnl Facility Cntngncy		1	3811000.00	3811.0	0	0.0	0		0.00	0.0	3811.0
** Subtotal **					3811.0			0			0.0	3811.0
*** Total ***					74680.4			253613			10955.1	85635.5

rev 2/5/92

Chemical Dynamics Research Laboratory

Schedule of Costs (FY92M$)

	FY94	FY95	FY96	FY97	FY98	Sum: 94 - 98
1. CDRL	**6.01**	**17.61**	**27.14**	**26.92**	**8.92**	**86.60**
1.1 Project management	**0.77**	**1.03**	**1.03**	**1.03**	**1.03**	**4.89**
1.2 Spec. research facilities	**3.11**	**9.90**	**11.81**	**11.10**	**5.87**	**41.79**
1.2.1 ED&I	1.63	2.23	2.23	2.23	1.57	9.89
1.2.1.1 IRFEL	0.84	1.09	1.08	1.09	0.67	4.77
1.2.1.2 ALS beamlines	0.27	0.39	0.40	0.41	0.18	1.65
1.2.1.3 Exper. Systems	0.52	0.75	0.75	0.73	0.72	3.47
1.2.2 Construction	1.48	7.67	9.58	8.87	4.30	31.90
1.2.2.1 IRFEL	1.01	3.99	4.78	4.48	1.13	15.39
1.2.2.2 ALS beamlines	0.00	0.98	1.74	1.39	1.20	5.31
1.2.2.3 Exper. Systems	0.47	2.70	3.06	3.00	1.97	11.20
1.3 Conventional facilities*	**0.98**	**3.26**	**9.49**	**10.04**	**0.00**	**23.77**
1.3.1 ED&I	0.98	0.86	0.29	0.30	0.00	2.43
1.3.2 Construction	0.00	2.40	8.28	5.95	0.00	16.63
1.3.3 Standard equipment	0.00	0.00	0.92	3.79	0.00	4.71
1.4 Contingencies	**1.15**	**3.42**	**4.81**	**4.75**	**2.02**	**16.15**
1.4.1 Project management	0.10	0.15	0.15	0.15	0.15	0.70
1.4.2 Special res. facilities	0.89	2.77	3.14	2.97	1.87	11.64
1.4.2.1 IRFEL	0.53	1.39	1.47	1.38	0.67	5.44
1.4.2.2 ALS beamlines	0.06	0.35	0.53	0.45	0.40	1.79
1.4.2.3 Exper. Systems	0.30	1.03	1.14	1.14	0.80	4.41
1.4.3 Conventional facililities*	0.16	0.50	1.52	1.63	0.00	3.81

*From revised BA/BO schedule

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

DETAILS OF COST ESTIMATE

CHEMICAL DYNAMICS RESEARCH LABORATORY
CONVENTIONAL FACILITIES

COST ESTIMATE - SCHEMATIC ESTIMATE

The cost estimate was prepared by Lee Saylor, Inc. (Construction Consultants, Concord, California) in December 1989 and re-summarized under the following categories:

1. Site Preparation
2. Utilities
3. Building
4. Special Building Facilities

The mark-ups recommended by the Cost Consultant were applied to the above categories and escalation was added using the DOE "Anticipated Economic Escalation Rates," updated August 1990.

LEE SAYLOR, INC.
CONSTRUCTION CONSULTANTS
1420 WILLOW PASS ROAD
CONCORD, CALIFORNIA 94520

S.F. 415-933-6000
L.A. 213-937-8181

COMBUSTION DYNAMICS FACILITY
Berkeley, California

SCHEMATIC ESTIMATE

LSI #A599B

January 11, 1990

Class Code 12.20

PROJECT MANAGEMENT • ESTIMATES • SCHEDULES • FEASIBILITY STUDIES • CONSTRUCTION CLAIMS

LEE SAYLOR, INC.
CONSTRUCTION CONSULTANTS
1420 WILLOW PASS ROAD
CONCORD, CALIFORNIA 94520
S F 415-933-6000
L A 213-937-8181

The design contingency has not been included in this estimate. The design contingency is an allowance for items or details that will be added to the drawings as the drawings progress from schematic to final stage. At the final stage the contingency will be dropped altogether. We recommend a design contingency of 10% on this schematic estimate.

PROJECT MANAGEMENT • ESTIMATES • SCHEDULES • FEASIBILITY STUDIES • CONSTRUCTION CLAIMS

1. The Lee Saylor Current Construction Cost Estimating Manual Data Base was used as a guide in providing unit costs for the various items. Prices vary from the manual due to the location, quality, degree of difficulty, uniqueness, large or small project, market factor, productivity and access to project.

2. The estimate is based on San Francisco Bay Area costs.

3. Prices are of December, 1989 costs. No escalation is included.

4. The following work is normally handled by the general contractor:

   All concrete work, installing cabinets, doors and toilet accessories, and any finish carpentry work.

   All other work is by subcontractors and their unit costs include: mobilization, bonds, overhead and profit.

5. General contractors prorates are not included in the estimate. We recommend the following prorates to be added to the estimate:

General Conditions	6%
OH and Profit	10%
Bonds	2%

6. Area Tabulation is as follows:

Basement	13,980 SF
1st Floor	11,320 SF
Interstitial Floor	3,990 SF
2nd Floor	9,490 SF
3rd Floor	7,220 SF
Penthouse	600 SF
Total	46,600 SF

ITEM	SF	$/SF	COST
SITE PREPARATION	46,600	$ 40.89	$ 1,906,091
UTILITIES	46,600	25.84	1,204,314
BUILDING	46,600	191.64	8,930,446
SPECIAL BUILDING FACILITIES	46,600	25.68	1,196,569
TOTAL		$284.06	**$13,237,420**

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	CONVENTIONAL FACILITIES				
	SITE PREPARATION				
02060	BUILDING DEMOLITION:				
1	Building Demolition	16,470	SF	7.50	$123,525
2	Curbs	60	LF	2.00	120
	SUBTOTAL				$123,645
02150	SHORING & UNDERPINNING:				
1	Shoring, 6 x 12 Treated Lagging, 30" Dia. Caissons x 32' Deep Tie Back 4 Ea @ Each Soldier Beam @ 5' O.C.	13,932	SF	25.00	$348,300
	SUBTOTAL				$348,300
02220	EXCAVATION:				
1	Mass Excavation Haul-Off Site	13,230	CY	18.00	$238,140
2	Fill at Stairs	340	CY	25.00	8,500
	SUBTOTAL				$246,640

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
02780	MODIFICATION TO EXISTING SYSTEMS:				
1	1200A, 15KV Vacuum CBS	2	EA	27,500	$55,000
2	Elect Duct Bank Relocation	1	LS	75,200	75,200
3	Telephone Duct Bank Relocation	1	LS	45,800	45,800
4	Demolish Duct Bank	600	LF	25.00	15,000
* 5	Fiber Splicing	1	LS	76,550	76,550
* 6	Relocation of Integrated Communication Systems ICS Note 2 Relocation incl. cabling from new location to CDF Building	1	LS	919,956	919,956
	SUBTOTAL				$1,187,506
	TOTAL - SITE PREPARATION				**$1,906,091**
*	Costs Provided by LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY
Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	UTILITIES				
	MECHANICAL				
02665	WATER DISTRIBUTION SYSTEMS:				
1	Abandon Existing Utilities	1	LS	5,769	$5,769
2	Water Distribution	1	LS	11,538	11,538
	SUBTOTAL				$17,307
02685	GAS DISTRIBUTION SYSTEMS:				
1	Abandon Existing Utilities	1	LS	5,769	$5,769
2	Gas Distribution	1	LS	11,538	11,538
	SUBTOTAL				$17,307
02700	SEWERAGE AND DRAINAGE:				
1	Abandon Existing Utilities	1	LS	500.00	$500
2	Sewerage and Drainage	1	LS	2,500	2,500
	SUBTOTAL				$3,000

Lee Saylor, Inc.

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Berkeley, California

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	COOLING TOWER				
02701	BUILDING 37 EXTENSION:				
* 1	Construction and Equipment	1	LS	1023740	$1,023,740
2	Utility Connection	1	LS	24,080	24,080
	SUBTOTAL				$1,047,820
02702	LOW CONDUCTIVITY WATER CONNECT:				
1	Low Conductivity Water	1	LS	32,690	$32,690
	SUBTOTAL				$32,690
02703	TREATED WATER CONNECTION:				
1	Treated Water Connection	1	LS	32,690	$32,690
	SUBTOTAL				$32,690

* Costs provided by LBL

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COMBUSTION DYNAMICS FACILITY

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	ELECTRICAL				
02790	15 KV POWER SERVICE				
1	Duct Bank 4-5"	150	LF	26.00	$3,900
2	1/C - 500MCM - 15KV, 6 Cables	4,800	LF	9.00	43,200
3	4/O Cable - Ground	1,600	LF	4.00	6,400
	SUBTOTAL				$53,500
	TOTAL - UTILITIES				**$1,204,314**

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COMBUSTION DYNAMICS FACILITY

Berkeley, California

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Checked By: R. Stauffer
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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	BUILDING				
	SITE WORK				
02500	PAVING & SURFACING:				
1	Patching of A.C. Paving	11,000	SF	2.50	$27,500
2	Overlay	14,740	SF	0.72	10,613
3	New A.C. Paving	760	SF	2.90	2,204
	SUBTOTAL				$40,317
02520	CYCLOTRON ROAD PARKING				
* 1	Structure and Paving	16	SPACE	4,675	$74,800
	SUBTOTAL				$74,800
02800	SITE IMPROVEMENTS				
1	Concrete Curb	580	LF	9.50	$5,510
2	Striping	120	LF	0.40	48
3	Stairs Treads	450	LF	15.00	6,750
4	Landings	275	SF	3.50	963
5	Railing	190	LF	19.50	3,705
6	Platform for Emergency	450	SF	45.00	20,250
	SUBTOTAL				$37,226
*	Costs Provided by LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

SCHEMATIC ESTIMATE

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
02900	LANDSCAPING				
1	Planters	675	SF	5.00	$3,375
2	Misc. Landscaping - Allowance (Provided by LBL)	1	LS	2,800	2,800
	SUBTOTAL				$6,175
	TOTAL - SITE WORK				**$158,517**

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
03300	CONCRETE				
1	2" Sand	83	CY	25.00	$2,075
2	Vapor Barrier	16,000	SF	0.08	1,280
3	6" Drain Rock	123	CY	26.00	3,198
4	6" Perforated Drain	510	LF	15.00	7,650
5	Under Slab Drain	1,000	LF	15.00	15,000
6	Working Slab	13,230	SF	2.20	29,106
7	Concrete Mat (5" Thick)	2,573	CY	78.00	200,694
8	Construction Joints	800	SF	5.50	4,400
9	Key Joints	480	LF	5.00	2,400
10	Sand Blast Joints	100	SF	1.00	100
11	Trowel	9,940	SF	0.50	4,970
12	Sealer	9,940	SF	0.20	1,988
	WALLS:				
13	Forming 1 Side	7,874	SF	5.50	43,307
14	Form Pilaster	514	SF	10.50	5,397
15	Concrete	380	CY	88.00	33,440
16	Miscellaneous Accessories	380	CY	12.00	4,560
17	Finish	8,388	SF	0.80	6,710
	COLUMNS:				
18	Forming	510	SF	10.50	5,355
19	Concrete	10	CY	103.00	1,030
20	Finish	510	SF	0.80	408
21	Miscellaneous Accessories	10	CY	12.00	120
	HEAVY WALLS:				
22	Forming	5,333	SF	12.50	66,663
23	Concrete	1,366	CY	88.00	120,208
24	Finish	5,333	SF	0.80	4,266
25	Miscellaneous Accessories	1,366	CY	12.00	16,392

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COMBUSTION DYNAMICS FACILITY

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	INTERIOR WALLS:				
26	Form 2 Sides	2,286	SF	5.50	12,573
27	Concrete	100	CY	88.00	8,800
28	Finishes	2,286	SF	0.80	1,829
29	Miscellaneous Accessories	100	CY	12.00	1,200
	SUPPORTED SLAB:				
30	Forming, Door Opening	217	SF	12.50	2,713
31	Soffit	80	SF	12.50	1,000
32	Supported Slab Soffit	9,940	SF	14.50	144,130
33	Concrete	3,310	CY	85.00	281,350
34	Trowel	13,230	SF	0.50	6,615
35	Miscellaneous Accessories	3,310	CY	12.00	39,720
	MISCELLANEOUS ITEMS:				
36	Water Stops	1,320	LF	7.00	9,240
37	Construction Joints	3,910	SF	5.50	21,505
38	Sand Blast Joints	3,910	SF	1.00	3,910
39	Key Joints (3 x 6)	2,500	LF	5.00	12,500
40	Drain Gravel	20	CY	26.00	520
41	Equipment Slabs	1,211	SF	4.50	5,450
42	RF Shielding	947	SF	15.00	14,205
43	Depressed Slab	80	LF	5.20	416
	CONCRETE SLIDING DOORS:				
44	Forming	680	SF	15.00	10,200
45	Concrete	31	CY	105.00	3,255
46	Rails - Embedded	64	LF	50.00	3,200
47	Finish	680	SF	1.00	680
48	Slab at Stairs	216	SF	5.00	1,080
	LIFT-UP PANELS:				
49	Forming	252	SF	8.50	2,142
50	Concrete	15	CY	105.00	1,575
51	Finish	252	SF	1.00	252
52	Lifting Inserts	8	EA	35.00	280

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COMBUSTION DYNAMICS FACILITY

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SCHEMATIC ESTIMATE

LSI No. A599B
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Date: January 11, 1990

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	REINFORCING:				
53	Reinforcing for All Concrete	873,276	LBS	0.52	454,104
	TOTAL - CONCRETE				**$1,625,160**

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COMBUSTION DYNAMICS FACILITY

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	METALS				
05120	STRUCTURAL STEEL:				
1	Steel Beams	300,815	#	0.75	$225,611
2	Bracing	103,190	#	0.80	82,552
3	Trusses	161,598	#	0.80	129,278
4	Tube Bracing	27,245	#	1.20	32,694
5	Columns	107,670	#	0.90	96,903
6	Support for Siding	49,800	#	0.70	34,860
7	Detail Steel	52,520	#	1.09	57,247
	SUBTOTAL				$659,145
05310	STEEL DECK:				
1	Metal Deck @ Interst Floor	30,278	SF	3.60	$109,001
2	Concrete Fill, Interstitial Floor, Light Weight	3,570	SF	2.50	8,925
3	Equipment Pads	1,773	SF	4.50	7,979
4	Seal Concrete	13,990	SF	0.20	2,798
5	Concrete Fill, 3" Lt. Wt.	10,640	SF	2.50	26,600
6	Concrete Fill, 2 1/2" Lt. Wt.	8,968	SF	2.35	21,075
7	Concrete Fill, 2" Lt.Wt.	7,100	SF	2.30	16,330
	SUBTOTAL				$192,707

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

SCHEMATIC ESTIMATE

LSI No. A599B
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ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
05500	METAL FABRICATION:				
1	Stairs, Flights	10	FLT	4,500	$45,000
2	Railings	360	LF	45.00	16,200
3	Railing at Catwalk	350	LF	35.00	12,250
4	Grating	680	SF	35.00	23,800
5	Embedded A. Bolts @ Col. Base	136	EA	12.00	1,632
6	Grout @ Column Base	34	EA	15.00	510
7	Bollards - Allow	5	EA	290.00	1,450
	SUBTOTAL				$100,842
	TOTAL - METALS				**$952,695**

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Berkeley, California

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	WOOD & PLASTIC				
06410	CUSTOM CASEWORK:				
1	Cabinets Under Hoods	66	LF	380.00	$25,080
2	Base Cabinets	50	LF	276.00	13,800
3	Reception Desk	15	LF	280.00	4,200
4	Vanities	28	LF	150.00	4,200
	TOTAL - WOODS & PLASTICS				**$47,280**

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	THERMAL & MOISTURE PROTECTION				
07100	WATERPROOFING:				
1	Bentonite	13,932	SF	2.20	$30,650
2	Waterproofing @ Terraces	2,760	SF	2.10	5,796
	SUBTOTAL				$36,446
07150	DAMPPROOFING:				
1	Waterproofing at Planters	1,775	SF	2.50	$4,438
	SUBTOTAL				$4,438
07200	INSULATION:				
1	6" Batt Insulation At Perimeter Wall	17,850	SF	0.65	$11,603
2	3 1/2" Batt Insulation @ Interior	2,500	SF	0.45	1,125
	SUBTOTAL				$12,728
07250	FIREPROOFING:				
1	Fireproofing of Steel	401	TONS	195.00	$78,195
	SUBTOTAL				$78,195

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
07460	PREFORMED METAL SIDING FACTORY FINISH				
1	Metal Siding, Smooth (Sandwich Panel)	10,750	SF	20.00	$215,000
2	Metal Siding, Ribbed (Sandwich Panel)	8,685	SF	20.00	173,700
	SUBTOTAL				$388,700
07500	MEMBRANE ROOFING:				
1	Membrane Roofing	6,783	SF	2.50	$16,958
2	Rigid Insulation	6,783	SF	2.85	19,332
	SUBTOTAL				$36,289

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
07620	SHEET METAL FLASHING:				
1	Sheet Metal Coping	475	LF	8.50	$4,038
2	Reglet	550	LF	6.20	3,410
3	Flashing	520	LF	6.30	3,276
	SUBTOTAL				$10,724
07900	SEALANTS:				
1	Caulking	46,600	SF	0.30	$13,980
	SUBTOTAL				$13,980
	TOTAL - THERMAL & MOISTURE PROTECTION				**$581,499**

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COMBUSTION DYNAMICS FACILITY
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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	DOORS & WINDOWS				
08100	METAL DOORS & FRAMES:				
1	Hollow Metal Frames	82	EA	130.00	$10,660
2	Hollow Metal Frames, Pair	17	EA	180.00	3,060
3	Hollow Metal Doors, Exterior	2	EA	250.00	500
4	Hollow Metal Frame	2	EA	130.00	260
5	Hollow Metal Door, 1 1/8 Hour	18	EA	290.00	5,220
6	Hollow Metal Frame	18	EA	130.00	2,340
7	Labor to Install Frame	120	EA	55.00	6,600
8	Labor to Install Doors	20	EA	65.00	1,300
	SUBTOTAL				$29,940
08210	WOOD DOORS:				
1	3'7" X 7'0" S.C. - Plastic Laminated	82	EA	210.00	$17,220
2	6'0" x 9'0" S.C. - Plastic Laminated	17	PAIR	420.00	7,140
3	Labor to Install Doors	116	EA	65.00	7,540
4	Allow for Glass in Doors	1	LS	1,500	1,500
	SUBTOTAL				$33,400
08331	OVERHEAD COILING DOORS:				
1	Roll-up Insulated Doors, (14 x 10)	2	EA	3,900	$7,800
2	Roll-up Doors, (14 x 10), Fire Rated	1	EA	3,900	3,900
	SUBTOTAL				$11,700

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SCHEMATIC ESTIMATE

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ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
08500	METAL WINDOWS:				
1	Glass & Sash, Double Glazed	3,870	SF	35.00	$135,450
	SUBTOTAL				$135,450
08700	HARDWARE:				
1	Hardware Sets	136	EA	425.00	$57,800
2	Labor to Install Hardware	136	EA	65.00	8,840
	SUBTOTAL				$66,640
08800	GLAZING:				
1	Storefront	278	SF	29.00	$8,062
2	Aluminum Entrance Doors (Non Automatic)	8	EA	1,600	12,800
	SUBTOTAL				$20,862
	TOTAL - DOORS & WINDOWS				**$297,992**

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	FINISHES				
09100	METAL SUPPORT SYSTEMS:				
1	Perimeter Metal Studs	24,482	SF	4.00	$97,928
2	Interior Metal Studs	39,194	SF	3.85	150,897
3	Interior M. Studs @ 2 Hrs Walls	18,145	SF	3.85	69,858
4	Furring	326	SF	3.00	978
5	Column Furring	12,178	SF	4.50	54,801
6	Planter Walls	1,180	SF	5.50	6,490
	SUBTOTAL				$380,952
09260	GYPSUM BOARD SYSTEMS:				
1	Furring	326	SF	3.00	$978
2	Gypsum Board	326	SF	1.45	473
3	Gypsum Board @ Perimeter	24,482	SF	1.45	35,499
4	Gypsum Board @ Interior Studs	78,388	SF	1.45	113,663
5	Gypsum Board @ 2 Hr Partition (2 Layers)	36,290	SF	2.65	96,169
6	Gypsum Board @ Columns	12,178	SF	2.10	25,574
8	Suspension System - Ceiling	2,859	SF	3.00	8,577
9	Gypsum Board - Ceiling	2,859	SF	1.45	4,146
	SUBTOTAL				$285,077

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
09300	TILE:				
1	Quarry Tile	1,016	SF	11.20	$11,379
2	Quarry Tile - Base	310	LF	12.00	3,720
3	Ceramic Tile - Floor	1,020	SF	7.50	7,650
4	Ceramic Tile - Base	900	LF	5.10	4,590
5	Ceramic Tile - Walls	3,456	SF	9.20	31,795
6	Quarry Tile at Terrace	2,460	SF	11.20	27,552
7	Quarry Tile - Base	575	LF	12.00	6,900
	SUBTOTAL				$93,586
09510	ACOUSTICAL CEILINGS:				
1	Acoustic Tile, 1 Hour	18,008	SF	2.30	$41,418
	SUBTOTAL				$41,418
09650	RESILIENT FLOORING:				
1	Vinyl Tile	7,609	SF	3.10	$23,588
2	VCT	350	SF	1.80	630
3	Base	100	LF	1.50	150
	SUBTOTAL				$24,368
09680	CARPET:				
1	Carpet	947	SY	35.00	$33,145
	SUBTOTAL				$33,145

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
09900	PAINTING:				
1	Paint Concrete Wall	2,858	SF	0.75	$2,144
2	Epoxy Floor	8,916	SF	2.50	22,290
3	Textured Walls	13,720	SF	1.00	13,720
4	Concrete Walls	11,837	SF	0.75	8,878
5	Concrete Ceiling	9,794	SF	0.80	7,835
6	Gypsum Board	109,880	SF	0.75	82,410
7	Metal Deck Exposed - Ceiling	6,802	SF	1.50	10,203
8	Doors & Frames	136	EA	45.00	6,120
9	Miscellaneous Painting	1	LS	3,500	3,500
10	Flashing	2,105	LF	1.20	2,526
11	Railings	890	LF	2.50	2,225
	SUBTOTAL				$161,850
	TOTAL - FINISHES				**$1,020,397**

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	SPECIALTIES				
10100	VISUAL DISPLAY BOARDS:				
1	Visual Display Boards	1	LS	2,500	$2,500
	SUBTOTAL				$2,500
10160	METAL TOILET COMPARTMENTS:				
1	Toilet Partitions	5	EA	390.00	$1,950
2	Handicap Partitions	4	EA	450.00	1,800
3	Urinal Screen	1	EA	110.00	110
	SUBTOTAL				$3,860
10210	METAL WALL LOUVERS:				
1	Louvers	700	SF	39.00	$27,300
	SUBTOTAL				$27,300

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SCHEMATIC ESTIMATE

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ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
10800	TOILET & BATH ACCESSORIES:				
1	Toilet Accessories	38	EA	35.00	$1,330
	SUBTOTAL				$1,330
	TOTAL - SPECIALTIES				**$34,990**

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
13810	ENERGY MANAGEMENT SYSTEM				
* 1	Energy Management Central Computing Control System	1	LS	190,000	$190,000
	TOTAL - ENERGY MANAGEMENT SYSTEM				**$190,000**
*	COSTS BY LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY
Berkeley, California

SCHEMATIC ESTIMATE

LSI No. A599B
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Date: January 11, 1990

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	CONVEYING				
14200	ELEVATORS:				
1	Elevator (10 x 13), 10,000 # 4 Stops, 50' - Hydraulic	1	EA	119,700	$119,700
2	Elevator (5 x 7), 3 Stop, 45'	1	EA	85,000	85,000
	SUBTOTAL				$204,700
14600	HOISTS & CRANES:				
1	Hoists, 15' Span Rail, 125 LF (5 Ton)	1	EA	57,910	$57,910
2	Hoists, 8' Span Rail - 31 LF (2 Ton)	1	EA	27,750	27,750
3	Crane - 70' Span, 70' Long, 5 Tons, To Hang From Trusses	1	EA	85,000	85,000
4	Embeds for Hoist Rails	1	LS	1,500	1,500
	SUBTOTAL				$172,160
	TOTAL - CONVEYING				**$376,860**

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY
Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	MECHANICAL				
15050	BASIC MATERIALS & METHODS:				
1	Treated Water Systems	46,600	SF	0.27	$12,582
2	Domestic Water Systems	90	FIX	840.00	75,600
3	Chilled & Heating Hot Water Systems	46,600	SF	2.98	138,868
4	Domestic Drain, Waste & Vent Systems	90	FIX	480.00	43,200
5	Bldg Gas Distribution Systems	46,600	SF	0.40	18,640
6	Bldg Storm Drainage Systems	46,600	SF	0.31	14,446
7	Underfloor Radiant Heating System	2,500	LF	12.50	31,250
	SUBTOTAL				$334,586
15250	MECHANICAL INSULATION:				
1	Pipe Insulation	7,260	LF	4.00	$29,040
2	Duct Insulation	46,600	SF	1.50	69,900
3	Equipment Insulation	1	LS	7,500	7,500
	SUBTOTAL				$106,440
15300	FIRE PROTECTION:				
1	Wet, Concealed - Ord Hazard	36,720	SF	1.80	$66,096
2	Halon	10,000	SF	12.70	127,000
3	Testing	1	LS	2,300	2,300
	SUBTOTAL				$195,396

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
15400	PLUMBING:				
1	Toilet Fixtures	30	EA	450.00	$13,500
2	Lab Fixtures	40	EA	550.00	22,000
3	Drinking Fountains	5	EA	700.00	3,500
4	Janitor Sinks	5	EA	500.00	2,500
5	Emergency Wash Equipment	10	EA	650.00	6,500
6	Hot Water Generation/ Circulation	1	LS	15,000	15,000
7	Rough In At Fixtures	90	EA	450.00	40,500
8	Drop Stations	40	EA	245.00	9,800
	SUBTOTAL				$113,300
15482	COMPRESSED AIR SYSTEM:				
1	Compressed Air System	12,730	SF	3.17	$40,354
	SUBTOTAL				$40,354
15484	DEIONIZED WATER SYSTEM:				
1	Deionized Water System	12,730	SF	1.48	$18,840
2	Hot Deionized Water	12,730	SF	2.41	30,679
	SUBTOTAL				$49,520
15485	LCW SYSTEM:				
1	LCW System	15,400	SF	1.82	$28,028
	SUBTOTAL				$28,028

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
15550	HEAT GENERATION:				
1	Heat Generation	200	HP	400.00	$80,000
	SUBTOTAL				$80,000
15650	REFRIGERATION:				
1	Refrigeration	400	TONS	690.00	$276,000
* 2	Allow for Chiller Conservation Items Based on Life Cycle Costs	1	LS	100,000	100,000
	SUBTOTAL				$376,000
15850	AIR HANDLING:				
1	Air Handlers	141.50	MCFM	1,750	$247,625
2	Exhaust Equipment	74.7	MCFM	250.00	18,675
3	Fume Exhaust Equipment	58	MCFM	750.00	43,500
4	Variable Speed Control On Fan Motors Average 7.5 HP	16	EA	4,500	72,000
	SUBTOTAL				$381,800
15880	AIR DISTRIBUTION:				
1	Ductwork And Accessories	61,500	LBS	6.00	$369,000
2	VAV Terminals	24	EA	550.00	13,200
3	Duct Mtd Heating & Cooling Coils	48	EA	375.00	18,000
4	Fume Duct	12,000	LBS	8.50	102,000
	SUBTOTAL				$502,200
*	Costs Provided by LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
15990	TESTING AND BALANCING:				
1	Testing and Balancing	1	LS	10,300	$10,300
	SUBTOTAL				$10,300
	TOTAL - MECHANICAL				**$2,217,924**

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	ELECTRICAL				
16300	12KV DISTRIBUTION:				
1	1500KVA Substation	1	EA	161,950	$161,950
2	2000KVA Substation Double Ended	1	EA	466,900	466,900
	SUBTOTAL				$628,850
16400	POWER SERVICE & DISTRIBUTION:				
1	Power Panels 480V, 16 EA	1	LS	57,890	$57,890
2	Capacitor 480V, 3 EA	1	LS	28,450	28,450
3	Transformers, 10 EA	1	LS	29,300	29,300
4	120/208 Panels, 30 EA	1	LS	42,800	42,800
5	Elevator Hook-ups, 100A	2	EA	500	1,000
6	Motor Control Centers, 5 EA	1	LS	35,000	35,000
7	Perimeter Ground	1	LS	4,500	4,500
	SUBTOTAL				$198,940
16407	EMERGENCY SYSTEM:				
1	300KW Generator, WP	1	LS	50,000	$50,000
2	ATS, 600A w/By Pass	1	LS	30,000	30,000
	SUBTOTAL				$80,000

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
16470	POWER & MOTOR FEEDERS:				
1	Power Feeders	1	LS	156,700	$156,700
2	Panel & Transfomer Feeders	1	LS	10,800	10,800
3	Motor Feeders	1	LS	39,000	39,000
	SUBTOTAL				$206,500
16500	LIGHTING:				
1	Basement Industrial Fluorescent	13,230	SF	2.50	$33,075
2	1st Floor Office 2 x 4 Lay-in Floor	2,000	SF	2.40	4,800
3	1st Floor Lab 2 x 8 Pendant Mounted	760	SF	3.50	2,660
4	1st Floor Exp. Hall Industrial Fluorescent	8,550	SF	2.50	21,375
5	Interstitial - Industrial Fluorescent	5,042	SF	2.50	12,605
6	2nd Floor Office & Corridors, 2 x 4 Lay-in	3,880	SF	2.40	9,312
7	2nd Floor Lab, 2 x 8 Pendant Mtd.	5,480	SF	3.50	19,180
8	Terrace Lighting	4	EA	350.00	1,400
9	3rd Floor Office & Corridors	6,550	SF	2.40	15,720
10	Terrace Lighting	10	EA	350.00	3,500
11	Roof & Penthouse Lighting	750	SF	2.50	1,875
12	Occupancy Sensors	1	LS	25,000	25,000
	SUBTOTAL				$150,502

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
Prepared By: L. Stamos
Checked By: R. Stauffer
Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
16600	MISCELLANEOUS POWER DEVICES:				
1	Basement Power Receptacles	13,230	SF	0.55	$7,277
2	Equipment Hook-ups	13,230	SF	0.88	11,642
3	1st Floor Offices Receptacles	2,000	SF	0.55	1,100
4	1st Floor Lab & Plug Mold	760	SF	1.25	950
5	1st Floor Exp Hall - 200A, Hook-ups	9	EA	500.00	4,500
6	Interstitial Power Receptacles	5,042	SF	0.55	2,773
7	2nd Floor Office Power Receptacles	3,880	SF	0.55	2,134
8	2nd Floor Lab	5,480	SF	1.25	6,850
9	Terrace Power	1	LS	300.00	300
10	3rd Floor Office Power Receptacles	6,550	SF	0.55	3,603
11	Terrace Power	1	LS	750.00	750
12	Roof & Penthouse Power	750	SF	1.00	750
13	Roll-up Doors, Hook-up	3	EA	300.00	900
	SUBTOTAL				$43,529
16700	COMMUNICATIONS:				
1	Telephone System	46,600	SF	0.17	$7,922
2	8 x 8 Wireway System	1,000	LF	40.00	40,000
3	12" Wide Cable Tray	600	LF	15.00	9,000
4	9" Wide Cable Tray, Labs	800	LF	10.00	8,000
5	Building Paging System	46,600	SF	0.27	12,582
6	P.A. System in Main Conferance Room	1	LS	2,500	2,500
7	Security Raceway System	46,600	SF	0.11	5,126
8	Universal ICS Wiring	70	EA	150.00	10,500
9	Fiber Optic System (FDD1)	1	LS	5,800	5,800
	SUBTOTAL				$101,430

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

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Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
16720	FIRE ALARM SYSTEM:				
1	Fire Alarm Detection System	46,600	SF	0.37	$17,382
	SUBTOTAL				$17,382
	TOTAL - ELECTRICAL				**$1,427,132**
	TOTAL BUILDING				**$8,930,446**

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY
Berkeley, California

SCHEMATIC ESTIMATE

LSI No. A599B
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Date: January 11, 1990

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
	SPECIAL FACILITIES				
11600	LABORATORY BENCHES:				
1	Lab. Benches	460	LF	285.00	$131,100
2	Acid Resistant Tops	460	LF	79.00	36,340
	SUBTOTAL				$167,440
11601	CHEMICAL STORAGE CABINETS:				
1	Storage Cabinet	40	LF	195.00	$7,800
	SUBTOTAL				$7,800
11602	FUME HOODS:				
1	Fume Hoods	66	LF	1,800	$118,800
2	Velocity & Room Pressure Control	11	EA	6,000	66,000
	SUBTOTAL				$184,800
15481	LIQUID NITROGEN DISTRIBUTION SYSTEMS:				
* 1	Liquid Nitrogen Distribution	1	LS	196,000	$196,000
	SUBTOTAL				$196,000
*	Costs Provided by LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

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SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
15482	VACUUM SYSTEMS:				
* 1	Vacuum Systems	7	EA	12,000	$84,000
	SUBTOTAL				$84,000
15483	ACID DRAIN SYSTEMS:				
1	Acid Drain System With Nutralization Basin	12,730	SF	3.93	$50,029
	SUBTOTAL				$50,029
16940	VACUUM, CHEMICAL AND LASER SAFETY CONTROL SYSTEMS:				
* 1	Laser Safety Control Systems (Cost Finished by LBL)	15	EA	1,700	$25,500
* 2	Vacuum Safety Control System	10	EA	3,000	30,000
* 3	Chemical Safety Control System	1	LS	185,000	185,000
	SUBTOTAL				$240,500
*	COSTS BY LBL				

Lee Saylor, Inc.

COMBUSTION DYNAMICS FACILITY

Berkeley, California

LSI No. A599B
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Date: January 11, 1990

SCHEMATIC ESTIMATE

ITEM NO.	DESCRIPTION	QUANTITY	UNIT	UNIT COST	TOTAL COST
16690	SPECIAL SYSTEMS:				
* 1	Equipment Racks	1	LS	42,000	$42,000
* 2	Data Acquistion System	1	LS	224,000	224,000
	SUBTOTAL				$266,000
	TOTAL SPECIAL FACILITIES				**$1,196,569**
	GRAND TOTAL				**$13,237,420**

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

ESTIMATE DETAIL

STRUCTURAL EXPANSION TO ROAD FOR PARKING SPACES (16 TOTAL)

Typical Bay 20' Long x 18' Deep (2 parking spaces per bay)

Concrete caissons 24" diameter	42	LF	60.00	2,520
Concrete grade beam	1.7	CY	250.00	425
Excavate for grade beam and haul away	3.5	CY	20.00	70
Imported fill at grade beam	1	CY	25.00	25
Structural steel framing	1.6	ton	1,800.00	2,880
Metal deck	360	SF	3.00	1,080
Concrete slab on metal deck	360	SF	3.50	1,260
Armco barrier including posts	20	LF	40.00	800
Precast parking stops	2	EA	35.00	70
Painting/Striping		LS		220
		1 Bay		9,350 x 8
	Subtotal Direct Cost			74,800

CHEMICAL DYNAMICS RESEARCH LABORATORY

CONVENTIONAL FACILITIES

DETAILS OF COST ESTIMATE
(FY 1990 DOLLARS)

Special Building Facilities

1. VACUUM SYSTEMS

4 ea Welch 1374B vacuum pumps 4 ea roughing bellows valve 2" diameter 4 ea thermocouple gauge and display 20 ft 2" diameter copper tubing and fittings	10,000
Installation (32 hrs)	2,000
Subtotal	12,000
TOTAL:	7@ 12,000 = 84,000

2. INSTRUMENT RACKS

8' tall, 30" deep, 4 sections wide, including rack base, breaker panels, A/C plug strips, A/C power connection to wall and installation	6,000
TOTAL:	7@ 6,000 = 42,000

3. VACUUM SAFETY CONTROL SYSTEMS

Vacuum monitoring/vacuum interlocks	3,000
TOTAL:	10@ 3,000 = 30,000

4. CHEMICAL SAFETY CONTROL SYSTEM

12,730 sq. ft. @ 14.50 = 184,585

(Based on cost/sq. ft. of installation in Building 2 at LBL, December 1989 estimate.)

5. DATA ACQUISITION SYSTEM

Communications Link to SNL Supercomputer
(price per K. Wiley, LBL Computation Center)

a.	T2 Link between LBL and SNL and UCB	6,000
b.	3 ea Network routers (17K ea)	51,000
c.	3 ea Encryption units (12.5K ea)	38,000
d.	3 ea CSU/DSU TI terminal units (4K ea)	12,000
e.	1 ea Router to interface to FDDI fiber	15,000
f.	Labor to extend LBL net to new building and interior cabling	17,000
g.	2 ea Video Conferencing System (42.5K ea)	85,000
	TOTAL:	224,000

6. LIQUID NITROGEN DISTRIBUTION SYSTEM

Outside Storage Tank	50,000
Piping - 12,730 sq. ft. @ 3.90	49,650
Distribution station including small tank (100 liters) metering system, vapor recovery system and subcooling system - 8 @ 12,000	96,000
TOTAL:	195,650

Standard Equipment

1. STANDARD LASER SYSTEMS

1 ea	either	
	ND-YAG laser with second and third harmonic output, Quantel model 682-20 with options DS, TS, WSP-2A	85,000
	or	
	Excimen laser, Lambda Physics LPX-240i	(85,000)
1 ea	High resolution dye laser, Lambda Physics model FL3002E	38,800
1 ea	UV Wavelength Extender, Spectra Physics model UVWEX-IC, with complete set of crystals and beam combiners	32,000
	Subtotal:	155,800
	TOTAL:	6@ 155,800 = 934,800

2. DIAGNOSTIC AND DETECTION SYSTEMS

1 ea	400 MHz oscilloscope Tektronics 2467B	12,000
1 ea	Digital delay, SRS model DG535	4,500
1 ea	Wavemeter, Burleight WA4500	18,800
1 ea	Laser table + legs + shelf, Newport KNS510-8	9,600
1 ea	Box-car integrator system, SRS 280, 2x250, 245, 235, 255, 240 and 560	15,900
1 set	Lab tools, optical mounts, optics, power meters and read-out units	13,200
	Subtotal:	74,000
	TOTAL:	6@ 74,000 = 494,000

3. ELECTRONIC BALANCE

2 ea	Electronic balance, Sartorius model 1601 (price per VWR cat.)	
	TOTAL:	4,000

4. COMPUTER WORKSTATIONS

(Price per list price from Stardent Computer Corp.)

IBM 6000 System 540	
192 MB Memory, 2.6 GB Disk	141,590
3D Color Processor	2,800
Model 120 XStation with	16,430
2.5 MB system memory and	
2.0 MB display memory 5@ 3,287	
19" Color Monitor, 6091-019	15,050
6 @ 2,508	
AIX V.3 System	4,680
XStation User Interface	1,250
XL Fortran Compiler	1,730
XL Pascal Compiler	1,730
Optimization Subroutine Library	8,000
Subtotal:	193,260
TOTAL:	4@ 193,260 = 773,040

CHEMICAL DYNAMICS FACILITY/LBL

CONVENTIONAL FACILITIES

ED&I ANALYSIS
(TY$K)

LBL Activities					
• Title I 16MM at 9.1/MM				=	150
Proj Arch 1 x 1.0 time x 6 mos	=	6			
Proj Team 3 x 0.55 time x 6 mos	=	10			
• Title II 37MM at 9.1/MM				=	340
Proj Arch 1 x 0.8 time x 18 mos	=	15			
Proj Team 3 x 0.4 time x 18 mos	=	22			
• Title III 31MM at 9.1/MM				=	280
Proj Arch 1 x 0.35 time x 33 mos	=	11			
Proj Team 3 x 0.2 time x 33 mos	=	20			
• Inspection 32MM at 9.1/MM				=	290
Inspectors (comb.) 0.8 x 33 mos	=	27			
Equipment Installation 0.3 x 18 mos	=	5			
• Consultants and Vendors					95
Soil Investigations			25		
3rd Party Structural Reviews			30		
Seismic Reviews			5		
Independent Cost Estimates			5		
Advertising			2		
Printing			2		
Equipment Testing (Elect/Mech)			26		
					1,155
A/E Activities					
9% of Designed Construction Costs (20,030) including Special Facilities of 1,830					1,805
Title I (30%)			540		
Title II (50%)			905		
Title III (20%)			360		
Total Estimated ED&I					2,960

Current FY92 Engineering Rate: $7.5K/MM

Then Year Engineering Rate: $7.5K/MM x 1.216* = $9.1K/MM

*Escalation of 21.6% to Midpoint of Construction (September 1996)

CHEMICAL DYNAMICS RESEARCH LABORATORY
CONVENTIONAL FACILITIES

ESTIMATE DETAIL

COOLING TOWER EXTENSION

UTILITIES

Provide 4 MW Cooling Tower including:

- Tower Structure
- Cooling Tower Cell with 50 HP Fan
- 2-40 HP Tower Water Pumps
- 3-75 HP TRW/LCW Pumps, Heat Exchangers
- Fire Protection
- Utility Connections from Tower to CDRL

References:

1. Existing Cooling Tower (Building 37) Actual 1986 Construction Cost

2. DOE Escalation Rates Dated 8/89

Escalation:	1987	1.90%
	1988	4.00%
	1989	4.40%
1986-1990 Compounded		10.64%

New Tower Equals 50% of the Capacity of Building 37 Tower

Building 37 Two-Cell Cooling Tower Structure (1986)	$1,137,000
Two Tower Cells, Pumps, HX, Tanks Pipes and Fire Protection (1986)	1,060,000
Total (1986)	2,197,000
Total Adjusted to 1989	2,430,760
One-Cell Extension Total (FY 1990)	$1,215,380*

*(Includes General Contractor's Prorates.)

COMBUSTION DYNAMICS FACILITY / LBL Building Automation System (B.A.S.) COST ESTIMATE									
		UPDATE:	11-Jan-90		CONTROL	ANALOG	ANALOG	DICRETE	DICRETE
	EQP	NO.	CAPACITY	FUNCTION	POINTS	INPUT	OUTPUT	INPUT	OUTPUT
	TEMP SENSORS			ROOM TEMP.		64			
				SUPPLY AIR, MIXED AIR, RETURN AIR TEMP.		36			
	OCC SENSOR INTERFACE			(ONE PER ZONE)				50	
FIRST, SECOND, THIRD FLOOR									
	GP	6		CIRCULATING PUMPS, HTG & CLG				6	6
	BL	6		EXHAUST FANS		6	6	6	6
	AHU	6		AIR HANDLING UNITS		6	6	6	6
	BR	3		BOILERS		3		3	3
	AC	3		AIR CONDITIONERS				3	3
	VFD	20		VARIABLE FREQUENCY DRIVES, FANS & PUMPS		20	20	20	20
	CV	54		ZONE CONTROL VALVES			54		
	CDE	2		ECONOMIZERS			2		
	AF	6		AIR FILTERS				6	
	VAV	24		VARIABLE AIR VOLUME ZONE BOXES			24		
BASEMENT									
	AHU	10		AIR HANDLING UNITS		10	10	10	10
	BL	10		EXHAUST FANS		10	10	10	10
	VFD	4		VARIABLE FREQUENCY DRIVES, FANS		4	4	4	4
	CV	20		ZONE CONTROL VALVES			20		
	CDE	6		ECONOMIZERS			6		
	AF	6		AIR FILTERS				6	
				TOTAL POINTS ==>		159	162	130	68
				POINT COST	EQUIP	$40	$50	$35	$50
					MATERIAL	$70	$200	$50	$50
					LABOR	$225	$150	$175	$100
					CONT O&P	$50	$60	$39	$30
					TOTAL	$385	$460	$299	$230
						$61,255	$74,520	$38,870	$15,640
				TOTAL B.A.S. COST ==>	$190,285				

Date: 19 Dec 89

Subject: Combustion Dynamics Facility Energy Conservation

To: D. Truchlikova

From: G. C. Bell

Per your request, the Energy Conservation Measures relating to the subject's chiller system are deliniated as follows:

1. Free Cooling Option	$18,000
2. Heat Recovery System	$42,000
3. Turbomodulator Option or Three Stage Compressor	$40,000
	========
ESTIMATED TOTAL	$100,000

These estimates are based upon 400 tons of chilling capacity. Other arrangements or capacities can significantly impact cost estimates.

ESTIMATE SHEET

TITLE: **CDF OUTSIDE PLANT TELEPHONE CABLE INSTALLATION**
Fiber Optic & Twisted Pair CABLES THRU TMH 589 TO TMH 590

DATE: 11/14/89
BY: JBR

TYPE:
REF: **Means, AT&T, CCR (TGS/SR) estimates**
DIV: 16

#	DESCRIPTION	UNIT	QTY	BARE UNIT PRICE MAT'L	BARE UNIT PRICE LABOR	MAT'L	LABOR	TOTAL
	CITY MODIFIERS (MCM, LCM)					108.1	153.4	
	Cost Estimate Guide: $xMCM+7%+10%, ($xLCM+45% Placing, $ Splicing F.O.)							
1	PLACE one 48 fiber 62.5/125 µ cable between 589 & 590	ft	210	12.37	0.43	$3.305	$201	$3.506
2	PLACE seven 16 fiber 62.5/125 µ cables between 589 & 590	ft	1470	4.46	0.37	$8.342	$1.210	$9.551
3	Splicing (16 fibers x 2 manholes x 7)	fibers	224	6.25	100	$1.781	$22.400	$24.181
4	Splicing (48 fibers x 2 manholes x 1)	fibers	96	2.08	100	$254	$9.600	$9.854
						$0	$0	$0
5	PLACE 1800 PR #24 PE-89 tel. cable TMH 589 to TMH 590	ft	210	16	2	$4.275	$934	$5.209
						$0	$0	$0
6	Splicing (1800 Pairs)x2	100 pr	36	50	24	$2.290	$1.922	$4.212
	complete splice closure (open, close)	ea	2		24	$0	$107	$107
	testing	100pr	18		48	$0	$1.922	$1.922
7	PLACE 1200 PR #24 PE-89 tel. cable TMH 589 to TMH 590	ft	210	11	1.9	$2.939	$887	$3.827
						$0	$0	$0
8	Splicing (1200 Pairs)x2	100 pr	24	50	24	$1.527	$1.281	$2.808
	complete splice closure (open, close)	ea	2		24	$0	$107	$107
	testing	100pr	12		48	$0	$1.281	$1.281
						$0	$0	$0
	Subtotal							$66.566
	Labor From: ME 161 165 1400-1500, ME161 150 2400-2800							
	Misc. supervision: waste, setup & testing		15%					$9.985
	SHEET TOTAL							$76.550

ESTIMATE SUMMARY SHEET

TITLE: **CDF - ICS NODE 2 RELOCATION - ELECT, MECH, SWITCH**
CDF Site #1 @ Bldg 10 Location

DATE: 11/14/89
BY: JBR

TYPE: **Class D**

REF: **MEANS ELEC. COST DATA 1989**

DIV:

#	DESCRIPTION	UNIT	QTY	BARE UNIT PRICE MAT'L	BARE UNIT PRICE LABOR	MAT'L	LABOR	TOTAL
1	IM Cabinets	ea	4	60000				$240,000
2	Microwave Link to Livermore	ls						$100,000
3	LBLnet equipment	ls						$100,000
4A	Distribution F[illegible]me wiring	ls						$50,000
4B	Outside Plant [illegible]abling	ls						$160,000
5	HVAC	ls						$20,000
6	Halon system							$15,000
7	Preaction sprinkler system							$10,000
8	Fuel system modification with buried tank							$5,000
9	Re-routing of liquid carrying piping							$20,000
10	Fire Alarm System							$5,000
11	20 kW Diesel Generator & Transfer Switch	ls						$16,000
12	Telephone exchange Distribution MC 171 870 2900	ft^2	600	12.3				$7,380
13	75kVA Dry type Distribution Transformer	ea						$5,500
14								
15	SUBTOTAL:							$753,880
16	Switch Cutover: Testing & Checkout of Parallel Systems	0.2						$150,776
17								
18	Duct bank from TMH 591 to Bldg 80 w 12-4" C	ls						$9,000
19	Duct Bank - Div 16 Installation	ls						$6,300
	SUBTOTAL:							$919,956
	General's sub contractor markup	10%						$91,996
	PROJECT TOTAL							$1,011,952

9-147

CHEMICAL DYNAMICS RESEARCH LABORATORY

ED&I Analysis

(Blank)

CHEMICAL DYNAMICS FACILITY/LBL
CONVENTIONAL FACILITIES

ED&I ANALYSIS
(TY$K)

LBL Activities				
• Title I 16MM at 9.1/MM				= 150
Proj Arch 1 x 1.0 time x 6 mos	=	6		
Proj Team 3 x 0.55 time x 6 mos	=	10		
• Title II 37MM at 9.1/MM				= 340
Proj Arch 1 x 0.8 time x 18 mos	=	15		
Proj Team 3 x 0.4 time x 18 mos	=	22		
• Title III 31MM at 9.1/MM				= 280
Proj Arch 1 x 0.35 time x 33 mos	=	11		
Proj Team 3 x 0.2 time x 33 mos	=	20		
• Inspection 32MM at 9.1/MM				= 290
Inspectors (comb.) 0.8 x 33 mos	=	27		
Equipment Installation 0.3 x 18 mos	=	5		
• Consultants and Vendors				95
Soil Investigations			25	
3rd Party Structural Reviews			30	
Seismic Reviews			5	
Independent Cost Estimates			5	
Advertising			2	
Printing			2	
Equipment Testing (Elect/Mech)			26	
				1,155
A/E Activities				
9% of Designed Construction Costs (20,030) including Special Facilities of 1,830				1,805
Title I (30%)			540	
Title II (50%)			905	
Title III (20%)			360	
Total Estimated ED&I				2,960

Current FY92 Engineering Rate: $7.5K/MM

Then Year Engineering Rate: $7.5K/MM x 1.216* = $9.1K/MM

*Escalation of 21.6% to Midpoint of Construction (September 1996)

CHEMICAL DYNAMICS RESEARCH LABORATORY

Geotechnical Report

REPORT 1529-00

Geotechnical Investigation Conceptual Design Report Combustion Dynamics Facility Lawrence Berkeley Laboratory Berkeley, California

December 22, 1989

Prepared for:

The Regents of the University of California
Lawrence Berkeley Laboratory
Berkeley, California

Geo/Resource Consultants, Inc.

GEOLOGISTS / ENGINEERS / ENVIRONMENTAL SCIENTISTS
851 HARRISON STREET, SAN FRANCISCO, CALIFORNIA 94107

9-152

GEOTECHNICAL INVESTIGATION

CONCEPTUAL DESIGN REPORT

COMBUSTION DYNAMICS FACILITY

LAWRENCE BERKELEY LABORATORY

BERKELEY, CALIFORNIA

Prepared for

THE REGENTS OF THE UNIVERSITY OF CALIFORNIA

LAWRENCE BERKELEY LABORATORY

Prepared by

GEO/RESOURCE CONSULTANTS

851 HARRISON STREET

SAN FRANCISCO, CALIFORNIA 94107

GRC JOB NO. 1529

DECEMBER 22, 1989

9-153

Geo/Resource Consultants, Inc.
GEOLOGISTS / ENGINEERS / ENVIRONMENTAL SCIENTISTS

CORPORATE HEADQUARTERS:
851 HARRISON STREET
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REGIONAL OFFICES
SAN FRANCISCO
SEATTLE
TUCSON/PHOENIX
WASHINGTON, D.C.

December 22, 1989
1529-00-0

LAWRENCE BERKELEY LABORATORY
1 Cyclotron Road
Berkeley, CA 94720

Attention: Mr. Donald G. Eagling,Plant Engineering

RE: GEOTECHNICAL REPORT
PROPOSED COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA

Dear Mr. Eagling:

We are pleased to provide you with this report presenting the results of our geotechnical investigation of the proposed Combustion Dynamics Facility at Lawrence Berkeley Laboratory.

Based on the project information available to us and the results of our investigation, we conclude that this project is feasible from a geotechnical standpoint. We refer you to the contents of this report for our conclusions and recommendations.

It has been a pleasure to work on this project. Please do not hesititate to call if you have any questions.

Very truly yours,
GEO/RESOURCE CONSULTANTS, INC.

Eric S. Ng, P.E., G.E.(Geotechnical Engineer #636)
Principal Engineer

Mark Wiegers

Mark O. Wiegers, R.G.(Registered Geologist #4157)
Project Geologist

REGISTERED PROFESSIONAL ENGINEER
ERIC SHI-YIU NG
No. 636
EXP. 3/31/93
GEOTECHNICAL
STATE OF CALIFORNIA

ESN/MOW:mb

9-154

228W: 1529-3

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1.0 INTRODUCTION

This report presents the results of our geotechnical investigation for the proposed Combustion Dynamics Facility to be located at Lawrence Berkeley Laboratory. The location of the site is presented in the Vicinity Map, Figure 1, and on the Site Plan, Figure 2.

We understand that the proposed building will be a three story reinforced concrete and steel frame building with one basement level. The proposed finished first floor will be approximately at an elevation of 881.5 feet. The basement will extend down to an elevation of about 861 feet. The building will be about 148 by 110 feet in plan dimensions.

The scope of our services, rendered in accordance with our proposal to you dated October 5, 1989, consisted of the following:

- Review of previous geotechnical data in the vicinity of the site;
- Drilling of three test borings at the proposed building site and logging of the subsurface conditions;
- Coordinating field investigation and performing soil analysis for the building foundation;
- Preparing a written report to furnish recommendations on
    1. Foundation bearing pressures;
    2. Lateral soil pressures;
    3. Shoring design parameters;
    4. Underpinning of adjacent buildings;
    5. Site drainage;
    6. Construction considerations;

During the course of our investigation, we have discussed the results of our findings and our preliminary recommendations with you.

2.0 FIELD EXPLORATION AND LABORATORY TESTING

2.1 Field Exploration

Field exploration at the site consisted of drilling 3 test borings to a depth of 40 feet. The locations of the test borings are shown on the Site Plan, Figure 2. Each boring extended more than 10 feet below the proposed elevation of the basement slab. All of the borings penetrated soft bedrock of the Orinda Formation within 10 feet below the ground surface. The borings were drilled with a trailer-mounted drill rig using solid flight augers. Boring and sampling procedures were directed on a full time basis in the field by our geologist, who logged each boring and obtained undisturbed core samples for visual examination and laboratory testing. Samples were obtained at regular intervals to the total depth of each boring with a Sprague and Henwood drive sampler (2.5 inch inside diameter) driven by a 140 pound hammer falling 30 inches. Blow counts were recorded for every 6 inches the sampler was driven. A detailed description of the soil and rock materials encountered are presented on the Logs of Borings, Figures 3 through 5. Soils are classified according to the Unified Soils Classification System as shown in Figure 6. Rocks are classified according to the rock classification system shown in Figure 7.

2.2 Laboratory Testing

The soil/rock samples were re-examined in our laboratory and their classification verified. Most of the rock samples were too disturbed to be tested for undisturbed strength due to natural fracturing of the rock material, which caused the samples to break up after extrusion. Moisture content and dry density tests were provided for selected samples to evaluate engineering properties.

3.0 SITE CONDITIONS

3.1 General Geology

The site is located in the Oakland-Berkeley Hills, which consists of a complex sequence of rocks that are primarily of sedimentary and volcanic origin. The rocks have been extensively folded and faulted by multiple periods of crustal deformation that have affected the region since Cretaceous time. Crustal deformation is still active as indicated by seismic activity and measurable fault movements in the region.

The Oakland-Berkeley Hills are bounded on the west by the Hayward fault, a right-lateral strike-slip fault that is a major branch of the San Andreas fault system. The hills east of the fault have been uplifted during the late Tertiary and Quaternary periods while the crustal block underlying San Francisco Bay west of the fault has subsided.

Rocks underlying the Lawrence Berkeley Laboratory include Cretaceous sedimentary rocks of marine origin (Knoxville Formation), Tertiary sedimentary rocks of both marine (Claremont Formation) and terrestrial origin (Orinda Formation), and Tertiary volcanic rocks (Moraga Formation). These rocks are cut by many faults which are considered to be inactive, including the inactive Wildcat fault on the east side of the compound. Many slopes in the area are covered with colluvial soils formed by weathering, decomposition and downslope movement of the underlying bedrock formations. Landslide deposits are found at various locations within the laboratory grounds.

3.2 Site Seismicity

The site is located in an area of high seismic activity. Several major faults in the region are capable of generating strong earthquakes that could affect the site. Major active faults with historic earthquake activity are shown on Figure 8.

Due to its close proximity to the site, the Hayward fault is considered to present the most significant seismic hazard. The fault is located just over 1000 feet west of the site. The Hayward fault is considered to be capable of producing an earthquake of Richter magnitude 7.0 or greater. It is possible that a strong earthquake on the Hayward fault could produce an intensity of up to IX on the Modified Mercalli Earthquake Intensity Scale.

3.3 Surface Conditions

Most of the area encompassed by the proposed building location is occupied by an existing building. The site is located near the south end of a relatively broad ridgetop on which several other large buildings currently stand. The Cyclotron building is located just to the north of the site. It is currently being remodeled and expanded for other uses. Part of the new addition of the Cyclotron building abuts the north edge of the proposed subject building. South, southeast and southwest of the proposed building site, steep slopes extend down from the ridge. The existing elevation at the proposed building site is approximately 880 feet above sea level.

3.4 Subsurface Conditions

Based on our test borings, the proposed building site is underlain by rocks of the Orinda Formation. The bedrock is covered by up to 8 feet of gravelly clayey fill soils at the west end of building site as indicated by borings B2 and B3. The Orinda Formation consists of poorly consolidated sandstone, siltstone, claystone and conglomerate. These rocks are soft and weak and are cut by small shear zones in many places. At the project site, soft, weak siltstone is the predominant rock type.

3.5 Groundwater Conditions

During the time of our field exploration, ground water was encountered at about 29 feet below ground surface in Boring B1. No groundwater was encountered at B2 and B3 locations. There is a potential that subsurface water may be encountered in

excavations due to seasonal fluctuations in groundwater levels or localized seepage within rock fractures.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 General

Based on the results of our investigation and information on the proposed development available to us, we conclude that the proposed construction is feasible from a geotechnical engineering standpoint. The primary geotechnical concerns are: 1) the deep excavation required for construction of the basement level, and; 2) the close proximity of the east end of the proposed building to the adjacent existing building foundation, where stress interference is to be considered.

4.2 Site Grading

Site grading will consist of an approximately 20-foot-deep excavation for the basement level, predominantly in soft, weak siltstone of the Orinda formation. We anticipate that excavation at the project site would require ripping with heavy construction equipment. In localized areas jackhammering in rock may also be required. Excavation would also require temporary shoring to protect the adjacent ground and nearby building and to provide for worker safety.

4.3 Foundation Support and Settlement Estimate

We recommend that the proposed building be supported by a reinforced concrete mat foundation founded on competent bedrock. The allowable bearing pressures on rock for foundation design should be limited to the following:

Loading	Allowable Bearing Pressures (psf)
Dead Load	4000
Dead plus Live Load	4500
Dead plus Live plus wind and Seismic	5000

Lateral resistance can be obtained by passive soil pressure acting on the side of the mat and/or frictional resistance along the base of the mat formation. We recommend that a passive pressure of 350 pcf, equivalent fluid pressure, and a frictional coefficient of 0.35 times the dead load be used.

We estimate that the settlement from the new foundation load will be negligible.

Prior to foundation installation, the bottom of the excavation should be checked by a qualified soil engineer or geologist. If there are any soft spots detected, they should be overexcavated and/or replaced by compacted fill.

4.4 Lateral Pressures on Basement Walls

The basement wall should be designed for an at-rest soil pressure of 65 pc,f equivalent fluid pressure, for level backfill. If there is traffic close to the building, the design should also include a traffic surcharge of 200 psf in the upper 5 feet of the wall.

To consider the dynamic soil increment acting on the wall during earthquakes, we recommended that the wall be designed for an additional soil pressure of 9H and 18H psf , where H is the height of the wall, for an effective ground acceleration of 0.2 g and 0.4 g, respectively. Recommended lateral pressures for the basement wall design are presented on Figure 9.

Along the east building line, the new basement wall will be located very close to existing footings. If the existing footings are not to be supported by new underpinning piers to transmit foundation load to the lower elevation at the base of the wall, the wall should be designed for lateral pressures induced by the adjacent footings. A recommended wall pressure for footing surcharge is provided in Figure 10.

The basement wall should be designed with a wall backdrain to minimize build-up of a hydrostatic pressure. The backdrain may consist of fabric drain such as Miradrain (or its equivalent) or conventional backdrains using perforated pipe and drain rock.

4.5 Excavation and Shoring Requirements

We recommend that basement excavations in close proximity to existing buildings be shored throughout the full depth of the excavation. A shoring system consisting of steel solder piles, wood lagging and tie backs can be used. The shoring system should be designed to resist lateral soil pressures, traffic surcharge and the dynamic soil increment. If the adjacent footings are not underpinned to transmit foundation load to the bottom of the excavation, the shoring system should also be designed for the surcharge from the adjacent footing stress.

For excavations that are out of the influence of existing structures and where there is enough open space, partial open cut excavations may be considered. We recommend that excavation slopes should be no steeper than 1H to 1V (Horizontal to Vertical) when the excavation is performed in the dry season. The slope may have to be flattened during the rainy season for protection against erosion.

4.6 Underpinning of Adjacent Structure

One of the primary concerns for the basement excavations is the close proximity of the east wall to the existing building which is supported on shallow footings. It will be necessary to design the wall to accomodate for the existing footing surcharge. One alternative is to provide foundation underpinning on the the structure to transmit the adjacent footing load to the bottom of the new wall elevation. The underpinning piers may consist of drilled caissons adjacent to the existing foundation.

4.7 Site Drainage Considerations

The site is located on a ridge and site drainage will be important to minimize erosion on the adjoining slopes and to maintain stability of the hillside. The roof drainage and surface drainage should be diverted to a suitable storm drain outlet through closed pipes. Wall backdrains should also be connected to closed pipes so that subsurface water can be carried away from the building.

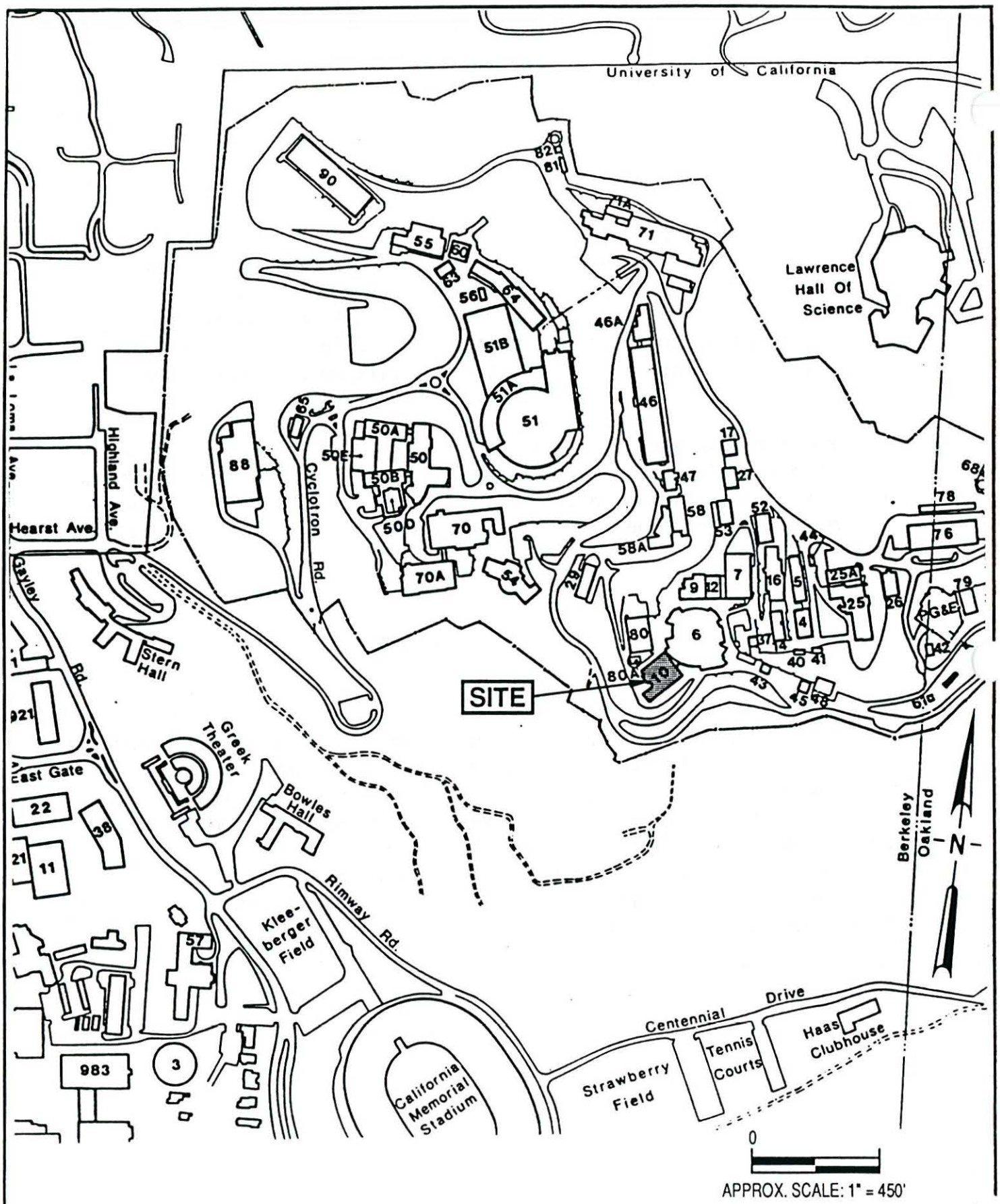
4.8 Construction Considerations

Primary construction considerations are proper shoring and underpinning to minimize adjacent ground and building settlements. The design of the shoring system and the underpinning schemes, if required, should be performed by a qualified structural engineer. The existing structure and shoring system should be monitored frequently throughout the excavation.

The proposed excavation could be severely affected by wet weather conditions. The bottom of the excavation may be too soft during periods of rain to support construction equipment. Site access is very limited and may present some difficulty to remove material.

5.0 LIMITATIONS

The above services consist of professional opinions and conclusions by the consulting engineer. The only warranty or guarantee made by the Consultant in connection with services performed for this project is that such services are performed with the care and skill ordinarily exercised by members of the profession practicing under similar conditions and in a similar locality. No other warranty, expressed or implied, is made or intended by rendition of these consulting services, or by furnishing written reports of the findings.

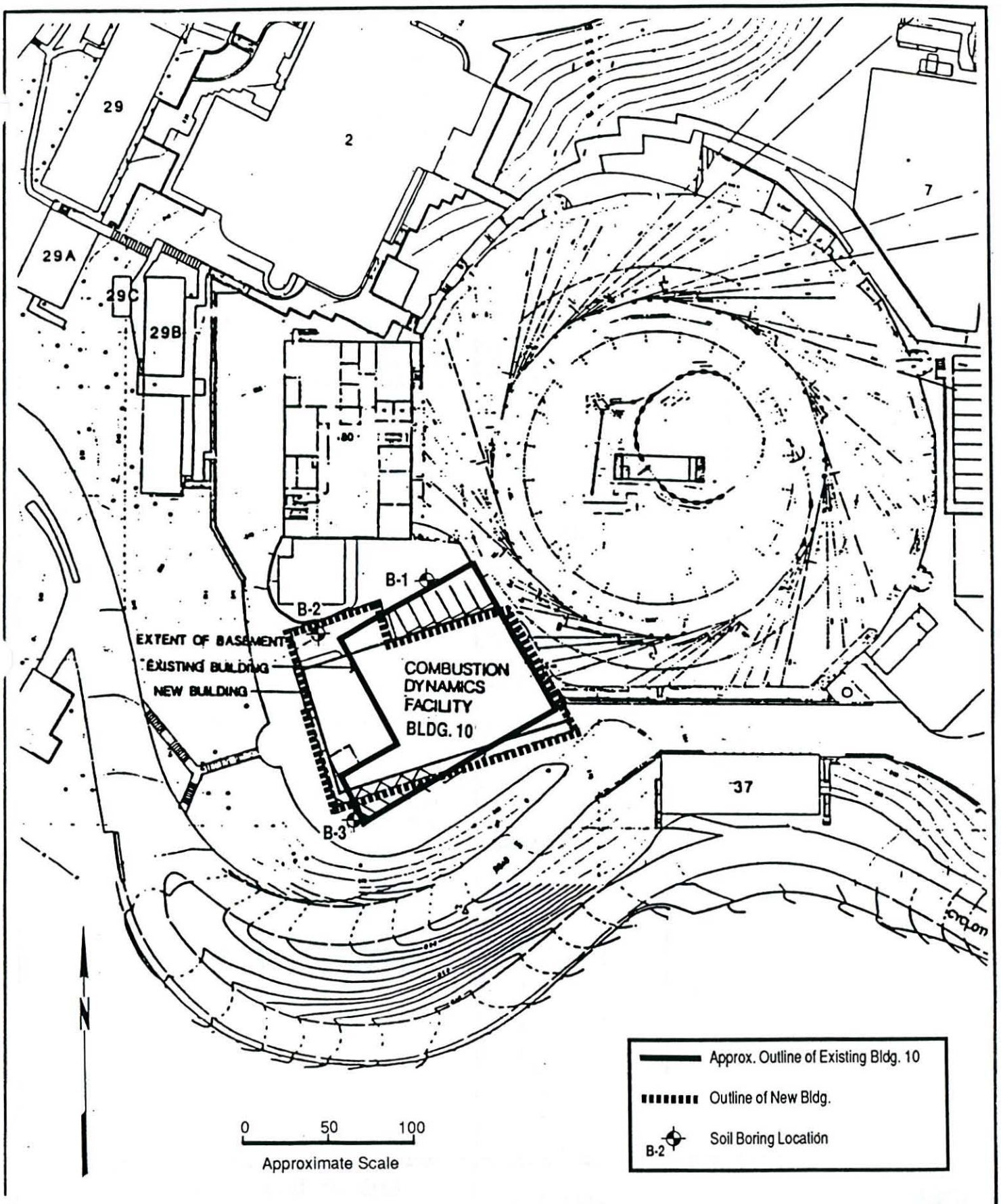


Geo/Resource Consultants, Inc.
GEOLOGISTS / ENGINEERS / ENVIRONMENTAL SCIENTISTS
851 HARRISON STREET, SAN FRANCISCO, CALIFORNIA 94107

Job No. _____ Appr. ESJ Date 12/28/89

VICINITY MAP
PROPOSED COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA
9-165

FIGURE
1



Geo/ Resource Consultants, Inc.
GEOLOGISTS / ENGINEERS / ENVIRONMENTAL SCIENTISTS
851 HARRISON STREET, SAN FRANCISCO, CALIFORNIA 94107

Job No. 1529-00 Appr. Date 12/28/89

SITE PLAN
PROPOSED COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA
9-166

FIGURE
2

LOG OF BORING B-1

Equipment: Solid Flight Auger

Elevation: ± 880 ft. Date: 11/11/89

Laboratory Analysis	Blows/ft.	Moisture Content (%)	Dry Density (pcf)
	67		
	39		
	77		
	88		
	99	10.8	123
	82/10"	8.8	133
	87/11"		
	90/11"		

Depth (ft.): 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50

Sample pnts.

Boring location predrilled to 4 ft below ground surface

YELLOW BROWN SANDSTONE (Orinda FM)
very soft, friable, little fractured
moderately weathered

GREEN BROWN SILTSTONE (Orinda FM)
soft, friable, moderately fractured,
moderately weathered
small inactive shear @ 10.5 ft. - 2" wide clay seam with slickensides

becomes moist, mottled with red brown, harder

change in color to predominantly red brown siltstone

Ground Water Level @ 29 ft. at time of drilling

BLUE GRAY SILTY CLAYSTONE (Orinda FM)
soft, friable to weak, intensely fractured,
moderately weathered, contains brown weathered zones

Boring Terminated @ 40 ft.

Geo/Resource Consultants, Inc.
Geologists / Engineers / Environmental Scientists

Job No. 1529-00 Appr: ES Date 12/28/89

LOG OF BORING B-1
PROPOSED
COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA

FIGURE 3

LOG OF BORING B-2

Equipment: Solid Flight Auger

Elevation: ± 880 ft. Date: 11/11/89

Laboratory Analysis	Blows/ft.	Moisture Content (%)	Dry Density (pcf)	Depth (ft.)	Sample pnts.	Description
				0		Boring location predrilled to 4 ft below ground surface
	13			5		BROWN SILTY GRAVEL (GC) (Fill) slightly moist, loose, gravel pieces, consists of friable sandstone and siltstone
						BROWN CLAYEY GRAVELLY CLAY (CL-GC) moist, soft to firm
	23			10		hard cobble @ 11 ft.
	36					GREEN BROWN SILTSTONE (Orinda FM) very soft, friable, closely fractured, severely weathered
	63			15		GRAY BROWN SILTSTONE (Orinda FM) soft, weak, closely fractured, moderately weathered
	67			20		
	75	8.0	112	25		BROWN SILTSTONE (Orinda FM) very soft, friable intensely fractured, moderately weathered
	80	7.3	123	30		
				35		slow drilling
	100/9"			40		Boring Terminated @ 40 ft.
				45		
				50		

Fill

Geo/Resource Consultants, Inc.
Geologists / Engineers / Environmental Scientists

Job No. 1529-00 Appr: [illegible] Date 12/28/89

LOG OF BORING B-2
PROPOSED
COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA

FIGURE 4

LOG OF BORING B-3

Equipment: Solid Flight Auger

Elevation: ± 880 ft. Date: 11/11/89

Laboratory Analysis	Blows/ft.	Moisture Content (%)	Dry Density (pcf)	Depth (ft.)	Sample pnts.	Description
				0		Boring location predrilled to 4 ft below ground surface
	22			5		BROWN GRAVELLY SILTY CLAY (CL) moist, stiff — Fill
	38	12.6	107	10		
	57			15		GREEN BROWN SILTSTONE (Orinda FM) very soft, friable, intensely fractured, severely weathered
	72	7.4	125	20		
	50/5"			25		
	100/9"			30		becomes soft, weak, moderately weathered
				35		slow drilling
	56/5"			40		Boring Terminated @ 40 ft.
				45		
				50		

Geo/Resource Consultants, Inc.
Geologists / Engineers / Environmental Scientists

Job No. 1529-00 Appr: ESJ Date 12/28/89

LOG OF BORING B-3
PROPOSED
COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA

FIGURE 5

UNIFIED SOIL CLASSIFICATION SYSTEM

MAJOR DIVISIONS				SOIL DESCRIPTION
COARSE GRAINED SOILS over 50% coarser than #200 sieve	GRAVELS over half of coarse fraction larger than No. 4 sieve	clean gravels with little or no fines	GW	Well Graded Gravels, Gravel - Sand Mixtures
			GP	Poorly Graded Gravels, Gravel - Sand Mixtures
		gravels with over 12% fines	GM	Silty Gravels, Poorly Graded Gravel - Sand - Silt Mixtures
			GC	Clayey Gravels, Poorly Graded Gravel-Sand-Clay Mixtures
	SANDS over half of coarse fraction finer than No. 4 sieve	clean sands with little or no fines	SW	Well Graded Sands, Gravelly Sands
			SP	Poorly Graded Sands, Gravelly Sands
		sands with over 12% fines	SM	Silty Sands, Poorly Graded Sand - Silt Mixtures
			SC	Clayey Sands, Poorly Graded Sand - Clay Mixtures
FINE GRAINED SOILS over 50% is finer than #200 sieve	SILTS AND CLAYS liquid limit less than 50		ML	Silts, Very Fine Sands, Silty or Clayey Fine Sands
			CL	Low Plasticity Clays, Sandy or Silty Clays
			OL	Low Plasticity Organic Silts and Clays
	SILTS AND CLAYS liquid limit greater than 50		MH	Micaceous or Diatomaceous Silts, Volcanic Ash, Elastic Silts
			CH	High Plasticity Clays - Fat Clays
			OH	High Plasticity Organic Silts and Clays
	HIGHLY ORGANIC SOILS		Pt	Peat and Other Fibrous Organic Soils

KEY TO SAMPLES

- "Undisturbed" 2.5" sample
- Disturbed Sample
- Indicates depth of sampling with no recovery
- Indicates depth and location of coring run
- Indicates depth of Standard Penetration Test and 2" sample

KEY TO TEST DATA

Shear Strength, psf

Confining Pressure or Normal Load, psf

TxUU	750	(2600)	Unconsolidated Undrained Triaxial
TxCU	540	(2600)	Conslidated Undrained Triaxial
TxCD	800	(2600)	Consolidated Drained Triaxial
DS	500	(2000)	Direct Shear
UC	400		Unconfined Compression
FVS	470		Field Vane Shear
FP	500		Field Penetrometer

PI = Plasticity Index
C = Consolidation Test

Geo/Resource Consultants, Inc.
Consulting Engineers, Geologists, Geophysicists

Job No. 1529-00 Appr: ESW Date 12/28/89

SOIL CLASSIFICATION CHART AND KEY TO TEST DATA

FIGURE 6

FORM 3-03 (85)

HARDNESS

Soft	Reserved for plastic material.
Friable	Easily crumbled or reduced to powder by fingers.
Low hardness	Can be gouged deeply or carved with a pocket knife.
Moderately hard	Can be readily scratched by a knife blade; scratch leaves heavy trace of dust.
Hard	Can be scratched with difficulty; scratch produces little powder and is often faintly visible.
Very hard	Cannot be scratched with knife blade.

BEDDING AND LAMINATION

Spitting Property	Stratification	Thickness
Massive	Very thick-bedded	>4.0 ft.
Blocky	Thick-bedded	2.0 to 4.0 ft.
Slabby	Thin-bedded	0.2 to 2.0 ft.
Flaggy	Very thin-bedded	0.05 to 0.2 ft.
Shaly or Platy	Laminated	0.01 to 0.05 ft.
Papery	Thinly laminated	less than 0.01 ft.

FRACTURE FILLING

Clean	No fracture filling materials noted.
Stained	Rock discoloration or thin coatings of mineral deposits, commonly iron or manganese.
Filled	Fractures filled or thickly coated with recognizable material, such as; carbonates, clay, quartz, or oxides.

FRACTURE WIDTH

Very wide	> 200 mm	(7 7/8 inches)
Wide	60 - 200 mm	(2 3/8 - 7 7/8 inches)
Moderately Wide	6 - 20 mm	(1/4 - 1 3/4 inhces)
Moderately Narrow	6 - 20 mm	(1/4 - 1 3/4 inches)
Narrow	2 - 56 mm	(1/16 - 1/4 inch)
Very Narrow	>0 - 2 mm	(>0 - 1/16 inch)
Tight	0	0

FRACTURE SPACING

Fracturing	Size range of pieces	Remarks
Crushed	-5 microns to 0.1'	Contains clay
Intensely fractured	0.05' to 0.1'	Contains no clay
Closely fractured	0.1' to 0.5'	
Moderately fractured	0.5' to 1.0'	
Little fractured	1.0' to 3.0'	
Massive	4.0' and larger	

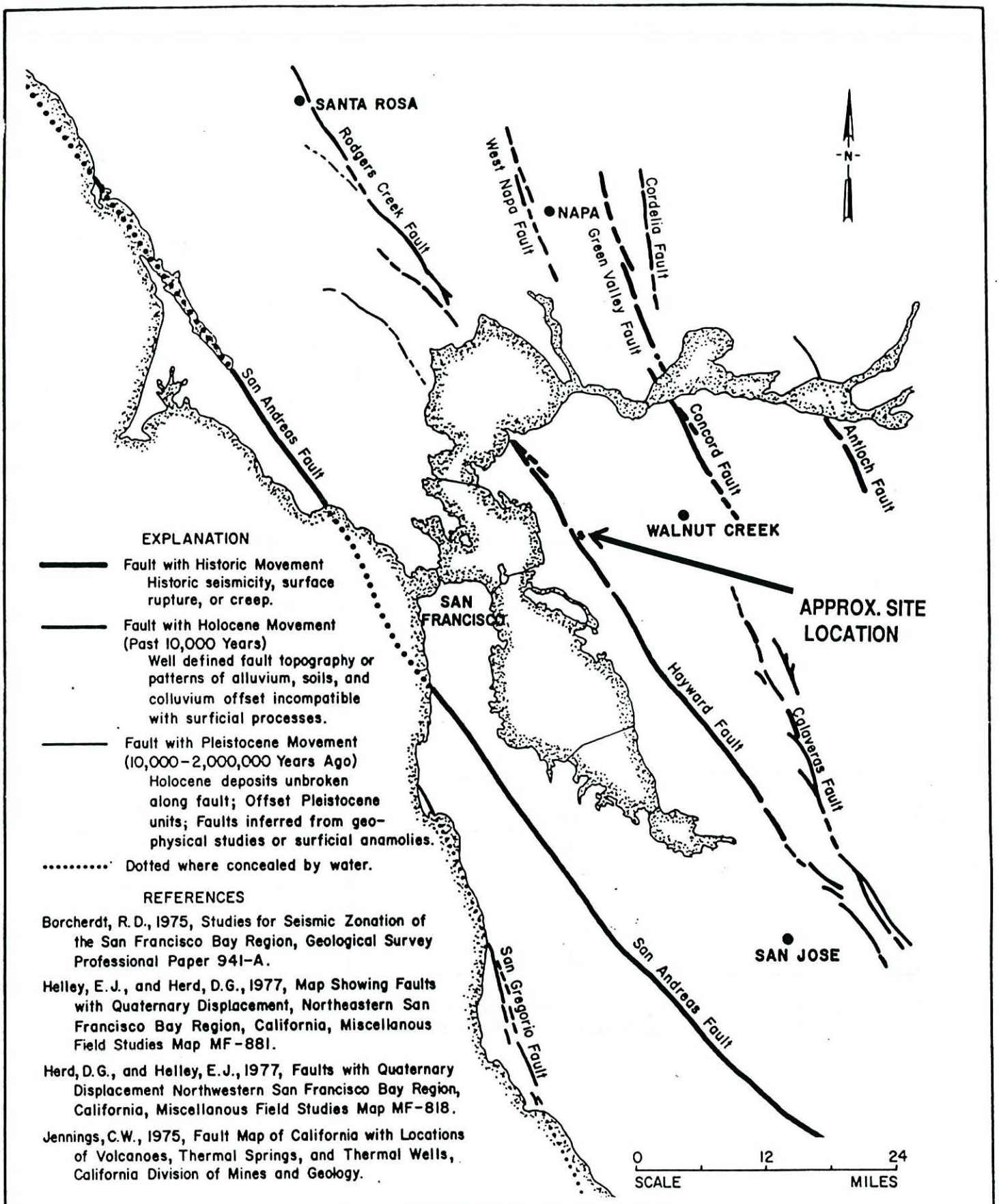
WEATHERING

FR	Fresh	The rock shows no discoloration, loss of strength or any other effect due to weathering.
SW	Slightly Weathered	The rock is slightly discolored, but not noticeably lower in strength than the fresh rock.
MW	Moderately Weathered	The rock is discolored and noticeably weakened, 2 inch diameter drill cores cannot usually be broken up by hand, across the rock fabric.
DW	Deeply Weathered	The rock is usually discolored and weakened to such an extent that 2 inch diameter cores can be broken readily by hand, across the rock fabric.
XW	Extremely Weathered	Rock is discolored and is entirely changed to a soil but the original fabric of the rock is usually preserved. The properties of the soil depend upon the composition and structure of parent rock.

STRENGTH

VW	Very Weak	Crumbles by rubbing with fingers.
W	Weak	An unfractured outcrop of such material would crumble under light hammer blows.
MS	Moderately Strong	An outcrop would withstand a few firm blows before breaking
S	Strong	An outcrop would withstand a few heavy ringing hammer blows but will only yield large fragments.
VS	Very Strong	An outcrop would resist heavy ringing hammer blows and will yield, with difficulty, only dust and small fragments

M 3-15(84)



EXPLANATION

Fault with Historic Movement
Historic seismicity, surface rupture, or creep.

Fault with Holocene Movement (Past 10,000 Years)
Well defined fault topography or patterns of alluvium, soils, and colluvium offset incompatible with surficial processes.

Fault with Pleistocene Movement (10,000-2,000,000 Years Ago)
Holocene deposits unbroken along fault; Offset Pleistocene units; Faults inferred from geophysical studies or surficial anamolies.

Dotted where concealed by water.

REFERENCES

Borcherdt, R.D., 1975, Studies for Seismic Zonation of the San Francisco Bay Region, Geological Survey Professional Paper 941-A.

Helley, E.J., and Herd, D.G., 1977, Map Showing Faults with Quaternary Displacement, Northeastern San Francisco Bay Region, California, Miscellanous Field Studies Map MF-881.

Herd, D.G., and Helley, E.J., 1977, Faults with Quaternary Displacement Northwestern San Francisco Bay Region, California, Miscellanous Field Studies Map MF-818.

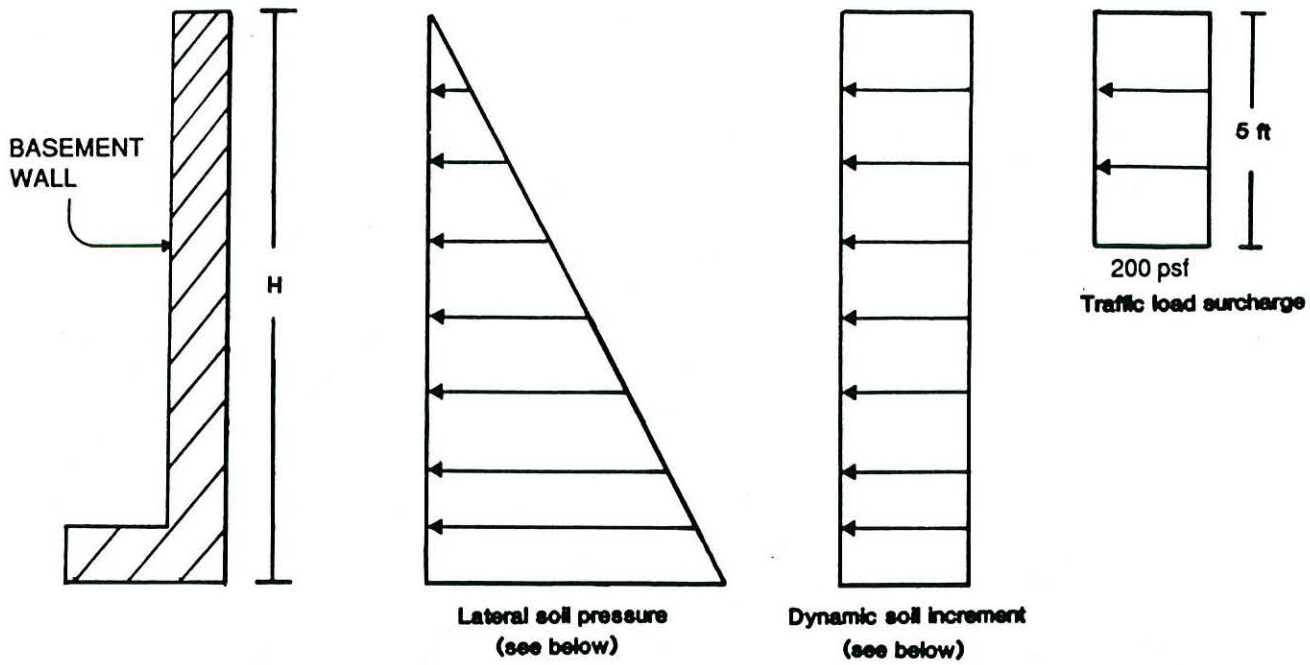
Jennings, C.W., 1975, Fault Map of California with Locations of Volcanoes, Thermal Springs, and Thermal Wells, California Division of Mines and Geology.

Geo/Resource Consultants, Inc.
CONSULTING GEOLOGISTS / ENGINEERS / GEOPHYSICISTS

Job no. 1529-00 Appr. EJL Date 12/28/89

Major Historic-Active Faults and Potential-Active Faults in the San Francisco Bay Area

FIGURE 8



Backfill slope	Lateral soil pressure Equivalent Fluid Pressure
	Restrained building wall
Level	65 pcf
3H:1V	75 pcf
2H:1V	85 pcf

Effective Acceleration in g's	Dynamic Soil Increment psf
0.2g	9H
0.4g	18H

* The pressure presented does not include any hydrostatic pressure. For surcharge from adjacent foundation, please refer to Figure 10.

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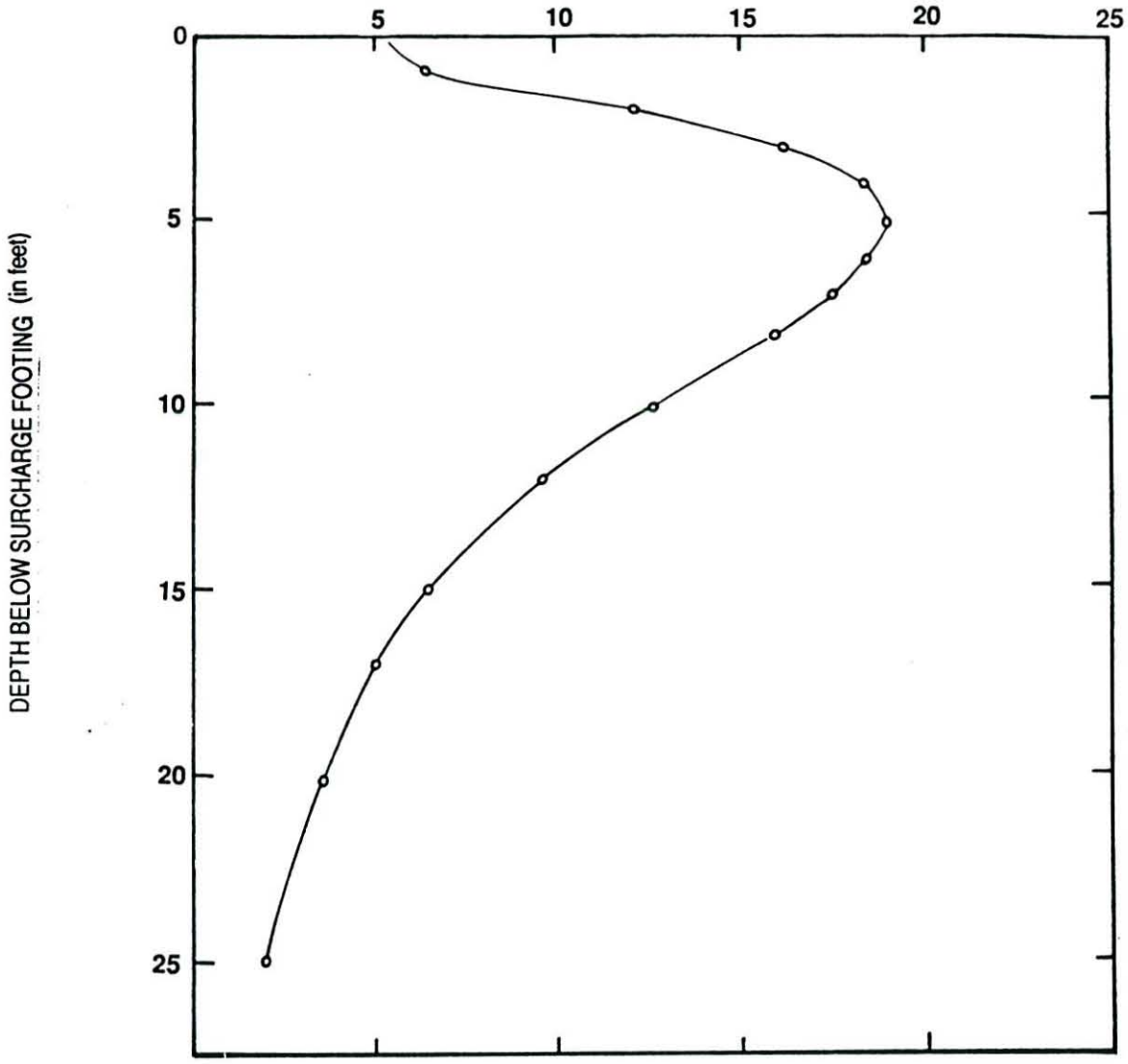
Job No. 1529-00 Appr. ESJ Date 12/28/89

LATERAL SOIL PRESSURE FOR BASEMENT WALL
PROPOSED COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA 9-173

FIGURE 9

ADDITIONAL HORIZONTAL PRESSURE DUE TO FOOTING IN PERCENTAGE OF SURCHARGE (PSF) *



*Assume footing within 10 feet of wall.

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851 HARRISON STREET, SAN FRANCISCO, CALIFORNIA 94107

Job No. 1529-00 Appr. GSJ Date 12/28/89

ADDITIONAL HORIZONTAL PRESSURE
DUE TO FOOTING SURCHARGE
PROPOSED COMBUSTION DYNAMICS FACILITY
LAWRENCE BERKELEY LABORATORY
BERKELEY, CALIFORNIA 9-174

FIGURE
10

CHEMICAL DYNAMICS RESEARCH LABORATORY

Structural Calculations

STRUCTURAL CALCULATIONS FOR COMBUSTION DYNAMICS FACILITY LAWRENCE BERKELEY LABORATORY

Description	Page
A. General	G-1 thru G-4
B. Roof Framing	RF-1 thru RF-2
C. Third Floor Framing	3F-1 thru 3F-2
D. Second Floor Framing	2F-1 thru 2F-9
E. First Floor Framing	1F-1 thru 1F-2
F. Lateral Forces	L-1 thru L-15
G. Foundations	F-1 thru F-5

NATIONAL 42 381 50 SHEETS 5 SQUARE 42 382 100 SHEETS 5 SQUARE 42 389 200 SHEETS 5 SQUARE

PROJECT DATA

Name: Combustion Dynamics Facility

Location: Lawrence Berkeley Laboratory
Berkeley, California

Design Criteria: DOE 6430.1A

1988 Uniform Building Code (UBC)

LBL Lateral Forces (Wind and Earthquake) Design Criteria August 15, 1989

$V = ZIKCSW$
$V = 0.20\,W$ min.

Type of Construction - Type II - 1988 UBC

Structural System:

Vertical: Complete vertical load carrying structural steel frame
Roof and Floors - (3rd, 2nd & Interstitual)
Light weight concrete fill (reinforced) over metal decking supported on structural steel beams

First Floor - Reinforced Concrete

Foundation - Reinforced Concrete Mat Foundation

Lateral: Vertical concentric braced structural steel frames

STRUCTURAL MATERIALS

Concrete: Compressive Strength (28 day minimum) = 4000 #/in²

Reinforcing Steel: ASTM A615
Grade 40 for No. 4 bars and smaller,
Grade 60 for No. 5 bars and larger.

Structural Steel: ASTM A36

Metal Decking: ASTM A446
Steel Sheet, zinc coated, hot-dipped galvanizing, Grade A

Foundation Design:

Geotechnical (Soils) Engineers

Geo/Resources Consultants, Inc
San Francisco, California

Report dated December 22, 1989
"Geotechnical Report
Combustion Dynamics Facility"

Allowable Soil Pressures:

Loading	
Dead Load	4000 #/ft²
Dead plus Live	4500 #/ft²
Dead plus Live plus Seismic	5000 #/ft²

ROOF LOADING

Item	Deck	Beam	Girder	Column	Seismic
Roofing	6	6	6	6	6
Insulation	3	3	3	3	3
2½ lt Conc + 2" 18ga. deck.	35	35	35	35	35
Mech.	3	3	3	3	3
Elec.	2	2	2	2	2
Ceiling	3	3	3	3	3
Beam.		3	3	3	3
Girder			3	3	3
Col.				2	2
Partitions					5
EDL	52	55	58	60	65
LL*	50	50	30	30	13*
TL	102	105	88	90	78

* Note:
1. Equipment Load = 1/4 LL = 50/4 = 13 #/ft² for seismic

THIRD FLOOR LOADING

Item	Deck	Beam	Girder	Column	Seismic
Flooring 2½ lt Conc + 2-18ga	35	35	35	35	35
Mech	3	3	3	3	3
Elec.	2	2	2	2	2
Ceiling	3	3	3	3	3
Beam		4	4	4	4
Girder.			4	4	4
Col.				2	2
Partitions	20	20	20	20	10
EDL	64	68	72	74	64
LL**	50	50	30	30	-
TL	114	118	102	104	64

** Note:
1. Office occupancy - Table 23-A, 1988 Uniform Bldg. Code
2. Roof Deck - Terrace - Same as area served

SECOND FLOOR LOADING

Item	Deck	Beam	Girder	Column	Seism.
Flooring	1	1	1	1	1
3" Lt Conc + 2"-18ga.	40	40	40	40	40
Mech	3	3	3	3	3
Elec.	2	2	2	2	2
Ceiling	3	3	3	3	3
Partitions*	-	-	-		
Beam		4	4	4	4
Girder (Truss)*			10	10	10
Column				4	4
EDL	49	53	63	67	67
LL	150	150	150	150	38**
TL	200	203	213	217	105

*Note
1. Do not include weight of partitions with LL = 150 #/ft²
2. Truss weighs 16.0 #/ft² × 1/2 = 8.0 #/ft² plus 2.0 #/ft² secondary bracing = 10 #/ft²

INTERSTITIAL LEVEL

Item	Deck	Beam	Girder	Column	Seismic
Flooring	-				
3" Lt Conc + 2"-18ga	40	40	40	40	40
Mech**	5	5	5	5	5
Elec.	2	2	2	2	2
Ceiling	3	3	3	3	3
Partitions	-	-	-		
Beam		4	4	4	4
Girder (Truss)**			10	10	10
Column				4	4
EDL	50	54	64	68	68
LL	75	75	75	75	20**
TL	125	129	139	143	88

** Note
1. Other mechanical equipment included in LL = 75 #/ft²
2. Truss weighs 16.0 #/ft² × 1/2 = 8.0 #/ft² plus 2.0 #/ft² for secondary bracing = 10.0 #/ft²
3. Equipment load for seismic = LL/4

BEAM RB-1 (W 12×26 (non composite))

Span 20' Spacing = 33'/4 = 8.25' A = 8.25×20 = 165

DL = 54 LL = 50 TL = 114 R = .08×(165-150) = 1.2

W DL = 165×54 = 8910
LL = 165×50 = 8250
TL = 165×104 = 17160

$M_o = WL/8 = 17.16 \times 20/8 = 42.9^{'k}$

$S_r = 42.9 \times .55 = 23.6\ in^3$ W12×26 Sp = 33.4

$\Delta_{LL} = \frac{8250 \times .1125}{18.75 \times 204} = 0.243\ in = \frac{L}{989}$

$\Delta_{TL} = 0.243 \times 17.16/8.25 = 0.505 = \frac{L}{475}$

BEAM RB-2 (W 12×40 (non-composite))

Span 26' Spacing = 8.25' A = 8.25×26 = 214.5

DL = 55 LL = 50(1.05) = 47.5 R = .08×(214.5-150) = 5.12

W DL = 214.5×55 = 11,800
LL = 214.5×47.5 = 10,200
22000

$M_o = WL/8 = 22.0 \times 26/8 = 71.5'k$

$S_r = 71.5 \times .55 = 39.33\ in^3$ W12×40, Sp = 51.9

$\Delta_{LL} = \frac{10200 \times .2472}{18.75 \times 310} = 0.434 = \frac{L}{720}$

$\Delta_{TL} = 0.434 \times 22000/10200 = 0.936 = \frac{L}{333}$

BEAM RB-1A (W 12×40 (non-composite))

Span 20' Spacing = (8.25+10.0)½ = 9.13

A = 9.13×20 = 182.5 Ratio = $\frac{182.5}{165}$ = 1.106

$S_r = 23.6\ in^3 \times 1.106 = 26.1\ in^3$
W12×26 Sp = $33.4\ in^3$

ROOF GIRDER RG-1 (W16×67 (non-composite))

Span 33', 10', 33'

Spacing = 20'

Area = 33×20 = 660 ft² $R = .08(660-150) = 40$

$R = 23.1(1+D/L) = 46$

DL = 57 LL = 50(1-.40) = 30 w #/

WDL = 57×660 = 37.6 k 1.16 k/' $M_o = wL/8$

LL = 30×660 = 19.8 .60

TL 57.4 k 1.76 $= \frac{57.4 \times 33}{8}$

$= 236.9$ 'k

$S_r = 236.9 \times .55 = 130.3$ in³

W 16×67 $S_p = 117.0$ in³

18×76 $S_p = 146.0$ in³

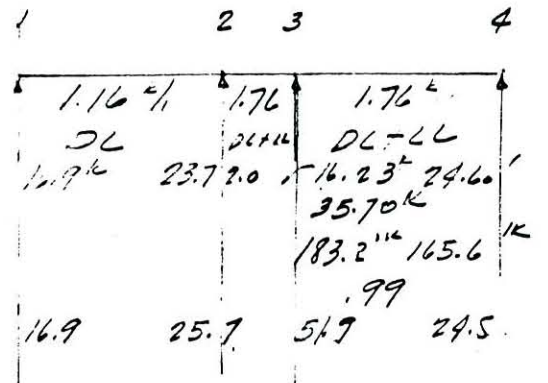
RISA Computer Program - W16×67

1. Loading

M_o $f_b = 18.81$ k/in² = .79

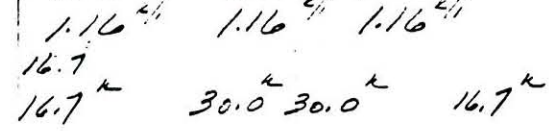
$F_b = 23.76$ k/in²

Δ_R = L/403 (TL)



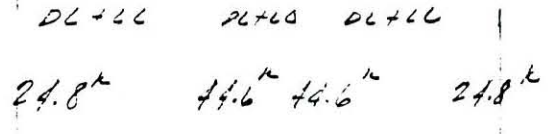
2. Loading

R

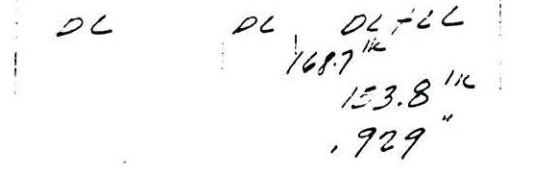


3 Loading

R



4 Loading



AISC Unity = 0.729

Δ

Design Moment = −183.2 'k = WL × .097

do do +165.6 'k = WL × .087

BEAM 3B-1 (W 12×26 (non-composite))

Span 20' Spacing = 25'4"/3 = 8.44'
A = 8.44 × 20 = 169 R = .08 (169 - 150) = 1.52%

DL = 68 LL = 50 TL = 138

		w #/'
WDL = 169 × 68 =	11.5 k	.573
LL = 169 × 50 =	8.5 k	.422
TL = 169 × 118 =	20.0 k	.995

Mo = WL/8 = 20.0 × 20.0/8 = 50.0 'k

Sr = 50.0 × .55 = 27.5 in³ W12×26 Sp = 33.4
Ip = 204

$$\Delta_{LL} = \frac{8500 \times .1125}{18.75 \times 204} = 0.25 = \frac{L}{960}$$

$$\Delta_{TL} = 0.25 \times 20.0/8.5 = 0.588 = \frac{L}{408}$$

BEAM 3B-2 (W 12×40 (non-composite))

Span 26' Spacing = 8.44 A = 8.44 × 26 = 219.4
R = .08 (219.4 - 150) = 5.5

DL = 72 LL = 50(1-.055) = 47.25
= 48

WDL = 219.4 × 68 =	14.9 k
LL = 219.4 × 48 =	10.5
TL = 219.4 × 116	25.4 k

Mo = WL/8 = 25.4 × 26/8 = 82.6 'k

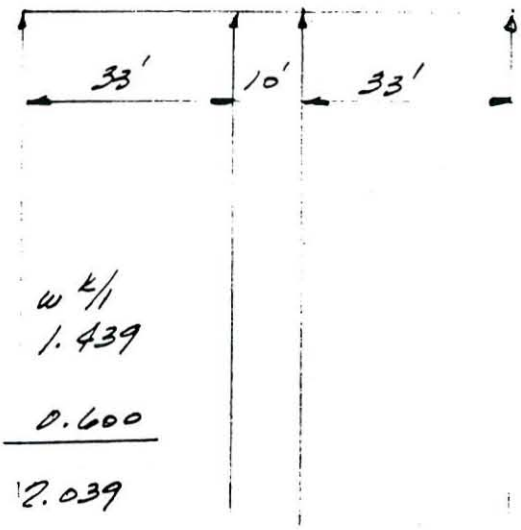
Sr = 82.6 × .55 = 45.43 in³ W12×40, Sp = 51.9
Ip = 310

$$\Delta_{LL} = \frac{10500 \times .2472}{18.75 \times 310} = 0.447 = \frac{L}{699}$$

$$\Delta_{TL} = 0.447 \times 25.4/10.5 = 1.08 = \frac{L}{289} < \frac{L}{240}$$

3rd FLOOR GIRDER 3G-1 (W 16×67 Non composite)

Span 33', 10', 33'
Spacing = 20'



Area = 33×20 = 660
R = .08 (660 - 150) = 40
R = 23.1 (1 + 72/50) = 56
LL = 50 (1 - .40) = 30
DL = 72

$W_{DL} = 72 \times 20 \times 33 = 47.5^k$ (1.44 k/')

$LL = 30 \times 20 \times 33 = 19.8^k$ (.600)

$TL = 67.3^k$

w k/'
1.439
0.600
2.039

$M_o = \frac{WL}{10} = \frac{67.3 \times 33}{10} = 222.1^{'k}$

$S_r = 222.1 \times .55 = 122.2 in^3$ W16×67: $S_p = 117.0 in^3$

RISA Computer Program - W16×67

1. Loading — DL | DL+LL | DL+LL

M_o fb = 21.60 = .908
Fb = 23.76
Δ_{TL} = L/342
R

	DL	DL+LL	DL+LL
M_o		210.1	
R	20.65k	32.5 58.7	28.1k
Δ		1.156"	

2. Loading — DL | DL | DL
R — 20.47k | 36.8k 36.8k | 20.47k

3. Loading — DL+LL | DL+LL | DL+LL
R — 28.6k | 51.44 51.44 | 28.6k

4. Loading — DL | DL | DL+LL
M_o — 208.0'k
Δ = L/341 — 1.16

Design Moment = -210.1'k = WL × .095
do do = +208.1'k = WL × .094

BEAM 2B-1 (W12×40 non composite) (W12×26 composite)

Span 20' Spacing = 25.33/3 = 8.44
A = 8.44×20 = 168) R = not taken

DL = 53 LL = 150 TL = 203 #/ft²

WDL = 169×53 = 8.96 k
LL = 169×150 = 25.35
TL = 169×203 = 34.31k

Mo = WL/8 = 34.3×20/8 = 85.8 ^k

Sr = 85.8×.55 = 47.2 in³ W12×40 Sp = 51.9 in³
Ip = 310 in⁴

$\Delta_{LL} = \frac{25350 \times .1125}{18.75 \times 310} = 0.491 = \frac{L}{488}$

$\Delta_{TL} = 0.491 \times 34.31/25.35 = 0.665 = \frac{L}{361}$

INRYCO Manual 21-12
Composite Design 3" Lt. Conc Slab +
(W12×27 - 5¼ total Slab) 2" QL-99-18 Decking

Effective Conc. Flange
1. b = 16t + bf = 16×5.75 + 4 = 88"
2. .25L = .25×12×20 = 60"
3. Spacing = 8.44×12 = 101.28

W12×22 (5¼" Total Depth) I Lt wt = 563.6
b = 50"

St = 95.92 nSt = 1343.0
Str = 47.0 in³ = 100% Vh
Vh (100%) = 116.5 k

V'h = .75×116.5 k = 87.38 k per ½ beam
110 #/ft³ Lign-weight - 3/4 studs
Q = 11.5 (.83) = 9.54 kips/stud
87.38 k / 9.54 = 9.15 Use 10×2 = 20 - 3/4 studs per 20' beam

$f_c = \frac{M_o}{nS_t} = \frac{85.8 \times 12000}{1343} = .766 < .45 f'_c = 1.35$ k/in²

$f_t = \frac{M}{S_t} = \frac{85.8 \times 12000}{47.0} = 21,906$ #/in² < 24,000 #/in²

BEAM 2B-2 (W12×53 Non-composite) (W12×40 Composite)

Span 26' Spacing = 8.44 A = 8.44×26 = 219
R = not taken
DL = 53 LL = 150 TL = 203 LL > 100 #/ft²

W_{DL} = 219×53 = 11.6 k
LL = 219×150 = 32.9 k
TL = 219×203 = 44.5 k

M_o = WL/8 = 44.5×20/8 = 111.3 'k

S_r = 111.3 × .55 = 61.20 in³ W12×53 S_p = 70.6
I_p = 425

$\Delta_{LL} = \frac{32900 \times .2472}{18.75 \times 425} = 1.02 = L/305 > L/360$

Δ_{TL} = 1.02 × 44.5/32.9 = 1.38 = L/226 > L/240

INRYCO Manual 21-12

Composite Design (3" Lt. Conc. + 2" QL-99-18)

Effective Flange b = .25L = 78"

W12×40 (5½" Conc. b = 70"
S_{tr} = 85.8 in³ nS_t = 2063.8 I Lt wt = 9537

V_h 100% = 212.4 k V'_h = .75 × 212.4 = 159.3 k per ½ beam
f'c = 3000 Lt wt = 110 pcf
Q = 11.5 × (.83) = 9.54 k/stud
N = 159.3/9.54 = 16.6 = 17 × 2 = 34 studs per 26' beam.

$f_c = \frac{M_o}{nS_t} = \frac{111.3 \times 12000}{2063.8} = 647 < .45 f'_c = 1350$

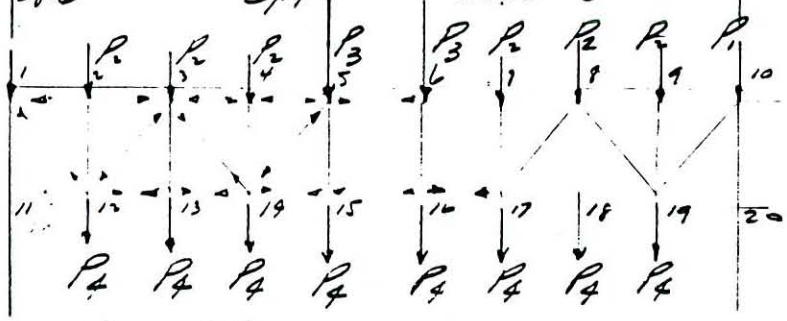
$f_s = \frac{M_o}{S_{tr}} = \frac{111.3 \times 12{,}000}{85.8} = 15600$ #/in² < 24,000 #/in²

TRUSS 2T-1

Span 76'-0" Spacing = 20' A = 1520 ft²

Loading

Roof	DL	16.7k	30.0k	Σ 46.7k	Roof
LL=50	LL	8.1k	14.6	22.7	
RLL=30	TL	24.8	44.6	69.4k × 2 = 138.8k	15'
3rd	DL	20.5	36.8k	73.6	3rd
LL=50	LL	8.1	14.6	22.7	
RLL=30	TL	28.6	51.4	96.3 × 2 = 192.6k	17'-0"
2nd					2nd
LL=150					12'-0"
RLL=150					
Inter.					Inter.
LL=75					
RLL=75					
ΣRLL = 285 #/ft²					



Load	DL	LL	TL
P_1	37.2	16.2k	= 53.4k
Siding	= 32 × 20 × 20 = 12.8k		
	12.8k		
	50.0k	16.2	= 76.2k

To Truss

	DL	LL	TL
P_2 =	9.0	25.4	34.4k × 6 = 54.0k 152.4k 206.4k
P_3 =	66.8k	29.2k	96.0k
P_2	9.0	25.4	34.4
ΣP_3 =	75.8k	54.6k	130.4k × 2 = 151.6k 109.2 260.8k
P_4 =	9.1k	12.67k	21.8k × 8 = 72.8k 101.4k 174.2k

Σ R + 3rd + 2nd + Inter + w/o truss = 278.4k 363.0k 641.4k

A = 1520 ft² w #/ft² = 183 239 422

Check	DL	LL	TL	DL	LL	TL
Roof	93.4	45.4	138.8k	60.0	29.2	89.2
3rd	147.2	45.4	192.6	73.6	29.2	102.8
2nd	72.0	203.2	275.2	72.0	203.2	275.2
Inter.	72.8	101.4	174.2	72.8	101.4	174.2

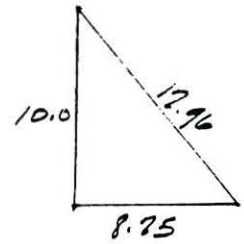
TRUSS 2T-1

Span 76'-0" Spacing = 20' Area = 1520 ft²

Preliminary Truss 2T-1 Design

	DL	LL	TL	Load Diagonal
Reaction Left	139.2k	181.5	320.7k	
Shear 1-2	139.2k	181.5k	320.7k	415.6k
$-(P_2+P_4)$ *	18.2	38.1	56.3	
2-3	121.0	143.4	264.4k	342.7k
$-P_2+P_4$	18.2	38.1	56.3	
3-4	102.8	105.3	208.1k	269.7k
$-P_2+P_4$	18.2	38.1	56.3	
4-5	84.6	67.2	151.8k	196.7k
$-P_2+P_4+P_3$	85.0	67.3	152.3k	
5-6	0	0	0	

* Diagonal ℄ to ℄ Top Chord = 10.0
Panel Point = 8.25
Diagonal = 12.96



Load in Diagonal (w/o Truss wt)
= Shear × 12.96/10.0 = 1.296

Load in Horizontal = Shear × 8.25/10.0 = .825

TRUSS 2T-1 (continued)

Top and Bottom Chord

Moment @ ℄ Truss Span

Item

P_2 8× 34.4^k = 275^k

P_4 8× 21.8 = 174.4^k

P_3 (w/o P_2) = = 96.0

do = 96.0

641.4^k

$M_o = \frac{wL}{8} = \frac{(275.4 + 174.4) \times 76}{8} = 4273.0^k$ (449.8)

$P_3 \times 38 - P_3 \times 5 = P_3 \times 33$ (96.0^k) = 3168.0

7,441.0$^{'k}$

Top Chord $F_c = \frac{7441.0}{10} = 744.1^k$

W 12× 136 $P_{allow} = 772.0^k$ $L = 10.0 = 120$

$A_p = 39.9 in^2$ $L/r = 120/3.16 = 38$ $f_{ca} = 19,350 \#/in^2$

$P_{allow} = 19,350 \times 39.9 = 772.0^k$ ✓

Bottom Chord $F_t = \frac{7441.0}{10} = 744.1^k$

$A_r = 744.1/20.0 = 37.2$

W 12× 136 $A_p = 39.9 in^2$

Member	Shear	Load			P_{allow}
1-3 (1-2)	320.7^k	-264.6^k	-264.6 ✓	W 12× 53	295.0^k
3-5 (2-3)	264.4^k	-218.1			
(3-4)	208.1^k	-171.7^k	-654.4 ✓	W 12× 120	702.0^k
5-6 (4-5)	151.8^k	-125.23	779.6 ✓ ^{k}	W 12× 136	795.0^k
12-14		+264.6 + 218.1	= +482.7 ✓ ^{k}	W 12× 87	
14-15	482.7	+171.7	125.23 = 779.6 ✓ ^{k}	W 12× 136	

TRUSS 2T-1 (continued)

WEB Member	Shear	Direct	Load	Area(r)	Section
1-12	320.7k		+415.6k	20.80 in² (1)	W12x72
2-12		-34.4k (5)			W12x40
3-12	264.4		-342.7k (3)		W12x72
3-13		+21.8k			W12x40
3-14	208.1k		+269.7k	13.50 in² (2)	W12x53
4-14		-34.4k			W12x40
5-14	151.8		-196.7k (4)		W12x50
5-15		+21.8			W12x40

Calculations

(1) $A_r = 20.8\ in^2$ W12x72 $A_p = 21.1\ in^2$

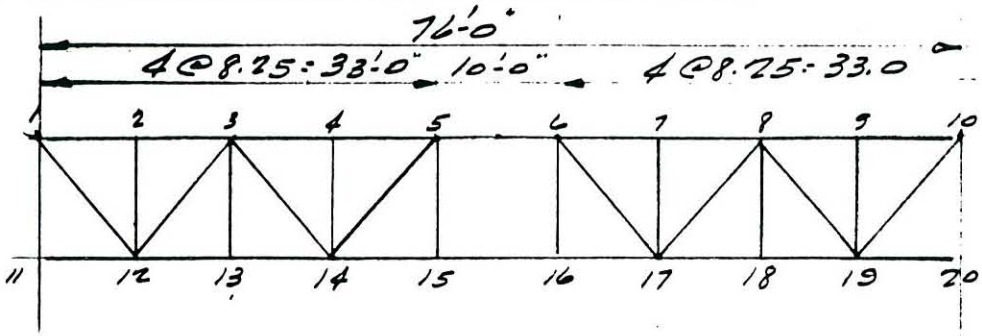
(2) $A_r = 13.5\ in^2$ W12x53 $A_p = 15.6\ in^2$

(3) Load = -342.7k $L = 12.96 \times 12 = 155''$ $L/r = 120$ max
$r = 1.296$ min
W12x72 $A_p = 21.1$ $r_y = 3.04$ $P_{allow} = 385.0^k$
$L/r = 51.0$ $f_{ca} = 18{,}260 \times 21.1 = 385.0^k$

(4) Load = -196.7k $L = 155''$ $L/r = 120$ max
W12x50 $A_p = 14.7$ $r = 1.96$ $P_{allow} = 226$
$L/r = 77$ $f_{ca} = 15{,}470 \times 14.7 = 227.0^k$

(5) Load = -34.4k $L = 120''$ $L/r = 120$ $P_{allow} = 180^k$
W12x40 $A_p = 11.8$ $r = 1.93$ $L/r = 62.17$ ok

TRUSS 2T-1 (continued)



Member	L	Size	Wt.
1-2	8.25	W12x53	440
2-3	8.25	do	440
3-4	8.25	W12x120	990
4-5	8.25	do	990
5-6	10.0	W12x136	1360
6-7	8.25	W12x120	990
7-8	8.25	do	990
8-9	8.25	W12x53	440
9-10	8.25	do	440
11-12	8.25	W12x87	720
12-13	8.25	do	720
13-14	8.25	do	720
14-15	8.25	W12x136	1120
15-16	10.00	do	1360
16-17	8.25	do	1120
17-18	8.25	W12x87	720
18-19	8.25	do	720
19-20	8.25	do	720
1-12	12.0	W12x72 x2	1730
2-12	10.0	W12x40 x do	800
3-12	12.0	W12x72	1730
3-13	10.0	W12x40	800
3-14	12.0	W12x53	1280
4-14	10.0	W12x40	800
5-14	12.0	W12x53	1300
5-15	10.0	W12x40 do	800

Σ 24,140#/76 = 317.63#/' = 15.88#/H Σ 24240#

BEAM IB-1 (W 12x 26 (non-composite)

Span 20' Spacing = 25.33/3 = 8.44' A = 8.44x 20 = 168.9

DL = 54 LL = 75 TL = 129

W_{DL} = 169x 54 = 9.13^k
LL = 169x 75 = 12.68

TL = 169x129 = 21.81^k

M_o = WL/8 = 21.81^{k}x 20/8 = 54.5$^{'k}$

S_r = 54.5x .55 = 30.0 in^3 W12x26 S_p = 33.4 in^3
I_p = 204

$\Delta_{LL} = \frac{12680 \times .1125}{18.75 \times 204} = 0.373 = \frac{L}{643}$

Δ_{TL} = 0.373x 21.8^k/12.68^k = 0.641 = L/374

STEEL DECKING

Area	Span	DL	LL	TL
Roof	33'/4 = 8.25'	52 #/ft²	50	102 #/ft²
3rd	25.33/3 = 8.44' (end)	64	50	114
	= 10.0' (cont)	64	50	114
2nd	= 8.44	64	150	214
	= 10.0 (cont)	64	150	214
Interstital	= 8.44'	64	75	119
	= 10.0 (cont)	64	75	119

Try H.H. Robertson

Non-Composite 2"-QL-99-18 Wt = 2.7 #/ft²
$I = .558\ in^4$ $S_+ = .525\ in^3$ $S_{(-)} = .519\ in^3$

Wallow = C_B/span² (2-span) = 6930/8.44² = 97 #/ft² N.G.

Composite 2"-QL-99-18 + 2½" conc. slab Ltw. Conc = 110 pcf
N = 14 f'c = 3000 psi
$I_c = 4.633\ in^4$ $S_{tc} = 2.588\ in^4$ $S_{bc} = 1.68\ in^4$ Wt = 35 #/ft²

2½" Conc. Slab, Span 8.5' Total/Superimposed Load/sq. foot = 275 #/sq. ft

Span 8.5' A = 8.5 W = 8.5 × 275 = 2338

Mo = 2338 × 8.5/10 = 1987 # fb = 1987×12 / (1.68 × 14) = 14,193 #/in²

Span 10.0' W(sl) = 189 (2½") / 2.588 = 658 #/in²
do 218 (3")

Reinforcing - 6 × 6 × W1.5 × W1.5

ICBO Report 273 - Page 5 of 19 - 2" Ltw. Conc.
Span 8'-0" Yallow = 1490 #/1 (4 puddle welds at supports)

FIRST FLOOR SLAB

Span (clear) = 45'-0"

Try 40" total depth = $\frac{40}{12} \times 150 = 500$ #/ft²

Live Load = 250

750 #/ft²

$W = .750 \times 45 = 33.8$ k/'

$M_{o\,ws} = \frac{WL}{8} = \frac{33.8 \times (45+2)}{8} = 198.6$ 'k/'

$f'_c = 4000 \quad f_y = 60{,}000$

$M_u = bd^2/20 \qquad d = \left(\frac{M_u \times 20}{b}\right)^{1/2}$

$M_u = 1.4DL + 1.7LL = 1.4 \times 500 = 700$ #/ft²

$1.7 \times 250 = 425$

1125 #/ft²

$W_u = 1.125 \times 45 = 50.6$ k/'

$M_u = \frac{50.6 \times (45+2)}{8} = 297.3$ 'k/'

$d = \left(\frac{297.3 \times 20}{12}\right)^{1/2} = 495.5^{1/2} = 22.5" + 2.5 = 25"$

Use 48" - 2.5 = 45.5

$A_s = \frac{M_u}{4d} = \frac{297.3}{4 \times 45.5} = 1.63$ in²/ft

#8 @ 6" = $A_{sp} = 1.6$ in²/ft

t ACI 318-83 Section 7.12 $A_t = .002 A_c$

48" $A_t = .002 \times 48 \times 12 = 1.152$ in² #7 @ 12 ea. face $A_s = 1.2$ in²

24" $A_t = .002 \times 24 \times 12 = 0.576$ in² #5 @ 12 ea. face $A_s = .62$ in²

60" $A_t = .002 \times 60 \times 12 = 1.44$ in² #8 @ 12 ea. face $A_s = 1.60$ in²

120 $A_t = .002 \times 120 \times 12 = 2.88$ in² #11 @ 12 ea. face $A_s = 3.12$ in²

FIRST FLOOR SLAB - ELECTRICAL SUBSTATION

Span (clear) = 23'-0"

Try 24" Conc. Slab

$DL = \frac{24}{12} \times 150 = 300 \times 1.4\ DL = 420\ \#/ft^2$

$LL = 500\ \#/ft^2 = 500 \times 1.7\ LL = 850$

$1270\ \#/ft^2$

$M_o = \frac{1.27 \times 23 \times (23+2)}{8} = 91.3\ 'K$

$d = \left(\frac{M_u \times 20}{b}\right)^{\frac{1}{2}} = \left(\frac{91.3 \times 20}{12}\right)^{\frac{1}{2}} = 152.2^{1/2} = 12.5$

2.5

15.0

Use d = 24"

$A_s = \frac{91.3}{4 \times 21} = 1.09$ #7@6 $A_s = 1.20$

LATERAL FORCES

Criteria

1. 1988 Uniform Building Code
2. LBL Lateral Force (Wind and Earthquake) Design Criteria - F. T. Anglis Aug. 15, 1989
3. DOE ORDER 6430.1A "General Design Criteria" April 6, 1989
4. UCRL 15910 "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards", May 1989

1988 UBC

$$V = \frac{ZICW}{R_w} = \frac{.4 \times 1.0 \times 2.75}{R_w} W = \frac{1.10W}{R_w}$$

Table No. 23-O
Concentric Braced Frames - Steel - $R_w = 8$

$$V = \frac{1.10R}{8} = 0.138\,W$$

1989 LBB

$$V = 0.2\,W$$

TRANSVERSE
LATERAL FORCE ANALYSIS

Note:
1. Calculate the weight of a unit width transverse strip across building

		Seismic Forces F_x k	F_x #/ft²
Roof			
Roof = 76' × 78 #/ft²	= 5.93 k/'		
Siding = 2 × 15/2 × 20	= .30		
W_r	6.23 k/'	2.1 k/'	27.6 #/ft²
3rd Floor			
3rd Flr. = 76' × 64	= 4.86 k/'		
Siding = 2 × 31.6 × 1/2 × 20	= .63		
W_3	5.49 k/'	1.4 k/'	18.4 #/ft²
2nd Floor			
2nd Flr. = 76' × 105	= 8.0 k/'		
Siding = 2 × 29.0 × 1/2 × 20	= .6		
W_2	8.6 k/'	1.4 k/'	18.4 #/ft²
Interstitial Floor			
Int Flr = 76 × 88	= 6.7 k/'		
Siding = 2 × 28.0/2 × 20	= .6		
W_i	7.3 k/'	.7 k/'	9.21
ΣW	27.62 k/'	5.6 k/'	73.60 #/ft²

Distribution

Item	W k/'	h	Wh 'k	wh/Σwh	W_x k	F_x	F_x/W_x
Roof	6.23 k/'	60	373.8 'k	.381	10.5 k	2.1 k/'	.337
3rd	5.49	45	247.1	.252	6.96	1.4	.255
2nd	8.60	28.42	244.4	.249	6.88	1.4	.163
Int.	7.30	16.00	116.8	.119	3.29	.7	.096
ΣW	27.62 k/'		982.1 'k	1.00	27.6 k/'	5.6 k/'	

$F_x = .20\,W_x$ $\quad \Sigma F_x = .20\,W = .20 \times 27.62 = 5.5$ k/'

DIAPHRAGM FORCES*

Item	W_x	ΣW_t	F_x	ΣF_i	$\frac{\Sigma F_i}{\Sigma W_t}$ vs	F_x/W_x
Roof	6.23 k/l	6.23	2.1	2.1	.337	.337
3rd	5.49	11.72	1.4	3.5	.30	.255
2nd	8.60	20.32	1.4	4.9	.24	.163
Int.	7.30	27.62	.7	5.6	.20	.096

* UBC Section 2312(h)2I Diaphragm Forces

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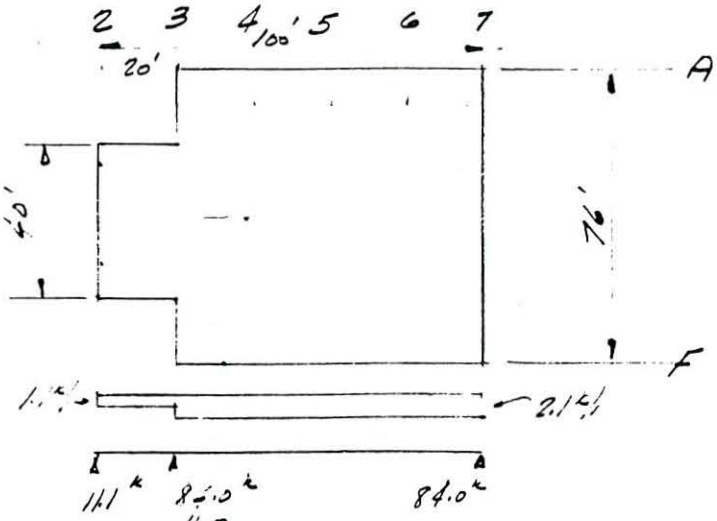
Roof

Roof 3-7 = 2.1 k/' × 80 = 168.0 k
2-3 = 1.1 × 20 = 22.0
190.0 k

Roof per 20' bay
= 2.1 × 20 = 42.0 k

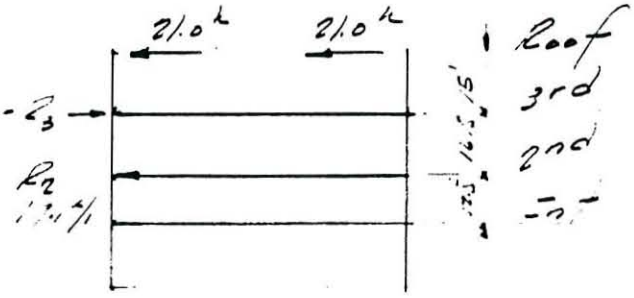


Bracing System A

1. Cantilever Columns Line A & F off 3rd Floor

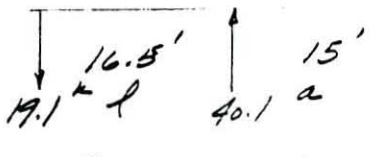
2. M_o @ 3rd Floor
$M_o = 21.0 \times 15 = 315$ 'k

3. $R_3 = \frac{21.0 \times 31.5}{16.5} = 40.1$ k
$R_3 = \frac{40.1}{20} \times 2 = 4.01$ k/'
$R_2 = \frac{21.0 \times 15}{16.5} = 19.1$ k



Scale: 1" = 50'

4. Steel Column $M_o = 315$ 'k $S_r = \frac{315 \times .55}{1.33} = 130 in^3$
21.0 k
W12×87 $S_p = 131 in^3$



$\Delta = \frac{Pa^2}{3EI}(l+a)$ $\Delta_{allow} = .005 \times 15 \times 12 = 0.9$

$I_r = \frac{Pa^2}{\Delta 3E}(l+a) = \frac{21{,}000 \times 180^2}{.9 \times 3 \times 30 \times 10^6}(198+180) = 3175 in^4$
8.4

W12×279 $I_p = 3110 in^4$
$S_p = 393 in^3$

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Roof

Bracing System B

1. Concentric Bracing Lines 3 & 7 - System 1

Line 3

$F_{roof} = 2.1 \times \frac{80}{2} = 84.0^k$

3-7

2-3 $= 1.1 \times 20/2 = 11.0^k$

95.0^k

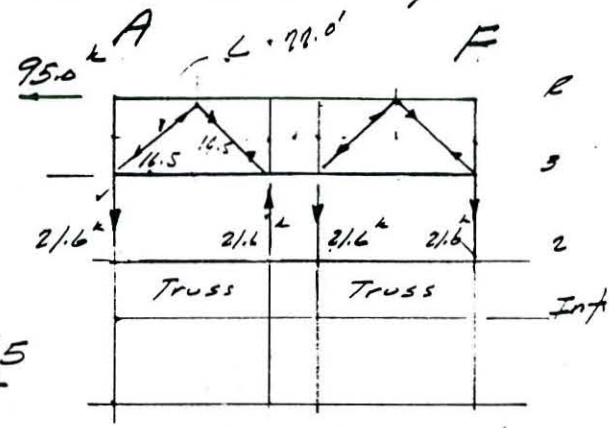
$T = C = \frac{95.0 \times 15}{2 \times 33} = 21.6^k$

$P = \frac{95.0}{4} \times \frac{22}{16.5} = 31.7^k \times 1.5 = 47.6^k$

$r = 22 \times 12/120 = 2.2$ in

$6 \times 6 \times \frac{3}{8}$ $P_a = 89.0^k$

$r = 2.27$ in.



Line 3 - System 1
Line 7 - System 1

2. Concentric Bracing Lines 3 & 7 - System 2

$P = \frac{95.0 \times 36}{2 \times 33} = 51.8^k \times 1.5 = 77.7^k$

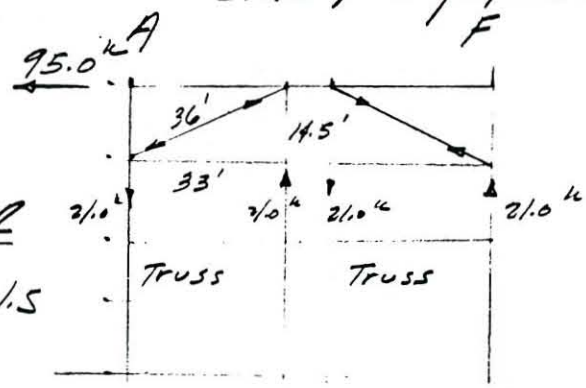
$r = 36 \times 12/120 = 3.60$ in

$10 \times 10 \times \frac{3}{8}$ $P_a = 172.0^k$

$r = 3.90$ in.

$8 \times 8 \times \frac{3}{8}$ $P_a = 84.0^k$

$r = 3.12$ in.



Line 3 - System 2
Line 7 - System 2

Scale 1" = 40'

$T = C = \frac{95.0 \times 14.5}{2 \times 33} = 21.0^k$

3. Roof Diaphragm

$V = 84.0^k/76 = 1.11^k/'$ or $V_{allow} = 1.49^k/'$

$T = C = \frac{168 \times 100}{8 \times 76} = 27.6^k$ $A = 27.6/26.6 = 1.03$ in² or

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3rd Floor

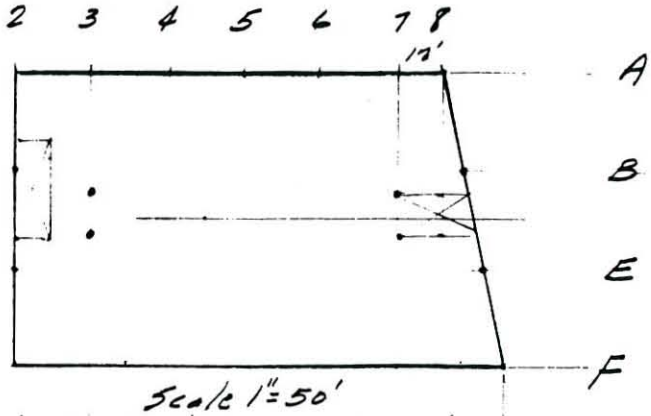
F_x

1-8 = 112 × 1.4 = 156.8 k/l

8-A to 8-F:

15 × 76 × 1/2 × 18.4 = 10.5 k

167.3 k

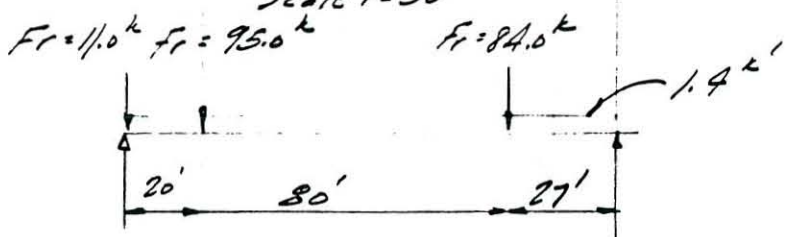


Scale 1" = 50'

F_x 3rd

Line 2 = 1/2 × 156.8 = 78.4 k

Line 8 = 1/2 × 156.8 = 78.4 k
10.5
88.9 k



Mo (over) - Line 2 Fr = 11.0

Froof = 11 × 31.5 = 346.5 k

F3rd = 78.4 × 16.5 = 1,293.6

97.9 × 16.5 = 1,615.4

Σ 187.3 k 3255.5 k

80.0
17.9 } 97.9 k
108.7 k

F3rd 78.4 + = 176.3 k
187.3 k

15.0
66.1 } 81.1 k
81.1 k = 170.0 k
88.9
170.0 k

T = C = 3255.5 k / 50.67 = 64.3 k

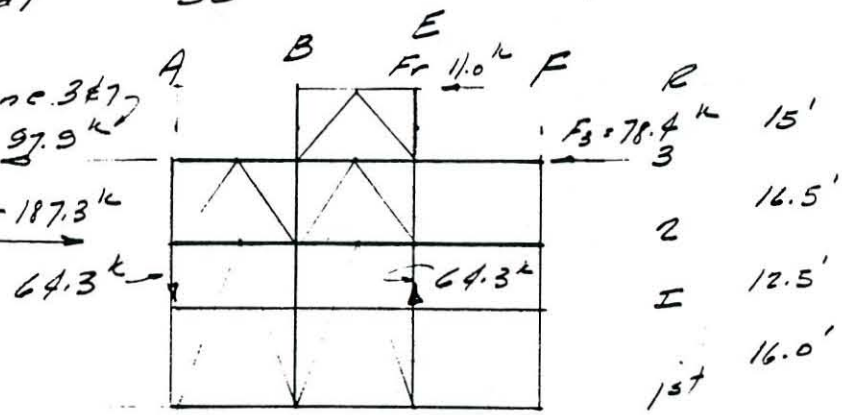
V R+3rd = 177.3 k / 33 = 5.37 k/l NG

V E+3rd = 170.0 / 66 = 2.576 k/l NG

V 3rd only = 78.4 k / 33 + 17 = 50 = 1.56 k/l ok

V 3rd only = 88.9 / 66 = 1.35 k/l ok

Note!
1. Need horizontal bracing truss to transfer Roof Forces to Braced Frames Line 2 & 8



Line 2

Scale 1" = 40'

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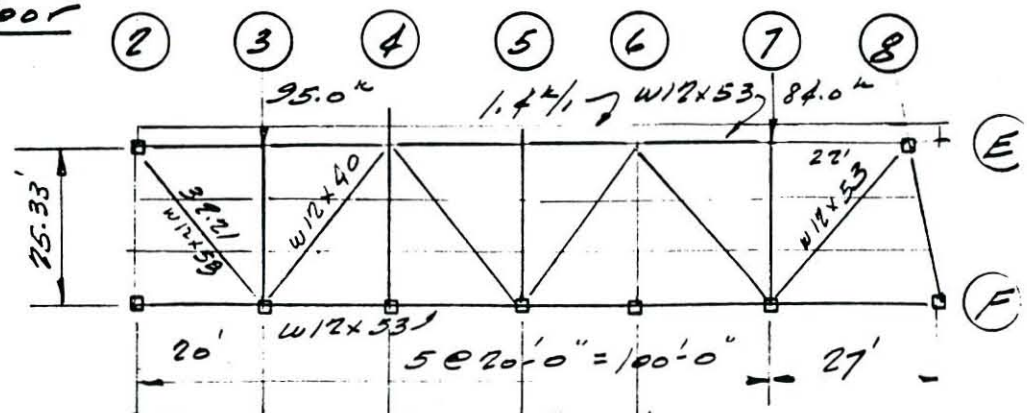
3rd Floor



R = 80.0k
17.9
78.4
176.3k

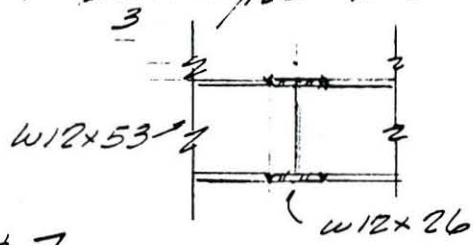
M_o = 176.3 × 58.1 = 10,240 'k
− 95.0 × 38.1 = − 3620
− 58.1² × 1.4 × ½ = − 2360
4260 'k

170.0 × (127.0 − 58.1) = 11 713 (68.9)
84.0 × 41.9 = 3520
68.9² × 1.4 × ½ = 3320
170.0k
4873

T = C = 4873 / 25.33 = 192.38k r = 20 × 12 / 120 = 2.0
W12x53 P_a = 209.0k r = 2.48 L = 20' y-y
$M_{o\,DL+LL}$ = 50.0 'k f_a = 192.3 / 15.6 = 12.37 k/in² × 1.176
= 14.5 k/in² ok

Diagonal · 2-3, E-F

P = 176.3k × 32.2' / 25.33' = 224.1k r = 32.21 × 12 / 20 = 1.08
W12x53 L = 8.25 × 1.4 = 11.6'
P_a (L = 12') = 236k r = 2.48 in



other diagonals W12x40
by inspection

Collector Struts · Line 3 & 7

W 16x67 P = 95.0'k L_{xx} = 33.0' L_{yy} = 8.25'
w k/ft = 2.04

Risa Computer Bmstrut AISC Unity = 0.933 *
× 1.176
= 1.097
ok

*UBC Section 2312 (h) 2I Diaphragm Forces
Ratio = .30 / .255 = 1.176

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2nd Floor

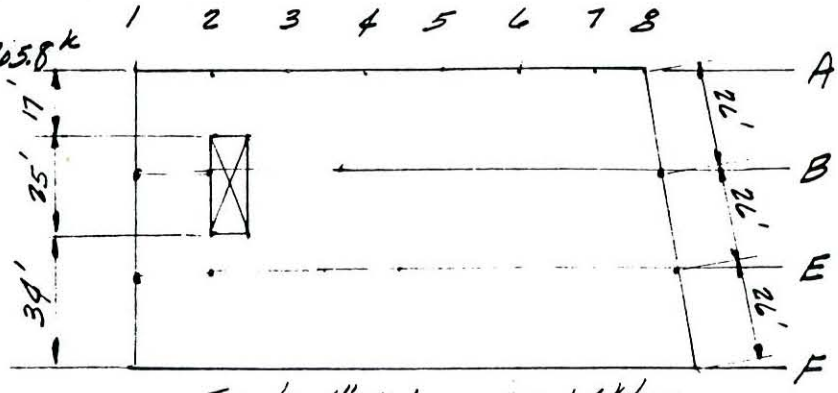
$F_x = 1.4^k/_1 \times 147 = 205.8^k$

$R_2 = \frac{1.4 \times 147^2}{2 \times 127} = 119.1^k$

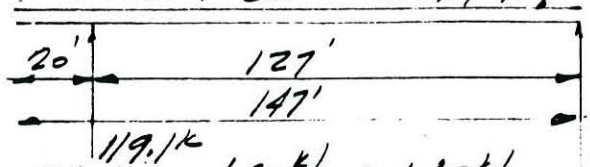
$R_8 = \frac{1.4 \times 147 \times (73.5 - 20)}{127} = 86.7$

$\Sigma = 205.8^k$ ✓

$V = 119.1^k - 20 \times 1.4 = 91.0^k$



Scale 1" = 50' $w = 1.4^k/_1$



$V = \frac{91.0^k}{33+17} = 1.82^k/_1$ vs $1.49^k/_1$ 3" Ltw Conc. + 2" Metal Deck

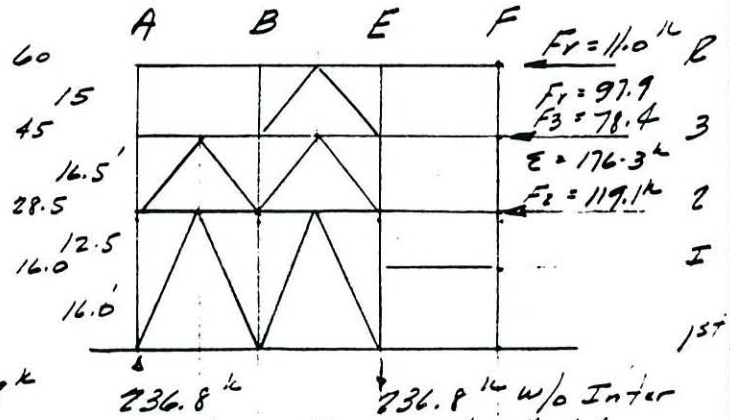
$\frac{86.7}{76} = 1.14^k/_1$

Note:
1. Need horizontal bracing truss to transfer 3rd Floor Forces to Braced Frames Line 2 & 8. in a more predictable manner.

Mo (over) - Line 2
w/o Interstitial Level

Roof = 11.0 × 60 = 660 k
3rd = 176.3 × 45 = 7934
2nd = 119.1 × 28.5 = 3395
12,000 k

$T = C = 12{,}000 / 50.67 = 236.8^k$

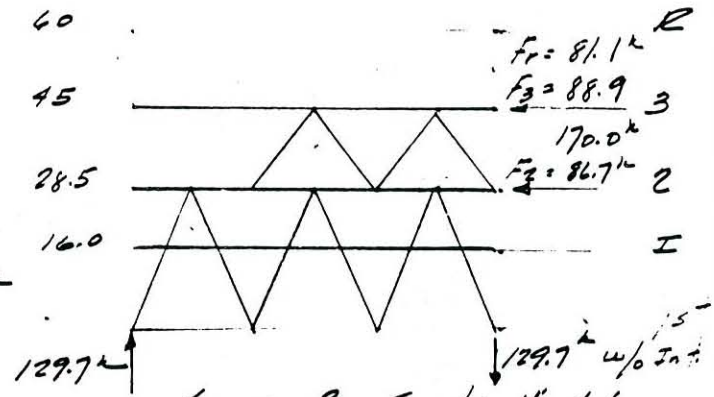


Line 2 Scale 1" = 40'

Mo (over) - Line 8

Roof = = 0
3rd = 170.0k × 45 = 7650
2nd = 86.7k × 28.5 = 2470
10120 k

$T = C = 10120 / 3 \times 26 = 129.7^k$
78



Line 8 Scale 1" = 40'

TRANSVERSE

Interstitial Level

$F_x = .8^k/' \times 147 = 117.6^k$

$R_2 = \frac{.8 \times 147^2}{2 \times 127} = 68.0^k \times 2 = 136.0^k$

$R_8 = \frac{.8 \times 147 \times 53.5}{127} = 49.6 \times 2 = 99.2^k$

$\Sigma\ 235.2^k = 2 \times 117.6^k$

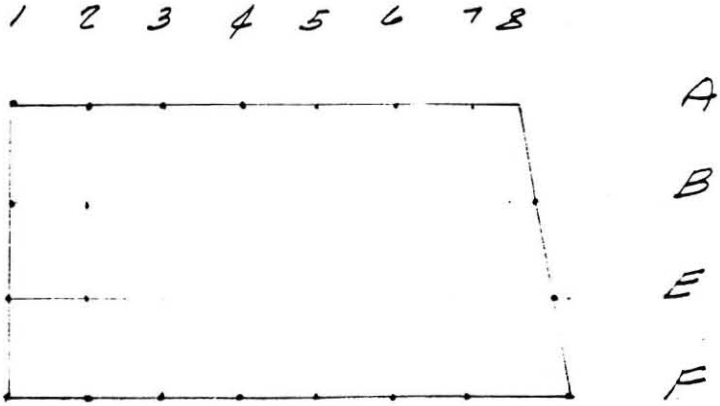
$V = 68.0^k - .8 \times 20 = 52.0^k \times 2 = 104.0^k$

UBC Section 2312(h) 2 I*

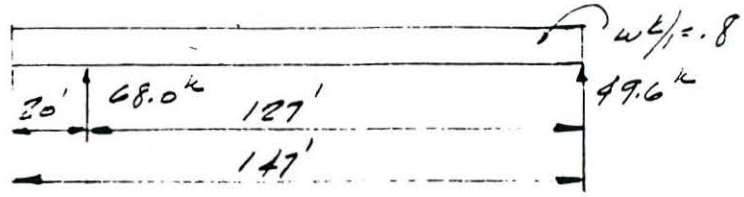
$F_x/w_x = .10$

*$F_t/w_t = .20$

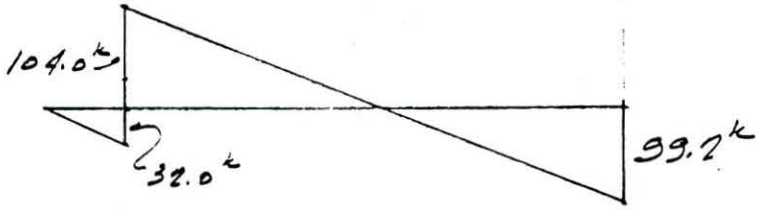
Increase loads by factor = 2.0 for design of diaphragm



Scale 1" = 50'



Scale 1" = 100k



NOTE:

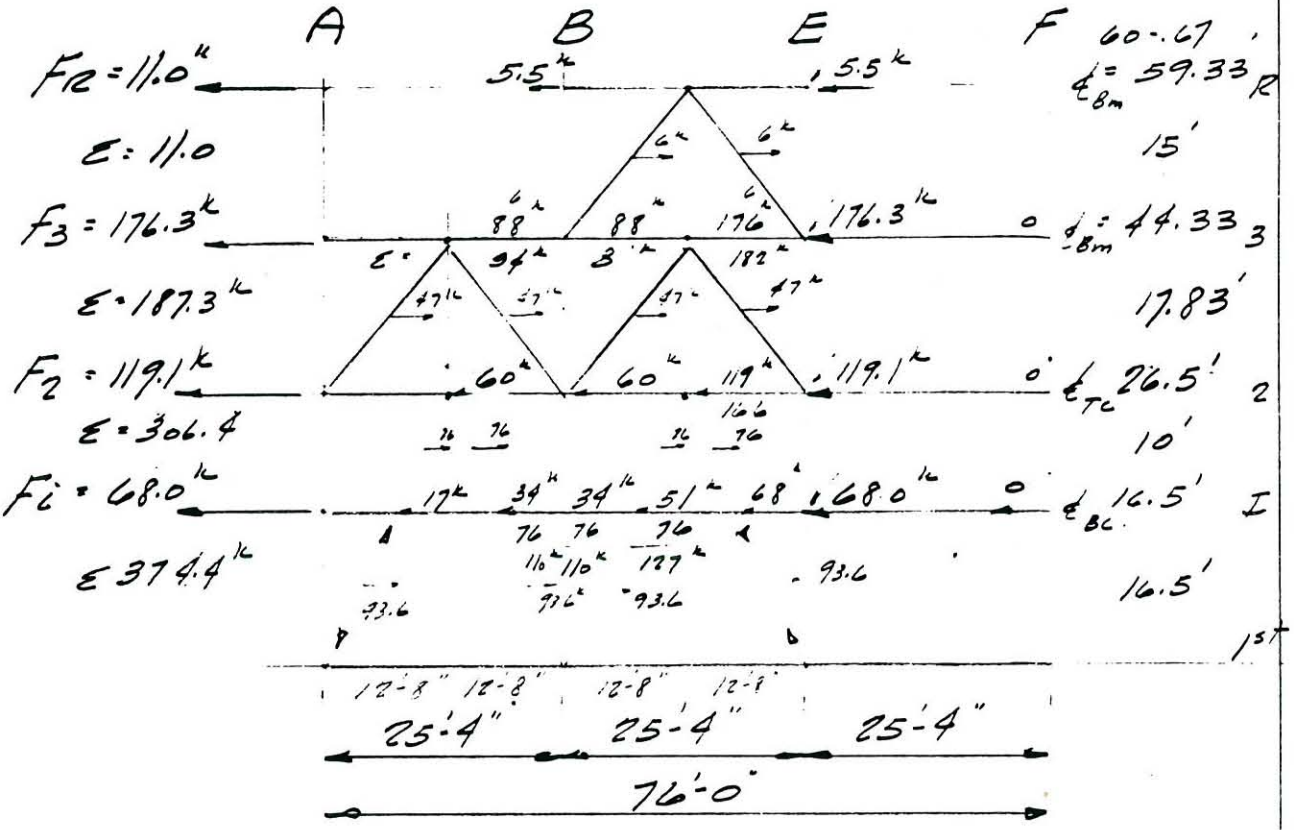
1. Use 3rd Floor horizontal truss design for Interstitial Level horizontal truss design Ratio .30/.255 = 1.176 3rd Floor

   3rd Floor $F_x/w_x = .255$ vs. .096

2. Use 3rd Floor horizontal truss design for Second Floor horizontal truss design. Ratio = .24/.163 = 1.472

   2nd Floor $F_x/w_x = .163$ vs. $.255 \times 1.176 = .30$

TRANSVERSE



LINE 2 Scale 1" = 20'

Mo (over)

3rd

$F_R = 11.0 \times 15 = 165.0^k$

$T = C = 6.5^k$

2nd

$F_R = 11.0 \times 32.83 = 361.1^k$

$F_3 = 176^k \times 17.83 = 3140.0$

ΣM^o 3501

$T = C = 69.0^k$

Int.

$F_r = 11.0 \times 42.83 = 471.1^k$

$F_3 = 176.0 \times 27.83 = 4898$

$F_2 = 119.1 \times 10.0 = 1191$

$\Sigma M_o = 6560$

$T = C = 129.5^k$

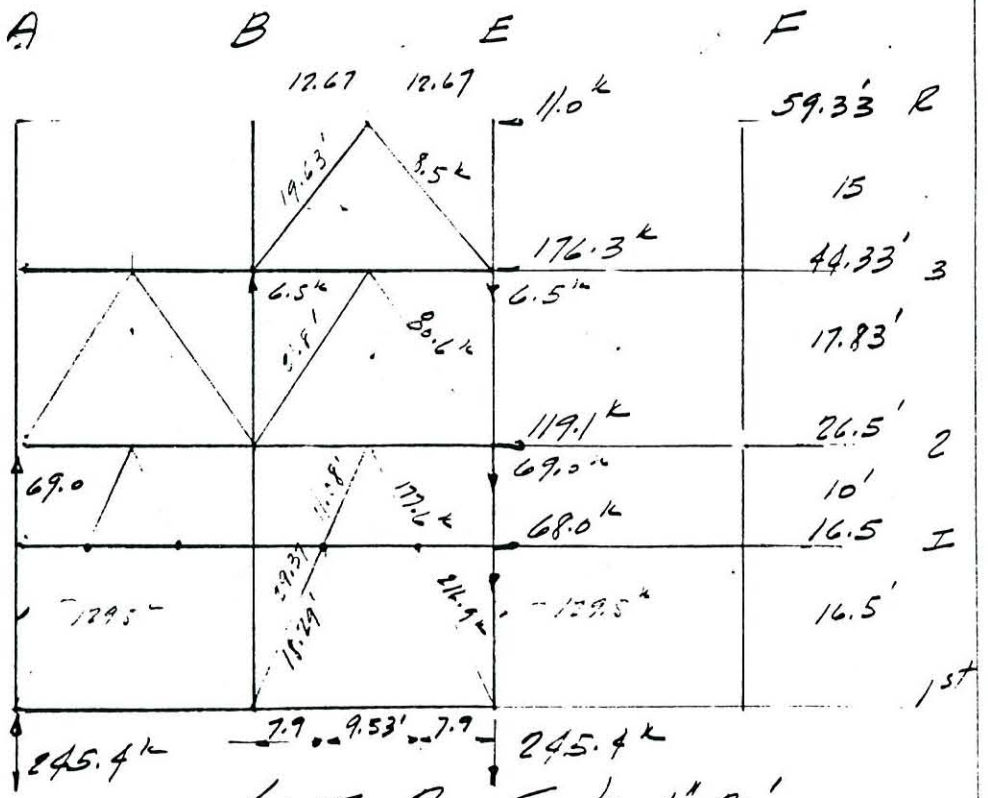
1st

$F_r = 11.0 \times 59.33 = 653$

$F_3 = 176 \times 44.33 = 7802$

$F_2 = 119.1 \times 26.5 = 3156$

$F_I = 68 \times 16.5 = 1122$



LINE 2 Scale 1" = 20'

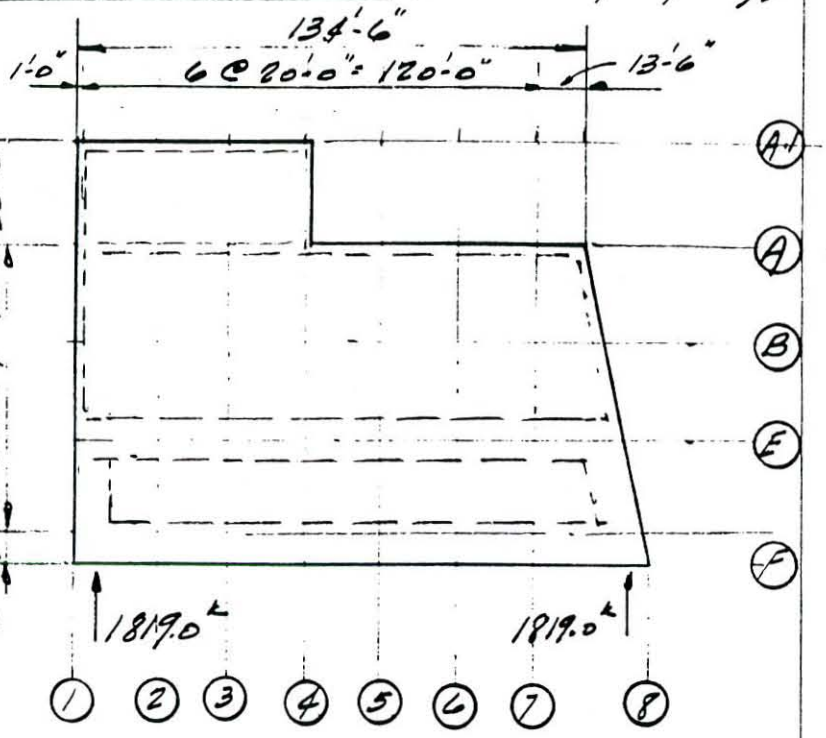
$\Sigma M_o = 12,433^k$ $T = C = 245.4^k$

TRANSVERSE (Basement Story)

Note:

1. Lateral Forces from Structural Steel Frame is transfered to 1st Floor 48" & 120" Slab.

2. Inertia forces from structure (Structural Steel frame + 1st Floor) assumed resisted by 120" walls x 40'-0" at lines ① & ⑧.



1st Floor Plan
Scale 1" = 50'

Total Transverse Seismic Force

Item	F_x
Roof	190^k
3rd	167.3
2nd	205.8
Inter	117.6

$\Sigma V = 680.7^k$

Distribute to Lines ① & ⑧

$V = 680.7 \times 1/2 = 340.4^k$

1st Floor $= 1479.0^k$

$\Sigma V_{①} \& V_{②} = 1819.0^k$

V_{shear} 10' wall $= \dfrac{1819.0}{120 \times 40 \times 12} = .032^k/' = 32^{\#}/m^2$ ok

1st Floor Mass to 881.5
− 10.0
Elev. 871.5

48" Slab = .6 x 44 = 26.4 k/'
120" Slab = 1.5 x 40 = 60.0
Wall A = .150 x 2 x 8.2 = 2.5 k/'
E = 1.5 x 5.2 = 7.8
F = 1.5 x 5.2 = 7.8
104.5 k/'

V = .20 x 104.5 = 20.9 k/'
ΣV = 20.9 x 140' = 2926.0^k
1/2 V = 1463.0^k
Wall ow = .2 x .3 x 6 x 44 = 15.9^k
1479.0^k

LONGITUDINAL

LATERAL FORCE ANALYSIS

Distribution of Lateral Force

	Seismic Force	Area	F_x
Roof	$27.6\ \#/ft^2$ =	$76 \times 80 = 6080$ $27 \times 22 = 594$ 6674	$6674 \times 27.6 = 184.2^k$
3rd Floor	$18.4\ \#/ft^2$ =	$\frac{76 \times (132 + 147)}{2}$ (139.5)	$10602 \times 18.4 = 195.1$
2nd Floor	$18.4\ \#/ft^2$ =		$10602 \times 18.4 = 195.1$
Inter. F/r	$9.21\ \#/ft^2$ =		$10602 \times 9.2 = 97.7$
			672.1^k

Distribution of Lateral Force Line A & F

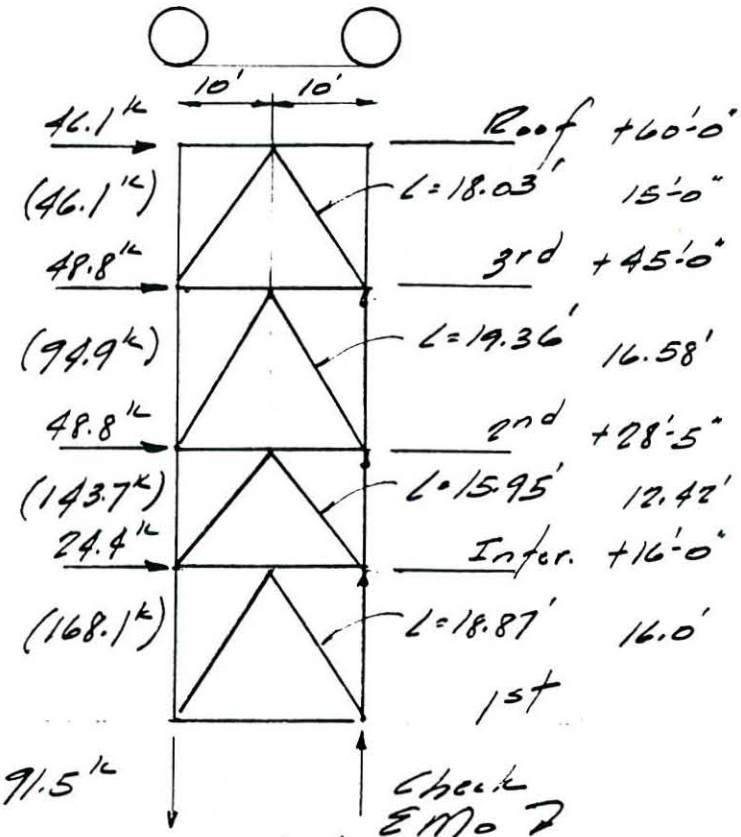
		Per Frame	
Roof = $184.2 \times 1/2$ =	92.1^k	46.1^k	46.1^k
3rd F/r = $195.1 \times 1/2$ =	97.6^k	48.8	94.9
2nd F/r = $195.1 \times 1/2$ =	97.6^k	48.8	143.7
Inter F/r = $97.7 \times 1/2$ =	48.9^k	24.4	168.1^k

Diaphragm Shear

Maximum at 3rd Floor $\frac{= 97.6}{132 - 20\ in} = 871\ \#/'$ ok

$V_a = 1490\ \#/'$

LONGITUDINAL



Forces In Diagonals

$\frac{46.1}{2} \times 18.03/10.0 = 41.6^k$

$\frac{94.9}{2} \times 19.36/10.0 = 91.9^k$

$\frac{143.7}{2} \times \frac{15.95}{10.00} = 114.6^k$

$\frac{168.1}{2} \times 18.87/10.0 = 158.6^k$

Overturning

3rd Story $46.1 \times 15.0 = 691.5^k$
$T = C = 34.58^k$

2nd $94.9 \times 16.58 = 1573.4^k$
ΣM_o 2264.9^k
$T = C = 113.25^k$

Infer. $143.7^k \times 12.42 = 1784.8'^k$
ΣM_o $4049.6'^k$
$T = C = 202.48^k$

1st $168.1^k \times 16.0 = 2689.6$
ΣM_o $6739.2'^k$
$T = C = 336.96^k$

Check ΣM_o

$46.1 \times 60.0 = 2766$
$48.8 \times 45.0 = 2196$
$48.8 \times 28.42 = 1387$
$24.4 \times 16.00 = 390$
$6739.0'^k$

Design Diagonals

1st Story & Infer. $P = 158.6 \times 1.5 \times \frac{3}{4} = 178.4^k$ $r_{min} = 2.26$
ST 8×8×5/16 $P_a = 180.0^k$ $r = 3.12$ $L = 18.87'$

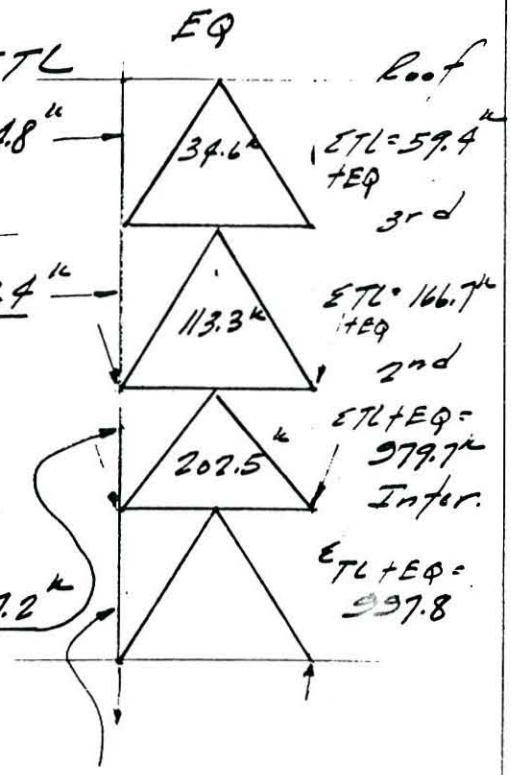
2nd Story & 3rd Story $P = 114.6 \times 1.5 \times \frac{3}{4} = 128.9^k$ $r_{min} = 2.32$
$L = 19.36'$
ST 8×8×1/4

MAIN COLUMN A-F-3, 4, 6, 7

Loading

See Design Truss 2T-1

Loading	DL	EDL	LL	ELL	TL	ETL
Roof	16.7k	16.7k	8.1k	8.1k	24.8k	24.8k
3rd	20.5		8.1		28.6	
	37.2k		16.2k		53.4k	
2nd						
P. (direct)	50.0k		16.2k		76.2k	
Truss 2T-1 Reaction	278.4		363.0k		641.4k	
Infer.			365.6k		411.6	777.2k
$\frac{20 \times 8.25}{2}$						
$82.5 \times (68 + 74)$	5.6		6.1k		11.7k	
Siding = 16 × 20 × 20 = 6.4						
E	12.0k	377.6	417.7k	6.4k 18.1k	795.3k	202.5k 997.8k



Column Design

1st Story $P_{DL+LL} = 795.3^k$ $P_{DL+LL+EQ} = 997.8^k \times \frac{3}{4} = 748.4^k$

$L = 16.0'$ AISC Table C 1.8.1

Condition (d) $K = 1.0$

Secondary Bending nominal

W14×176 $P_a = 961.0^k$ Elev. 0'-0" to 28'-5"

$A_p = 51.8$ Use W14×176

$r_y = 4.02$

Ratio $r_x/r_y = 1.60$ Elev. 28'-5" to 60'-0"

Outside Inside Use W14×61

Depth = 15 1/4 12.65"

Flange = 15 5/8

W14×61 $P_a = 278.0^k$

O. Depth = 13 7/8 Flange = 10" Inside Depth = 13.875 - 1.29 = 12.58

LONGITUDINAL (Basement Story)

Note

1. Lateral forces from structural steel braced frames lines Ⓐ & Ⓕ transfered to 1st Floor 48" & 120" slab

2. Inertial forces from structure (Structural steel + 1st Floor to Elev. 871.5, assumed resisted by 120" walls × 145' at Lines Ⓔ & Ⓕ.

Total Longitudinal Seismic Force

Σ Roof + 3rd + 2nd + Inter = 680.7^k

1st Floor

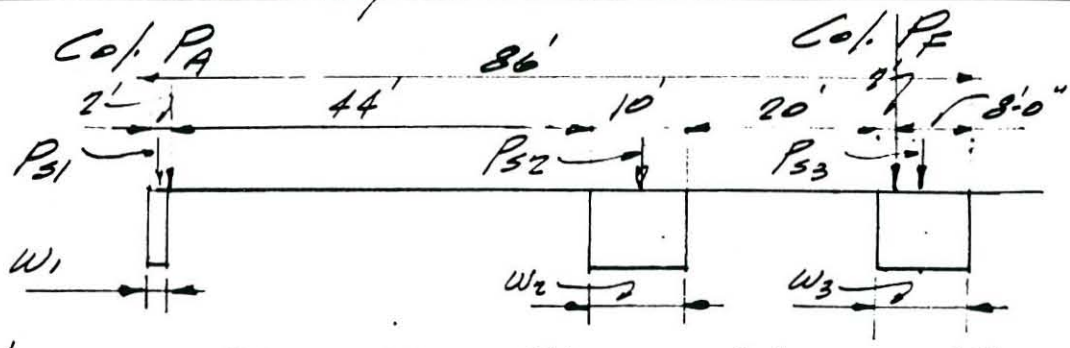
46 × 140 × .60 = 3,864.0^k
44 × 145 × 1.50 = 9570.0
W_{1st} = 13,434.0

$V = 13,434.0^k \times .20 = 2686.8^k$

ΣV (total) = 680.7 + 2686.8 = 3,370^k

Assume ½ V to Line E = 1684^k

V (shear) 10' wall = $\frac{1684^k}{120 \times 140 \times 12}$ = 8 #/in² OK

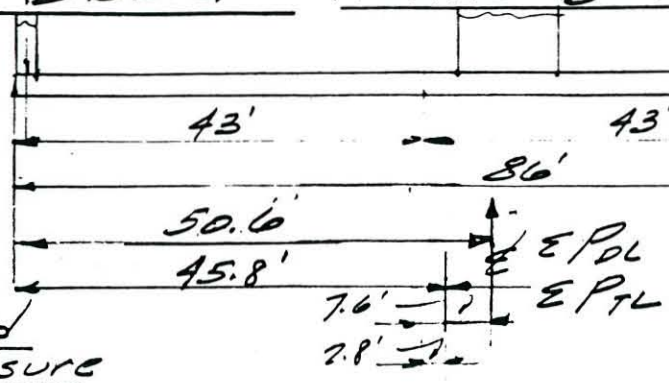


Loading	DL	LL	TL	EMoDL (Left)	EMoTL (Left)
P_{S1}					
(2+44+5) = 51					
51 × 4.0 × .150 × 1/2 = 15.3^k	× 1.0			15.3^k	
51 × 250 × 1/2 = 6.4^k					
			21.7^k × 1.0		21.7^k
P_A					
1/20	(18.9^k) 377.6^k	20.9^k × 2.0		37.8^k	
1/20		417.7			
1/20			(39.8^k) 795.3 × 2.0		79.5^k
		(EQ)	± 202.5^k = (10.1^k) / 20		
W_1					
16.33 × 300	4.9^k × 1.0		4.9	4.9^k	4.9
P_{S2}					
15 × 1.50 × 1/2	15.3				
15 × 250 × 1/2 (.125)	11.3				
	26.6^k × 51.0			1,356.6^k	
		6.4 + 1.8			
		8.2^k	34.8^k × 51'		1,774.8^k
W_2 =					
5 × 6 × .150	4.5				
10 × 10 × .150	15.0				
	19.5^k × 51.0'		19.5^k	994.5^k	994.5^k
P_{S3}					
(15+5) × 10 × .150 = 30.0^k × 81.0' (200)				2430.0^k	2430.0
20 × 250		5.0	35.0^k		
W_3 =					
10.33 × 10 × .150 = 15.5^k × 81.0			15.5	1,255.5^k	1255.5
P_F					
1/20	(18.9) 377.6^k × 78' (20.89)			1472.6	
1/20		417.7^k			
1/20			(39.8) 795.3^k × 78		62033^k
		(EQ)	± 202.5^k		
Σ	149.6^k	61.4^k	211.0^k	7567^k	9662.6^k

X_{DL} = 7567 / 149.6 = 50.58

X_{TL} = 9662.6 / 211.0^k = 45.80'

MAT DESIGN MAIN BUILDING



Dead Load
Soil Pressure

$SP_{DL} = \frac{149.6}{86} = 1.74\ k/ft^2$

$M_o = (\overset{7.6}{50.6-43}) \times 149.6^k = 1136.9^{'k}$

$\frac{M_o c}{I} = \frac{M_o}{S} = \frac{1136.9^{'k}}{1232.7}$ $\pm .92$

$S = \frac{bd^2}{6} = \frac{1.0 \times 86^2}{6} = 1{,}232.7\ ft^3$

Net Up $2.66\ k/ft^2$
$+ .75$
Max Total $= 3.41\ k/ft^2$
Min $= 1.57\ k/ft^2$
$\Delta = 1.84\ k/ft^2$

Dead Load + Live Load
Soil Pressure

$SP_{DL+LL} = \frac{211.0}{86} = 2.45\ k/ft^2$

$M_o = (\overset{2.8}{45.8-43.0}) \times 211.0 = 591.1^{'k}$

$\frac{M_o c}{I} = \frac{591.1}{1232.7}$ $\pm .48$

Net Up $2.93\ k/ft^2$
$.75$
Total $3.68\ k/ft^2$

Bending - Up Span 44'-0" (Pinned, Fixed)

$M_o = \frac{3.0 \times 44.0 \times 44.0}{8} = 726.0^{'k}$

$W_u = \frac{1.4 \times 2.66\ k/ft^2}{3.724} + 1.7 \times (\overset{.27}{2.93-2.66}) = 4.18\ k/ft^2$
$.459$

$M_o = 4.18 \times 44^2/10 = 809.2^{'k}$

$d = \left(\frac{M_o \times 20}{b}\right)^{1/2} = \left(\frac{809.2 \times 20}{12}\right)^{1/2} = 36"$ $d = 60 - (3+2) = 55$

$A_s = \frac{M_o}{4 \times d} = \frac{809.2}{4 \times 55} = 3.68\ in^2$ #11 @ 6" = $A_{sp} = 3.12$

MAT DESIGN (continued)

Bending-Up Span 20'-0" (Fixed, Fixed)

$M_o = \frac{4.18 \times 20^2}{12} = 139.3^{'k}$

$A_s = \frac{139.3}{4 \times 51} = 0.68 \text{ in}^2$ A_{sp} #9@12 = 1.00

$A_t = .002 \times 60 \times 12 = 1.44 \text{ in} = 0.72 \text{ in}^2/\text{face}$

#11 @6 $A_{sp} = 3.12 \text{ in}^2$
#9@12 do = 1.00

MAT DESIGN ELECTRIC SUBSTATION

Span 23'-0" (clear)

Assume Soil Pressure = $2.0^k/ft^2 \times 1.5$
$= 3.0^k/ft^2$

$W = 23 \times 3.0 = 69^k$

$M_o = \frac{69^k \times 25'}{9} = 192^{'k}$ $d = \left(\frac{192 \times 20}{12}\right)^{\frac{1}{2}} = 18''$

Assume 36" Mat Slab $d = 36 - 4 = 32''$

$A_s = \frac{192^{'k}}{4 \times 32} = 1.50 \text{ in}^2/ft$ #8@6 $A_{sp} = 1.60 \text{ in}^2/ft$

$A_t = .002 \times 36 \times 12 = 0.86 \text{ in}^2/ft$ #8@12
$A_{sp} = 0.86 \text{ in}^2/ft$

FOUNDATION LOADS - ALS Building

Col. C.3-21

	DL	LL	TL
Roof = $20 \times 16 \times (54 + 16)$ (320, 70) =	17.3^k	5.12^k	22.4^k
Me33 = $8 \times 16 \times (100 + 50)$ (128) =	12.8^k	6.4^k	19.2^k
Footing = $10.5^2 \times 3.5 \times 150$ =	57.9	-	57.9^k
	88.0^k		99.5^k
Soil Pressure A = 110.3	.800 $^k/ft^2$		.90 $^k/ft^2$

Col. C.3-21.5

Roof = $21.5 \times 17 \times (54 + 16)$ (365.5, 70)	19.7^k	5.9^k	25.6^k
Me33 = $(8+2) \times 17 \times (100 + 50)$ (170, 150)	17.0	8.5^k	25.5
Footing = $4 \times 17 \times 3.5 \times .150$	35.7	-	35.7
	72.4	14.4	86.8^k
Soil Pressure A = $4 \times 17 = 68$ =	1.06 $^k/ft^2$		1.28 $^k/ft^2$
	= 4.24 $^k/ft$		5.11 $^k/ft$

ELECTRICAL SUBSTATION WALL

Soil Pressure = 65 #/ft³

$p = wh = 65 \times 20 = 1.3^{k}/ft^{2}$

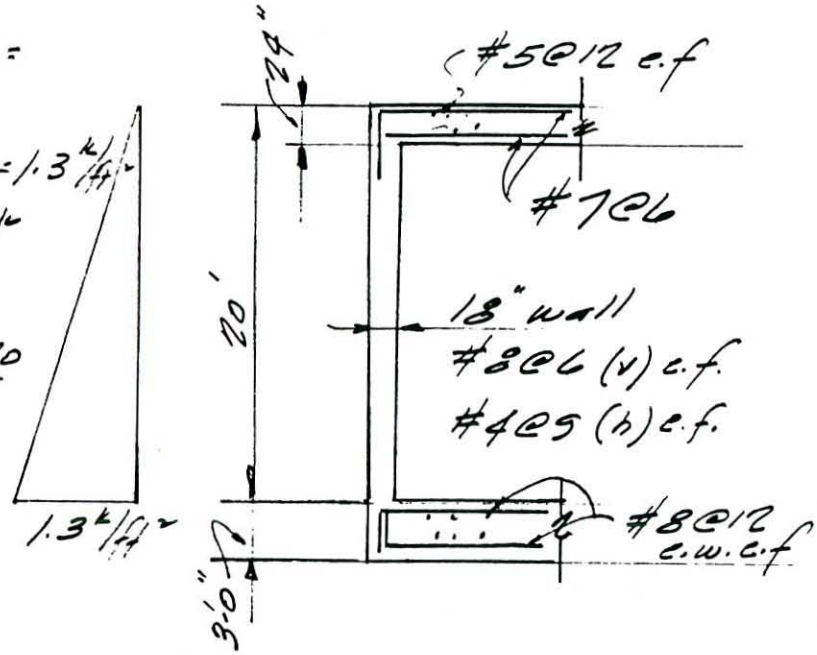
$\Sigma P = \frac{1.3 \times 20}{2} = 13.0^{k}$

$M_{o_{sp}} = \frac{\Sigma P \times h}{8} = \frac{13.0 \times 20}{8}$

$= 32.5^{'k}$

$M_{ov} = \frac{3 \times 65 \times 20^{2}}{8}$

$= 9.8^{k}$



$\Sigma M_o = 42.3^{'k}$ $\quad d = \left(\frac{M}{k \times b}\right)^{\frac{1}{2}} = \left(\frac{42.3 \times 12{,}000}{270 \times 12}\right)^{\frac{1}{2}} = 12.5 + 2.5$
$= 15.0$

Use 18" $\quad A_s = \frac{42.3^{'k}}{1.76 \times (18 - 2\frac{1}{2})} = 1.55$ $\quad$ #8@6
15.5 $\quad A_{s_p} = 1.60 in^{2}$

$A_{st} = .002 \times 18 \times 12 = 0.43$ Use #4@9 e.f.

CHEMICAL DYNAMICS RESEARCH LABORATORY

Mechanical Data and Calculations

COMBUSTION DYNAMICS FACILITY

OUTLINE OF HVAC SYSTEMS

1. IRFEL Vault

Design criteria:
- Room temperature @ 75°F±2°F, about 30% RH, no humidity control.
- Air flow determined by HVAC cooling load, equipment capable of purging area with 100% outside air.

Equipment:
- 2 - 50% air handling units, 6,000 CFM each with filter, heating coil, cooling coil and fan; economizer cycle included.
- 2 - 50% return/exhaust fans.
- Distribution ductwork to the vault.

2. Klystron / Screen Room

Design criteria:
- Room temperature @ 75°F±5°F, about 30% RH, no humidity control.
- Air flow determined by HVAC cooling load, equipment capable of purging area with 100% outside air.

Equipment:
- 2 - 50% air handling units, 2,500 CFM each with filter, heating coil, cooling coil and fan; economizer cycle included.
- 2 - 50% return/exhaust fans.
- Distribution ductwork to the vault.

3. Laboratories

Design criteria:
- Room temperature @ 75°F±2°F, no humidity control.
- H-7 occupancy; to avoid hazardous location requirements, provide 4 CFM/sq. ft. and 100% outside air.

Equipment:
- 2 - 50% air handling units, 15,000 CFM each with filter, preheat coil and fan.
- Distribution ductwork to the 8 laboratories; duct mounted heating coil and cooling coil for each laboratory.
- 2 - 50% exhaust fans for fume hoods and room air; fume hoods include face velocity controllers.
- For estimation purpose, variable frequency drives are included for the supply and exhaust fans.

4. Experimental Hall

Design criteria:
- Room temperature @ 75°F±2°F, no humidity control.
- H-7 occupancy; to avoid hazardous location requirements, provide 4 CFM/sq. ft. and 100% outside air.
- Hall divided into 2 HVAC zones.

Equipment:
- 2 - 50% air handling units, 13,000 CFM each with filter, preheat coil and fan.
- Distribution ductwork to the hall; duct mounted heating coil and cooling coil for each of the 2 HVAC zones in the hall.
- 2 - 50% exhaust fans for fume hoods and room air; fume hoods include face velocity controllers.
- For estimation purpose, variable frequency drives are included for the supply and exhaust fans.

5. Offices

Design criteria:
- Room temperature @ 78°F summer 72°F winter, no humidity control.
- Supply minimum 15% outside air.

Equipment:
- 2 - 50% air handling units, 13,000 CFM each with filter, preheat coil and fan; economizer cycle included.
- Distribution ductwork to the hall; duct mounted VAV boxes, heating coil and cooling coil for each office zone.
- 2 - 50% return/exhaust fans.
- For estimation purpose, variable frequency drives are included for the supply and return/exhaust fans.

6. Pump Room

Design criteria:
- Room temperature @ 95°F maximum 65°F minimum, no humidity control.
- Supply minimum 15% outside air.

Equipment:
- 2 - 50% air handling units, 2,500 CFM each with filter, heating coil, cooling coil and fan; economizer cycle included. (Cooling coil included to reduce the size of the air handling unit.)
- 2 - 50% return/exhaust fans.

7. Equipment Racks Room

Design criteria:
- Room temperature @ 95°F maximum 65°F minimum, no humidity control.
- Supply minimum 15% outside air.

Equipment:
- 2 - 50% air handling units, 2,500 CFM each with filter, heating coil, cooling coil and fan; economizer cycle included. (Cooling coil included to reduce the size of the air handling unit.)
- 2 - 50% return/exhaust fans.

8. Basement Mechanical Room

Design criteria:
- Room temperature @ 95°F maximum 65°F minimum, no humidity control.
- Supply minimum 15% outside air.

Equipment:
- 1 - 100% air handling unit, 15,000 CFM with filter, heating coil, and fan.
- 1 - 100% return/exhaust fan.
- For estimation purpose, variable frequency drives are included for the supply and return/exhaust fan.

9. Basement Electrical Room

Design criteria:
- Room temperature @ 95°F maximum 65°F minimum, no humidity control.
- Supply minimum 15% outside air.

Equipment:
- 1 - 100% air handling unit, 7,500 CFM each with filter, heating coil, cooling coil and fan; economizer cycle included. (Cooling coil included to reduce the size of the air handling unit.)
- 1 - 100% return/exhaust fan.
- For estimation purpose, variable frequency drives are included for the supply and exhaust fan.

10. Computer Room

Design criteria:
- Room temperature @ 75°F±2°F, no humidity control.

Equipment:
- Room supply from office HVAC system.
- Additional water-cooled computer room cooling module.

11. Control Room

Design criteria:
- Room temperature @ 75°F±2°F, no humidity control.

Equipment:
- Room supply from office HVAC system.
- Additional water-cooled computer room cooling module.

COMBUSTION DYNAMICS FACILITY

OUTLINE OF UTILITY SYSTEMS

1. Low Conductivity Water (LCW)

   - Site LCW supplied to dedicated heat exchangers for cooling Klystron and IRFEL.
   - Site LCW supplied directly to molecular beam machines, large and small laser systems for cooling. Molecular beam machines and laser systems to be located in experimental hall and 8 laboratories.

2. Treated Water (TRW)

   - Site TRW supplied to HVAC chiller condensers.

3. Potable Cold Water (CW)

   - Site CW supplied to domestic and industrial users.

4. Domestic Cold Water and Hot Water

   - Supplied to toilets and janitors' closets.
   - Supplied to sinks in laboratories.
   - Domestic hot water tank in basement Boiler Room.

5. Heating Water (HW)

   - Circulated from boilers to preheat coils in air handling units and heating coils in the HVAC zones.

6. HVAC Chilled Water (CHW)

   - Circulated from HVAC chillers to cooling coils in the HVAC zones.

7. Deionized Water and Hot Deionized Water

   - Water treatment for providing deionized water.
   - Supplied to sinks in laboratories.

8. Drain Systems

   - Sanitary drain system.
   - Acid drain from each fume hood in the laboratories to an acid neutralization system.

9. Compressed Air System (CA)

- Site compressed air supplied to HVAC and machine controls.
- Site compressed air supplied to drop stations in laboratories.

10. Natural Gas (G)

- Natural gas supplied to boilers.
- Natural gas supplied to drop stations in laboratories.

11. Vacuum

- House vauum system.
- Vacuum connections to drop stations in laboratories.

12. Nitrogen

- Liquid nitrogen storage tank outside of building.
- One liquid nitrogen supply station in each of 8 laboratories; each station includes a small tank, piping, metering system, vapor recovery system and subcooling system.

13. Fire Protection

- Fire sprinklers in building except the LINAC vault and Screen Room.
- Halon system in LINAC vault, Screen Room, Computer Room and Control Room.

PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

DESIGN BASIS

1) BUILDING DESIGN AS SHOWN IN DRAWING DATED 10/8/89

2) EQUIPMENT LOAD BASED ON INFORMATION FROM 7/27 AND 7/28 MEETINGS
INFORMATION REVISED 10/4/89

3) ELECTRICAL LOAD BASED ON INFORMATION FROM 7/27 AND 7/28 MEETINGS
INFORMATION REVISED 10/4/89

4) HVAC DESIGN BASED ON DOE 6430.1A

5) UNIFORM BUILDING CODE

6) COOLING TOWER DESIGN BASED ON BUILDING 37

7) LBL DESIGN PRACTICES

DESIGN CRITERIA

1) IRFEL:
IRFEL MAINTAINED AT 120° ± 0.5°F BY LCW
LCW @ 10°F TEMPERATURE RISE (80°F ENTRY, 90°F EXIT)
HEAT DISSIPATED BY HEAT EXCHANGER TO SITE COOLING TOWER SYSTEM

WHEN KLYSTRON IS OFF, HEATER IN LCW SYSTEM MAINTAINS LINAC AT 120° ± 0.5°F

2) KLYSTRON:
HEAT DISSIPATED BY HEAT EXCHANGER TO SITE COOLING TOWER SYSTEM

3) LASERS & MOLECULAR BEAM MACHINES:
95% OF LOAD COOLED BY LCW OR DEIONIZED WATER
WATER @ 10°C (18°F) MAX. TEMPERATURE RISE
HEAT DISSIPATED BY HEAT EXCHANGER TO SITE COOLING TOWER SYSTEM

4) IRFEL VAULT:
ROOM DESIGN @ 75°F ± 2°F, ABOUT 30% RH (NO CONTROL REQD.)
SYSTEM CAPABLE OF PURGING ROOM WITH 100% OUTSIDE AIR

5) KLYSTRON ROOM:
ROOM DESIGN @ 75°F ± 5°F, ABOUT 30% RH (NO CONTROL REQD.)
SYSTEM CAPABLE OF PURGING ROOM WITH 100% OUTSIDE AIR

6) EXPERIMENTAL HALL & LABORATORIES:
ROOM DESIGN @ 75°F±2°F, NO HUMIDITY CONTROL

PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

H-7 OCCUPANCY: TO MITIGATE HAZARDOUS LOCATION REQUIREMENTS, PROVIDE 4 CFM/SQ. FT. 100% OUTSIDE AIR

7) OFFICES:
ROOM DESIGN @ 78°F SUMMER & 72°F WINTER, NO HUMIDITY CONTROL

8) MACHINE & EQUIPMENT ROOMS:
ROOM DESIGN @ 95°F MAX. & 65°F MIN., NO HUMIDITY CONTROL
VENTILATION AND HEATING ONLY

9) TRANSPORTATION OF EQUIPMENT IN & OUT OF BASEMENT BY FREIGHT ELEVATOR MEASURING 14'6" x 10'6"; ACCESS LIMITATION CONSIDERED IN EQUIPMENT SELECTION

COOLING LOAD ESTIMATION

BUILDING AREA:

BASEMENT	11,800 SQ. FT
LEVEL 1	11,200 SQ. FT
LEVEL 2	9,400 SQ. FT
INTERSTITIAL LEVEL	3,800 SQ. FT
LEVEL 3	6,800 SQ. FT
TOTAL	43,000 SQ. FT

PROCESS LOAD:

1) IRFEL (BASEMENT)		40.00 KW
HEAT EXCHANGER LCW RATE	27.304 GPM @ 10°F DIFF.	
2) 2 KLYSTRONS (BASEMENT)		80.00 KW
HEAT EXCHANGER LCW RATE	54.608 GPM @ 10°F DIFF.	
3) EXPERIMENTAL HALL (LEVEL 1)		
4 MOLECULAR BEAM MACHINES		38.00 KW
3 LARGE LASERS		285.00 KW
4 SMALL LASERS		7.60 KW
4) LABORATORY (LEVELS 1 & 2)		
MOLECULAR BEAM MACHINE	9.50 KW	
LASER SYSTEM	71.25 KW	
MISC. EQUPIMENT	9.50 KW	
SUBTOTAL	90.25 KW	
8 LABS TOTAL		722 KW
BASEMENT PROCESS LOAD SUBTOTAL		120 KW
75% DIVERSITY (MAGNETS MOSTLY ON)		90 KW
ADD 20% CONTINGENCY		18 KW

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PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

ADJUSTED SUBTOTAL		108 KW
HEAT DISSIPATED BY HEAT EXCHANGER TO SITE COOLING TOWER SYSTEM		
UPPER FLOORS PROCESS LOAD SUBTOTAL		1052.6 KW
50% DIVERSITY		526.3 KW
ADD 20% CONTINGENCY		105.26 KW
ADJUSTED SUBTOTAL		631.56 KW
UPPER FLOORS EQUIPMENT COOLING DIRECTLY WITH SITE LCW		
LCW FLOW RATE		431.10 GPM @ 10°F DIFF.
PROCESS LOAD TOTAL		739.56 KW
EQUIVALENT TO		2524118 BTU/H
		210 TONS

HVAC LOAD:

1) BUILDING ELECT. DISTRIBUTION @ 20 VA/SQ. FT.		
50% DISSIPATED AS HEAT		430.00 KW
2) IRFEL VAULT		65.00 KW
3) KLYSTRON ROOM		20.00 KW
4) EXPERIMENTAL HALL		
4 MOLECULAR BEAM MACHINES		2.00 KW
3 LARGE LASERS		15.00 KW
4 SMALL LASERS		0.40 KW
5) LABORATORY		
MOLECULAR BEAM MACHINE	0.50 KW	
LASER SYSTEM	3.75 KW	
MISC. EQUIPMENT	0.50 KW	
SUBTOTAL	4.75 KW	
8 LABS TOTAL		38 KW
ITEMS 1) THRU 5) SUBTOTAL		570.4 KW
75% DIVERSITY		427.8 KW
CONVERT TO TONNAGE		121.67 TONS
6) OUTSIDE AIR FLOW		
OFFICES @ 4 AC/HOUR	8900 CFM	
LABS & EXP. @ 4 CFM/SQ. FT.	58000 CFM	
VAULT @ 4 AC/HOUR	4000 CFM	
SUBTOTAL	70900 CFM	
O.A. COOLING 83°F TO 72°F		70.19 TONS
ALLOW FOR BLDG. TRNS. & SOLAR		50 TONS

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TOTAL ESTIMATED HVAC LOAD	242 TONS

9-224
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PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

ADD 20% CONTINGENCY	48 TONS
ADJUSTED HVAC LOAD	290 TONS

HVAC LOAD COOLED WITH 2-60% CHILLERS, 200 TONS EACH.

PROCESS LOAD + HVAC LOAD: 501 TONS
FOR ESTIMATION, USE 210 TONS PROCESS LOAD AND 300 TONS HVAC LOAD.

HEATING LOAD ESTIMATION

OFFICES @ 4 AC/HOUR	8900 CFM	
O.A. HEATING 34°F TO 72°F		365256 BTU/H
LABS & EXP. @ 4 CFM/SQ. FT.	58000 CFM	
O.A. HEATING 34°F TO 75°F		2568240 BTU/H
VAULT @ 4 AC/HOUR	4000 CFM	
O.A. HEATING 34°F TO 75°F		177120 BTU/H
SUBTOTAL		3110616 BTU/H
ADD 20% FOR LOSS THRU WALLS & ROOF		622123 BTU/H
TOTAL		3732739 BTU/H
+10% CONTINGENCY		373274 BTU/H
ADJUSTED TOTAL		4106013 BTU/H

IN ADDITION, HEATING IS REQUIRED FOR DOMESTIC HW & HOT DI.

USE 2-50% GAS-FIRED WATER BOILERS, 100 HP EACH;
TOTAL OUTPUT APPROXIMATELY 7,400,000 BTU/H.

MECHANICAL EQUIPMENT

1) COOLING TOWER

EXTEND COOLING TOWER B-37 TO PROVIDE 50% ADDITIONAL CAPACITY.
4 MW OR 1,200 TONS CAPACITY ADDED FOR CDRL & FUTURE EXPANSION;
PERCENTAGE OF TOTAL CAPACITY USED BY CDRL: ABOUT 45 %

TOWER WATER @ 3 GPM/TON, TOTAL 2,700 GPM;
1 TOWER FAN: 50 HP

2) PUMPS AT COOLING TOWER

2 TOWER WATER PUMPS, 1500 GPM 40 HP EACH	80 HP
3 TRW/LCW PUMPS, 600 GPM 75 HP EACH	225 HP

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PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

3) CHILLERS

2 - 60% HVAC CHILLERS, 200 TONS EACH
200 KW EACH, BOTH OPERATING — 400 KW

4) AIR HANDLING UNITS (AHU'S)

	QUANTITY	TOTAL HP
OFFICES (2 - 50% CAPACITY AHU, 2 CFM/SQ. FT.)		
13000 CFM, 5"SP, 15 HP	2	30
LABS (2 - 50% CAPACITY AHU'S, 4 CFM/SQ. FT.)		
15000 CFM, 2.5"SP, 10 HP EACH	2	20
EXPERIMENTAL HALL (2 - 50% CAPACITY AHU, 4 CFM/SQ. FT.)		
13000 CFM, 2.5"SP, 10 HP EACH	2	20
CONTROL ROOM (1 - 100% CAPACITY AHU, 2.5 CFM/SQ. FT.)		
1000 CFM, 1.5"SP, 1 HP	1	1
COMPUTER ROOM (1 - 100% CAPACITY AHU, 2.5 CFM/SQ. FT.)		
1000 CFM, 1.5"SP, 1 HP	1	1
KLYSTRON / SCREEN ROOM (2 - 50% CAPACITY AHU'S)		
2500 CFM, 2.5"SP, 2 HP	2	4
VAULT (2 - 50% CAPACITY AHU'S)		
6000 CFM, 2.5"SP, 5 HP	2	10
BASM'T MECH. ROOM (1 - 100% CAPACITY AHU)		
15000 CFM, 2.5"SP, 10 HP	1	10
PUMP ROOM (2 - 50% CAPACITY AHU'S)		
2500 CFM, 2.5"SP, 2 HP	2	4
EQUIP. RACKS (2 - 50% CAPACITY AHU'S)		
2500 CFM, 2.5"SP, 2 HP	2	4
BASM'T ELECT. SUBSTATION (1 - 100% CAPACITY AHU)		
7500 CFM, 2.5"SP, 5 HP	1	5
TOTAL	18	109

5) RETURN FANS FOR OFFICES, VAULT, ETC.
EXHAUST FANS FOR HOODS, BATHROOMS, ETC.

6) HEAT EXCHANGERS & ASSOCIATED PUMPS

LINAC HX	30.00	GPM @ 10°F DIFF.
KLYSTRON HX	60.00	GPM @ 10°F DIFF.
MOL. BEAMS & LASERS **	250.00	GPM @ 18°F DIFF.

** COOLED DIRECTLY WITH SITE LCW

7) 2-50% GAS-FIRED WATER BOILERS, 100 HP EACH

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PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L. CHAN

ESTIMATED POWER CONSUMPTION

MAJOR MECHANCIAL EQUIPMENT	TOTAL NO.	EST. LOAD	DESIGN LOAD
COOLING TOWER	1 OPERATING	50 HP x 1	50 KW
TOWER WATER PUMPS	2 OPERATING	40 HP x 2	100 KW
LCW/TRW PUMPS AT TOWER	3 OPERATING	75 HP x 3	250 KW
SUBTOTAL, TOWER & PUMPS		400 KW	
HVAC CHILLERS	2 OPERATING	200 KWx2	400 KW
AIR HANDLING UNITS	18 OPERATING		100 KW
AIR COMPRESSORS & VACUUM PUMPS			100 KW
MISC. FANS, PUMPS & EQUIPMENT			250 KW
SUBTOTAL, CDRL BLDG. MECH. EQUIPMENT		850 KW	

ENERGY CONSERVATION REQUIREMENTS

1) ALL HVAC SYSTEM:
   - ECONOMIZER CYCLE

2) OFFICE AREA HVAC SYSTEM:
   - VARIABLE AIR VOLUME (VAV) SYSTEM

3) VARIABLE FREQUENCY DRIVES (VFD) FOR ALL FANS IN THE FOLLOWING SYSTEMS:
   - OFFICES
   - LABORATORIES
   - EXPERIMENTAL HALL
   - BASEMENT MECHANICAL ROOM
   - BASEMENT ELECTRICAL SUBSTATION

4) DIRECT DIGITAL CONTROL (DDC) COMPATIBLE WITH SITE WIDE ENERGY MANAGEMENT CONTROL SYSTEM (EMCS)

5) ENERGY CONSERVATION CONTROLS FOR HVAC CHILLERS

UTILITY SYSTEMS

1) DROP STATION(S) IN EACH LAB, CONTAINING:
   - INDUSTRIAL COLD WATER & HOT WATER
   - NATURAL GAS
   - COMPRESSED AIR (OIL-FREE, CHEMICAL-DRIED)

PROJECT: COMBUSTION DYNAMICS FACILITY

BY: L CHAN

- VACUUM

CHECK VALVES PROVIDED IN ALL LINES

2) LIQUID NITROGEN SYSTEM
   - 20,000 LITER LIQUID NITROGEN STORAGE TANK OUTSIDE BUILDING
   - LIQUID NITROGEN SUPPLY STATION IN EACH OF 8 LABS
   - EACH SUPPLY STATION CONTAINS 100 LITER TANK, PIPING, METERING SYSTEM, VAPOR RECOVERY SYSTEM AND SUBCOOLING SYSTEM

3) LCW TO:
   LINAC, KLYSTRON, MOLECULAR MACHINES & LASERS
   PVC OR STAINLESS STEEL PIPES

4) SINK(S) IN EACH LAB CONTAINING:
   CW & HW (DOMESTIC)
   DI & HOT DI WATER

5) ACID DRAIN FOR EACH FUME HOOD CONNECTED TO:
   ACID WASTE COLLECTION & NEUTRALIZATION SYSTEM

6) FLOOR DRAIN(S) FOR EACH LAB

CHEMICAL DYNAMICS RESEARCH LABORATORY

Electrical Data and Calculations

ELECTRICAL FACILITIES

General:

The electrical system for the Combustion Dynamics Facility (CDF) will consist of, but not be limited to the following:

A 12.47 kV main power service from the Original Lab Site Substation. This service will consist of the installation of two (2), 1200 ampere, 15 kV vacuum circuit breakers and two (2), 15 kV cable feeders (1-500 MCM per phase). These feeders will supply firm and interruptible power to the CDF. The 15 kV cables will be installed in an underground duct bank, running from the Original Lab Site Substation to Electrical Manhole (EMH) No. 139. A new duct bank, containing 4 - 5" conduits, will be installed from EMH-139 to the CDF substation.

The new CDF electrical substation will be located in the basement at to the northwest corner of the CDF building and will have a capacity of 5500 kVA. The substation will be comprised of three 12.47 kV to 480/277 volt power centers, complete with liquid filled transformers, secondary distribution feeder breakers and automatic power factor correction capacitors. An emergency power diesel-generator set will be included and will be located on a pad outside the building. Electrical distribution equipment will include:

480/277 volt, 3 phase, 4 wire distribution system, including panelboards, branch circuit panels and step down transformers.

208/120 volt, 3 phase, 4 wire distribution system, including panelboards, branch circuits, receptacles, motor control centers and control wiring for pumps, fans, thermostats, etc.

277 volt lighting system, including panelboards and branch circuit breakers.

An NFPA, Level 1 emergency power distribution system, including an automatic power transfer switch, to transfer the emergency circuits to a 300 kW engine-generator set, during power outages.

Telephone, computer, intercom conduits, raceways and terminating boards.

A complete fire alarm system.

Conduits and outlet boxes for card key and door alarms.

Cable tray systems for communications and laboratory power systems.

Power:

Motors for building utilities, such as fans, air-conditioning, compressors and pumps, larger than 1/2 HP, will utilize 480 volt, 3 phase power with 120 volt control. Motors smaller than 1/2 HP will be 120 volt, 1 phase.

Each laboratory will have, on at least three walls, surface mounted 120 volt plug strip convenience receptacles, spaced approximately 18 inches on centers.

Electrical Load Analysis:

The estimated electrical power demand on the substation, serving the CDF building is as follows:

	kW
Klystrons	360
Vacuum Pumps	50
Air Handling Units	90
HVAC Chillers	350
LINAC Cooling	70
Freight Elevator	100
Boilers	175
Air Compressor	90
Beam Transport	60
LINAC System	120
Large Lasers	300
Small Lasers	10
Experimental Labs	800
Electronic Racks	40
Passenger Elevator	20
Air Return Fans	55
Hood Exhaust Fans	55
Misc. Fans & Pumps	220
Lighting	450
Misc. Power & Receptacles	350
System Losses	185
Future Reserve Capacity (20%)	1000
TOTAL	4950
Transformer Capacity @ 0.9 PF	5500

Two 2000 kVA, OA/FA rated unit substations will be installed to provide power service to the IRFEL, Experimental Hall and Laboratories and one 1500 kVA, OA/FA rated unit substation will be installed to provide power to other building loads.

Lighting:

Power groove fluorescent fixtures will be used in high bay areas. General lighting fixtures in offices, laboratories, shops, corridors, conference rooms and areas with two foot by four foot modular acoustical ceilings will be two foot by four foot recessed fluorescent fixtures with acrylic, prismatic lenses, high-frequency electronic ballasts and specular reflectors to give the following intensities:

Control rooms and Research areas - Not to exceed ANSI/IES RP7, "Practice for Industrial Lighting" levels at the Work station.

Laboratories - general - 50 FC

Offices - 50 FC

Corridors, lobby, and means of egress - 10 FC

Conference rooms - 30 FC to 50 FC with dimming controls.

Equipment rooms - 30 FC

Exterior lighting will be H.I.D. type at walkways at not more than 2 FC.

Lighting controls will be zoned and automated, where practical, and integrated with the Energy Monitoring and Control System. Small offices will be individually switched and controlled with occupancy sensors. Where natural light is available, automatic dimming will be utilized.

Emergency lighting will be provided in corridors, research areas, laboratories, stairwells and other public areas by connecting selected fixtures of the general lighting system to emergency power circuits.

Task lighting will be provided where required.

Communications:

The new hillwide ICS equipment, serving the central portion of the Laboratory area, is now located in Building B10A and will have to be replaced, prior to any major CDF site construction. This equipment will be located in a conditioned, dedicated space of approximately 600 square feet in the basement of Building 80.

The CDF will be equipped with telephone, communications and fiber optics data (FDDI) circuits supplied by the Integrated Communications System. A separate, 400 pair, dedicated ICS trunk will be run from the (relocated) ICS central Node Site 2 to the new building. Within the CDF, ICS communications and fiber optics

data (FDDI) wireways and raceways will be run to experimental and office areas of the building.

Utility Relocations:

Prior the start of construction for the Combustion Dynamics Facility, certain power and communications facilities will have to be either relocated. These include the underground duct banks in Roadway "N" which parallel the water lines running to the south and west sides of Building 10.

Electrical power duct bank (210 feet), running from EMH 137 to EMH 138. This duct bank contains the following conduits and cables:

- 4 - 5" C., 5 - 4" C. and 4 - 3" C.
- 6 - 250 MCM, 15 kV, Shielded cables and 2 - #4/0 Gnd.
- 3 - 350 MCM, 15 kV, Shielded cables and 1 - #4/0 Gnd.
- 3 - 350 MCM, 600 V, and 1 - #2 Gnd.
- 13 - 500 MCM, 600 V, and 4 - #1/0 Gnd.

Telephone (ICS) duct bank (210 feet), running from TMH 589 to TMH 590. This duct bank contains the following conduits and cables:

- 4 - 4" C.
- 2 - 1200 pair telephone cables.
- 7 - Fiber optics cables.

CHEMICAL DYNAMICS RESEARCH LABORATORY

Detailed Cost Data - Sandia National Laboratory

2/28/92
PE:CDRL:CDR

9-233A

Chemical Dynamics Research Laboratory

Detailed Cost Data

from

Sandia National Laboratories

The following pages contain cost estimate details provided by Sandia National Laboratories for their component of the *Experimental Systems* and *Standard Equipment*. These elements have been incorporated into the CDRL project estimate (TEC) into the Work Breakdown Structure (WBS) as follows:

WBS	Description
	Experimental Systems:
1.2.2.3.1.6	Chemical Dynamics Imaging Experimental Station
1.2.2.3.1.7	Chemical Kinetics Experimental Station
1.2.2.3.1.8	Experimental Station Enhancements
	Standard Equipment:
1.3.3.10	Equipment for SNL Upstairs Lab

The costs were originally estimated in FY 1990 dollars (except for the Experimental Station Enhancements which were estimated in FY 1992 dollars) and escalated using the DOE Departmental Price Change Index for FY 1993 (dated August, 1991). The escalation analysis is shown on the last page of this section.

2/7/92

Detailed Cost Data - Sandia National Laboratories

I Chemical Dynamics Imaging Exp. Station

A. Vacuum Chamber and Pumps	Unit cost	Qty	Total k$
1 Main scattering Chamber	$20,000	1	$20.00
2 Source Chamber	$5,000	2	$10.00
3 Roots Blower incl. inert fluid	$26,000	1	$26.00
4 Molecular beam Source/Driver	$3,500	2	$7.00
5 10" Diff pump	$3,300	2	$6.60
6 Diff Pump cont.	$2,000	2	$4.00
7 10" Gate valve	$5,000	2	$10.00
8 400 l Turbo pump/controller	$20,000	2	$40.00
9 1000 l Turbo pump	$30,300	1	$30.30
10 Roughing pumps	$10,000	3	$30.00
11 Cryogenic Refrigerator	$285,000	1	$285.00
12 Cryogenic manifold	$10,000	1	$10.00
13 Ion Gauge	$400	3	$1.20
14 Skimmer	$300	2	$0.60
15 Foreline trap	$300	2	$0.60
16 Foreline pressure gauge	$150	3	$0.45
17 Liquid N2 feeder/sensor	$1,300	2	$2.60
18 Mixing vacuum manifold	$4,500	1	$4.50
19 XYZ Translators	$4,500	2	$9.00
20 Stand	$1,000	1	$1.00
21 Misc. tubing, flanges, valves	$10,000	1	$10.00
22 RGA	$7,500	1	$7.50
subtotal			**$516.35**

B. Detector System	Unit cost	Qty	Total k$
1 Camac Crate	$3,700	1	$3.70
2 Computer Interface for CAMAC	$600	1	$0.60
3 Camac Crate Controller	$5,700	1	$5.70
4 Low noise amplifier	$2,200	2	$4.40
5 Equipment rack	$1,200	2	$2.40
6 Prog. A/D converter	$1,700	1	$1.70
7 Pulse delay generator	$4,500	3	$13.50
8 Computer Work Station	$15,000	1	$15.00
9 Software for Work Station	$5,000	1	$5.00
10 400 MHz digital scope	$20,000	1	$20.00
11 2 GHz transient digitizer	$32,000	1	$32.00
12 Box car Averager	$3,000	2	$6.00
13 High voltage puls gen	$15,000	1	$15.00

14 CCD Camera and controller	$25,000	1	$25.00
15 PC for control of Exp	$10,000	1	$10.00
16 Imaging detector	$19,000	1	$19.00
17 Photomultiplier tube and housing	$3,000	1	$3.00
18 Fast diodes	$1,000	2	$2.00
19 Laser Power Meters	$2,000	2	$4.00
subtotal			**$188.00**

C. Lasers	**Unit cost**	**Qty**	**Total k$**
1 Laser table	$8,500	2	$17.00
2 Mounts	$300	15	$4.50
3 Optics/Mirrors/Lenses/Filters	$15,000	1	$15.00
4 Nd:YAG mode-locked laser	$76,000	1	$76.00
5 Nd:YAG regenerative amplifier	$115,800	1	$115.80
6 Second harmonic Gen for ML YAG	$14,000	1	$14.00
7 Nd:YAG power amp	$70,000	1	$70.00
8 Synch Pumped Dye pico/femto	$27,500	1	$27.50
9 Cavity Dumper	$27,000	1	$27.00
10 tunable Dye amp	$25,000	1	$25.00
11 Dbleing Xys and separation	$10,000	2	$20.00
12 Inrad Tracking system (DBL +MIX)	$20,000	2	$40.00
13 Pulsed wavemeter	$20,000	1	$20.00
14 Optical isolators	$6,000	2	$12.00
15 Single Pulse Autocorrelator	$12,500	1	$12.50
16 Translation Stages	$700	3	$2.10
17 Translation Stage Controller	$15,000	1	$15.00
18 Excimer Laser	$82,000	1	$82.00
19 Dye laser for Excimer	$58,000	1	$58.00
20 Safety Cover for laser	$6,000	1	$6.00
21 Hood for Excimer gases	$7,500	1	$7.50
subtotal			**$666.90**

D. Installation	**Hours**	**Rate**	**Total k$**
1 Installation Engineer	250 hrs	56.40	$14.10
2 Installation Technician	400 hrs	44.40	$17.76
subtotal			**$31.86**

TOTAL	$1,403.11
EDI FOR EXP. STATION (@30%)	$420.93
CONTINGENCY (@30%)	$547.21
GRAND TOTAL $FY90	**$2,371.26**
GRAND TOTAL $FY92	**$2,518.04**
GRAND TOTAL TYM$	**$3,027.38**

II Chemical Kinetics Exp. Station

A. Vacuum Chambers and Pumps	Unit cost	Qty	Total k$
1 Main Chamber	$20,000	1	$20.00
3 Photolysis/LIF/Absorp Module	$25,000	1	$25.00
4 Differentially pumped Detector Chambers	$20,000	3	$60.00
5 Gas mixing/storage system	$25,000	1	$25.00
6 Roots Blower incl. inert fluid	$26,000	1	$26.00
7 Flow/Press. Control System	$28,000	1	$28.00
8 400 l/s Turbo pump/controller	$20,000	2	$40.00
9 10" diffusion pump	$3,300	1	$3.30
10 Diffusion pump controller	$2,000	1	$2.00
11 10" gate valve	$5,000	1	$5.00
12 Roughing pumps	$10,000	3	$30.00
13 Molecular beam pulsed valve/controller	$3,500	1	$3.50
14 Ion Gauge and Controllers	$2,300	4	$9.20
15 Foreline pressure gauge	$150	3	$0.45
16 Support stands	$3,000	1	$3.00
17 Tubing, flanges, valves	$22,000	1	$22.00
18 Cryogenic traps/controllers	$15,000	1	$15.00
subtotal			**$347.45**

B. Detector System	Unit cost	Qty	Total k$
1 High Res QMS (+,-)	$40,000	1	$40.00
2 Multichannel Scaler	$20,000	1	$20.00
3 Camac Crate	$3,700	2	$7.40
4 Camac Computer Interface	$600	1	$0.60
5 Camac Crate Controller	$5,700	1	$5.70
6 Low noise amplifier	$2,200	2	$4.40
7 Equipment rack	$1,200	2	$2.40
8 Prog A/D converter	$1,700	2	$3.40
9 Pulse delay generator	$4,500	2	$9.00
10 400 MHz digital scope	$20,000	1	$20.00
11 2 GHz transient digitizer	$32,000	1	$32.00
12 Boxcar Averager	$3,000	2	$6.00
13 Ion Target/PMT assembly	$10,000	1	$10.00
14 PC for control of Exp	$10,000	2	$20.00
15 Software for PCs	$5,000	1	$5.00
16 Photomultiplier tube and housing	$3,000	4	$12.00
17 Laser Power Meters	$2,000	3	$6.00
18 Photodiodes	$250	4	$1.00
subtotal			**$204.90**

C. Lasers	Unit cost	Qty	Total k$
1 Laser table	$8,500	2	$17.00
2 Optics/Mirrors/Filters/Mounts	$35,000	1	$35.00
3 Doubling Xtals and sep.	$10,000	2	$20.00
4 UV wavelength extender	$32,000	1	$32.00
5 Optical isolators	$6,000	2	$12.00
6 Excimer Laser / dye laser	$150,000	1	$150.00
8 Single-mode Ti:Dye	$100,000	1	$100.00
9 Amplifier for Ti:Sapphire	$25,000	1	$25.00
11 Hi Rep Rate Yag for TI:Al2O3	$150,000	1	$150.00
12 Hood for Excimer gases	$7,500	1	$7.50
13 Safety Cover for laser	$6,000	1	$6.00

D. Installation	Hours	Rate	Total k$
1 Installation Engineer	250 hrs	56.40	$14.10
2 Installation Technician	400 hrs	44.40	$17.76
subtotal			**$31.86**
TOTAL			$1,297.41
EDI FOR EXP. STATION(@30%)			$389.22
CONTINGENCY (@30%)			$505.99
GRAND TOTAL $FY90			**$2,192.62**
GRAND TOTAL $FY92			**$2,328.35**
GRAND TOTAL TYM$			**$2,793.50**

III Experimental Station Enhancements

	Unit cost	Qty	Total k$
1 Experimental station enhancements	$1,500,000	1	$1,500.00
TOTAL			$1,500.00
EDI FOR EXP. STATION(@30%)			$450.00
CONTINGENCY (@25%)			$490.00
GRAND TOTAL $FY92			**$2,440.00**
GRAND TOTAL TYM$			**$3,000.00**

IV Upstairs Lab at CDRL

A. Reaction Chamber	Unit cost	Qty	Total k$
1 Main Scattering Chamber	$20,000	1	$20.00
2 Source Chamber	$5,000	2	$10.00
3 Molecular Beam Source	$3,500	2	$7.00
4 10" Diffusion Pump	$3,500	2	$7.00
5 Diffision Pump Cont.	$2,000	1	$2.00
6 10" Gate Valve	$5,000	1	$5.00
7 400l Turbo pump/controller	$20,000	2	$40.00
8 Roughing Pumps	$10,000	2	$20.00
9 Ion Gauge	$400	3	$1.20
10 Skimmer	$300	3	$0.90
11 Foreline Trap	$300	4	$1.20
12 Foreline Pressure Gauge	$150	3	$0.45
13 Mixing Vacuum Manifold	$2,500	1	$2.50
14 Stand	$1,000	1	$1.00
15 Misc. Tubing, Flanges, Valves	$15,000	1	$15.00
16 RGA	$5,000	1	$5.00
subtotal			**$138.25**

A. Kinectics Facility	Unit cost	Qty	Total k$
1 Reaction Chambers	$15,000	2	$30.00
2 400 l Turbo pump/controller	$20,000	2	$40.00
3 Roughing pumps	$10,000	2	$20.00
4 Flow/Press Controllers	$28,000	1	$28.00
5 Foreline pressure gauge	$150	3	$0.45
6 Gas Mixing/Storage System	$25,000	1	$25.00
7 Stands	$1,000	1	$1.00
8 Tubing, flanges, valves	$15,000	1	$15.00
subtotal			**$159.45**

B. Detector System	Unit cost	Qty	Total k$
1 Camac Crate	$3,700	2	$7.40
2 Multichannel Scaler	$20,000	1	$20.00
3 GCMS	$100,000	1	$100.00
4 Low noise amplifier	$2,200	4	$8.80
5 Equipment rack	$1,200	2	$2.40
6 Prog A/D converter	$1,700	1	$1.70
7 Pulse delay generator	$4,500	4	$18.00

8 Computer / Software Work Station	$20,000	2	$40.00
9 2 GHz digital scope	$35,000	2	$70.00
10 400 MHz Scope	$13,000	2	$26.00
11 Transient Digitizer	$5,000	1	$5.00
12 Box car Averager	$3,000	4	$12.00
13 High voltage puls gen	$15,000	3	$45.00
14 CCD Camera and controller	$45,000	1	$45.00
15 PC/software for control of Exp	$15,000	3	$45.00
16 Imaging detector	$15,000	1	$15.00
17 Photomultiplier tube and housing	$3,000	6	$18.00
18 Fast diodes	$1,000	6	$6.00
19 Laser Power Meters	$2,000	3	$6.00
20 Chart Recorder	$1,500	2	$3.00
subtotal			**$494.30**

C. Lasers	**Unit cost**	**Qty**	**Total k$**
1 Laser table	$8,500	4	$34.00
2 Optics and Mounts	$65,000	1	$65.00
3 Doubling Xtals and separation	$10,000	4	$40.00
4 UV wavelength extender	$32,000	2	$64.00
5 Optical isolators	$6,000	4	$24.00
6 Excimer Laser / 2 dye laser	$150,000	2	$300.00
7 30 Hz YAG/Ti:Sapphire System	$200,000	1	$200.00
8 Single Mode CW AR+/Ti:dye	$200,000	1	$200.00
9 Wavemeter	$12,000	1	$12.00
10 Hood for Excimer gases	$7,500	1	$7.50
subtotal			**$946.50**

D. Installation	**Hours**	**Rate**	**Total k$**
1 1 Installation Engineer	300 hrs	54.50	$16.35
2 2 Installation Technicians	480 hrs	37.10	$17.81
subtotal			**$34.16**

TOTAL	$1,772.66
EDI (@0%)	$0.00
CONTINGENCY (@11%)	$194.99
GRAND TOTAL $FY90	**$1,967.65**
GRAND TOTAL $FY92	**$2,081.77**
GRAND TOTAL TYM$	**$2,518.59**

Summaries TEC

I Chemical Dynamics Imaging Exp. Station	**Total k$**
Vacuum Chamber	$516.35
Detection	$188.00
Lasers	$666.90
Installation	$31.86
Total base cost ($FY90)	$1,403.11
Grand Total EDI + Cont. + Escalation	**$3,027.38**

II Chemical Kinetics Experimental Station	
Vacuum Chamber	$347.45
Detection	$204.90
Lasers	$713.20
Installation	$31.86
Total base cost ($FY90)	$1,297.41
Grand Total EDI + Cont. + Escalation	**$2,793.50**

III Experimental Station Enhancements	
Total base cost ($FY92)	$1,500.00
Grand Total Cont. + Escalation	**$3,000.00**

IV Upstairs lab	
Reaction Chamber	$138.25
Kinetics Facility	$159.45
Detector System	$494.30
Lasers	$946.50
Installation	$34.16
Total base cost ($FY90)	$1,772.66
Grand Total EDI + Cont. + Escalation	**$2,518.59**

Total SNL (TEC) Budget	**$11,339.47**

SNL Component (TYM$)

rev 2/6/92

	FY94	FY95	FY96	FY97	FY98	Total
Chem. Dynamics end station	0.23	0.61	1.02	0.84	0.34	3.03
Chem. Kinetics end station	0.23	0.61	0.89	0.73	0.34	2.79
Exper. station enhancements		0.42	0.98	0.95	0.65	3.00
Upstairs lab			0.63	1.26	0.63	2.52
SNL TEC	0.46	1.63	3.52	3.78	1.95	11.34
OPC	0.10	0.10	0.20	0.20	0.10	0.70
SNL TPC	0.56	1.73	3.72	3.98	2.05	12.04

SNL Component (FY92M$)

	FY94	FY95	FY96	FY97	FY98	Total
Chem. Dynamics end station	0.21	0.53	0.85	0.67	0.25	2.52
Chem. Kinetics end station	0.21	0.53	0.74	0.58	0.25	2.33
Exper. station enhancements		0.37	0.82	0.76	0.49	2.44
Upstairs lab			0.52	1.04	0.52	2.08
SNL TEC	0.42	1.43	2.93	3.05	1.52	9.36

Average escalation = 11.34 / 9.36 = 1.21

SNL Component (TYM$)

rev 2/6/92

	FY94	FY95	FY96	FY97	FY98	Total
Chem. Dynamics end station	0.23	0.61	1.02	0.84	0.34	3.03
Chem. Kinetics end station	0.23	0.61	0.89	0.73	0.34	2.79
Exper. station enhancements		0.42	0.98	0.95	0.65	3.00
Upstairs lab			0.63	1.26	0.63	2.52
SNL TEC	0.46	1.63	3.52	3.78	1.95	11.34
OPC	0.20	0.20	0.30	0.30	0.20	1.20
SNL TPC	0.66	1.83	3.82	4.08	2.15	12.54

SNL Component (FY92M$)

	FY94	FY95	FY96	FY97	FY98	Total
Chem. Dynamics end station	0.21	0.53	0.85	0.67	0.25	2.52
Chem. Kinetics end station	0.21	0.53	0.74	0.58	0.25	2.33
Exper. station enhancements		0.37	0.82	0.76	0.49	2.44
Upstairs lab			0.52	1.04	0.52	2.08
SNL TEC	0.42	1.43	2.93	3.05	1.52	9.36

Average escalation = 11.34 / 9.36 = 1.21

An Infrared Free-Electron Laser

for the Chemical Dynamics Research Laboratory

Design Report

February 1992

Lawrence Berkeley Laboratory
University of California

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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1.

OVERVIEW

THROUGHOUT the history of scientific inquiry, electromagnetic radiation has been the dominant tool for probing nature's secrets. Visible light, at first unaltered by human artifice, then refracted by the lenses of telescopes and microscopes, played the leading role until this century. Today, we have learned to interrogate nature's universe, from the cosmic to the subatomic, with radiation of all wavelengths, from x-rays to microwaves. In some respects, though, visible light still plays at center stage. The first lasers were visible-light lasers, and no tunable lasers have yet operated much beyond the red end of the visible spectrum. Practical sources of *broadly tunable, coherent* light, therefore, remain essentially unavailable at ultraviolet and x-ray wavelengths, or at wavelengths beyond the near-infrared.

This situation, however, is soon to change. The development of periodic magnetic devices known as wigglers and undulators, together with advances in particle accelerator technology and design, now offer the possibility of laserlike sources at both longer and shorter wavelengths. Third-generation synchrotron radiation sources, beginning with LBL's Advanced Light Source (ALS), will soon produce radiation in the ultraviolet and x-ray regions that is significantly akin to laser light. Further, free-electron lasers (FELs) have already operated successfully at infrared and microwave wavelengths, and their application to scientific research on a large scale, especially in the infrared, awaits only their incorporation into suitable user facilities.

This document describes such an FEL, proposed as part of the Chemical Dynamics Research Laboratory (CDRL), a user facility that also incorporates several advanced lasers of conventional design and two beamlines for the ALS. The FEL itself addresses the needs of the chemical sciences community for a high-brightness, tunable source covering a broad region of the infrared spectrum—from 3 to 50 μm. All of these sources, together with a variety of sophisticated experimental stations, will be housed in a new building to be located adjacent to the ALS. The radiation sources can be synchronized to permit powerful two-color, pump-probe experiments that will further our fundamental understanding of chemical dynamics at the molecular level, especially those aspects relevant to practical issues in combustion chemistry.

The technical approach adopted in this design makes use of superconducting radio-frequency (SCRF) accelerating structures. The primary motivation for adopting this approach was to meet the user requirement for wavelength stability equal to one part in 10^4. Previous studies concluded that a wavelength stability of only one part in 10^3 could

be achieved with currently available room-temperature technology. In addition, the superconducting design operates in a continuous-wave (cw) mode and hence offers considerably higher average optical output power. It also allows for various pulse-gating configurations that will permit simultaneous multiuser operation. A summary of the comparative performance attainable with room-temperature and superconducting designs is given in Table 1-1.

The FEL described in this report provides a continuous train of 30-ps micropulses, with 100 μJ of optical energy per micropulse, at a repetition rate of 6.1 MHz. The device can also deliver pulses at a cw repetition rate of 12.2 MHz, with a peak power of 50 μJ per micropulse. In both cases, the average optical output power can exceed 600 W. The length of the micropulse can also be varied. For shorter micropulse lengths (from 30 ps to below 2 ps), chirping techniques can be used that will still provide up to 100 μJ per micropulse. Grating techniques can be used to provide longer pulse lengths, up to ~100 ps, but only at the expense of a linear decrease in output power.

A layout of the proposed FEL is shown in Fig. 1-1. The injector prepares a properly bunched electron beam at 6 MeV that matches the phase space requirements of the

Table 1-1. Performance characteristics of FELs based on room-temperature and superconducting linacs.

	Room-temperature linac	Superconducting linac
Accelerator:		
Type	SW side-coupled	SCA
Frequency [MHz]	1300	500
Maximum energy [MeV]	~50	~55
General properties:		
Wavelength, λ [μm]	3–50	3–50
Line width	Transform-limited	Transform-limited
Wavelength stability, $\delta\lambda/\lambda$	10^{-3}	10^{-4}
Intensity stability	0.1	≤0.1
Average optical power [W]	≤20	≥600
Micropulse properties:		
Energy [μJ]	100 (at 50 MeV)	100
Duration [ps]	10–25	30 (≤2 ps via pulse compression)
Repetition rate [MHz]	36.6	6.1
Macropulse properties:		
Energy [J]	0.36	—
Duration	100 μs	>10 ms
Repetition rate	60 Hz	Flexible to cw

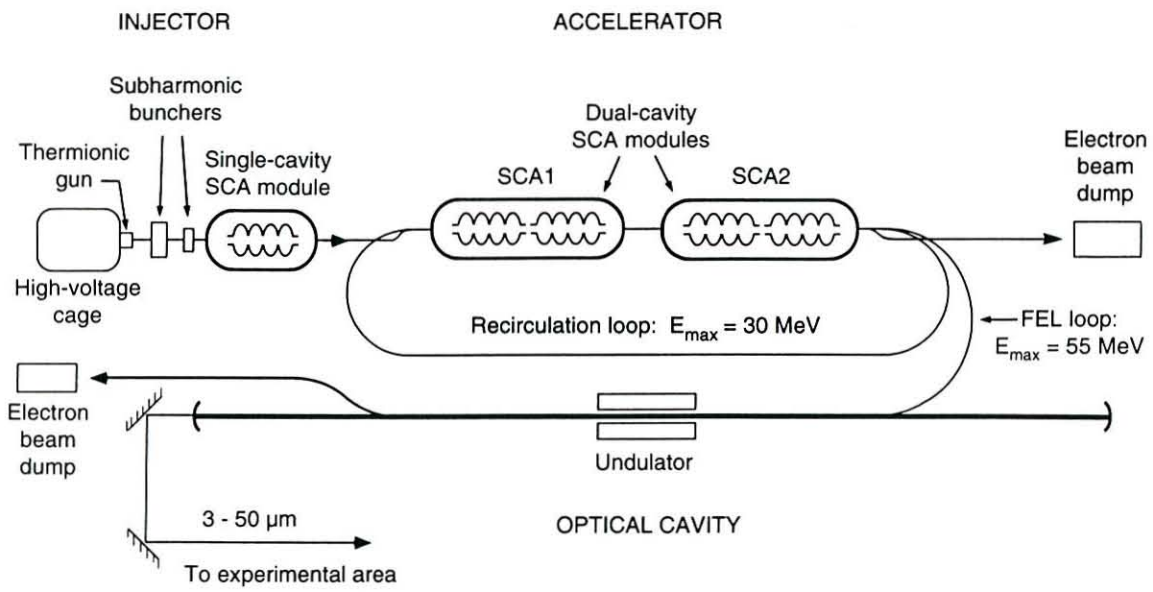


Figure 1-1. Schematic plan view of the infrared free-electron laser, located in the basement vault of the Chemical Dynamics Research Laboratory building. [XBL 921-5511]

accelerator section. The injector includes a thermionic gun; two subharmonic, room-temperature buncher cavities; and a single-cavity, 500-MHz SCRF accelerating module. The accelerator section consists of two dual-cavity, 500-MHz SCRF modules that accelerate the beam to ~30 MeV in a single pass. In both injector and accelerator sections, the SCRF cavities are designed to operate with a nominal accelerating gradient of 5 MV/m.

An achromatic and isochronous beam transport section then recirculates the beam for a second pass through the accelerator section for further acceleration to ~55 MeV. A similar beam transport system then delivers the fully accelerated beam to a 2-meter undulator that forms part of a 24-meter-long optical cavity. Optical power is outcoupled through a hole in one of the cavity end mirrors and transported to the experimental area.

The total estimated cost of the FEL is about $25 million, in FY1992 dollars. This estimate includes all accelerating and optical components, as well as the radio-frequency power and cryogenic systems. It also includes the costs of the associated design and engineering efforts required to make this a reliable user facility, and an appropriate allowance has been made for contingencies, consistent with DOE guidance and practice. The overall project schedule for the CDRL requires five years to complete, with construction beginning in FY1994. The total estimated cost of the FEL, adjusted for inflation in accordance with this schedule, is approximately $31 million in "then-year" or "as-spent" dollars.

2.

INTRODUCTION

ON the following pages, we outline some of the research opportunities that await construction of an IRFEL, together with the other facilities associated with the CDRL. Of particular note, this agenda of proposed research imposes special requirements on the performance of the IRFEL; the most important of these are listed in section 2.1.2. In sections 2.2 and 2.3, we then briefly describe the proposed FEL facility and tabulate its most significant performance parameters—parameters that fully meet the needs of the chemical dynamics research community.

2.1 SCIENTIFIC OPPORTUNITIES WITH THE IRFEL

The proposed research program for the CDRL ranges from basic reaction dynamics studies to experiments aimed at providing data that may ultimately lead to reductions in pollution from power plants and automobile engines, at the same time improving their efficiency. The following paragraphs offer a brief review of the research to be made possible with the IRFEL in particular; for a more comprehensive and detailed overview of research opportunities at the CDRL, see the *Combustion Dynamics Facility Scientific Program Summary* [1990].

Over 90% of all energy utilized in the U.S. today is generated by combustion. The National Energy Strategy, the latest Clean Air Act, and many state and local laws require that combustors be designed and operated with unprecedented fuel efficiency and low levels of emitted pollutants. If these requirements are to be met, combustion chemistry and its interaction with fluid flow must be understood at a much deeper level. For example, the oxides of nitrogen (NO_x) and sulfur (SO_x) are major components of pollutants, and industry continues to search for tailor-made fuels that reduce NO_x and SO_x emissions. To aid in the search, accurate critical paths for the oxidation of nitrogen and sulfur compounds in fuels and exhausts must be established. Fundamental information on potential energy surfaces, barrier heights, reaction dynamics, and kinetics will ultimately serve as the foundation for effective NO_x and SO_x abatement strategies.

Soot is another important combustion-generated pollutant—one that is now better understood as a result of recent basic research. Studies of the C–H bond strength in acetylene have now led to a new model for soot formation from acetylene fuel, and more research may someday allow us to control soot formation in this and similar processes.

In short, all combustion-related phenomena—engine knock and CO emission to name but two—are linked to fuel-consuming processes that begin with free-radical reactions. Many different reaction products and many different chemical processes are involved, but clearly an understanding of the fuel cycle cannot be complete without a thorough fundamental study of the chemistry of combustion.

At the CDRL, the scientific research program will focus on gaining a rigorous molecular-level understanding of combustion and other energetic molecular processes. These studies will build foundations of basic knowledge to underlie scientific and technological leadership in the combustion-systems and control-technology industries.

Researchers at the CDRL will explore these topics by

- Determining the structure and chemical behavior of highly reactive polyatomic radicals and unusual transient species.
- Providing microscopic details of mechanisms and dynamics for elementary chemical reactions and primary photodissociation processes.
- Probing the nature of intra- and intermolecular energy relaxation.
- Searching for bond-selective or mode-selective means to modify and manipulate chemical reactivity.
- Establishing a sound theoretical foundation for understanding chemical reactivity and as a basis for experimental efforts.
- Developing novel methodologies and tools to investigate important but currently unsolvable problems in chemical and combustion dynamics.

Input from the user community has been the key to preparing the scientific program for the CDRL. Particularly important roles were played by recent national workshops and symposia, including the Workshop on Opportunities for Chemistry Related Combustion Science (July 1986), the Workshop on Chemical Reaction Dynamics (November 1988), a chemistry user community review (October 1989), and a combustion dynamics workshop in April 1990. These workshops and reviews identified research in combustion and reaction dynamics as critically dependent upon advanced technologies and techniques, including free-electron lasers.

The CDRL will allow, for the first time, the integrated and simultaneous use of dedicated IRFEL and synchrotron-radiation beamlines for pump-probe experiments, as shown conceptually in Fig. 2-1. One mode will use the ALS photon beam as the pump and the IRFEL photon beam as the probe; in this mode, researchers will be able to study the vibrational structure of highly excited and superexcited molecules. The other mode—IRFEL pump and ALS probe—will yield infrared spectra of transient species (combustion diagnostics); new information on ionization potentials and bond energies (reactivity) of transient species; new vibrational spectra of ions; and insight into regioselective photochemistry. Experiments involving new-generation crossed molecular beams can also be integrated with studies using the IRFEL.

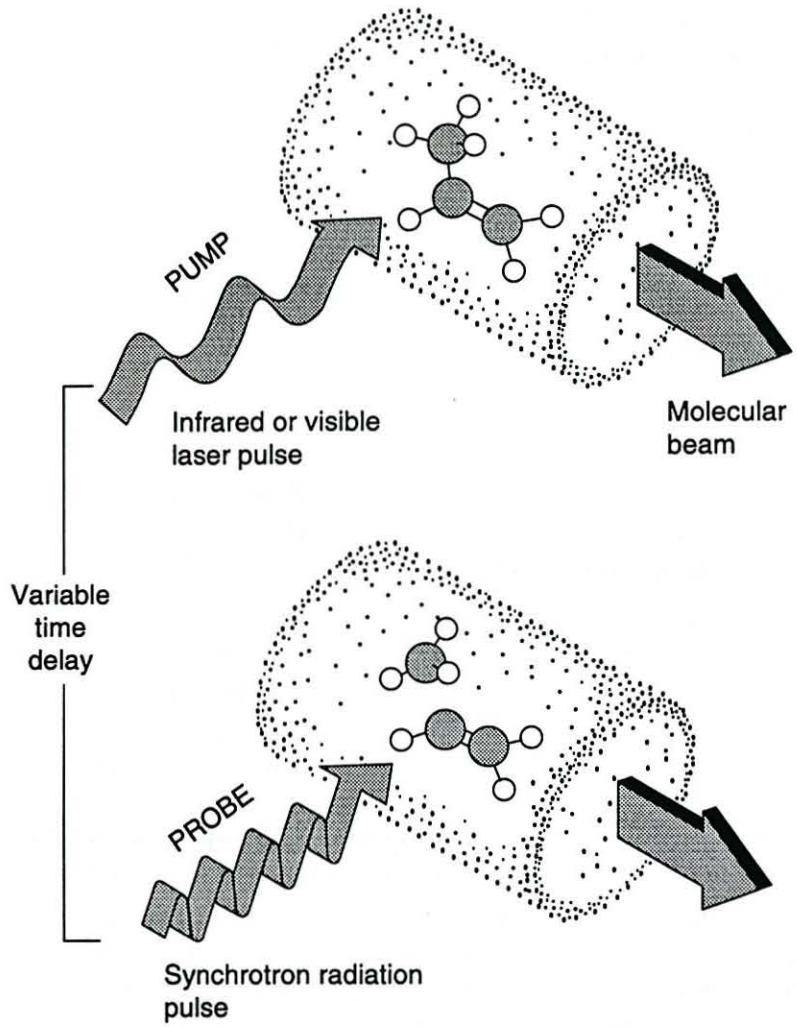


Figure 2-1. Diagram of a "two-color," pump-probe experiment. One source of radiation is used to excite or ionize the molecules in a molecular beam, and a second is used to characterize, or "probe," the resulting species. [XBL 9012-6761B]

2.1.1 Proposed Research

A number of proposals for using the IRFEL, either independently or in conjunction with the other resources of the CDRL, have been put forth, especially at the workshops mentioned above. The following paragraphs summarize just a few of the ideas that have been suggested; their variety and uniqueness underscore the unprecedented opportunities that await the chemical dynamics community.

Infrared Multiphoton Excitation (IRMPE). IRMPE and dissociation under collision-free conditions will be made much more widely applicable by the IRFEL. Thus far, this powerful technique has been used only to study molecular species that can be excited by a CO_2 laser, which has limited tunability. The IRFEL, with its broad tunability, will

expand the range of applicability across the entire periodic table, providing experimental access to practically all molecular species. Using the IRFEL, chemists and surface scientists will be able to probe basic molecular dissociation processes and produce unusual transient species such as organic free radicals, reactive intermediates, and radical-containing clusters.

Important IRMPE applications using the IRFEL include

- Studies of dissociation dynamics and reaction mechanisms of aromatic hydrocarbons, which are abundant in low-grade fuels.
- Selective decomposition of undesirable minor species of molecules in gaseous matter.
- Separation of isotopes.
- Regioselective chemistry, in which vibrational modes at specific sites in a molecule are excited by a properly chosen IRFEL wavelength; these experiments might be combined with photoionization initiated by a VUV beam from the ALS.

Chemistry and Spectroscopy of Surfaces. Surface studies, which will also be enhanced by the IRFEL, are significant because surfaces play an important role in many chemical processes involved in the combustion cycle, including particulate formation and the creation and destruction of pollutants. Optical techniques, being nondestructive and widely applicable, are very attractive for this research.

A relatively new, yet fully developed, technique for surface vibrational spectroscopy—detection of a coherent output whose frequency is the sum of the laser input frequencies—provides vibrational "fingerprints" of surfaces and selective detection of adsorbed molecular species. However, one of the advantages of the technique, its high degree of surface specificity, also hampers its use—another handicap resulting from the narrow tuning range of currently available infrared lasers. The IRFEL would be a major breakthrough in this technique, allowing the study of any molecule or radical. A particularly exciting application, for which few other techniques exist, is spectroscopy of buried interfaces. The picosecond time structure of the beam would also make this technique extremely useful for studies of surface dynamics, as well as for following reaction paths step by step, which is necessary for truly understanding a reaction. The technique is not limited to gas-solid interactions; any interfaces accessible to light could be studied.

Prospects for the IRFEL in semiconductor studies include "hole-burning" experiments, performed with infrared and visible laser light, that would allow the first direct measurements of the coupling between electronic and vibrational degrees of freedom. Another possibility is real-time dynamic study of excitation and relaxation phenomena associated with defects in semiconductors, using the IRFEL and standard lasers.

Vibrational Dynamics of Reactions in Solution. It is currently infeasible to probe vibrational dynamics in solutions on an extremely fine time scale because of the lack of high-power infrared sources at the appropriate vibrational frequencies. The IRFEL, in combination with existing lasers and the ALS, will allow direct studies of such

phenomena, greatly increasing our understanding of how chemical reactions proceed in solution.

Two-Color Threshold Photoelectron Spectroscopy. The CDRL will enable investigation of a set of asymmetric vibrational modes of ground state ions that cannot be excited directly from the vibrational ground state of the neutral molecule; the energy of these modes is unknown for many ions, even some as simple as CO_2^+. The IRFEL beam will be used to excite an infrared mode of the molecule; subsequent ionization by an ALS beam (to which the IRFEL beam is synchronized) will produce the new vibrational state.

Two-Color Fluorescence Studies. Superexcited molecules can dissociate not only into ions, but also into other entities, including electronically excited neutral fragments. This form of decay is usually the sole route below the ionization limit, and it can even compete with ionization several electron volts above the ionization limit. Population of a specific vibrational-rotational state with infrared laser light, followed by further excitation with synchrotron light, can produce a superexcited state whose dispersed neutral decay products fluoresce. This means of studying excited dissociation channels has been established at other synchrotron radiation facilities as a powerful tool in the understanding of predissociation dynamics, and it would be enhanced significantly with the IRFEL.

Spectroscopy of Gas-Phase Free Radicals. Research on gas-phase free radicals will benefit greatly from the combined availability of the ALS and the IRFEL; in fact, the combination has been referred to as a "universal free-radical spectrometer." In these experiments, a cold molecular beam containing a small concentration of radicals will be excited by intense light from the IRFEL, tunable across the absorption spectrum. Since the density of radicals in the beam is not high enough to allow the direct measurement of absorption, a VUV beam from the ALS will be used to detect the infrared-excited states of molecules by selectively ionizing the vibrationally excited radicals. (The VUV photons will not ionize the ground-state radicals.) Then, narrow-line-width infrared lasers will be used for higher-resolution studies at frequencies found with the tunable "search" beam of the IRFEL.

Cluster Energetics and Dynamics. Neutral and ion clusters are formed by pulsed laser desorption of solid material, followed by nucleation and cooling in a high-pressure flow of helium gas. The IRFEL can then be used to excite the clusters, which can subsequently be dissociated or ionized by the ALS or a high-power laser. Spectroscopic and structural information can thus be extracted. Such measurements interact with one another in a very helpful way. Excited-state studies of ion clusters have led to significant insights into the structure and dynamics of transition states.

These studies can dramatically enrich our fundamental understanding of matter interactions, bridging the gap between the gas-phase properties of atoms and molecules and the very different worlds of aerosols, liquids, and solids. The structure, energetics, and kinetics of carbonaceous clusters have important consequences for modeling soot-producing flames. Similar approaches can be used to look at metal clusters, which are of

great fundamental importance and have possible energy-oriented applications in catalysis and other areas.

Optical Diagnostics. At present, optical techniques are recognized as best for probing reacting media in a nonperturbing way. Their application is limited, however, by the fact that the spectroscopic data base necessary for their application exists for very few species containing more than two atoms. At the CDRL, unparalleled resources will be brought to bear on spectroscopic investigations of radicals and other transient species important in combustion. The IRFEL will, for example, allow scientists to excite the internal modes of transient species in a way that simulates the combustion environment. The information obtained will be useful in its own right in expanding our understanding of the properties of these species, but it will also provide a crucial data base for developing optical diagnostic probes for species in flames.

2.1.2 Performance Requirements

Much of the research described above will require the simultaneous use of unique facilities, such as the ALS beamlines, the IRFEL, advanced conventional lasers, and molecular-beam experimental stations. In general, the proposed research will benefit from high wavelength resolution in all the photon sources. In addition, special requirements are imposed on the IRFEL if its full promise is to be realized in pursuing combustion-related fundamental research.

The key characteristics required of the IRFEL include

- A wavelength range from at least 3 to 20 μm
- Wavelength stability equal to a fraction of the resolution
- High peak and average power
- Picosecond pulse duration
- Continuous tunability over any 20% segment of the wavelength range
- Capability to be synchronized to the pulse train of the other CDRL sources

2.1.3 Scientific Horizons for the CDRL

In conclusion, it should be reemphasized that the IRFEL is part of a larger facility, offering an enormous range of research possibilities. Besides providing unique and important opportunities for understanding the dynamics of combustion, the available resources will advance the broader field of chemical dynamics in general, and the opportunities for related benefits to science and society are considerable. Combustion studies will benefit from techniques and spectroscopic information derived from experiments designed to study dynamical processes in the condensed phase, in novel solid-state materials, semiconductors, metal clusters, inorganic crystals, and polymers. These experiments will further broaden the utility of the facilities and will provide unmatched U.S. leadership in the study of dynamic chemical processes for many years to come.

2.2 FACILITY DESCRIPTION

The electron beam systems of the FEL must be enclosed by a considerable thickness of radiation shielding to protect operators and users of the facility. These shielding requirements impose a significant constraint on the design of the FEL facility. It was necessary to develop a layout that makes economical use of space, yet allows for easy maintenance and, at the same time, leaves the door open to future expansion of the basic system. Accordingly, the FEL will be housed in a concrete vault that also serves as part of the foundation of the CDRL building. The walls and roof of this vault will be formed with approximately 10 feet of conventional, poured-in-place concrete, and access to this area will be carefully controlled and monitored: No access will be possible during operation, and only controlled access will be permitted at other times. Therefore, systems that require occasional tuning or maintenance during operation are located outside the shielded vault area. Components inside the shielded vault include the injector and accelerator sections, all electron beam transport components, the undulator and optical cavity, and the electron beam dumps.

Consideration was given to a variety of layout arrangements, the most attractive of which were variations of two basic configurations, shown schematically in Fig. 2-2. The first is a linear arrangement in which the injector, accelerator, and optical axes are nearly collinear, and in which the electron beam does not reverse direction between the SCRF

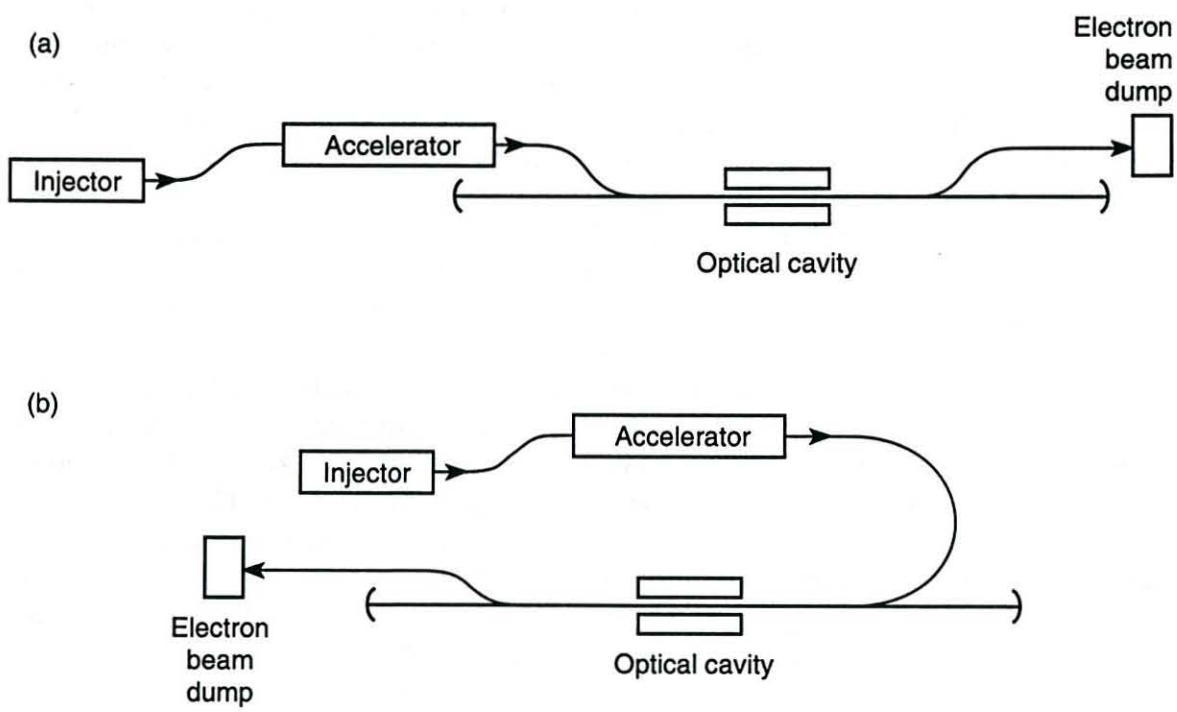


Figure 2-2. Schematic illustrations of (a) linear and (b) folded design configurations for the FEL. [XBL 921-5512]

cavities and the undulator. The second arrangement is a "folded" configuration in which the electron beam is bent by 180° before passing through the undulator section. The folded configuration is more compact and requires considerably less concrete shielding, whereas the linear configuration allows a somewhat simpler electron beam transport system and offers a clearer opportunity to exploit the possibilities of a future second undulator. Preserving this opportunity is very desirable, as it would provide users with two independently tunable infrared sources, driven quasi-simultaneously by the same accelerator. In the linear configuration, with its larger vault, a second full-energy optical cavity could readily be accommodated downstream of the accelerator, parallel to the first cavity. In the folded configuration shown in Fig. 2-2b, a second undulator could be added only in the recirculation loop and optimized for use in the 10- to 50-μm wavelength range. If a second undulator/optical cavity with full-energy capability were considered essential and economically justified, the linear arrangement would be preferred. For reasons of economy, however, we adopted a folded arrangement for the present design. The additional cost of the beam transport system in this configuration is modest and does not offset the savings associated with the smaller vault required for the more compact design.

A layout of the folded FEL configuration is shown in Fig. 2-3, as it would appear inside the vault designed as part of the basement of the CDRL building. Separate shielding is provided at one end of the vault for a closed-loop water system used to operate two beam dumps. These dumps are identical and designed to safely absorb a 55-MeV beam with 800 kW of power. They are housed inside separate concrete bunkers within the main vault. One of these dumps is located near the exit of the accelerator and will be used primarily for commissioning, development, and debugging. The second dump is located near the point where the electron beam exits the optical cavity; this dump will become the primary dump once routine operation is established. Access to the beam dumps will be required only infrequently. They will therefore be kept under separate lock and key, and access will be permitted only to persons accompanied by a designated safety officer.

Space is also required outside the vault for a variety of power, control, and cryogenic systems, together with their associated equipment racks. Most of these systems are shown in Fig. 2-4, which shows a plan view of the basement level of the proposed CDRL building. Five commercially available 500-MHz power amplifiers, each utilizing two klystrons, are located in a 20×50 foot room just outside the shielding wall adjacent to the SCRF cavities. This room also houses the associated equipment racks, the klystron crowbar system, and water control systems for thermal stabilization of the room-temperature subharmonic bunchers. The power supplies for these bunchers are located nearby in a separate 20×20 foot room Power from the amplifiers is transmitted to the cavities by means of waveguides. Circulators and "magic tees" are used to prevent reflected power from damaging the klystron amplifiers. An electrical substation that supports all of the building electrical systems (including the FEL) is also located in the basement level of the building, as can be seen at the top of Fig. 2-4.

The cryogenic systems provide both helium at 4 K and liquid nitrogen at 80 K. Commercially purchased liquid nitrogen will be delivered by a house supply line from a nearby storage tank to points throughout the building. The helium will be generated on site by a 600-W refrigerator/compressor system. The helium system consists of the

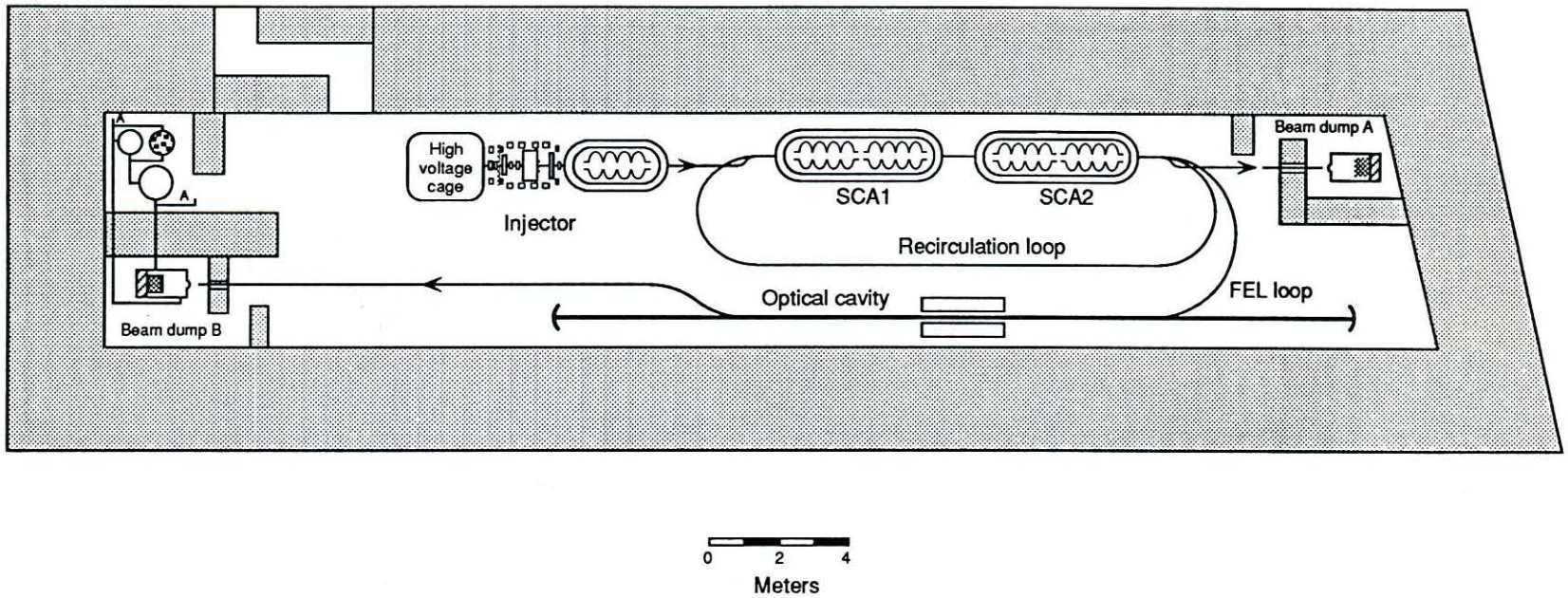


Figure 2-3. Layout of the FEL inside the vault of the CDRL building.

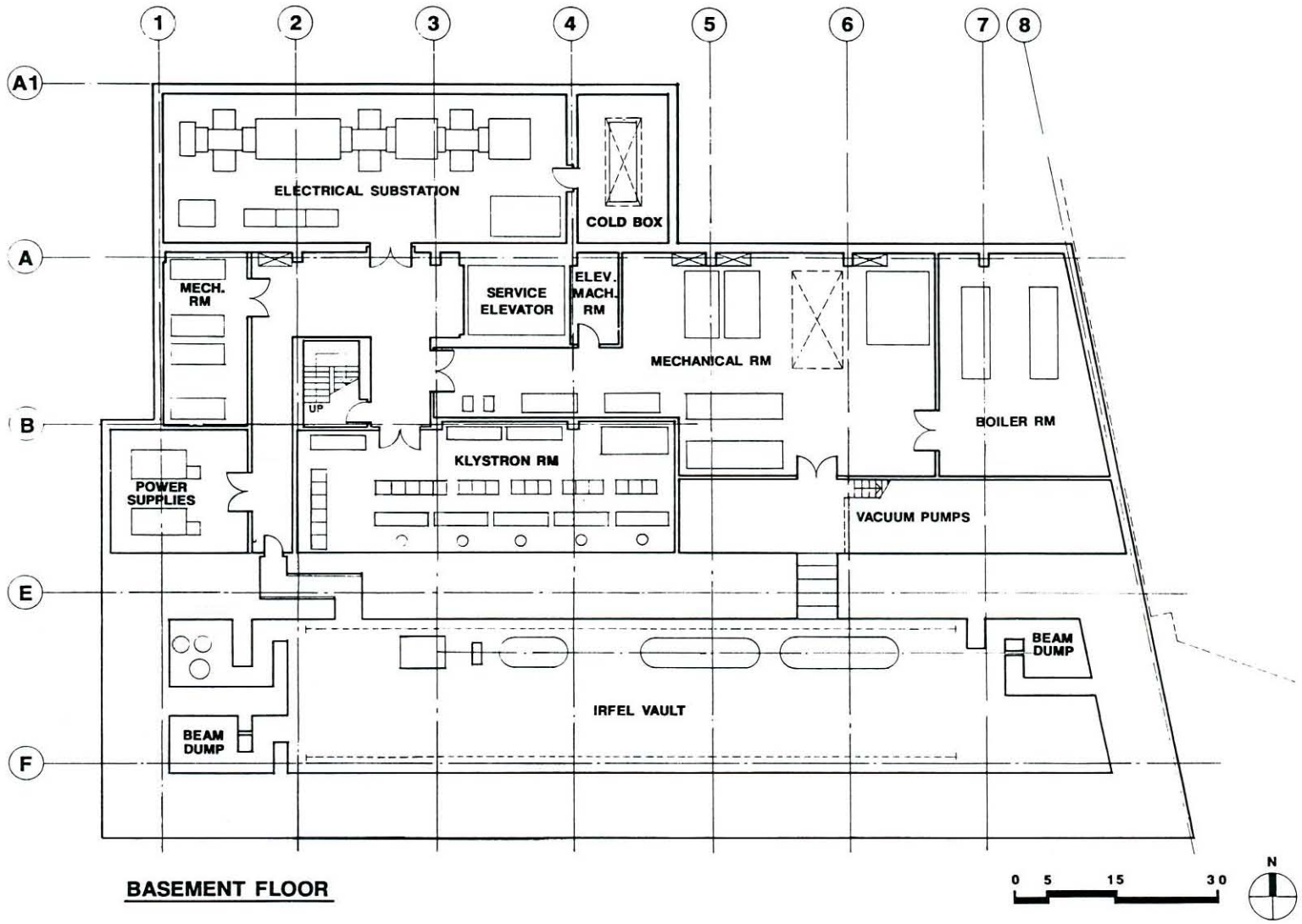


Figure 2-4. Plan view of the basement level of the proposed CDRL building.

refrigerator/compressor, gaseous helium storage, and connecting cryogenic plumbing. The refrigerator is located in the basement level of the building approximately 70 feet from the cryostats in the vault (see Fig. 2-4). To isolate both noise and vibration, the compressor is located in a separate utility building approximately 200 feet away.

Equipment racks for other systems, primarily the electron beam transport system, are located on the basement level beneath an elevated platform used to support mechanical vacuum pumps servicing equipment in the experimental hall on the main floor. The FEL control room is also located on the main floor of the building, directly above the FEL, and is adjacent to the experimental hall to promote good communication with the users.

2.3 IRFEL PERFORMANCE PARAMETERS

The IRFEL proposed here will provide intense, tunable, and coherent radiation in the infrared region of the spectrum between 3 and 50 μm as direct laser output. Further, this wavelength range can be extended to 1.5 μm, should that be desirable, by optical harmonic generation techniques. Extension to lower energies—wavelengths longer than 50 μm—is also direct and straightforward but will probably suffer from reduced performance and reliability, since such an extension must rely on a careful and controlled use of a very-low-energy electron beam.

The general characteristics of the IRFEL are listed in the right-hand column of Table 1-1 in section 1. In addition, the infrared pulses from the FEL will be delivered with a special time structure, allowing synchronization with the ultraviolet pulses from the ALS and with other lasers at the CDRL. The IRFEL pulse structure and its synchronization with the ALS is depicted in Fig. 2-5.

The FEL is driven by a relativistic electron beam, prepared with phase space properties to allow lasing, by an injector, an electron linac, and a carefully designed transport system. The basic electron beam parameters, including the requirements on its stability, are given in Table 2-1. The stability requirements and the other parameters are elaborated on in section 3.1. The constraint on beam energy stability is driven by the required laser wavelength stability $\delta\lambda/\lambda \leq 10^{-4}$, the charge stability by the acceptable laser intensity fluctuations, the repetition rate modulation stability by the fundamental physics of FEL gain, and the steering stability by the requirements on matching in the optical cavity and on directional stability of the FEL output.

The goal of the entire accelerator system is to provide stable, high-quality pulses of electrons to the FEL cavity. The free electrons are produced in a conventional thermionic electron gun. The parameters of the electron gun are listed in Table 2-2. The gun produces electron pulses with a duration of 1.5 ns, at an average current of 1.6 A (2.5 nC of charge); the pulses are squeezed into 30-ps, 33-A bunches by a sequence of three bunchers operating at fundamental frequencies of 61, 171, and 500 MHz. The 500-MHz buncher is a superconducting structure; the other two operate at room temperature. Details regarding buncher design and their operating parameters can be found in section 3.2.

The bunched low-energy electron beam then enters the linac for further acceleration. The design of the main accelerating RF structure is based on the need to maximize

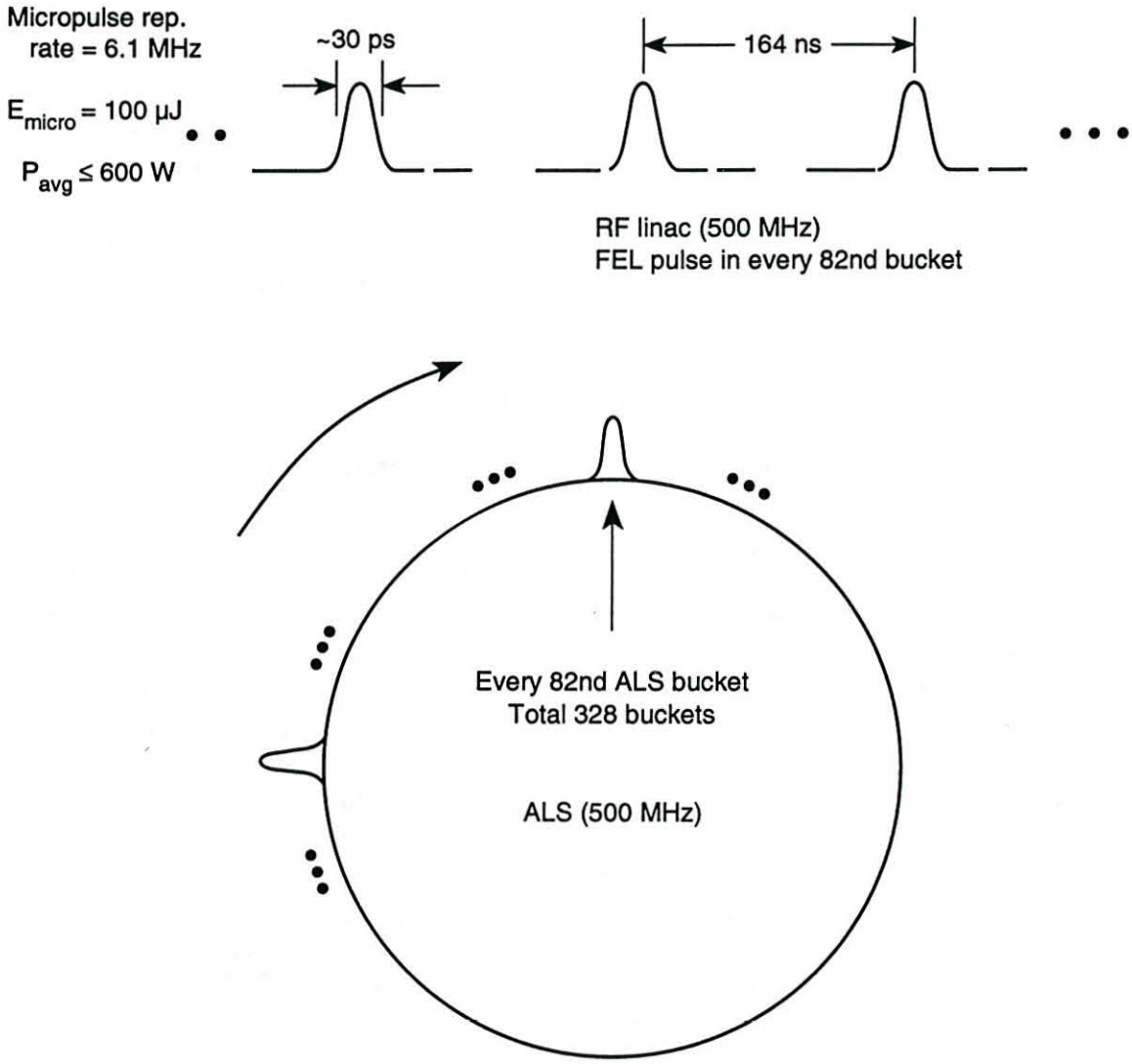


Figure 2-5. Schematic depiction of the time structure of pulses from the FEL, showing their synchronization with ALS pulses. [XBL 921-5513]

Table 2-1. Major electron beam parameters.

Maximum energy [MeV]	55.3
Energy spread, $(\Delta\gamma/\gamma)_{FWHM}$, at 55 MeV [%]	0.35
Micropulse peak current [A]	30–60
Charge per micropulse, q [nC]	1–2
Micropulse duration (FWHM) [ps]	33
Micropulse repetition rate [MHz]	6.1
Normalized emittance, $\gamma\sigma_x\sigma_{x'}$, $\gamma\sigma_y\sigma_{y'}$ [mm·mrad]	11
Stability:[a]	
Beam energy, $\delta E/E$	$\leq 5 \times 10^{-5}$
Charge, $\delta q/q$	<0.05
Freq. modulation of pulse rep. rate, $\delta\omega_{RF}/\omega_{RF}$	$<10^{-7}$
Position steering, $\delta x/\sigma_x$	≤0.1
Angular steering, $\delta x'/\sigma_{x'}$	≤0.1

[a]For slow fluctuations on a time scale longer than 1.6 μs or for frequencies lower than 0.1 MHz.

Table 2-2. Electron gun parameters. The gun is a conventional thermionic gun with a Pierce electrode geometry and dispenser cathode.

Voltage [kV]	300
Nominal pulse length [ns]	1.5
Nominal charge/pulse [nC]	2.5
Nominal average pulse current [A]	1.6
Cathode diameter [cm]	1
Gun pulser frequency [MHz]	6.1
Average RF gun power [kW]	6
Average electron current [mA]	15

stability and control. We selected a low-frequency (500-MHz) structure, based on standing-wave superconducting cavities. Standing-wave structures usually allow better control, compared with traveling-wave structures or waveguides. The choice of a superconducting, rather than room-temperature, structure was based on considerations of electron beam energy stability: Continuous-wave (cw) operation of superconducting cavities allows more time for feedback control, as well as a higher feedback loop gain over a narrow resonance width, and hence assures better stability. This will be discussed in more detail in section 3.1. Further, by use of time gating and other techniques, cw operation will allow the FEL beam to be exploited simultaneously by multiple users.

The frequency choice for the accelerator was again based predominantly on stability considerations: Low frequencies imply large transverse dimensions and a greater cavity volume. Thus, the cavity stores more energy, relative to the beam, and wake-field effects arising from the proximity of metallic boundaries to the beam are minimized—both of which improve stability. The cost penalty due to larger structures is not significant for superconducting cavities. The basic parameters for the superconducting RF linac are summarized in Table 2-3. The linac system design is described in detail in section 3.3, and the details of the associated cryogenic system are covered in section 3.5.

The injector-accelerator complex is responsible for conditioning the electron beam so that it has a suitable distribution around the nominal operating point. However, selecting the good beam core requires further removal of undesirable tails from the energy distribution and the temporal profile, using appropriate filters. These are discussed in sections 3.2 and 3.3. In addition, diagnostic equipment, on-line and off-line, for monitoring the electron beam are distributed throughout the facility and are described in detail in section 3.4. A detailed description of the beam dump, as well as the facility shielding, are provided in section 3.7.

Once suitably prepared, the beam must be carefully transported from the linac exit to the undulator in the optical cavity. This transport must be "achromatic," so as not to introduce any transverse jitter due to magnet fluctuations, and "isochronous," so as not to produce any additional pulse lengthening. In addition, the transport system must match the transverse profile of the electron beam to the optical cavity laser mode, it must be tunable to cover the full 3- to 50-μm wavelength range, and it must bring the beam back to the linac entrance with near-identity transformation for acceleration to higher energies. The transport line is thus constrained by many challenging demands. The design described in section 3.6 meets all of these requirements.

The transported beam interacts with the undulator magnetic field in the FEL optical cavity to generate the optical beam, as shown schematically in Fig. 2-6. The goal of the FEL design is to provide wide wavelength coverage while minimizing operational interruptions. At a fixed electron energy, the wavelength can be tuned between λ_{min} and $\lambda_{max} = 2.28\lambda_{min}$ by varying the magnet gap from 23 to 36 mm. As shown in Table 2-4, the entire wavelength range from 3 to 50 μm can be covered by operating the accelerator at four different energies. By changing the electron beam energy by ±1%, one can also fine tune the wavelength by ±2%. (In addition, an energy-modulating cavity can be envisioned to switch electron beam energy, and hence the wavelength of the optical beam, on a pulse-to-pulse basis.) Major parameters for the undulator and the optical cavity are summarized in Table 2-4. The physics of the FEL, the design of the undulator

Table 2-3. Superconducting linac parameters.

Type	Niobium cavities
Frequency [MHz]	500
Accelerating gradient [MV/m]	5.25
Unloaded quality factor,[a] Q_0	2×10^9
Shunt impedance/Q, R/Q [Ω/cell]	125
No. of cells/cavity	4
No. of cavities/cryostat	2
No. of cryostats	2
Operating temperature [K]	4
Electron energy at linac exit, first pass [MeV]	30
Voltage/cell [MV]	1.5
Stored energy/cell [J]	5.7
Average electron beam current [mA]	12.2

[a]Loaded quality factor Q_L, with 12 mA of average electron beam current, is expected to be 10^6.

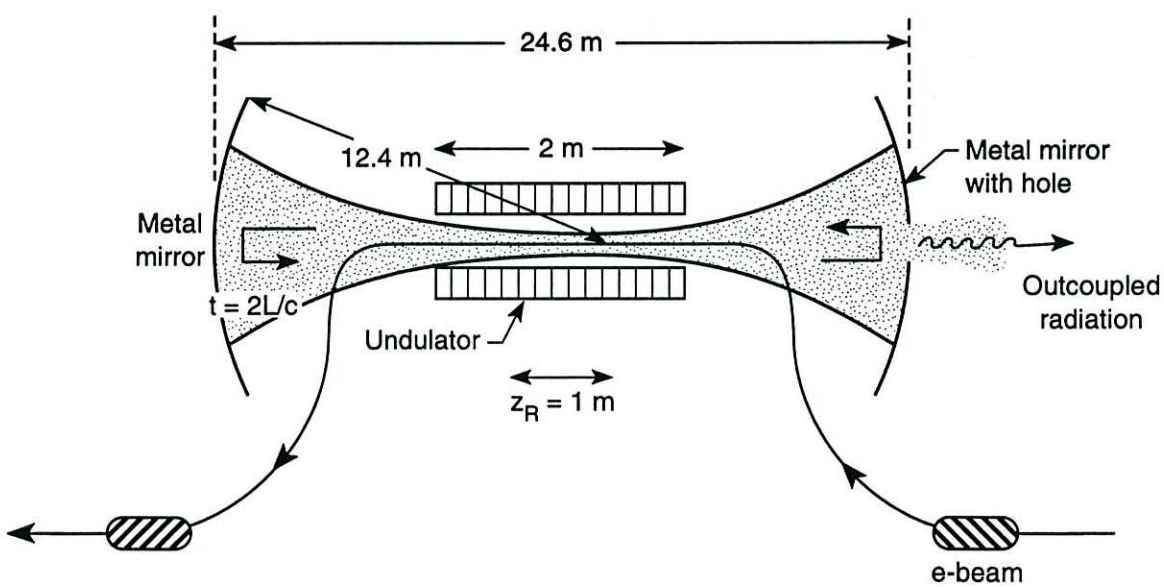


Figure 2-6. Schematic of the FEL optical cavity; z_R is the Rayleigh length and t is the round-trip time for the infrared radiation. [XBL 921-5514]

Table 2-4. Undulator and optical cavity parameters.

Cavity geometrical length [m]	24.6
Raleigh length [m]	1
Total round-trip loss [%]	~10
Hole output coupling efficiency [%]	~50
Single-pass FEL gain [%]	~50
Undulator type	SmCo-steel hybrid (Halbach design)
Undulator period, λ_u [cm]	5
No. of undulator periods	40
Wavelength ranges [μm]for beam energies:	
55.3 MeV	3–6.84
39.1 MeV	6–13.7
27.7 MeV	12–27.4
19.6 MeV	24–54.7

and the optical cavity, and issues related to outcoupling and optical diagnostics are discussed in detail in sections 4.1–4.4.

Every effort has been made in the present design to keep the facility as flexible as possible from an operational point of view. Pulse duration, peak current, and beam energy can all be adjusted over a wide range by varying the gun grid voltage, buncher RF phases, buncher voltages, relative phasing of the accelerator tanks, focusing magnet strengths, etc. These changes can be implemented on-line with relative ease. Our design also allows for the future incorporation of a second undulator and optical cavity—a useful prospect for a multiuser facility.

3.

ACCELERATOR SYSTEMS

WE define accelerator systems as those components of the IRFEL facility responsible for delivering the electron beam to the undulator, together with associated diagnostics and safety systems. This section is devoted to a description of these systems. Underlying their design are a number of accelerator physics issues, most notably stability requirements. These accelerator design issues are discussed in section 3.1. In the next two sections, we then describe the injector and RF linac systems, emphasizing especially the beam physics requirements that constrain the designs. Diagnostics and feedback systems are described in section 3.4, followed by the cryogenic system in section 3.5. The requirement for beam recirculation raises serious accelerator physics issues and imposes severe constraints on the design of the electron beam transport lines of the FEL. Careful beam simulations were required to ensure that neither single-bunch nor multibunch instabilities would threaten the system. The results of these simulations and a description of the beam transport system are included in section 3.6. Finally, section 3.7 describes the FEL shielding requirements, together with the design of the electron beam dumps.

3.1 ACCELERATOR DESIGN ISSUES

Assuring the stability of the optical beam is perhaps the central design issue for the FEL. In line with the demands of experiments planned for the CDRL, fluctuations in the FEL output spectrum and in the intensity must be held to less than 10^{-4} and 10^{-1}, respectively. Accordingly, stringent requirements must be imposed on the stability of the electron beam. These requirements dictate the use of superconducting RF structures and cw operation.

3.1.1 Electron Beam Stability Requirements

The effect of electron beam fluctuations on FEL performance depends upon whether the fluctuations occur on a time scale faster or slower than the response time of the FEL. The FEL response time is given by the cavity Q time, $t_Q = 2L/c\alpha$, where L is the length of the optical cavity and α is the fractional loss per round trip. In the frequency domain, the

characteristic frequency f_Q is related to t_Q by $2\pi f_Q\, t_Q \cong 1$. For the design described here, for which $L = 24.6$ meters and α is typically about 0.1, we have $t_Q \cong 1.6\ \mu$s and $f_Q \cong 0.1$ MHz.

Thus, we distinguish between slow and fast fluctuations as follows: Slow fluctuations are changes in the electron beam parameters that occur on a time scale longer than 1.6 μs, or, equivalently, at frequencies lower than 0.1 MHz. The effect of such fluctuations on FEL output is equivalent to a dc change in the electron beam parameters. Fast fluctuations, by contrast, are changes in the beam parameters that occur on a time scale shorter than 1.6 μs, or at frequencies higher than 0.1 MHz. The main effect of fast fluctuations is to reduce the gain, in a manner similar to energy spread or emittance.

Here we wish to consider two types of slow fluctuations—fluctuations in the energy of the electron beam and fluctuations in the interval between electron micropulses. Since we require a wavelength stability $\delta\lambda/\lambda$ better than 10^{-4}, and since fluctuations in the electron beam energy E produce optical wavelength fluctuations that are twice as large, the constraint on slow fluctuations in the electron energy is given by

$$\delta E/E < 5 \times 10^{-5} \tag{3-1}$$

Fluctuations in the interval T between electron micropulses is equivalent to fluctuations in the cavity length, or detuning, according to the relation $\delta T = 2\delta L/c$. As described in section 4.1, fluctuations in L should lie in region II of the detuning curve (Fig. 4-1), the width of which is $0.1 g\lambda N$ (see section 4.1.2). Thus

$$\delta T < 0.2 g\lambda N/c \tag{3-2}$$

where g is the FEL gain per pass, λ is the optical wavelength, and N is the number of undulator periods. Note that the constraint on fluctuations in T is a constraint on the variation in micropulse arrival times. It is thus equivalent to a constraint on the error in the RF frequency:

$$\frac{\delta\omega_{\mathrm{RF}}}{\omega_{\mathrm{RF}}} = \frac{\delta L}{L} < \frac{0.1 g\lambda N}{L} \tag{3-3}$$

Taking $g = 0.3$, $\lambda = 3\ \mu$m, $N = 40$, and $L = 24.6$ m, we find

$$\frac{\delta\omega_{\mathrm{RF}}}{\omega_{\mathrm{RF}}} < 10^{-7} \tag{3-4}$$

Fast fluctuations in the electron beam energy produce the same effects as does energy spread. Accordingly, the tolerance on fast fluctuations in the beam energy is equivalent to the tolerance on the energy spread, which in our case is 5×10^{-3}. The tolerance on fast fluctuations in the micropulse timing, $\delta T/T$, is determined by requiring that the overlapping of the optical beam with the electron beam be accurate to within one-tenth of the pulse length, that is, $\delta T/T \leq 2 \times 10^{-5}$. The tolerances on fast fluctuations are therefore much less stringent than those on slow fluctuations.

User requirements also demand that intensity fluctuations in the optical pulses be minimized. To limit the intensity fluctuations caused by charge fluctuations in the electron beam to less than 5%, we require

$$\delta q/q < 0.05 \tag{3-5}$$

where q is the bunch charge.

Finally, transverse stability of the electron beam must be maintained to ensure the corresponding stability of the output. The requirement imposed by the user community on the fluctuations in the position δx and the angle $\delta x'$ of the electron beam are

$$\delta x \leq 0.1\,\sigma_x \tag{3-6}$$

and

$$\delta x' \leq 0.1\,\sigma_{x'} \tag{3-7}$$

where σ_x and $\sigma_{x'}$ are the rms values of the beam's transverse size and angular divergence, respectively.

3.1.2 Comparison of Superconducting and Room-Temperature Designs

Figure 3-1 is a schematic representation of an RF cavity interacting with an electron beam and an external power source. Neglecting for a moment the feedback loop, and writing the field quantities in the form

$$e^{i\omega t} \times \text{(quantities varying slower than } \omega) \tag{3-8}$$

the cavity voltage V is given by

$$\left(\tau \frac{d}{dt} + 1 + iQ_L \frac{\omega - \omega_0}{\omega_0}\right) V = \frac{2\beta}{1+\beta}(V_+ - Z_0 I_B) \tag{3-9}$$

with

$$\beta = \frac{Z_c}{Z_0} = \frac{Q_0}{Q_{\text{ext}}}$$

$$Q_L = \frac{Q_0}{1+\beta}$$

$$\tau = \frac{2\,Q_L}{\omega_0}$$

$$V_+ = \sqrt{2\,Z_0\,P_+}$$

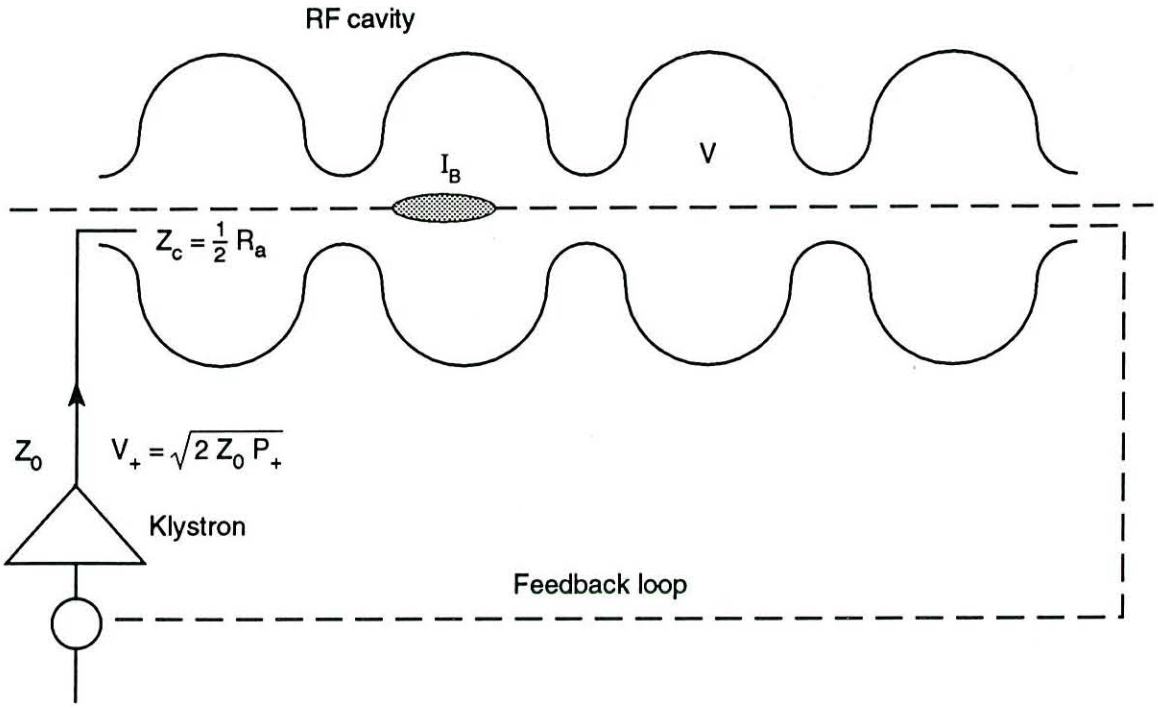


Figure 3-1. A schematic of an RF cavity. V = peak cavity voltage; I_B = beam current; $R_a = 2Z_c$ = cavity shunt impedance; Z_0 = wave impedance of the input line; V_+ = voltage of the input wave; P_+ = klystron power. [XBL 921-5515]

In the above, τ is the cavity decay time, Q_L is the loaded Q, Q_0 is the unloaded Q, Q_{ext} is the external Q, ω is the RF frequency, ω_0 is the resonance frequency, β is the coupling coefficient, Z_0 is the wave impedance of the input guide, Z_c is the cavity impedance, V_+ is the voltage wave traveling toward the cavity, I_B is the beam current, and P_+ is the klystron power. We assume that the reflected wave, $V_- = V - V_+$, is fully absorbed as it passes through a circulator (not shown in the figure). The power dissipated in the cavity wall is

$$P_c = \frac{1}{2} \frac{V^2}{Z_c} \tag{3-10}$$

The time scale for the RF cavity response is given by the cavity decay time τ or by the cavity bandwidth

$$\Delta f_c = \frac{1}{2\pi\tau} \equiv \frac{f_c}{2\,Q_L} \tag{3-11}$$

Note that Δf_c and τ are the RF cavity equivalents of f_Q and t_Q, respectively, for the optical cavity discussed in the previous section. For slow fluctuations, that is, those for which $f << \Delta f_c$, the derivative term in Eq. 3-9 can be neglected. For operation at the resonance, $\omega = \omega_0$,

$$V = \frac{2\beta}{1+\beta}(V_+ - Z_0 I_B) \tag{3-12}$$

The optimum value of the coupling coefficient β is determined by requiring that there be no reflected wave, that is, that $V_- = 0$. Thus,

$$\beta = 1 + \frac{2Z_c I_B}{V} = 1 + \frac{P_B}{P_c} \tag{3-13}$$

where $P_B = I_B V$ is the power gained by the electron beam in the cavity. For a room-temperature cavity, P_B/P_c is usually small, so that $\beta \cong 1$. On the other hand, P_c is negligible for the superconducting cavities described in section 3.3, so that $\beta >> 1$.

The fluctuations δV in the cavity voltage due to fluctuations in the beam current I_B, when $f << \Delta f_c$, is [Krafft et al., 1990]

$$\frac{\delta V}{V} = -\frac{\beta - 1}{\beta + 1}\frac{\delta I_B}{I_B} \tag{3-14a}$$

The factor $(\beta - 1)/(\beta + 1)$ is referred to as the coefficient of the slow disturbance before feedback. The voltage fluctuation after feedback is given by

$$\frac{\delta V}{V} = -\frac{1}{G}\frac{\beta - 1}{\beta + 1}\frac{\delta I_B}{I_B} \tag{3-14b}$$

The quantity $(\beta - 1)/(\beta + 1)G$, referred to as the coefficient of slow fluctuation after feedback, is a measure of the achievable RF stability.

Feedback reduces the voltage fluctuations. The gain characteristics of the loop are as follows: The peak gain G within the fluctuation bandwidth Δf (= Δf_c for the slow fluctuation) must be sufficiently large to reduce the fluctuations to an acceptable level. At higher frequencies, the gain generally falls off as $1/f$, and it must decline to unity at the frequency f_1, where the loop phase shift becomes 180°. Several factors contribute to the loop phase shift, including the length of the loop, high-order-mode resonances, etc. It turns out that f_1 is about 1 MHz for the cases we are interested in [Simrock et al., 1990]. This is illustrated in Fig. 3-2. The allowable peak gain G is therefore

$$G = \frac{1\ \text{MHz}}{\Delta f_c} \tag{3-15}$$

The cavity bandwidth Δf_c is much narrower in the superconducting case than in the room-temperature case. Thus, although the voltage fluctuation (Eq. 3-14a) is larger in the superconducting case, the feedback is much more effective, leading to stability that is better by an order of magnitude compared with the room-temperature case.

Equation 3-14a is not applicable when the fluctuations are faster than the cavity response, that is, when $f >> \Delta f_c$. In this case, let δq be the fluctuation in the bunch charge

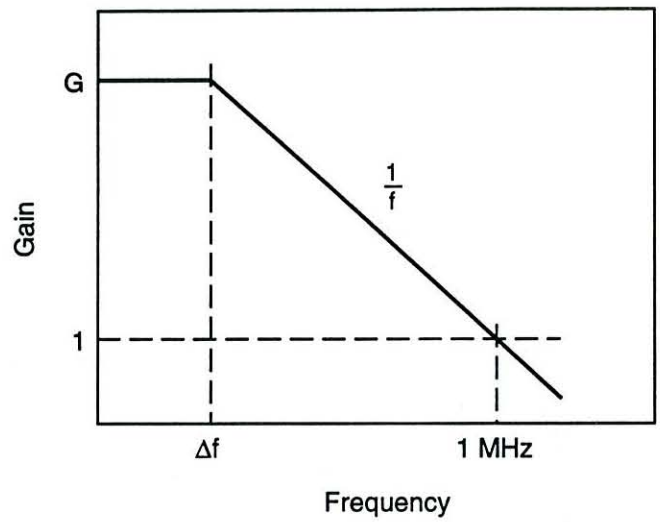


Figure 3-2. Typical Bode plot for the RF feedback circuit, illustrating the 1/f roll-off of the gain. The gain must decrease to unity at f ≅ 1 MHz to ensure the stability of the feedback loop. [XBL 921-5517]

passing through the cavity. The voltage fluctuation calculated from the fluctuation of the stored energy is

$$\frac{\delta V}{V} = \left(\frac{1}{2}\,\frac{R}{Q}\,\frac{\omega_0\, q}{V}\right)\frac{\delta q}{q} \tag{3-16}$$

where $R/Q \equiv Z_c/2Q_0$ is the shunt impedance. The quantity within the parentheses is referred to as the coefficient of the fast disturbance. In general, this turns out to be a small number, so that feedback is not required for fast fluctuations. The coefficient of the fast fluctuation scales as ω_0^2. For the superconducting case, an accelerator system based on a lower RF frequency ω_0 is feasible because of the low cavity loss P_c. Thus, the superconducting option is also superior also from the point of view of controlling fast fluctuations.

Table 3-1 provides a quantitative comparison of the stability performance of different RF options: (i) the previously documented CDRL FEL design using room-temperature 1.3-GHz structures [*Conceptual Design Report: Chemical Dynamics Research Laboratory,* 1991]; (ii) the FEL design documented here, which uses superconducting 0.5-GHz structures; (iii) a possible CDRL FEL design using superconducting 1.5-GHz structures; and (iv) the CEBAF accelerator design using superconducting 1.5-GHz structures. For the room-temperature design, the coefficient of the slow disturbance before feedback is about 0.1, the allowed gain G is about 14, and the coefficient of the slow disturbance after feedback is $0.1/13.8 \cong 7.2 \times 10^{-3}$. Assuming the current fluctuation to be about 0.1, we find that the fluctuations in the RF voltage can only be reduced to about 10^{-3}. For the superconducting CDRL design, the achievable stability should be $0.1 \times 2.5 \times 10^{-4} \cong 2.5 \times 10^{-5}$, which is smaller by more than an order of magnitude and also meets the constraints imposed by user requirements. The fast

Table 3-1. Accelerator performance parameters for four FEL designs.

	CDRL RT 1.3 GHz	CDRL SC 0.5 GHz	CDRL SC 1.5 GHz	CEBAF SC 1.5 GHz
RF wavelength [m]	0.231	0.600	0.200	0.200
Q_0	2.0×10^4	2.0×10^9	2.0×10^9	2.4×10^9
R/Q (per cell) [Ω]	289	125	100	96
R (per cell) [MΩ]	5.78	2.5×10^5	2.0×10^5	2.3×10^5
Accelerating gradient [MV/m]	8	5	6	5
Voltage per cell [MV]	0.923	1.50	0.600	0.500
Power dissipated per cell [W]	1.47×10^5	9.0	1.80	1.09
Stored energy per cell [J]	0.361	5.73	0.382	0.276
Beam current [mA]	36	12	12	0.8
Power transferred to beam (per cell) [kW]	33.2	18.0	7.2	0.40
Coupling parameter, β	1.23	2000	4000	370
Loaded Q	8.99×10^3	9.99×10^5	5.00×10^5	6.48×10^6
Filling time [μs]	2.2	636	106	1370
Cavity bandwidth [kHz]	72.3	0.250	1.50	0.116
Coeff of fast disturbance (at 1 nC)	1.28×10^{-3}	1.31×10^{-4}	7.85×10^{-4}	9.04×10^{-4}
Allowed gain, G	13.8	4000	666	8630
Coeff of slow disturbance				
before feedback	0.1	1.0	1.0	1.0
after feedback	7.2×10^{-3}	2.5×10^{-4}	1.5×10^{-3}	1.2×10^{-4}

fluctuations are also smaller for the 0.5-GHz superconducting option because of the lower RF frequency.

The third column of Table 3-1 shows that the slow fluctuations after feedback for a possible CDRL design using superconducting structures of higher frequency are about $0.1 \times 1 \times 1/700 = 1.4 \times 10^{-4}$, which does not meet the requirement of Eq. 3-1. The stability improves for the CEBAF design (column 4), which also uses 1.5-GHz superconducting cavities, because the beam current for nuclear physics applications is

lower. The beam current enters into the stability because it influences the value of β (Eq. 3-13) and thus limits the maximum gain G in light of Eq. 3-15.

3.2 INJECTOR SYSTEM

The injector system is of critical importance to the overall performance of the FEL. The brightness, energy spread, current, and bunch length of the electron beam are all primarily determined by the performance of the injector. In the injection system, space charge terms are large, and the growth of the transverse and longitudinal emittances are most significant. The requirements at the end of the injector, based on overall system requirements, are summarized in Table 3-2.

3.2.1 Design Approaches

We evaluated several design approaches in light of the performance demands of Table 3-2. The design ultimately adopted uses a conventional thermionic cathode, subharmonic bunchers, and fundamental acceleration. This arrangement is shown schematically in Fig. 3-3. It is possible to meet or exceed all of the design requirements with this approach. The injector output characteristics are given in Table 3-3.

An alternative approach that was considered would have made use of an RF superconducting cavity with an internal photocathode. This approach entails using a cryogenic photocathode in a very-high-gradient half-cell superconducting structure. The laser pulse length would be 50–100 ps, and the accelerating gradient would be 10–15 MV/m (15–20 MV/m at the photocathode). This approach was attractive from a beam physics point of view, for it would have eliminated most of the difficulties associated

Table 3-2. Injector output requirements, based on overall system performance requirements.

Energy stability	$<1 \times 10^{-4}$
Peak current, at 2 nC [A]	>60
Charge [nC]	1–2
Bunch length [ps]	≤33
Normalized rms emittance [mm·mrad]	<25
Energy spread	
at 30 MeV	≤0.5%
at 6.4 MeV	<120 keV (FWHM)
Energy [MeV]	>6
Bunch frequency [MHz]	6.10 (499.65/82)

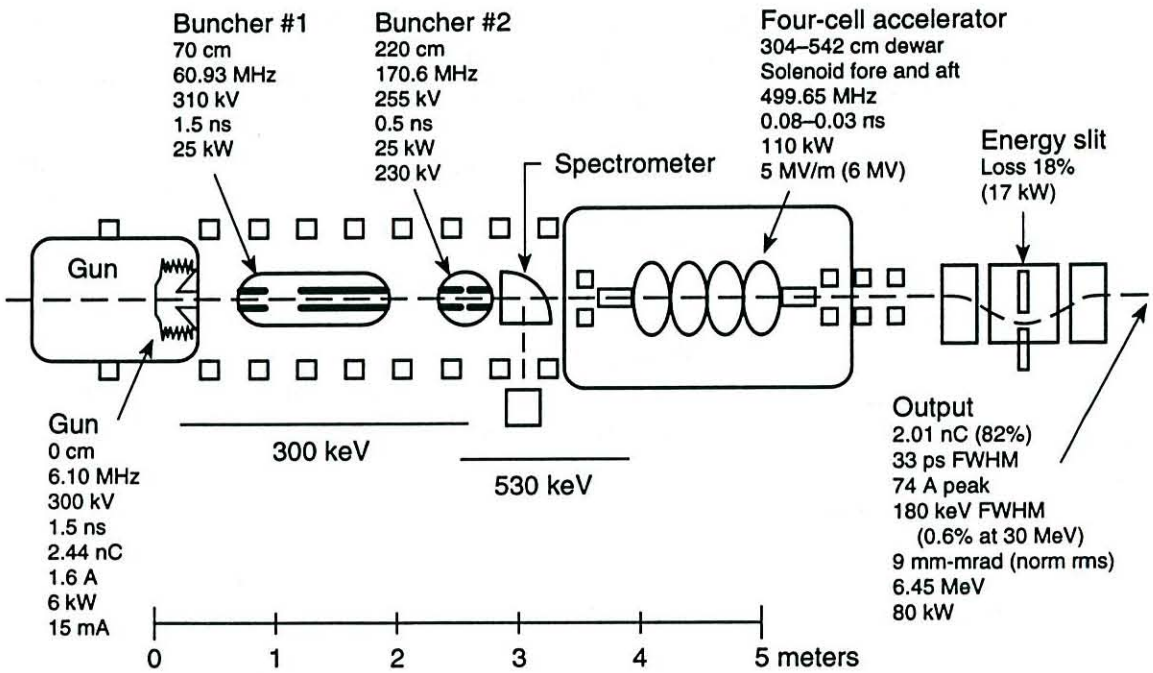


Figure 3-3. Schematic of the FEL injector. [XBL 922-5620]

Table 3-3. Performance characteristics of the FEL injector.

Charge per bunch [nC]	2.0
Bunch length [ps]	33
Average current [mA]	12
Peak current [A]	74
Bunch repetition rate [MHz]	6.10
Energy spread, at 30 MeV	180 keV or 0.6%
Normalized rms emittance [mm·mrad]	9
Energy [MeV]	6.45
Power (after slits) [kW]	80
Loss on slits	18% (17 kW)

with space charge forces in the adopted design. However, both the cryogenic photocathode and the superconducting structure suffer from uncertain lifetimes. The known mechanisms of contamination are suppressed at cryogenic temperatures, but photocathode and superconducting structure lifetimes have not been demonstrated in this

configuration. Work is in progress at the University of Wuppertal [Chaloupka et al., 1988] and at CEBAF on developing this technology, but it is likely to remain insufficiently advanced to serve as the basis for a reliable user facility for the next three to five years.

The third plausible approach would have incorporated a high-voltage dc photocathode just upstream of the second buncher in the design of Fig. 3-3 The dc gun voltage would be 500–600 kV, with a gallium arsenide photocathode and a 100- to 300-ps laser pulse. This injector configuration is also being developed at CEBAF [Sinclair, 1987] and the University of Illinois [D. Engwall, Ph.D thesis in progress]. This technology may be mature within one or two years, though many uncertainties remain.

Both photocathode approaches require lasers with very high average power. Although such lasers have been successfully demonstrated, the laser cost is high and the reliability is lower than needed for a user facility. A backup laser would be required to ensure the requisite reliability.

3.2.2 Injector Design and Modeling Results

The adopted injector design has several unique properties. First, it operates cw at a high average current (15 mA). The charge per bunch can be as high as 2.5 nC or 1.6×10^{10} electrons (allowing for a 20% loss before reaching the accelerator). The frequency (499.65 MHz) is lower than the typical injector (1300–3000 MHz), and the gun voltage is higher than the typical 100–150 kV. The accelerating structure is superconducting, and because it is to be an "off-the-shelf" design, the structure is not graded for β and the entrance beam pipe is large and long. This leads to large fringe fields at the entrance to the accelerating structure that decelerate the beam by about 200 keV before acceleration begins. Also, in this region, all magnetic fields are excluded by the superconductor. Therefore, to avoid significant space charge growth, the beam energy must be about 500 keV before the beam enters this region. Accordingly, the gun voltage is high and the second buncher provides additional acceleration.

The gun bunch frequency was picked to synchronize with the ALS synchrotron radiation pulses, which have a 12.19-MHz frequency when the storage ring is filled with eight equally spaced electron bunches. Half this frequency (6.10 MHz) was chosen for the injector gun to reduce the required RF power. The buncher frequencies are then the 10× and 28× multiples of the 6.10-MHz bunch frequency. The first buncher frequency was chosen such that the entire gun charge, assuming a 1.5-ns-wide pulse and 300-ps rise and fall times, would fall within ±20° of phase. The frequency of the second buncher is about three times that of the first, owing to the ~3× bunching between bunchers. The four-cell accelerating structure is matched to the ALS frequency of 499.65 MHz.

The gun provides 15 mA in a pulse train at 300 kV. As mentioned above, the bunches are 1.5 ns wide (FWHM), with rise and fall times (10–90%) of 300 ps. These characteristics produce a 2.4-nC bunch with a peak current of 1.6 A. A 2-cm^2 gridded thermionic cathode provides the needed current. TRW has built and tested a gun that runs at 500 kV with this bunch format. Their pulser uses step recovery diodes to produce the fast rise and fall times. Their pulser and gun designs meet the present FEL

requirements, and they have demonstrated a higher voltage capability than required here [Lazar et al., 1991].

Both bunching cavities use quarter-wavelength coaxial cavities in the fundamental TEM mode, where the center coax is the beam pipe, with a gap at one end (see Fig. 3-4). The lengths of the first and second bunchers are 123 and 44 cm, respectively.

The four-cell superconducting structure is modeled after the DESY four-cell structure built by Dornier [Willeke and Proch, 1991]. We also adopted the design gradient of 5 MV/m and Q_0 of 2×10^9 for the present design. To ensure good transport into the four-cell structure, a solenoid was added within the cryogenic dewar, around the stainless-steel thermal isolation beam pipe near the junction to the superconducting niobium. This solenoid is shielded from the RF superconductor to avoid quenching problems. It will run at a few hundred gauss and will be turned off during cool-down. It will put an extra 10 W (approximately) into the liquid nitrogen shield.

We used PARMELA as the primary computer tool to investigate the phase space development of the electron beam as it traverses the injector. URMEL was used to generate the fundamental-mode field profile. PARMELA uses the first 40 spatial harmonics derived from URMEL to calculate all of the RF fields.

Simulations show a low-energy tail on the bunch from the injector that must be removed before further acceleration. A chicane with a high-power energy slit capable of scraping up to 30 kW, or 25%, of the beam is therefore needed between the injector and the accelerator. This chicane must produce a dispersion of 30 cm per fractional momentum change at the location of the slit. The layout of the chicane and the slit is shown in Fig. 3-5. Positioned three standard deviations from the beam axis, the slit removes electrons in the tail of the spectrum more than 150 keV below the mean of

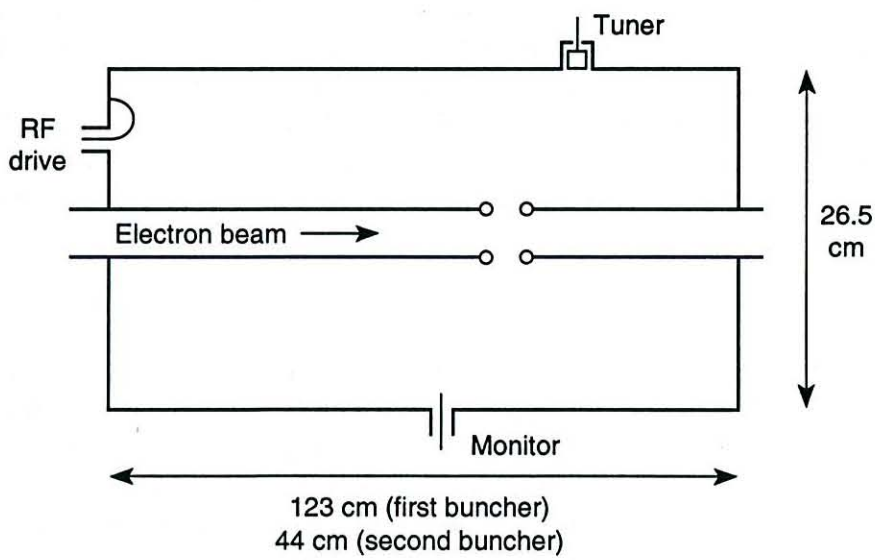


Figure 3-4. Schematic of the first and second subharmonic bunchers. [XBL 921-5561]

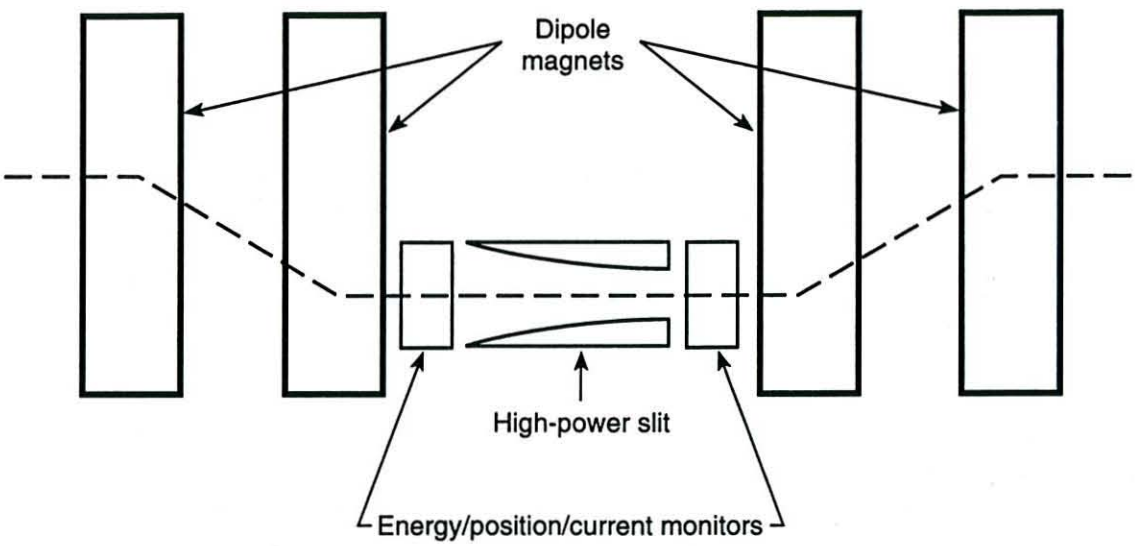


Figure 3-5. Schematic of the chicane at the injector exit, showing the configuration of the high-power slit. [XBL 921-5562]

the energy distribution. The high-power slit is an adaptation of the water-cooled copper photon stops within the ALS ring, which are capable of handling 500 W/cm^2 [Digennaro and Swain, 1990]. The slit is approximately 1 meter long, and its cross-sectional shape conforms to a 15° arc of a 4-meter-radius circle, with one end tangent to the beam. The power density will thus remain everywhere well below the 500-W/cm^2 limit. Local x-ray shielding will be provided, but the 6.4-MeV beam will produce no neutrons and no component activation.

Figure 3-6 shows the PARMELA output for the injector, both up- and downstream of the energy slit (Figs. 3-6a and 3-6b, respectively). Downstream of the slit, the energy spread is 180 keV. When the cosine curvature of the RF acceleration to 30 MeV is folded in, the energy spread becomes 0.6% at the FEL. The bunch is 33 ps long (FWHM), with a peak current of 74 A, a bunch charge of 2.01 nC, and a normalized rms emittance of 9 mm·mrad. The beam energy is 6.45 MeV, which corresponds to a beam power of 80 kW.

3.2.3 Sensitivity/Stability Analysis

Using PARMELA we performed a sensitivity/stability analysis of the injector to determine, among other things, the phase and amplitude requirements for the bunchers and four-cell structure. Each parameter was varied in turn, while all other parameters were held fixed, to establish how large a deviation could be tolerated in that single parameter. Limits on the tolerable deviations were determined by the tolerances on the injector output; injector tolerance requirements were dictated in turn by stability requirements on the electron beam and, ultimately, the FEL. The first column in Table 3-4 lists these injector output requirements. As will be seen below, voltage stability, bunch timing stability, and the FEL detuning curve imposed the tightest limits on the injector parameters.

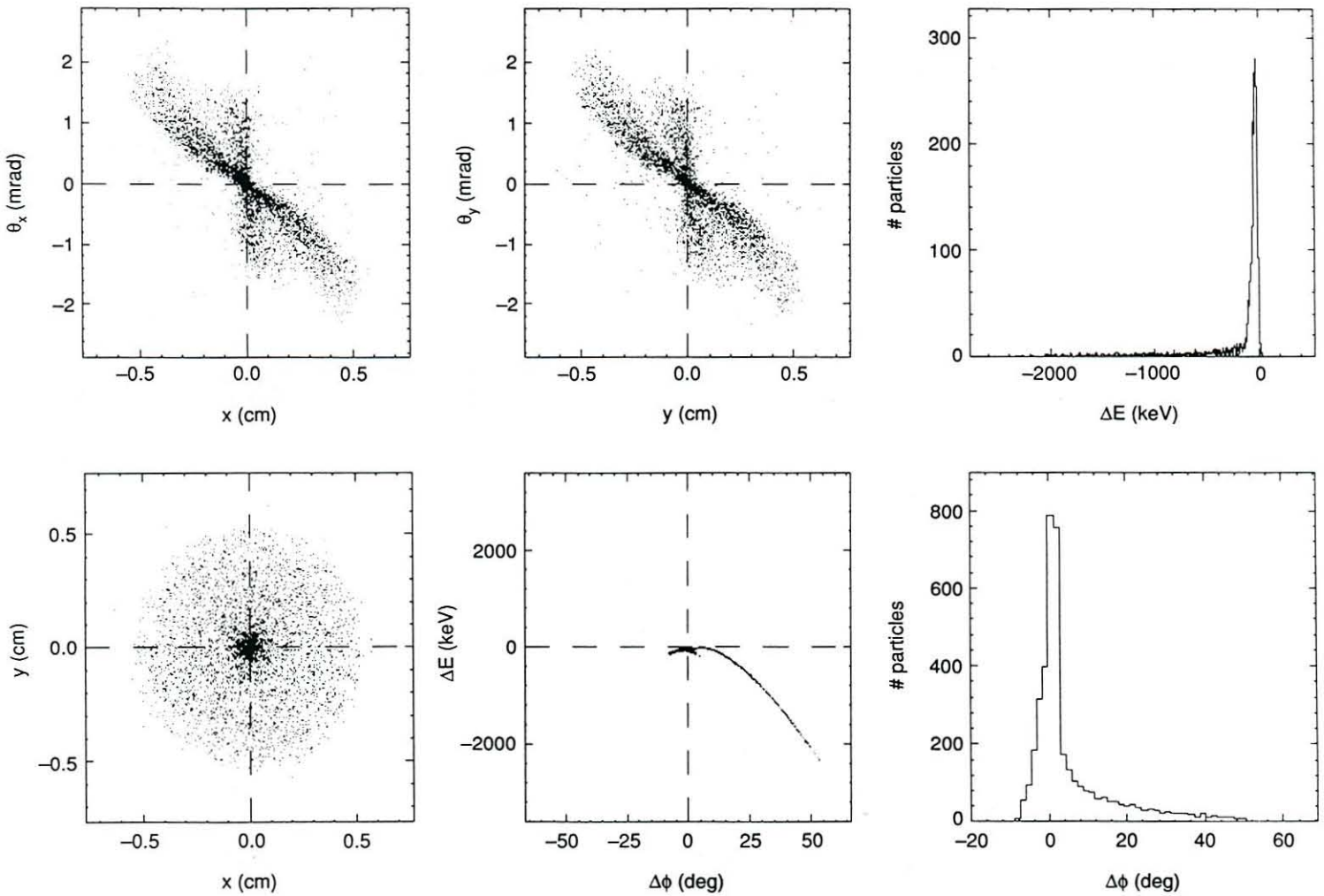


Figure 3-6a. Electron beam characteristics at the injector exit, upstream of the slit. The scatter plots at the upper left and upper center show the x and y phase space profiles, and the plot at the lower left shows the x-y beam profile. The plot at the lower center depicts the energy as a function of particle phase (z position). At the far right, histograms display the energy and phase distributions of the particles. [XBL 922-5587]

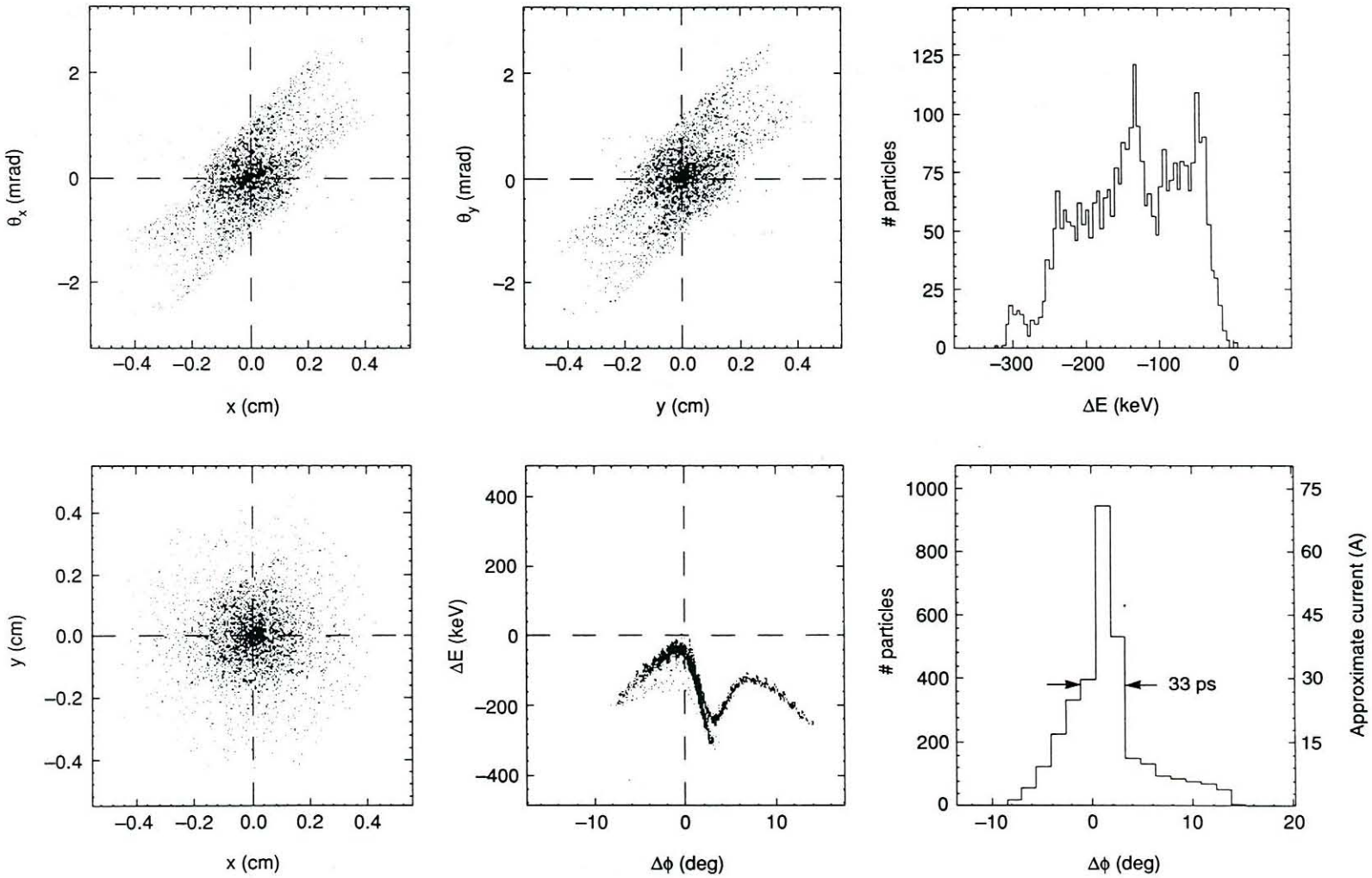


Figure 3-6b. Electron beam characteristics at the injector exit, downstream of the slit. See Fig. 3-6a for explanation. [XBL 922-5588]

Table 3-4. Results of a stability analysis of the FEL injector. Each column represents a single operational parameter; each figure in the column then gives the tolerable variation in that parameter, given the allowable variation in a single output parameter. The most stringent requirements are highlighted. See text for an explanation of the entries in the bottom two rows.

	Tolerance on injector output	Gun pulser phase (deg)	Buncher #1 phase (deg)	Buncher #2 phase (deg)	Four-cell phase (deg)	Gun voltage (kV)	Buncher #1 amplitude (kV)	Buncher #2 amplitude (kV)	Four-cell amplitude (MV/m)	Gun current (%)	Gun bunch length (%)
1	Charge, <1%	2.6	0.22	0.45	0.32	0.45	1.9	1.1	0.20	1.0	0.26
2	Voltage, $<1\times10^{-4}$	**1.2**	0.040[a]	**0.15**	**0.16**	0.16	**0.58**	**0.50**	**0.00053**	**0.82**	**0.14**
3	Bunch length, <5%	4.9	0.29	1.7	1.4	1.4	5.8	5.0	0.68	5.8	4.4
4	Bunch timing, <3 ps	32	**0.14**	1.3	1.4	0.75	4.7	2.3	0.15	21	8.2
5	Emittance, <5%	2.0	0.25	1.3	1.3	0.92	2.6	71	3.8	12	1.8
6	Energy spread, <10%	20	1.8	5.9	5.0	4.6	14	12	0.68	24	6.4
7	Beam size, <10%	9.3	1.1	4.5	7.0	3.6	10	29	0.43	18	6.5
8	Beam divergence, <10%	6.9	0.85	5.7	3.8	2.9	12	34	0.26	16	6.1
9	FEL detuning curve[b]	4.0	0.23	0.43	1.2	**0.048**	9.0				0.52
10	Buncher beam loading[b]									3.0	
	Derived requirement[c]	0.60 (3.4 ps)	0.070 (3.2 ps)	0.075 (1.3 ps)	0.080 (0.44 ps)	0.024 (0.008%)	0.29 (0.094%)	0.25 (0.098%)	2.5×10^{-4} (0.005%)	0.41 (0.41%)	0.070 (0.07%)

[a]Removed by changing buncher phase by 1° to curve maximum, thus defining the required operating phase.

[b]See text for explanation.

[c]Equal to one-half of boldface entry above to allow compounding of errors.

In addition, we considered the beam loading effects in the bunchers, together with the resulting requirements on gun current and gun timing stability. This led to more restrictive stability requirements on gun current and voltage than did the single-parameter analysis alone, where the buncher's phase and amplitude were held constant.

For these analyses, three time regimes are important: times short compared to the FEL optical decay time, times longer than the optical decay time but shorter than the RF fill time of the cavity in question, and times long compared with the RF fill time. The RF fields in an RF cavity are under feedback control for times longer than the cavity's fill time, and for shorter times, the cavity fields are constant, apart from possible beam loading changes. The gun current, voltage, and timing can change rapidly, and these fluctuations are important for times longer than the optical decay time. For the intermediate times, the gun fluctuations may be important and can cause beam loading amplitude and phase changes in the RF cavities. For times longer than the RF fill time, the gun parameters, the phase of the RF drive, and the amplitude may vary. In addition, the tune of the cavity can fluctuate in response to microphonics.

Although the PARMELA analysis is not sensitive to the time scale of these instabilities, the stability requirements shown in Table 3-4 are for times longer than the optical decay time. The FEL performance is largely insensitive to faster beam fluctuations, which are stabilized by the optical storage. Consequently, for times shorter than the optical decay time, the stability requirements are more relaxed and do not impose restrictive requirements. See section 3.1.1 for a more detailed discussion.

The tolerance on gun current due to buncher beam loading (row 10 in the table) was obtained as follows: For times between the optical cavity decay time (1.6 μs) and the buncher fill time (52 μs), phase fluctuations in the first buncher are dominated by charge fluctuations from the gun. The beam loading in this buncher is such that its phase is changed by 0.0072° per nanocoulomb of change in charge. This is true for times short compared with the feedback phase correction time, taken to be close to the cavity fill time. To keep the buncher phase variation within 0.14°, the most restrictive requirement in Table 3-4, the maximum allowable charge deviation over the fill time is 19 nC, or 0.059 nC/bunch, which in turn requires gun current stability equal to 3%. As a result, buncher loading does not impose the most restrictive requirement on gun current stability (the voltage stability requirement is four times more restrictive).

The gun voltage fluctuations are limited by the FEL detuning curve (see section 4.1), which requires that the pulse arrival frequency at the FEL be constant to 1.2×10^{-7}. The maximum allowable timing error over the optical cavity decay time is then $1.2 \times 10^{-7} \times 1.6\ \mu s = 0.19$ ps. For the gun voltage, if we scale from the bunch timing entry in Table 3-4 (0.75 kV for 3-ps stability), this implies a stability requirement of 48 V, which becomes the most restrictive constraint on this parameter.

The bold entries in Table 3-4 are the most restrictive. To allow for compounding of errors, each injector parameter requirement is then taken to be half of the most restrictive entry. The resulting requirements are shown in the bottom two lines of Table 3-4. Figures in the final line are expressed in picoseconds (for the first four parameters) or percent change (for the rest).

Constraints on the injector parameters approach state-of-the-art levels. However, workers at Stanford [Frisch and Edighoffer, 1990] and CEBAF [Bisognano et al., 1991] have achieved better than the required amplitude and phase control. In addition, TRW

[Lazar et al., 1991] has demonstrated a suitable gun pulser with the required tolerances. The approaches used in these successful efforts offer a proven path to meeting the requirements of Table 3-4.

3.3 RF LINAC SYSTEM

Superconducting RF was chosen for the accelerating system primarily because it provides the only sure means of achieving the required wavelength stability of 10^{-4}. As shown in Table 3-5, existing superconducting accelerators have produced electron beam energies sufficiently stable to meet the constraints implied by this requirement. In particular, the RF stability we require has been demonstrated at Stanford and CEBAF, both in amplitude and in phase, though not at the average power levels we demand. Our requirements, as determined by the stability analysis of the section 3.2.3, are for an amplitude stability of 5×10^{-5} and a phase stability of 0.08° in the main accelerator. (The energy stability must

Table 3-5. Selected parameters for operating and proposed superconducting RF linear accelerators. Parameters for the operating linacs were taken from Tuckmantel [1991].

	Frequency (MHz)	Gradient without beam (MV/m)	Gradient with beam (MV/m)	Current (mA)	No. of cavities	Q_0	Operating experience (hr)	Stability
Stanford (SCA)	1300	3.5	2.5[a]	0.2	7	2×10^8	3×10^6	3×10^{-5}
Cornell (CESR)	1497	8.0	5.0	20	few	5×10^9	$\sim 10^2$	10^{-4}
Darmstadt	300	5.6	4.2	low	11	$1\text{–}2\times10^9$	4×10^3	1×10^{-3}
CERN (SPS)	352	7.1	5.5[b]	6	1	3×10^9	2×10^4	$< 10^{-4}$
CERN (LEP)	352	5	3.6[b]	6	4(of 156)	$2\text{–}3\times10^9$	4×10^2	10^{-2}
KEK (Tristran)	508	9.25	4.7[b]	5	32	2×10^9	1×10^4	10^{-2}
DESY (HERA)	500	5	3.5	low	16	1×10^9	4×10^2	—
CEBAF	1497	9.0	5.0	0.1	2(of 350)	6×10^9	2×10^2	$< 3\times10^{-5}$
Cornell B factory (proposed)[c]	500	10	10	1980	16	2×10^9	0	$< 10^{-4}$
CDRL IRFEL (proposed)	500	5.5	5.25	24	5	2×10^9	0	5×10^{-5}

[a]Limited by an old design with multipactoring problems.

[b]Believed to be limited by stray synchrotron radiation, because of the low quench limit of the cavity closest to the bend; the CDRL FEL will produce little significant synchrotron radiation.

[c]See *CESR-B: Conceptual Design for a B Factory Based on CESR* [1991].

be twice a good as the required wavelength stability, since the FEL wavelength is inversely proportional to the square of the electron energy.) The higher average power we demand means that our Q_L and the cavity fill times are less than those at Stanford or CEBAF. This in turn means that the cavity is more tightly coupled to the RF drive, thus reducing the phase shift due to microphonics, because the resonance is broader. Some trade-off of gain for bandwidth is required, so that the gain at low frequencies is comparable to the Stanford and CEBAF values, which means reducing the bandwidth of the feedback loop below that of the cavity. See section 3.1 for a complete discussion of these considerations.

Table 3-5 further suggests that the other IRFEL design goals are likewise reasonable, though no single accelerator has demonstrated all of our design goals simultaneously, in part because none was designed specifically for an FEL. The most significant extension of existing technology will be to produce the high average current, and therefore the high average beam power, that we require. This average current is much higher than has been produced by any accelerator apart from CESR. Reaching the design current will demand that great care be taken to control higher-order modes and to optimize beam transport—both topics to be discussed in detail below.

The field of superconducting RF linac design is moving forward rapidly, and a gradient of 5–6 MV/m is now considered routine. Gradients of 7–9 MV/m are expected to be commonplace within three to five years. (Indeed, Cornell has proposed a B factory to operate at 10 MV/m [*CESR-B*, 1991].) Several manufacturers currently produce superconducting cavities, and most will guarantee performance at 5–6 MV/m and a Q_0 of 2×10^9, which will satisfy our design requirements for 5.25 MV/m and $Q_0 = 2 \times 10^9$. Examples include Siemens (Interatom), Dornier, Mitsubishi, NTG, and Babcock and Wilcox. Figure 3-7 shows a 500-MHz, four-cell structure manufactured by Interatom for INFN/Frascati, and Fig. 3-8 is a cutaway of a 500-MHz, four-cell structure manufactured by Dornier for the HERA project at DESY. The RF structures ultimately chosen for the IRFEL will be based on a proven, off-the-shelf design from an experienced manufacturer. Indeed, we expect our needs to be met at the time of construction by units in production for CERN, DESY, CEBAF, or another large facility. Be this means, we expect to minimize the cost, as well as to ensure the reliability of the structures.

3.3.1 Design Overview

Figure 3-9 shows the layout of the accelerator section, together with the injector discussed in section 3.2. Table 3-6 summaries the accelerator parameters. These parameters are derived from the required wavelength range of the FEL (3–50 μm), the required energy per optical pulse (100 μJ at 6 MHz delivered to the user), and the constraint on wavelength stability (10^{-4}), together with practical considerations of feasibility and cost. The injector, for example, must be capable of 2 nC of charge per bunch to produce the required optical energy per pulse over the full wavelength range. The peak current must be at least 20 A so that the FEL gain exceeds the cavity losses. The FEL also requires that the unnormalized rms emittance be less than one-quarter of the wavelength and that the energy spread (FWHM) be less than $1/N$, where $N = 40$, the

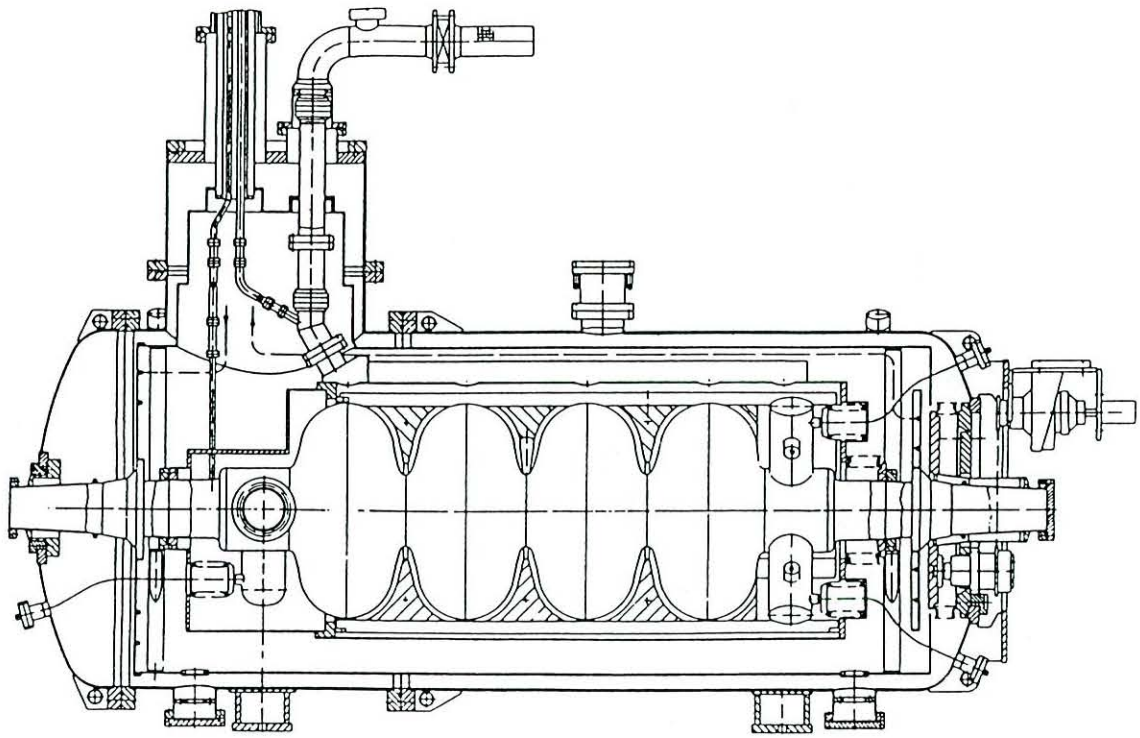


Figure 3-7. Cutaway of a 500-MHz superconducting accelerator module produced for INFN/Frascati.

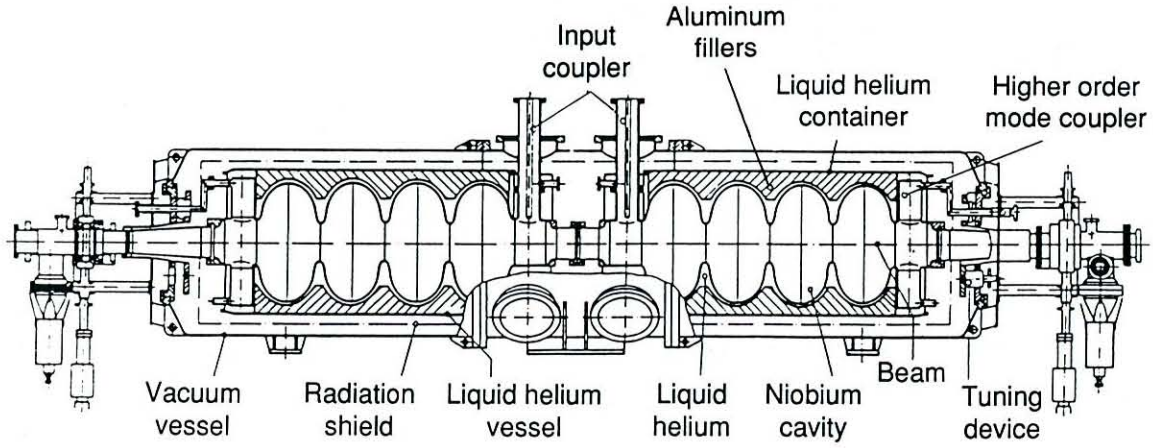


Figure 3-8. Cutaway of a 500-MHz superconducting accelerator module produced for HERA.

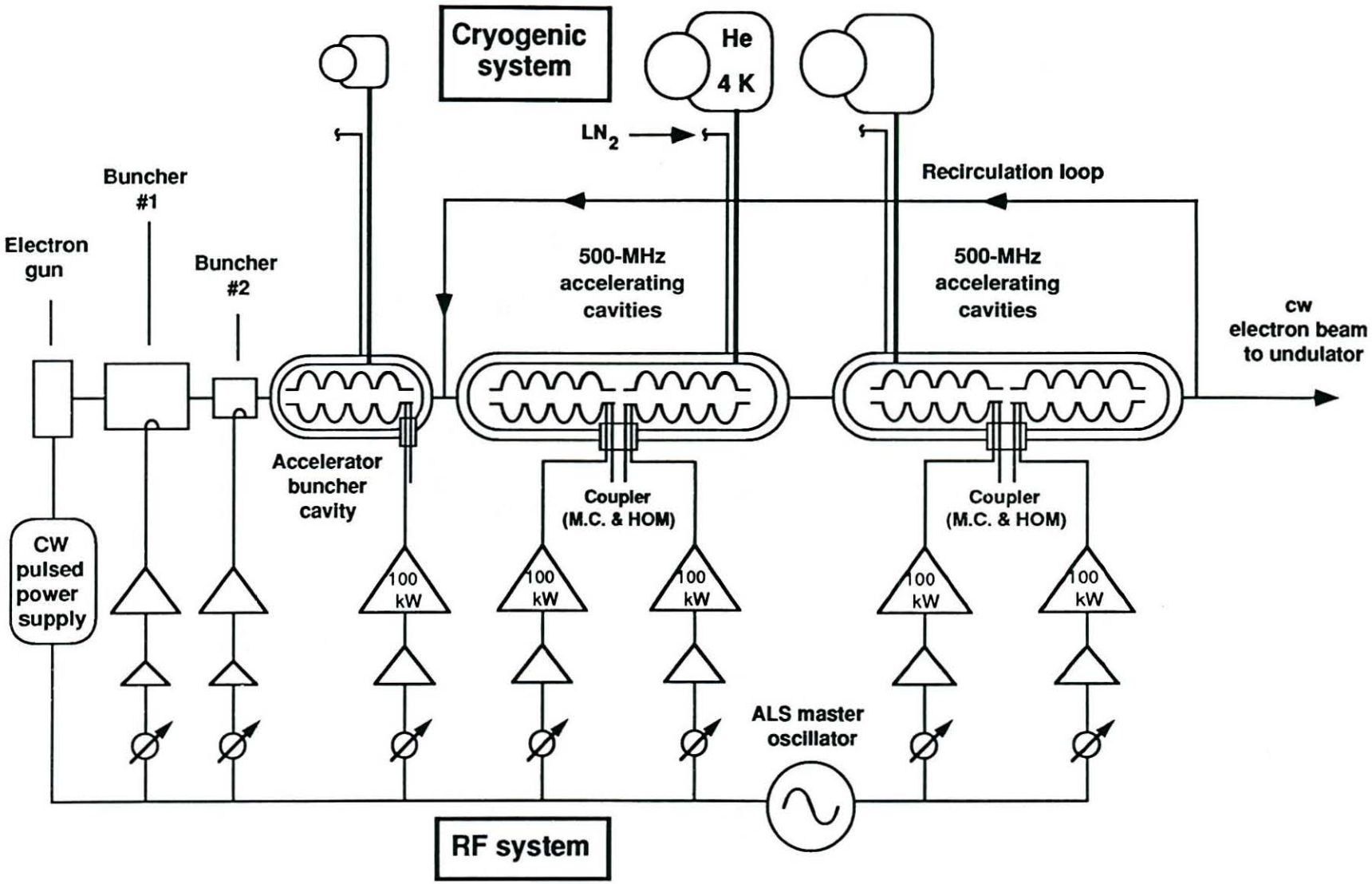


Figure 3-9. Schematic illustration of the RF accelerator system, together with the injector described in section 3.2. [XBL 922-5609]

Table 3-6. Design parameters for the superconducting RF accelerator section.

Accelerating gradient [MV/m]	>5
Frequency [MHz]	499.65
Peak beam current [A]	>60
Charge per bunch [nC]	>2
Bunch repetition rate [MHz]	6.10 (82nd subharmonic)[a]
Bunch length [ps]	<33
Normalized emittance, rms [mm·mrad]	<25
Beam energy [MeV]	15–55 MeV
Energy spread, FWHM	<0.5%
Energy fluctuations[b]	$<5 \times 10^{-5}$
Frequency stability	$<1 \times 10^{-7}$
Charge fluctuations	<5%
Spatial jitter	<10% of beam size
Angular jitter	<10% of beam divergence

[a]Can also be operated at 12.19 MHz at half the nominal bunch charge.

[b]Fluctuations on time scales longer than the optical decay time (~1.6 μs); the constraint on higher-frequency fluctuations is relaxed by an order of magnitude.

number of undulator periods. The stability requirement on the electron pulse frequency arises from the FEL optical cavity detuning width, which must be accurate to 3 μm out of 24.6 meters, or about 10^{-7}. And finally, the charge fluctuations and the spatial and angular jitter were specified to avoid significant FEL performance fluctuations.

Figure 3-10 shows the limits on beam power and charge per bunch as functions of wavelength. At wavelengths shorter than 10 μm, the RF drive power limits the beam loading per accelerator cavity to 73.2 kW and therefore restricts the charge per bunch that is produced by the injector to less than 2 nC. The power decreases in going from 10 to 3 μm because the injector, which operates at fixed voltage (5.25 MV/m), delivers less power. This reduction can be mitigated to the extent that the injector can be run at a higher voltage at the reduced charge per bunch. For wavelengths longer than 10 μm, the

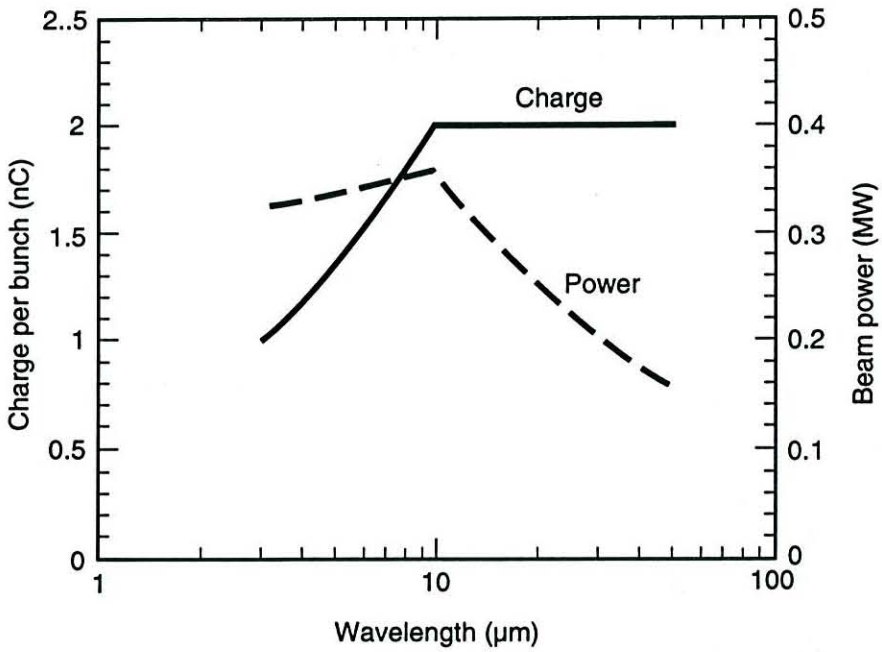


Figure 3-10. Plot of beam power and charge per bunch as functions of optical wavelength. For wavelengths shorter than 10 μm, the RF drive power limits the beam loading per cavity to 73.2 kW and thus restricts the charge per bunch that comes from the injector. At longer wavelengths, the limit is the injector design limit of 2 nC per bunch. [XBL 921-5563]

limits arise from the injector design limit of 2 nC per bunch. By reducing the injector voltage or by providing more RF power, more charge per bunch could be made available, albeit at the cost of increased emittance and energy spread. The FEL output roughly follows the power curve of Fig. 3-10, with about 0.5% converted to optical power and about 0.2% delivered as usable laser power to the user. Section 4.1 discusses FEL output performance in more detail.

3.3.2 Recirculation

The IRFEL requires a recirculation loop to operate at wavelengths shorter than 10 μm (see Figs. 1-1 and 3-9). This leads to potential instabilities. First, because of the beam's second pass, the average current in the accelerator structures is doubled, driving some higher-order modes (HOMs) more strongly. Second, the beam can couple a transverse kick received during the first pass to a displacement on the second pass, potentially leading to a regenerative recirculation instability. Third, a beam loading, or longitudinal recirculation, instability can be driven if an energy-sensitive beam current loss occurs in the transport section. That is, a small change in energy can cause a concomitant change in the fraction of the beam recirculated, thus causing a change in beam loading, which, in turn, causes an additional change in the accelerating voltage. Under certain conditions of phasing and gain, this instability can become uncontrolled. At Los Alamos, this

instability was observed when an energy slit was placed in the recirculation loop during energy recovery FEL tests.

The first instability mentioned requires that the HOM coupling be designed for the higher current, or that the required loaded Q's be halved. Data for the loaded DESY cavity [Willeke and Proch, 1991] indicate that the HOMs are sufficiently damped for us to adopt the DESY design as is. (More recent designs appear to offer even better performance, and our final design will take advantage of the latest available technology.) With the DESY couplers, the instability threshold is about 1 A; our design current is only 24 mA.

A study of the regenerative recirculation instability is described in detail in section 3.6.1. Using the parameters of the DESY structure and a simple recirculation loop, we obtained a threshold of about 340 mA for this instability [Krafft and Xie, 1991]. In addition, the transport optics described in section 3.6.2 is designed as a unity transport from the first pass to the second; this will further suppress this instability. Nonetheless, the threshold for this instability is fairly sensitive to the length of the recirculation loop, especially the equivalent number of RF cycles. It is thus important that the transport loop be adjustable by several RF wavelengths. One wavelength of adjustment is needed just to set the recirculated beam at the peak accelerating phase. Such an adjustment can be made by mechanically moving both recirculation bends by 15 cm. We have therefore allowed for a half-meter of translation in each bend, enough to change the path length by about three RF cycles.

The third potential instability, the longitudinal recirculation instability, can be eliminated by ensuring that very little beam is lost around the transport loop. This is necessary in any case because of the extremely high electron beam power. Only a few hundred watts can be lost in the transport line without causing physical damage. This level corresponds to less than 0.1% of the beam power, well below the 5–10% loss necessary to encounter this third instability. To minimize beam loss, the transport apertures must be equal to 4σ or 5σ, assuming roughly Gaussian tails on the transverse beam distribution. Accordingly, the transport loop described in section 3.6 has a minimum aperture of 5σ (larger in most places). As discussed in section 3.4, x-ray monitors along the transport line will detect even very small beam losses, and interlocks will protect the beam pipe and vacuum chamber.

3.3.3 Superconducting RF Issues

Microphonics constitute a potentially significant contribution to the RF amplitude and phase errors. We are currently collaborating with Stanford, TRW, and Brookhaven in exploring ways to minimize microphonics. The most likely modifications to current practice will be to use rigid stiffening ribs to interconnect the cells' outer rims; this will increase the mechanical resonant frequency and reduce the amplitude of vibrations coupled into the structure. Second, much of the mechanical coupling to the cavities' surroundings will be minimized by making the pipe and dewar connections very flexible.

Multipactoring has also been a problem with superconducting RF structures, but cavity geometries have now been demonstrated that avoid multipactoring at accelerating gradients above 10 MV/m. Such geometries incorporate spherical or rounded cavity

shapes and thus eliminate the mid-plane multipactoring that plagued the flat mid-plane geometries used in early structures. The off-the-shelf design we adopt will have demonstrated freedom from this problem.

The input couplers must provide 100 kW of power to each structure. The couplers most widely used today have been tested to 70–80 kW and are rated at 150 kW. In addition, available designs exist for couplers rated at up to 500 kW. As part of the LBL-Stanford-TRW-Brookhaven collaboration, we are working to improve the 70- to 80-kW couplers to handle higher power levels. The present design also includes adjustable RF cavity coupling for the input couplers. This approach broadens the range of gradients and beam-loading levels to which we can properly match the RF. It also allows RF processing of the structures at high fields with very low input power to avoid damaging the cavities during processing.

The HOM couplers will be selected from available designs, such that all HOMs are damped to Q's less than 2000. The HOM couplers will be tested as part of the ongoing collaboration with Stanford, TRW, and Brookhaven.

Tuning requires a fast tuner and a slow tuner. The rigid ribs used to mitigate the microphonics will reduce the tuning to the end half-cells. This will reduce the tuning range from about 500 kHz to about 20 kHz. After the structures have been properly bench tuned, they will need only about 10 kHz of cold tuning to hit the design frequency. The fast tuner must have an amplitude comparable to that of the microphonics, estimated to be about 200 Hz, which corresponds to a few tens of micrometers of cavity wall displacement. Fast tuning will be done with piezoelectric tuners at speeds up to a few hundred hertz to cancel the dominant microphonics modes.

The dewars, transfer lines, and refrigeration systems are commercially available. The cryogenic system is described fully in section 3.5. High vacuum will be used throughout the transport and accelerator, with electrostatic precipitators at the ends of the dewars to prevent dust from entering the superconducting structures. Should chemical polishing of the superconducting structures be necessary, it will be done off-site, at the manufacturing facility or other suitable site.

3.3.4 RF Drive

Figure 3-9 shows the layout of the RF system. The frequency of the accelerator structures is 499.65 MHz, derived from the ALS master oscillator. (As discussed in section 3.2, the gun pulser frequency is derived by dividing down the accelerator frequency by a factor of 82; the buncher frequencies are then phase locked to 10 and 28 times the gun pulser frequency.) A number of choices of RF sources are available, including klystrons, solid-state klystrodes, and hard-tube triodes. Klystrons were chosen because of their reliability, low cost, and proven success in this application.

The RF feedback loop is shown in Fig. 3-11. The klystrons are two 64-kW EEV K3772 tubes, combined through a magic tee to provide the necessary 100 kW of RF at the input coupler to the superconducting structure. Several probes will sense the field in the superconducting structure, which is compared with the field set point. The field will be compensated by adjusting the RF input to the klystrons. Both Stanford and CEBAF have used this type of control circuit to achieve the level of phase and amplitude stability

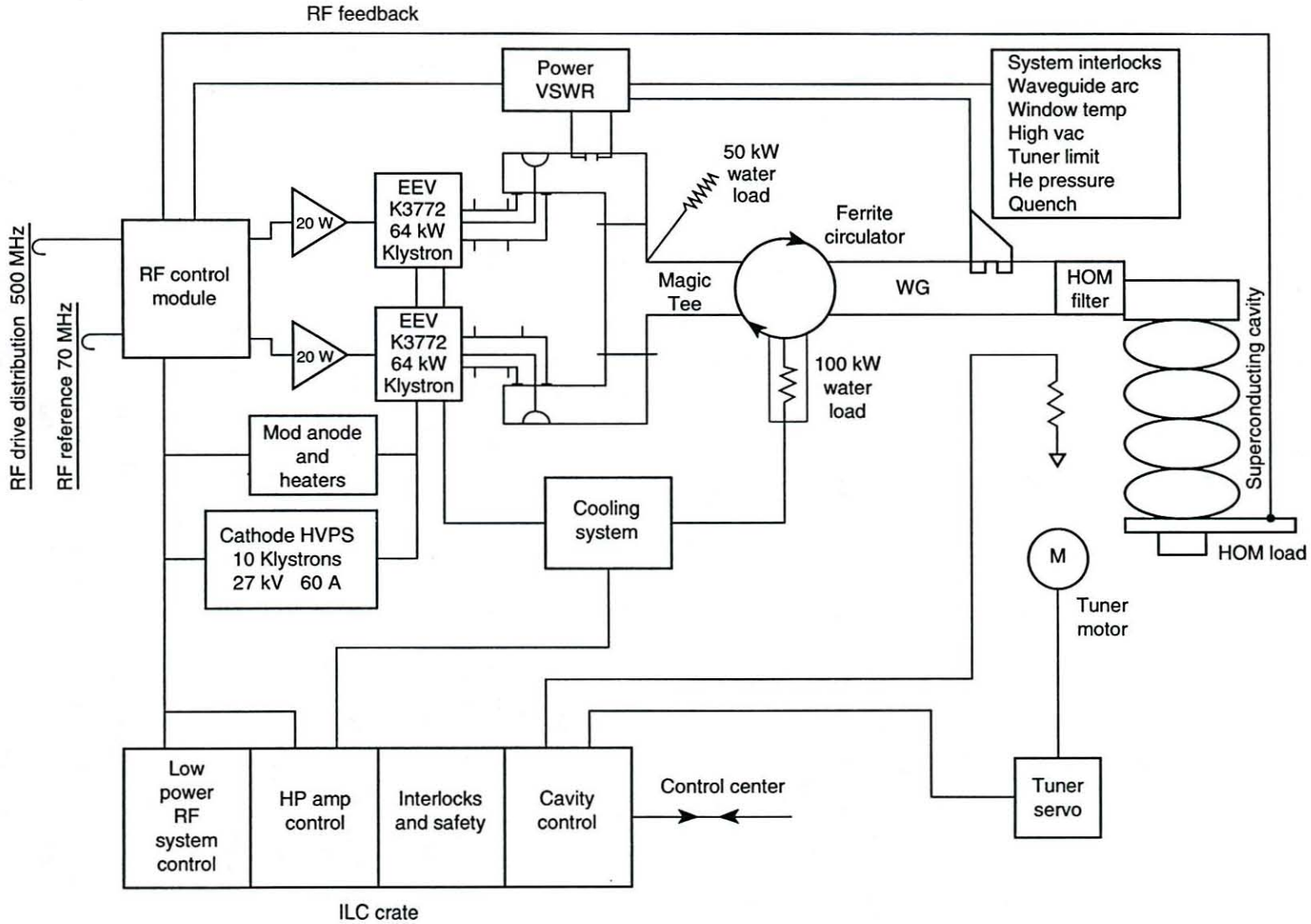


Figure 3-11. Schematic of the high-power RF system for the superconducting accelerator. [XBL 9111-6853]

we require. In addition, a tuning feedback loop is included to minimize the frequency shifts of the structure, caused by microphonics and helium pressure changes. This will be done by matching the phase of the cavity probes with the phase of the power into the input coupler. The phase shift is proportional to the tune shift for small tune deviations from the drive frequency. This feedback loop will minimize the reflected power as well.

Each buncher requires 25 kW of power, one at 60 MHz and one at 170 MHz. Again, two tubes at the appropriate frequencies are combined with hybrids and fed into the cavities. The setups are shown in Fig. 3-12. The stability requirements from section 3.2 for the two bunchers are 10^{-3} in amplitude and 0.07° in phase.

3.4 ELECTRON BEAM DIAGNOSTICS AND FEEDBACK

3.4.1 General Considerations

Since the electron beam power can approach a megawatt during routine FEL operation, the beam must, at all times, be kept far from the walls. Any significant loss can melt the vacuum enclosure almost instantaneously. As a consequence, the design incorporates an unusually large number of noninterfering position and current monitors. In addition, x-ray monitors will be used to detect beam loss and to provide fast interlocks. The transport system provides for a minimum clearance of 5σ—in most places, much more than that. Assuming that the wings of the beam are gaussian, beam loss will be limited to less than 100 W throughout the transport. Avoiding loss in the region of the undulator is particularly important. Accordingly, a cooled collimator is provided at the undulator entrance. During tune-up, intercepting monitors will be used at extremely low repetition rates.

Beam position, momentum, emittance, energy spread, charge, bunch length, current, and bunch timing all require measurement, continuous monitoring, and in some cases, active feedback. All beam parameters will be monitored at a resolution two to five times better than that demanded by stability requirements.

Monitoring and diagnostics requirements can be summarized by categorizing the instrumentation as follows:

- Stripline monitors to provide beam current and position information throughout the injector, accelerator, undulator, and transport sections.
- Insertable fluorescent TV screens and steering magnets throughout.
- Low-energy spectrometer between the second buncher and the four-cell accelerator for injector tuning.
- Stripline monitors to make energy measurements using transport dispersion, downstream of the injector and in the 180° bends.
- Synchrotron radiation monitors to provide energy and energy spread measurements using transport dispersion, in the 55-MeV bend.
- Fluorescent TV monitors to provide emittance measurements based on spot size and quadrupole strength, downstream of the injector and downstream of the accelerator section.

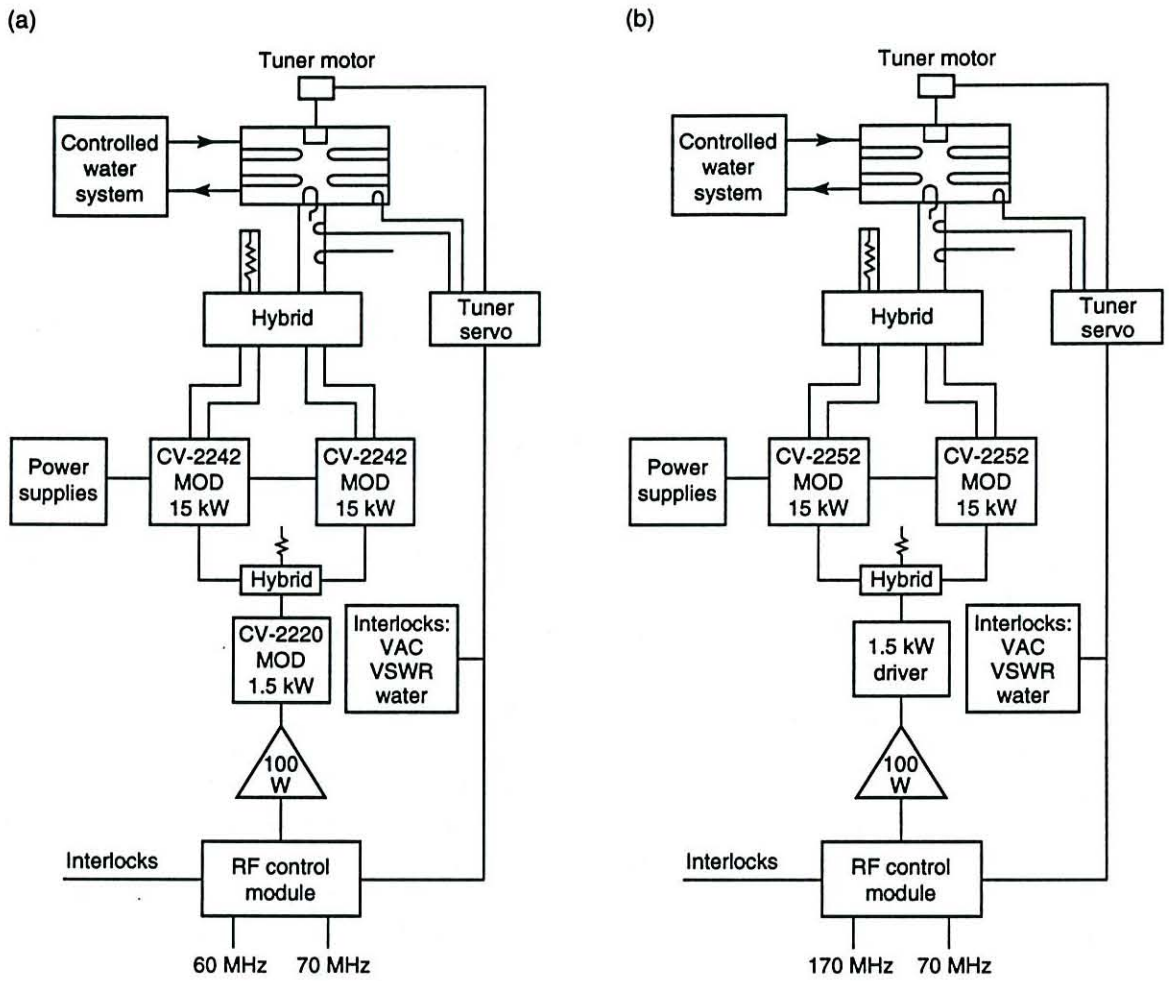


Figure 3-12. Schematic of the RF power system for the (a) first and (b) second bunchers. [XBL 9111-6854/5]

The main noninterfering diagnostics are four-section stripline position/current monitors, eight in the injector, a pair up- and downstream of each bend, two at the maximum-momentum-resolution points within each bend, one in the middle of the recirculation loop, one each up- and downstream of the undulator, six in the beam combiners, and four in the beam dumps. A steering corrector is associated with each monitor. In summary, the facility requires 41 striplines, 4 synchrotron imaging monitors, and 25 phosphor screens.

3.4.2 Diagnostic Measurements

The full range of beam parameters must be monitored closely during both commissioning and operational phases; during routine operation in particular, complete diagnostics not only provide the only means of meeting the user-imposed stability requirements, but also ensure the safety of the hardware.

Emittance will be determined by the transverse profile of the beam as a function of an upstream quadrupole strength. At low repetition rates, the profile will be displayed on the phosphor screens; at high current and high energy, it will appear on the synchrotron radiation imaging monitors. In addition, in the long straight sections with at least eight quadrupoles, the emittance can be determined by the quadrupole signal on the stripline monitors.

Momentum will be measured nondestructively by using the stripline position information in the bends. As a backup to this important measurement, the synchrotron radiation image will also provide momentum information. The requirement that the energy be stable to 5×10^{-5} requires this measurement to have a resolution of $1\text{–}2 \times 10^{-5}$. This in turn requires that the dipole power supplies be regulated to $1\text{–}2 \times 10^{-5}$, that the position monitors be accurate to 5–10 μm, that the dipoles be thermally stable to about 0.5°C, and that the magnet alignment be thermally and vibrationally stable to 5–10 μm. A minimum of three striplines, along with entrance angle and position information, are required to get a momentum measurement. Momentum signals must be developed and processed rapidly so that they can be used for feedback. A fast matrix multiplication of the sensor positions will provide the required momentum error signal. The matrix coefficients will be under computer control and will be determined directly from beam measurements.

Energy spread will be measured by the synchrotron light monitors. Also, at the high dispersion points in the bends, the ellipticity can be measured by the quadrupole signal on the stripline monitors; from this the energy spread can be inferred.

Current will be measured by the striplines and by fast current transformers. During commissioning, a Faraday cup will be used. Current loss will be monitored by the x-ray detectors.

A streak camera looking at the synchrotron light in the last bend will be used to measure bunch length. The bunch length from the injector can be measured during tune-up at low repetition rates, using the main accelerator shifted by 90°. A fast photodiode looking at the synchrotron light near the entrance to the undulator will also be used to monitor the bunch arrival timing, to an accuracy of 2–5 ps.

Processing the stripline signals involves forming the sum and the difference of signals from opposing strips. The processing is done by a network of broadband ferrite-type hybrid junctions. The resulting sums and differences are sampled and held with a minimum detectable charge of 100 fC at the bunch frequency. These sampled signals can be used directly in feedback systems or digitized for further processing. The position measured by the stripline is calculated approximately from the formula difference/sum $= 2\Delta x/r$, where r is the pipe radius. Assuming that a 2-nC bunch will generate an estimated 0.2-nC charge on each sample-and-hold, the difference/sum resolution is (100 fC)/(0.2 nC) $= 5 \times 10^{-4}$. The resolution in Δx is half that, or 2.5×10^{-4} of the pipe radius. For a 2-cm pipe, the resolution is about 5 μm. Averaging could improve this further. Position resolution of 5–10 μm is required for the energy feedback loop (see below); therefore, resolution should be adequate for charges greater than 1–1.5 nC, below which averaging will be necessary.

Synchrotron light can be used to image the beam profile nondestructively, as well as its temporal structure. At 55 MeV the critical wavelength is 350 nm and the critical angle, 8.7 mrad. Using a 10% bandwidth optical filter around 400 nm will give about 3.6×10^6 photons/bunch. This beam will be monitored by three instruments. First, a gated CCD camera will capture single-bunch profiles, as well as averaging many pulses. Second, a fast linear diode array will generate transverse one-dimensional profiles at a 10-kHz rate. This can also be used for measuring energy and energy spread. Third, a fast photodiode capable of 15- to 30-ps rise times will, with poor resolution, directly measure the bunch temporal profile and timing jitter to about one-tenth of that, or about 3 ps. Also, a streak camera will be used, giving a resolution of about 2 ps.

The injector includes a low-energy 90° spectrometer between the second buncher and the four-cell dewar. The spectrometer is necessary for measuring the phase and amplitude of the bunchers and for measuring low-energy beam bunching.

3.4.3 Feedback System

The time constants of the RF structures and the optical cavity determine the required speed of the feedback system. Table 3-7 lists the pertinent parameters. Feedback is provided in layers, starting with power supplies, followed by RF control loops, energy feedback, and finally optical feedback. These layers serve different functions and have different time constants.

Table 3-7. Time constants for the bunchers, accelerator, and optical cavity.

Fill times ($2Q_L/\omega$) [μs]	
First buncher	~52
Second buncher	~18
Accelerator	~636
Optical cavity decay time [μs]	1.6

Regulation of the power supplies for the magnets, gun voltage, and klystrons will be provided by standard commercial control of voltage and current ripples. The primary problems are related to the ac line frequency and its harmonics. Regulation equal to 10^{-3}–10^{-4} is typical of commercial units; 10^{-5} is available at higher cost and will be needed in two places: the dipoles within the injector-to-accelerator dogleg and in the final bend upstream of the undulator. Energy measurements at these points, which can be no better than the dipole magnet stability, must be accurate to $1–2 \times 10^{-5}$. Current stability requirements for the remaining magnets will be met with commercially available units with 10^{-3}–10^{-4} regulation.

As discussed in section 3.2.3, the gun voltage is required to be stable to ±24 V out of 300 kV, or ±0.008%. To achieve this level of control requires a temperature-controlled and temperature-compensated high-voltage resistive divider, controlling a 200-V, 15-mA series regulator supply. To be fast enough, this loop must be between the high-voltage deck and the cathode. The relevant time is the optical cavity decay time.

The RF amplitude and phase stability requirement for the klystron power supply, without further feedback, would require voltage stability equal to 4×10^{-5} ($2/5 \times 2 \times 5 \times 10^{-5}$). Regulating the voltage to 0.1% makes the RF amplitude and phase control gain requirements modest.

Radio-frequency feedback is the second layer in the feedback structure. We require control of RF amplitude, phase, and tuning. The RF controls used by CEBAF have demonstrated stability at the level we require, namely, 5×10^{-5} in amplitude and 0.05°–0.10° in phase. (The derivation of these requirements was discussed in section 3.2, and they are summarized in Table 3-4.) The CEBAF control system converts amplitude and phase into in-phase and out-of-phase components, a process that breaks the normal coupling between amplitude and phase controls, allowing greater independence of the two loops. For our design, we have adopted the CEBAF system without significant change.

An additional tuning loop is controlled by the phase difference between the cell and the input RF. The difference is zero at the peak of the tuning curve and varies linearly away from the peak. This can be used on a fast tuner to counter microphonics. This loop will minimize the reflected power, as well.

Energy feedback serves as the third layer of feedback control. Just downstream of the injector and just upstream of the optical cavity, the energy will be measured continuously with a sensitivity of $1–2 \times 10^{-5}$. The resulting momentum error signals can be fed back to any of the accelerator structures, the bunchers, or even the gun. Long-term stability is best served by feeding back to the superconducting structures, whereas the fastest response is available by feeding back to the gun. Accordingly, the injector will be stabilized by feedback to the gun and the four-cell structure; the accelerator will be stabilized by feedback to one of the structures. Within the gun itself, given that the high voltage will require an intermediate gun anode, the best feedback approach is to capacitively couple to this anode with a time constant somewhat smaller than the optical decay time. Such feedback will provide a fast response by means of small current changes that will correct the energy fluctuations. On a time scale longer than the fill time, feedback to the superconducting structure will provide similar correction. In terms of feedback gain, the two loops display a crossover point at about half the structure fill time. This is illustrated in Fig. 3-13.

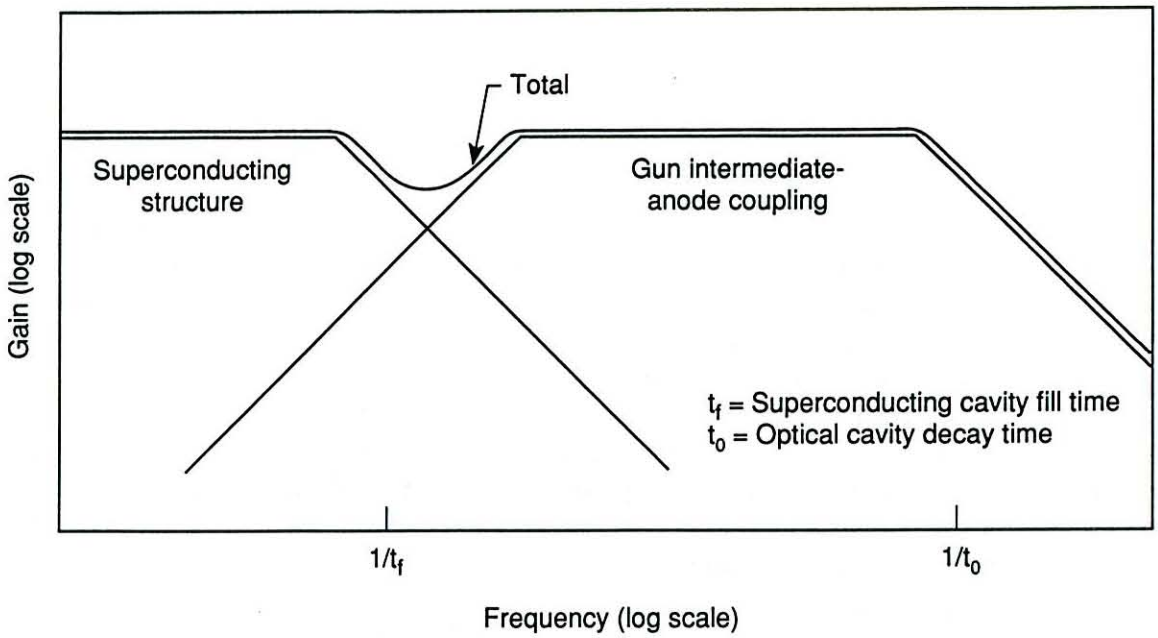


Figure 3-13. The gain of the energy feedback loops as a function of frequency. The total gain is the sum of the gains for loops operating on the four-cell superconducting cavity and on the intermediate-voltage gun anode. [XBL 922-5571]

The final feedback layer is provided by the FEL parameters themselves—the only parameters of interest to the users and the ultimate source of all other design requirements. The two most important parameters are FEL power and wavelength stability. The variables that control these parameters are the electron beam current and energy. FEL power feedback to the gun current will occur on a time scale longer than the structure fill time to avoid conflict with the energy loop described just above.

Wavelength control requires that we continuously monitor the FEL wavelength to an accuracy of 10^{-5}. A 1-meter grating monochromator with 2×10^4 lines (20 cm at 100 lines/mm) will provide sufficient dispersion. The output slit will be removed. To measure wavelength stability, the spectral light is divided into long- and short-wavelength halves, then focused onto two mercury cadmium telluride detectors, which are then differenced to get a wavelength error signal. (At wavelengths longer than 20 μm, helium-cooled, doped germanium detectors will be used.) This signal is then added to the amplitude of the one of the structures, as in the energy feedback loop.

In addition, for any given experiment in which a single FEL parameter is critical, that parameter can be used in a feedback loop. For example, if a user is measuring the autocorrelation, which is sensitive to the peak power and the bunch length, it will be possible to control either the power or the bunch length to maintain a constant autocorrelation. Flexibility is the key to providing the best FEL beam to a wide variety of users.

3.5 CRYOGENIC SYSTEM

The cryogenic system required to cool the superconducting components of the IRFEL consists of the cryostats that house the RF cavities, a refrigerator and gas storage system, and a distribution system. As discussed below, each subsystem makes use of standard, operationally proven units. A simplified schematic of the system is shown in Fig. 3-14.

The cryostats function as high-vacuum housings for the RF cavities (see, for example, Figs. 3-7 and 3-8). The main components of each include (i) a vacuum vessel with a cavity anchor adjustment system and beam alignment reference points, (ii) an 80-K liquid nitrogen–cooled thermal radiation shield, (iii) a magnetic mu-metal shield, (iv) penetrations for RF power couplers, (v) a liquid helium vessel for cooling the cavities, (vi) an insulating vacuum system with pump connections and instrumentation, (vii) a separate beam vacuum system with instrumentation and isolating gate valves at each end, and (viii) instrumented isolating and control valves with connecting bayonets for helium and nitrogen supply and return.

Table 3-8 lists parameters for cryosystems at DESY, KEK, and CERN.

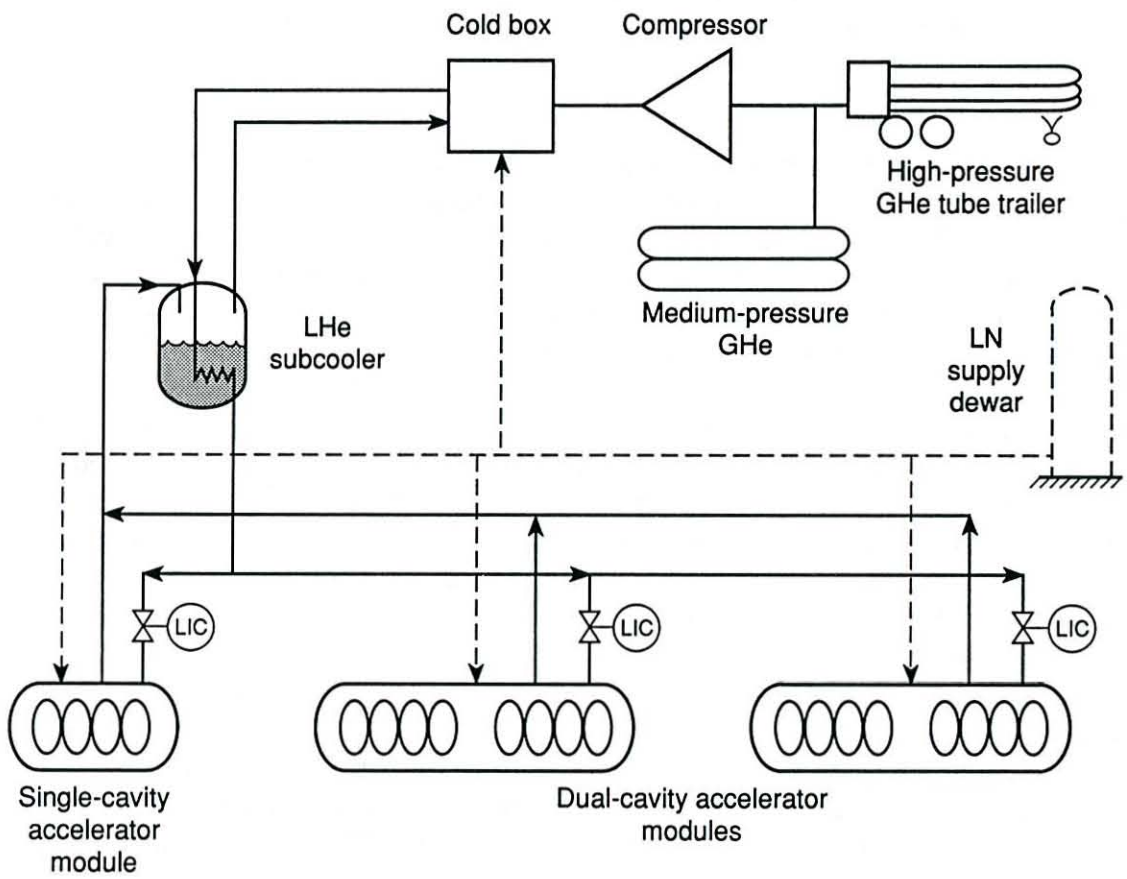


Figure 3-14. Schematic of the IRFEL cryogenic system. LN = liquid nitrogen; GHe = gaseous helium; LHe = liquid helium; LIC = level-indicating controller. [XBL 922-5570]

Table 3-8. Parameters for DESY, KEK, and CERN cryosystems; MLI is multilayer insulation.

	DESY	KEK	CERN
Operating frequency [MHz]	500	508	350
Operating temperature [K]	~4.5	~4.5	~4.5
Max. operating pressure [bar]	~3.0	~3.0	~3.0
Cavity material	Nb	Nb	Nb/Cu
Cryostat insulation	Vacuum/MLI	Vacuum/MLI	Vacuum/MLI
Cryostat radiation shield	He, 40/80 K	LN, 80 K	MLI only
Cryostat magnetic shield	μ-metal	μ-metal	—
Input RF coupler cooling	He, 20 K	H_2O	—
HOM RF coupler cooling?	Yes	Yes	Yes
Static freq. adjustment	Mechanical	Mechanical	Ni thermal
Dynamic freq. adjustment	—	Piezoelectric	Magnetostrictive
Filler for low He inventory	Aluminum	None	Curved He vessel
LHe inventory/cryostat [liters]	200	830	—
He cooling system	Bath	Bath	Bath
No. of cells per cavity	4	5	4
No. of cavities per cryostat	2	2	4
Manufacturer(s)	Dornier	Mitsubishi	Interatom Ansaldo CERCA

3.5.1 Heat Loads and Choice of Operating Temperature

The boiling points of coolants at one atmosphere establish common fixed operating temperatures—for example, 78 K for nitrogen and 4.2 K for helium. Other temperatures are achieved by varying the pressure according to the vapor pressure curve. However, varying the pressure on the coolant liquid is sometimes difficult and expensive. Moreover, when increasing the pressure on helium, the critical temperature, 5.2 K, is soon reached (at 2.26 bars). At lower pressures, helium goes from He I to He II, a unique state of superfluidity, at 2.17 K and 0.05 bar. The lowest practical (engineering) temperature for helium is 1.8 K (0.016 bar). Reaching these lower temperatures requires considerable effort, together with a significant investment in heat exchangers and vacuum pumps. In terms of the IRFEL, an obvious constraint on the operating temperature of the

cavities is that it must be well below the superconducting transition temperature for niobium, 9.2 K.

Rode and Proch [1989] derived the optimum operating temperatures for given values of accelerating gradient, frequency, and Q (the quality factor). For CERN, as an example, operating at 5 MV/m and 350 MHz, the ideal temperature is 4.5 K; at CEBAF, operating at 1500 MHz, it is 2.0 K. For the IRFEL described here, operating at 500 MHz and 5.25 MV/m and with $Q = 2 \times 10^9$, similar considerations led us to select 4.5 K, an operating temperature easily achieved with a standard helium refrigerator.

The most important aspect of cooling system design is a careful calculation of the expected heat loads. Holding the temperature constant requires a balance between the total heat load of the cryomodules and the capacity of the cryogenic refrigerator to remove the heat generated. Extra capacity is needed to assure reliability and the proper cool-down speed, and to allow for possible future upgrades in gradient. The three primary heat loads arise from the static load, the temperature-independent residual surface resistance, and the temperature-dependent (Bardeen-Cooper-Schrieffer) surface resistance. The static load stems from metallic conduction (center supports, tuners, power coupler, etc.), radiation, and convection. The residual surface resistance is caused by small local resistive areas where impurities, defects, or surface dirt disturbs the RF current and superconducting properties. The temperature-dependent resistance is due to unbound Cooper pairs of electrons. It increases with increasing frequency and decreases as the operating temperature decreases.

The power loss per unit length on the cavity wall can be based on the INFN-Frascati design [Byrns, 1989]. In terms of cavity impedance:

$$P = \frac{E_a^2}{(R/Q)Q_0} \tag{3-17}$$

where $E_a = 5.25$ MV/m is the accelerating gradient, $R/Q = Z = 383\ \Omega$/m is the geometric characteristic impedance, and $Q_0 = 2 \times 10^9$ is the unloaded quality factor at 4.2 K. The power loss for each 1.2-meter cavity is thus 43 W, or 215 W for the five cavities of the injector and accelerator systems. (According to Eq. 3-17, operation at higher gradients or any deterioration in Q_0 can cause large changes in the dynamic heat load.)

Table 3-9 summarizes the estimated cryogenic heat loads.

3.5.2 Refrigerator and Storage System

A 600-W helium refrigerator should provide reserve capacity and a safety margin that allows for system entropy gain, decay of Q, vacuum leaks or static heat increases, higher gradients, etc. Such refrigerators are now readily available, and reliable systems can be obtained to meet our performance goals in terms of capacity, operating mode, and temperature.

The refrigerator system (see Fig. 3-14) comprises a compressor, which compresses helium gas at ambient temperature to ~15 bars; a vacuum-insulated cold box, containing counterflow heat exchangers, expansion engines, and Joule-Thomson valves to produce coolant at 2.5 bars; purifiers; and automatic controls. The expanders may be turbines or

Table 3-9. Estimated heat loads for the five RF cavities (2.5 cryostats) of the injector and accelerator systems. All loads are given in watts.

	at 4.5 K	at 80 K
Static loads		
Control/isolation valves (8)	8	20
Bayonet connections (8)	8	15
25-m supply line (incl. "U" tubes)	8	15
25-m return line	8	—
Subcooler	10	—
Cryostats[a]		
12 W per cryostat	30	—
120 W per cryostat	—	300
Total static load	**72**	**350**
Dynamic (RF on)		
RF loss per cavity (43 W per cavity)	215	—
HOM loss (3 W per cryostat)	8	—
Tuners and misc. (8 W per cryostat)	20	—
Total refrigeration loads	**315**	**350**

[a]From Byrns et al. [1991].

reciprocating pistons, but we have specified the latter. Reciprocating engines are less sensitive to process gas system impurities, they are more efficient (throughout a wide mass-flow range), and they can be maintained on-site. Joule-Thomson valve expansion in the cold box will be at 2.5 bars to supply supercritical helium to the cryostats, as in the DESY-HERA system [Byrns et al., 1991].

The helium compressor is an oil-flooded screw type, self-contained and skid mounted for easy installation and service. Screw compressors, now the industry standard, have a slide valve for variable capacity and complete oil removal systems to assure purity levels well below 0.5 ppm. Flow delivery for 600 W should be 64 g/s at 220 psig and 310 K. The compressor room is located remotely and will be completely sound shrouded to reduce the exterior sound level to a value below 70 dB.

A cryogenic purifier-adsorber is part of the cold box and will remove all trace impurities (N_2, O_2, H_2O, argon, etc.) above 80 K. A bypass valve will permit on-line regeneration. The control system will use a simple industrial microprocessor or even

relays, as there should be only two primary loads—static and dynamic. Transient operations such as cool-down and warm-up can be set up manually.

Helium gas will be supplied by a helium tube trailer, with a capacity of about 36,000 ft^3 at 2200 psi. Gas will feed from the tube trailer via a high-pressure line and demand valve directly to the helium refrigerator. In addition, six 1000-gal warm-gas storage tanks will allow all the liquid helium in the cold system (~600 liters) to be stored as gas (at 250 psi) and will also serve as a ballast volume for the compressor and refrigerator operations.

3.5.3 Distribution System

A three-pass transfer line, insulated by high vacuum and with multilayer insulation, connects the cold box to the three cryostats. It contains one supply pass for liquid nitrogen, together with supply and return lines for the helium at 4.5 K. The length is approximately 25 meters. An end box with a thermostatically controlled valve will maintain the supply line temperature at 4.5 K. Connections from the supply line to each cryostat are made with bayonets and flexible "U" tubes. Each cryostat has its own helium system valve box, with a 4.5-K liquid-level-controlled fill valve (expanding to 1 bar) and a 4.5-K return isolation valve. Other valves will permit individual warm-up, cool-down, and pump and purge operations with gaseous helium at 300 K.

The distribution system also contains an in-line subcooler just upstream of the first cryostat, to assure good temperature control of the liquid helium supply and to provide some ballast volume to suppress oscillations in the return liquid helium transfer line. This should serve to damp microphonics and frequency shifts in the cavities.

Liquid nitrogen will be used for the 80-K cryostat shields (350 W) and for precooling continuous flow to the helium refrigerator (1200 W). System needs (350 W + 1200 W = 1550 W) can be met by a flow of about 35 liters/hr from a 3600-gal vertical storage tank on the periphery of the ALS building. Supply to both the cryostats and the helium refrigerator will be via vacuum-insulated lines and automatic demand values. Gaseous nitrogen will be vented outside the CDRL building to prevent any possible oxygen deficiency hazard.

3.5.4 Automatic Controls and Operating Modes

Control of the cryogenic system will be by automatic valves controlled by liquid level, pressure, or temperature. For the simplest steady-state operating modes—during either FEL operation or standby—the controls will be simple industrial microprocessors or relays. Cool-down or warm-up can be preset manually for the short periods involved. Interfacing for computer control, including control of all pressure, temperature, and liquid-level sensors, will be available to complete the feedback loops and to provide data logging for system diagnostics.

The cool-down from 300 to 4.5 K will be handled via gaseous helium–liquid nitrogen heat exchange and final transfer of liquid helium, though it may be necessary to cool first to 150 K and then cool rapidly to 4.5 K, to avoid any H_2 diffusion problems in the niobium shell. (Cool-down from 150 to 4.5 K is expected to take 21.5 hr, based on

experience at DESY.) Each cryostat can be warmed up in a controlled manner with warm gaseous helium from the refrigerator or with the cryostat heaters.

The 4.5-K cryostat in standby mode is affected only by static heat loads (see Table 3-9). Accordingly, to minimize costs, the refrigerator will have a good turn-down ratio in both liquid nitrogen and power consumption. A 600-W refrigerator with 1200 W of liquid nitrogen precooling feed can be expected to produce 300 W without liquid nitrogen.

As mentioned earlier, each cryostat will be separately operable through thermal cool-down, RF pulse, and warm-up, thus allowing complete flexibility for component diagnostics and repair.

3.6 ELECTRON BEAM TRANSPORT

3.6.1 Beam Transport Design Parameters

The constraints and main features of the beam transport design can be summarized as follows:

- The injector supplies a 6-MeV beam with a normalized rms emittance of 30 mm·mrad and a 4% momentum spread (FWHM), plus a long low-energy tail.
- A magnetic compressor follows the injector with matrix element m_{56} equal to approximately 0.4, indicating a significant measure of non-isochronism.
- This compressor also contains an energy slit, eliminating beam more than 100 keV below the nominal 6 MeV, a step that reduces the current by about 20%. The slit will be no closer than 3σ from the undeflected beam, with the rms vertical size no smaller than 1 cm to limit the power density on the slit.
- The beam will be accelerated by two 12-MeV superconducting accelerator (SCA) structures, each in a 6-meter-long dewar. The beam size must be as small as possible in the SCA structures to minimize coupling to fringe fields.
- The beam will be accelerated on the crest of the field in the SCA structures, so the momentum spread will be approximately 0.8% (FWHM) at 30 MeV.
- The beam will be recirculated through two 180° arcs for further acceleration to a maximum of about 55 MeV by the same cavities. In the recirculation loop, the beam will be displaced by 2.35 meters from the SCA axis to provide room for the SCA dewars, space for a possible future undulator in the 30-MeV beamline, and clearance for the undulator in the 55-MeV beamline.
- The 180° arcs must be achromatic and isochronous. The chromatic correction will be sufficient to ensure that the beam transverse and angular displacements do not change by more than 10% of the ellipse parameters for momentum changes of up to 1%. This requires correction through third order in the 180° arcs.
- To satisfy the microtron condition, the path length around the recirculation orbit must be an integer multiple of $\beta\lambda$. The integer must be variable over a narrow

range to provide flexibility in avoiding any dangerous higher-order modes in the cavities.

- To avoid transverse beam breakup, the transverse matrix in the recirculating loop must be unity, which suppresses the second-turn regeneration caused by first-turn angular kicks (see section 3.6.3). The symmetric design of the recirculation loop symmetrizes the transfer matrix and forces the matrix to be unity around any point of the recirculating loop.
- The transverse beam function at the undulator must match the undulator gap spacing, with the vertical beam betatron function β_y variable over a range of approximately 0.33 to 0.73 meters, with β_x fixed at 1 meter.
- The 6-, 30-, and 55-MeV beams must be separated as soon as possible up- and downstream of the SCA sections and directed through their own focusing channels to provide maximum independence of tuning and matching.
- Room must be provided in the 180° arcs for diagnostic equipment to monitor relative momentum shifts with a resolution of 10^{-5}.
- Because of the high beam power, the stay-clear distance must be at least 5σ throughout the entire beamline.
- The energy spread of the beam entering the undulator at 55 MeV is expected to be 0.4% (FWHM), increasing to 2% downstream of the undulator.
- The design must not preclude an upgrade in which the beam is recirculated for deceleration in the SCA structures, a scenario that would save RF power and avoid activation of the high-energy beam dump.
- The optical cavity length of 24 meters constrains the distance between the 180° arcs. The undulator axis lies 3.44 meters away from the SCA axis, providing sufficient room for all components in the 7-meter-wide vault.

3.6.2 Transport Line Configuration

The transport line was designed and is described below as consisting of separate sections:

- 180° achromatic, isochronous arcs, corrected to second order.
- Transport sections between the SCA cavities and the 180° arcs, and from the 55-MeV 180° arc to the undulator.
- Beam "separators" at the ends of the SCA section.
- Energy slit and magnetic compressor at the exit of the 6-MeV injector.
- Transport lines to the beam dumps.

Figure 3-15 shows the overall beam transport system. The design is highly modular, and each section can be individually tuned and verified. The high degree of symmetry results in an optimized optics solution and reduces the number of operating controls and power supplies. The 6-MeV beam enters the combiner through an achromatic dogleg at

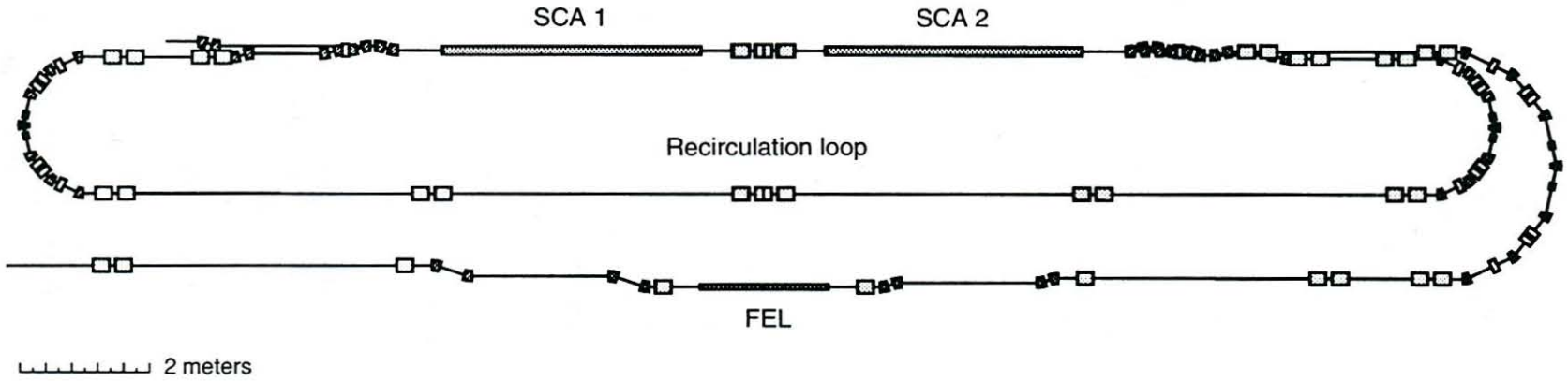


Figure 3-15. Plan view of the electron beam transport system, showing the location of the magnetic elements. The sizes of the magnets are not to scale. [XBL 922-5582]

the upper left of the figure and is accelerated through the two RF cavities to a maximum of 30 MeV. If the beam requires further acceleration, the separator at the exit of the cavities directs it to the recirculation loop and a second pass through the accelerating cavities. Following a second pass, the beam is then directed around a third, broader arc to the FEL undulator. The optical axis of the undulator is translated 22.7 cm from the exit of the final 180° arc to provide clearance for the optical components. The beam emerging from the undulator is achromatically translated 34 cm to pass around the cavity mirror and is directed to the beam dump.

The Arcs. Three arcs are provided, two mirror-image arcs for the recirculated 30-MeV beam and a 55-MeV arc that directs the beam to the entrance of the undulator. Each 30-MeV arc spans 2.35 meters; the 55-MeV arc, 3.21 meters. Each arc has a symmetric distribution of optical elements about its center and supports a beam envelope symmetric about its center. Each comprises seven identical dipoles, three families of quadrupoles, and one family of sextupoles. The locations of the quadrupoles and sextupoles are symmetric about the arc center point. The seven dipoles are necessary to achieve a third-order correction sufficient to ensure adequate performance at a ±1% momentum spread. A small beam size and smooth envelope are provided by this configuration. Figure 3-16 shows the physical layout of the magnetic components in the 55-MeV arc.

Each arc is achromatic and nearly isochronous, so as to preserve beam emittance and bunch length. To compensate for the slight non-isochronism in the dogleg translations in the beam separators and the offset of the undulator optical axis from the exit of the high-energy 180° arc, an equal negative non-isochronism is introduced in each of the 180° arcs. In addition, some additional bunch compression can be obtained by introducing an additional amount of nonzero m_{56} in the arcs, if required.

A pair of sextupoles straddling the central bending magnet in each arc corrects most achromatic terms to second order. This correction also reduces the third-order chromatic aberration significantly, so that the beam displacement and angular error are held to within 10% of the ellipse parameters for momentum offsets up to ±1.5%.

Sufficient focusing in each arc keeps β_x below 1 meter over most of the arc, with the dispersion amplitude peaking at 0.5 meter, thus providing convenient locations for stripline beam monitors in any of the three arcs.

The 30-MeV arcs are mechanically movable as a unit to allow variation in the path length around the recirculation loop.

The Transport Sections. The beam is matched from the accelerator section, through the beam separators, into the 30- and 55-MeV arcs by a pair of quadrupole doublets. After the first 30-MeV arc, the beam is transported to the second 180° arc by a symmetric arrangement of quadrupole doublets (and a triplet at the symmetry point). This straight section of the recirculation loop was designed to allow the future insertion of a second undulator and optical cavity.

The beam from the 55-MeV 180° arc is matched into the undulator by an arrangement of five quadrupoles and a four-dipole dogleg. The quadrupoles allow the vertical betatron function β_y to be smoothly varied over a range from 0.33 to 0.73 meters, depending on the undulator gap spacing, with β_x held at a constant 1 meter. The dogleg is necessary because the optical clearance required near the cavity mirrors is larger than the magnet

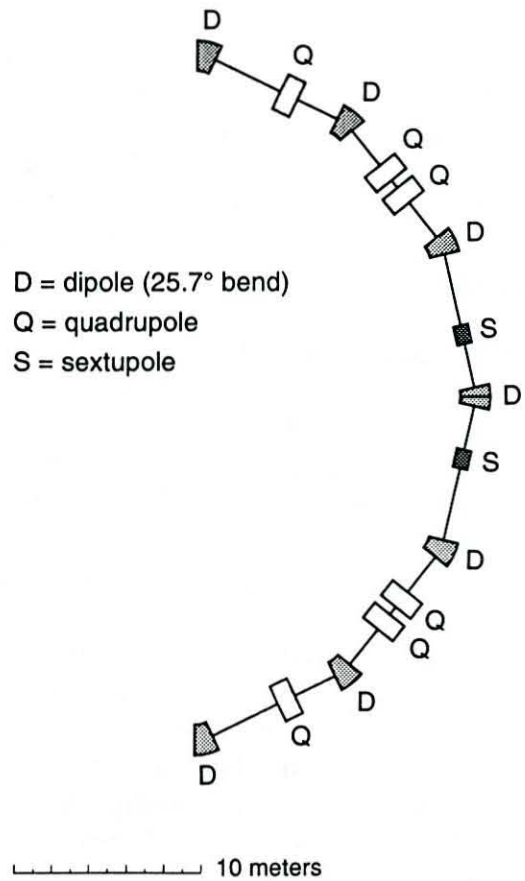


Figure 3-16. Plan view of the high-energy 180° arc. The recirculation arcs are essentially similar. [XBL 922-5583]

apertures. Near the undulator, the optical clearance radius is less than the 2.5-cm-radius magnet apertures, thus allowing nearby elements to be on the optical axis.

The total transfer matrix around the recirculation loop is unity, thus suppressing regenerative beam breakup in the SCA sections. The phase advance around the loop is a multiple of 2π, and the betatron amplitudes β_x and β_y are adjusted to the optimal value of 6 meters between the two SCA sections. In addition, the beam is matched in all three 180° arcs to produce a symmetric envelope around each symmetry point. All of these constraints are satisfied by the quadrupole arrangements in the straight sections on each side of the three arcs.

The 6-MeV beam from the injector is directed to the first SCA section by an offset section comprising four identical dipoles, described in more detail below. The 55-MeV beam from the undulator is displaced by 34 cm from the optical axis by an achromatic translation section with a similar configuration.

The Beam Separators. Each of the two SCA sections provides an energy gain of up to about 12 MeV. The 6-MeV beam from the injector is thus accelerated to a maximum of about 30 MeV on the first pass and can then be recirculated and further accelerated to a

maximum of about 55 MeV on the second pass. The beam orbits must be separated at the exit of the second SCA section and directed into their respective beam transport systems. Likewise, the beam combiner at the entrance to the first cavity must merge the orbits of the 6-MeV beam from the injector with that of the beam from the recirculation loop.

A single separator design was chosen for both the entrance and the exit of the accelerator section, in part to preserve the option of a future energy-recovery upgrade in which the 55-MeV beam would be returned to the accelerator section for deceleration. (Both combiner and separator are described here as "separators," since the magnetic design is the same in each case.) This separator must merge the orbit of a 6-MeV beam with that of a beam with energy equal to 6 MeV + ΔE, where ΔE is the energy gained in the two SCA cavities. Likewise it must separate beams with energies of 6 MeV + ΔE and 6 MeV + $2\Delta E$. The nominal 30- and 55-MeV beams must be provided stay-clears of at least 5σ, along with at least 1 cm of magnetic septum width for further bending. The betatron amplitude at this point is about 12 meters in both planes, and the normalized rms emittance is 30 mm·mrad.

The nominal separator design (Fig. 3-17a) provides first for the separation of the 6-MeV beam, returning higher-energy beams to the axis; it then separates the two remaining beams, returning only the highest-energy beam to the axis. Some of the dipoles are magnetic (iron) septa; the rest are conventional. Not all elements of this nominal design are needed in practice: At the entrance to the accelerator section (Fig. 3-17b), only the 6-MeV injected beam and the beam from the recirculation loop are present; at the exit (Fig. 3-17c), only the two higher-energy beams must be separated.

The magnet group nearest SCA 1 allows the 6-MeV beam to clear a septum and to be translated away from the recirculated beam, which is returned to the axis regardless of its energy. The magnet group downstream of SCA 2 separates "one-pass" and "two-pass" beams, returning the higher-energy beam to the axis and directing it to the larger 180° arc. In this second group, the lower-energy beam is offset 19.8 cm toward the inside of the ring and is directed to the smaller 180° arc. The smallest (worst-case) separation of these two beams is 4.2 cm; it occurs in the middle of the second group of four dipoles when the SCA is providing its maximum 24-MeV energy gain. The two 180° recirculation arcs are identical, so the offsets provided for the recirculated beam at each end of the SCA section are also the same. All dipoles are 12 cm long, running at 0.056 T in the entrance separator and 0.3922 T in the exit separator. The design of Fig. 3-17 satisfies the requirement that the acceleration gain in the cavities may vary, whereas the injection energy is always 6 MeV. Likewise, the design permits a low-energy beam from the accelerator section to be sent directly to the undulator.

The bumps and doglegs of the separators are achromatic, but not isochronous. An equal and opposite non-isochronism is introduced in the 180° arcs, as described above. The separator dipoles themselves strongly focus the beam, which is taken into account in the placement of the quadrupoles used to control the peak beam sizes.

The Energy Slit and Magnetic Compressor. The four-magnet translation for the 6-MeV beam (see Fig. 3-17b) also serves as a magnetic energy compressor and energy selection slit. The m_{56} (isochronous) matrix element for the translation will be set by the final choice of geometry at about 0.4, and the dispersion η_x is about 0.33 meter, where the matched beam amplitude β_x is about 0.55 meter. This is more than sufficient to give a

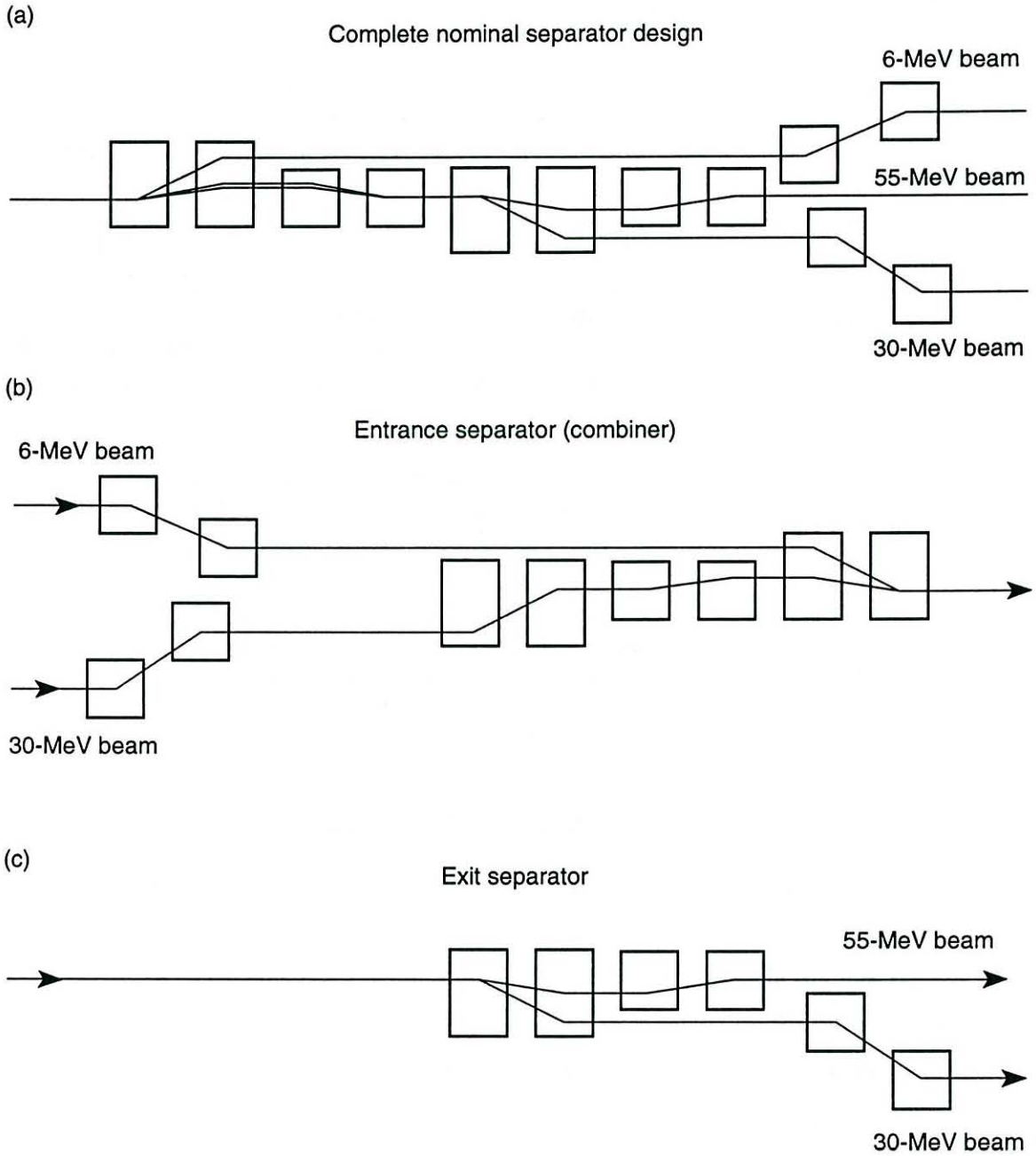


Figure 3-17. Schematics of three separator configurations: (a) the nominal separator design, which provides for the separation of the 6-MeV injected beam, a medium-energy (typically, 30-MeV) beam, and a high-energy (typically, 55-MeV) beam; (b) the entrance "separator," which combines the injected beam and the recirculated beam; and (c) the exit separator, which directs beam to the two arcs downstream of the accelerator section. [XBL 922-5568]

100-keV slit at a 5σ beam radius, with a normalized emittance of 30 mm·mrad. As this double translation is essentially a drift space in the vertical plane, the vertical beam size can be made as large as desired by external focusing to reduce the peak power density on the energy slit.

Transport System to the Beam Dumps. The beam is transported to the beam dumps by a conventional optics configuration. Beam from the accelerator section can be dumped simply by turning off the power to the first dipole in the 180° arc. With an average power of more than 600 kW at the highest energy and current, the beam must be spread over an area of at least 80 cm^2 at the dump. A raster scanner avoids the demands for precise steering and the long transverse-distribution tails associated with quadrupole or higher-multipole beam spreaders. A fast scanning-failure monitor is also required to protect the target. During commissioning the raster scanner will be installed at the beam dump downstream of the accelerator section. It will then be moved to the second beam dump (downstream of the undulator) for routine operations, and a multipole beam spreader will be installed at the first dump.

Summary. An inventory of the required magnetic elements is given in Table 3-10, along with the number of families needing independent power supplies. The dipoles are all short, typically 10 cm long, with modest fields and less than a 2-cm gap. The

Table 3-10. Inventory of the dipole and quadrupole magnets required for the electron beam transport system, excluding the transport lines from the injector and to the beam dump downstream of the accelerator section.

	Quadrupoles		Dipoles	
	No.	Families	No.	Families
First recirculation arc	6	3	7	1
Second recirculation arc	6	3	7	1
High-energy arc	6	3	7	1
30-MeV SCA line	8	4		
55-MeV SCA line	4	4		
Recirculation line	11	6		
Undulator line	10	8	8	1
Entrance separator	1	1	10	2
Exit separator	1	1	6	2
Total	**53**	**33**	**45**	**8**

quadrupoles are typically 25 cm long, with modest gradients equal to less than 15 T/cm. Magnet elements needed in the beam transport systems from the injector and to the beam dump downstream of the accelerator section, as well as sextupoles, are not included in Table 3-10.

The design of the electron beam transport will easily accommodate future upgrades. In particular, the configuration allows for the future addition of a second undulator in the recirculation loop, adjacent to the undulator currently planned. In addition, the beamline configuration allows inclusion of an energy-recovery deceleration option, which would save RF power and reduce the power deposited in the beam dump.

3.6.3 Beam Dynamics of Recirculation

As described above, the electron beam must pass twice through the accelerator section to reach a beam energy greater than 30 MeV. A recirculation path thus routes the 30-MeV beam back to the entrance of the first RF cavity for further acceleration to energies up to 55 MeV. The major beam dynamics issues of recirculation are (i) the multipass beam breakup (BBU) instability and (ii) electron beam emittance growth. The former arises from the fact that the high-Q superconducting RF structures retain a "memory" of previous beam passage. Under suitable phase conditions, this can lead to a resonance, resulting in beam loss caused by fast growth in the amplitude of coherent beam motion. The second concern, emittance growth, arises from growth of beam phase space due to prolonged sampling of longitudinal and transverse electromagnetic wakefields in the linac.

Multipass Beam Breakup. The threshold current for multipass beam breakup was simulated with the multibunch code TDBBU [Krafft and Bisognano, 1987], using a simple model of a four-cavity accelerator. The accelerator was modeled as a full FODO cell having a 60° phase advance (first pass) and a half-cell length of 6 meters (Fig. 3-18).

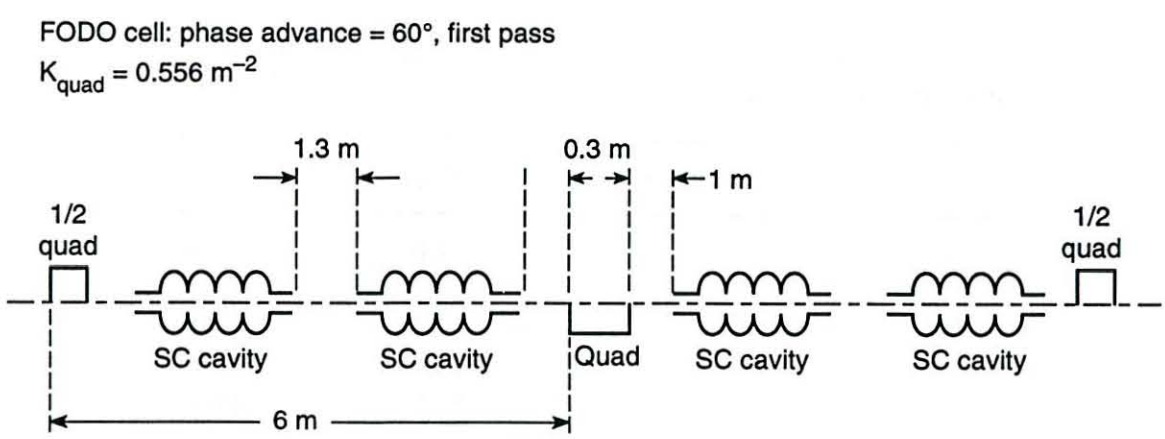


Figure 3-18. Model of the SCRF cavity and magnet configuration, used for simulation of multipass beam breakup. [XBL 922-5569]

The focusing was provided by 30-cm quadrupole magnets with focusing parameter $K = 0.556\ \mathrm{m}^{-2}$ (again, for the first pass only). Within each half-cell were two 500-MHz superconducting cavities, each with an acceleration length equal to 1.2 meters. The cavities were placed 1 meter from the quads on either side of the half-cell and 1.3 meters from each other. Eight (four × 2 polarizations) transverse higher-order modes (HOMs) were assumed to deflect the beam transversely at the center of each cavity. The HOM properties are summarized in Table 3-11. These values, from measurements at DESY on 500-MHz copper cavities [Willeke and Proch, 1991], will be replaced by measurement results from cold superconducting cavities when they become available. (These values also reflect only a selected set, presumed to be harmful, from the full set of HOMs.) The frequencies of the HOMs were assumed to be equal for all cavities, suggesting that the threshold current is underestimated by the simulation, because the frequencies of the HOMs will, in fact, have some spread due to manufacturing differences in the individual cavities. The pass-band mode with the largest R value was chosen, because, all other things being equal, the threshold current is proportional to $1/R$.

The beam was taken to have an injection energy of 5 MeV, and the recirculation time delay was taken as equal to 52 RF periods. Examples of simulation results are shown in Figs. 3-19 through 3-21, where the initial excitation is provided by a displacement of the injected beam. The figures show the momentum of every 500th bunch as a function of bunch number (that is, time). In Fig. 3-19, the current is 90 mA, below the threshold current of 100 mA. In Fig. 3-20, the current is 100 mA, still slightly under the threshold current. The oscillations, which are due to the RF fluctuations, decay relatively slowly compared to those in Fig. 3-19. In Fig. 3-21, the current is 110 mA, and the oscillation grows due to the BBU instability. The 977-MHz horizontal mode in the final cavity is the main electromagnetic mode responsible for the instability.

Table 3-12 summarizes the results of threshold calculations for the conditions described above, and for situations in which recirculation is used to decelerate the beam and in which the injection energy is lower. The deceleration scenario causes a 10-mA reduction in the instability threshold; whereas reducing the injection energy to 2.5 MeV

Table 3-11. Cavity parameters for the IRFEL multipass BBU instability simulation.

Frequency (MHz)	Polarization	R/Q (Ω)	Q
651	x	17.0	6200
651	y	17.0	6200
729	x	15.4	16000
729	y	15.4	16000
977	x	51.8	16000
977	y	51.8	16000
1107	x	4.8	1000
1107	y	4.8	1000

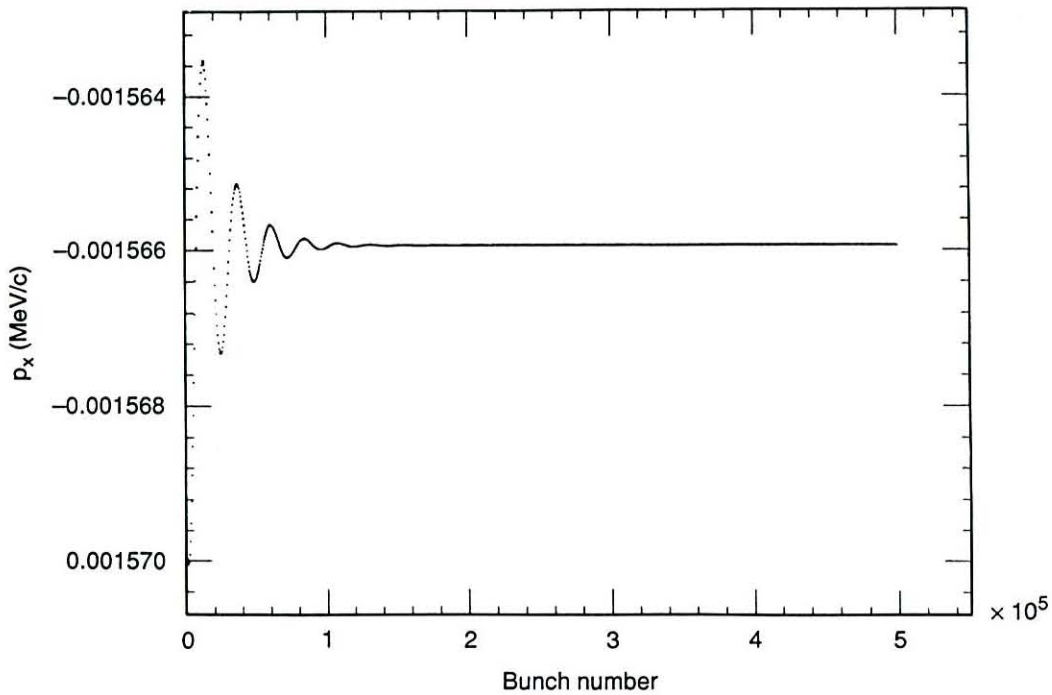


Figure 3-19. Bunch momentum as a function of bunch number for I = 90 mA. [XBL 922-5584]

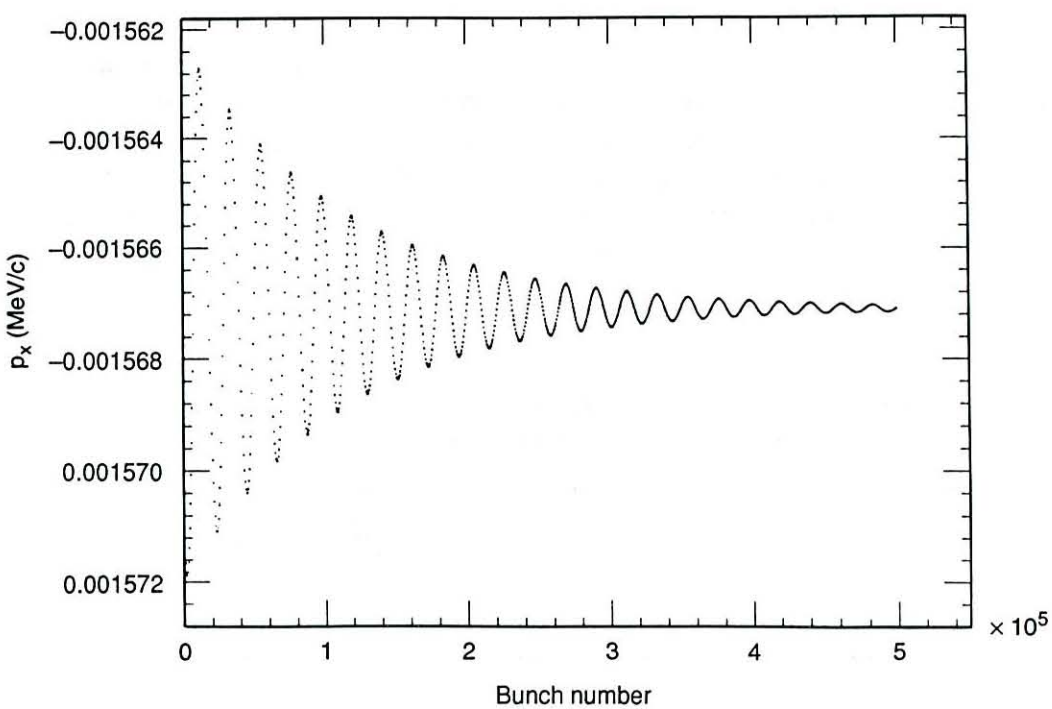


Figure 3-20. Bunch momentum as a function of bunch number for I = 100 mA. [XBL 922-5585]

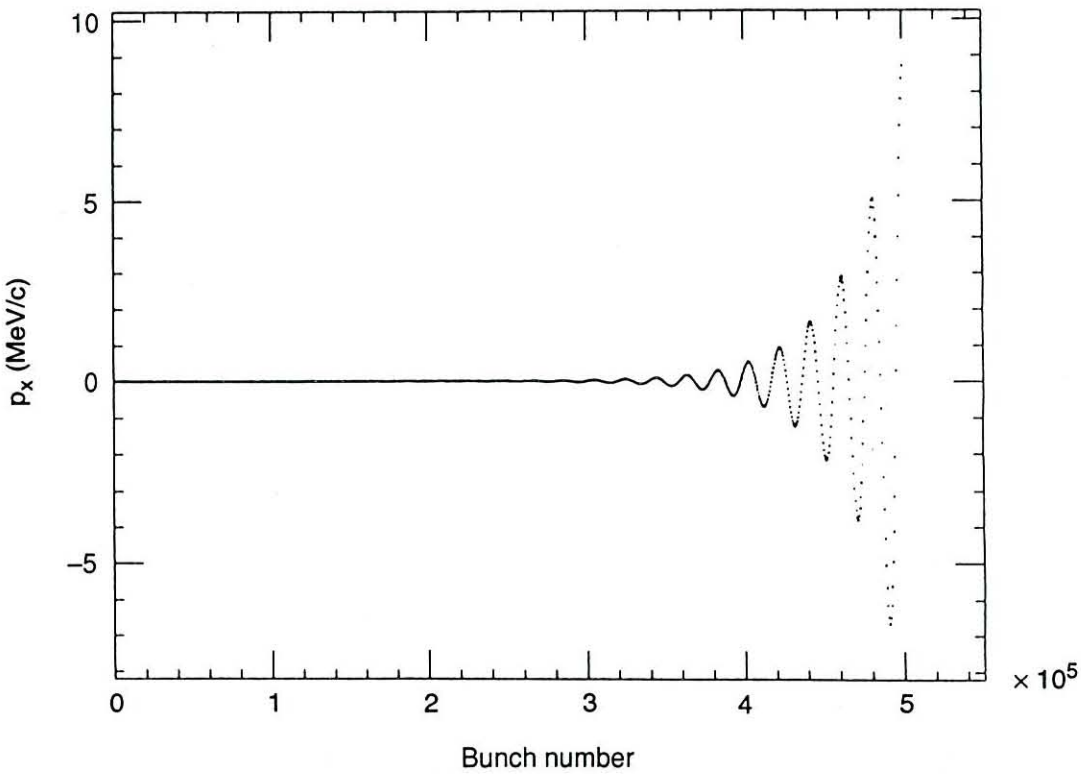


Figure 3-21. Bunch momentum as a function of bunch number for I = 110 mA. [XBL 922-5586]

reduces the threshold by 5 mA. The threshold is relatively insensitive to the injection energy because the resulting energy difference at the final cavity is only 10%.

The threshold current is much more sensitive to the recirculation time delay. For example, given the conditions first described, but with a time delay of 53 RF periods instead of 52, the threshold current increases to 157 mA. The same mode goes unstable, but sin ($\omega_{HOM}\tau$) gets closer to zero, thus increasing the threshold [Krafft et al., to be published]. If the time delay is 54 RF periods, the threshold current rises to 340 mA.

Table 3-12. Threshold currents for the multipass BBU instability, for four operating scenarios.

	Instability threshold (mA)	
	2.5-MeV injection	5-MeV injection
Accelerating recirculation	95	100
Decelerating recirculation	85	90

However, now the 110-MHz horizontal mode is the one that goes unstable. For the 977-MHz mode, $\sin(\omega_{HOM}\tau) \cong 0$ at 54 cycles of recirculation time delay.

Finally, simulations were performed with a 30° phase advance on the first pass. The threshold current was found to be 102 mA, suggesting little sensitivity to the phase advance. Also, simulations were undertaken of the case where an accelerating recirculation was followed by two decelerating recirculations. Again, the threshold current was about 100 mA.

Single-Bunch Phenomena. If care is taken to minimize changes in vacuum chamber cross section, then the short-time impedance is due mainly to the cavity contributions. The longitudinal wake for five-cell CEBAF cavities is 4.7 V/pC at 10 ps, providing an overestimate for the four-cell DESY cavities of 1.6 V/pC at 30 ps. The uncorrected full-width energy spread for a 1.6-nC bunch would be 4×10^{-4}, yielding about 1×10^{-4} after correction [Krafft and Bisognano, 1989].

The transverse-wake slope parameter is 1 V/(pC·cm^2), again scaled from CEBAF values. When such a slope parameter is used in a series of single-bunch simulations, Fig. 3-22 results. The emittance growth is substantial only for peak currents greater than 200 A, well beyond the operating range of the IRFEL.

Conclusions. The threshold currents for multipass beam breakup were found to be significantly higher than the IRFEL design current of 30 mA; therefore, no further damping of DESY-type cavities is necessary to assure stable operation. Because there are only a few cavities, and because only one HOM in one cavity is the main contributor to

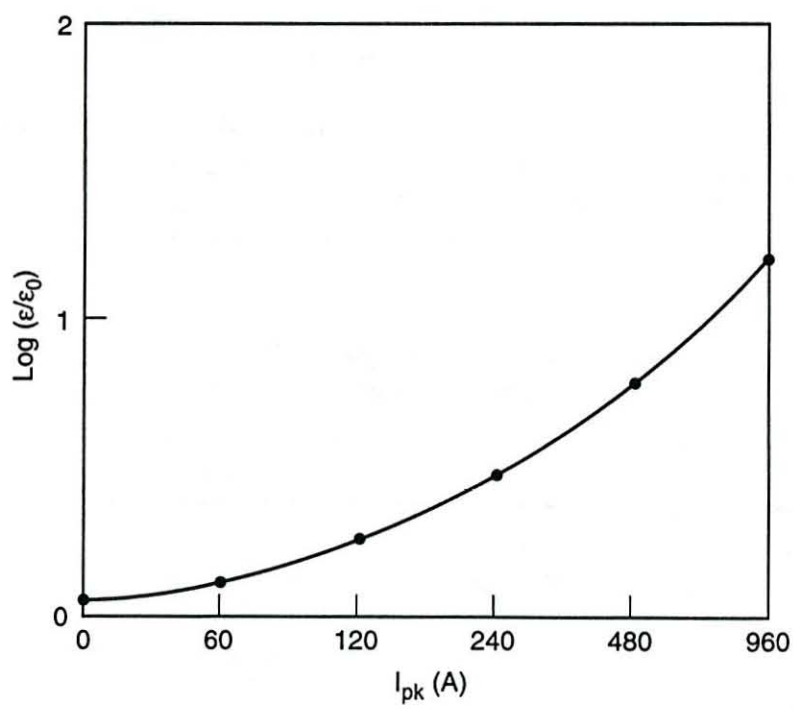


Figure 3-22. Emittance growth as a function of peak current, assuming a transverse-wake slope parameter scaled from CEBAF values. [XBL 922-5575]

the instability, the threshold current is strongly dependent on the recirculation time delay. A recirculation time delay of 54 RF cycles increases the threshold current by a factor of three, to at least 340 mA, where a different mode goes unstable. Our design includes flexibility in adjusting this parameter, to help ensure stable operation with recirculation.

Single-bunch instability was also computed, assuming that the machine impedance arises mainly from the superconducting cavities. For the peak operating currents of the IRFEL, emittance growth will be insignificant compared with the initial emittance, and the energy spread in the bunch should be about 1×10^{-4}.

3.7 FEL SHIELDING AND BEAM DUMPS

3.7.1 Shielding Design Criteria

The DOE limits for occupational workers and for the general public are summarized in Table 3-13 [USDOE Order 5480.11, 1989; USDOE Order 5400.5, 1990]. Since the IRFEL will be located adjacent to the ALS, the personnel and site boundary exposures attributable to the FEL alone must be kept low enough to ensure that the overall exposures (IRFEL + ALS + others) are held to their historically low values. For this reason, our objective was to design the shielding such that radiation exposures outside the shielding will be less than or equal to *100 mrem per 2000 hr*, assuming conservative beam loss scenarios. This will ensure that the FEL's contribution to personnel exposure and site boundary exposure is consistent with the ALARA (as low as reasonably achievable) criterion.

3.7.2 Shielding Design: Assumptions and Results

The IRFEL is capable of producing about 600 kW of 55-MeV electrons. For purposes of radiation shielding design, we assumed that beam is lost at a rate of 10% of full beam power (about 60 kW, 55 MeV) continuously at any point inside the accelerator vault. This is a conservative estimate, since most beam components may not withstand the

Table 3-13. DOE radiation exposure limits for occupational workers and the general public.

	Dose
Occupational exposure	
Maximum allowed	5.0 rem·yr^{-1}
Design objective	1 rem·yr^{-1}
	(0.5 mrem·hr^{-1})
Public exposure	
On site	100 mrem·yr^{-1}
Site boundary	10 mrem·yr^{-1}

thermal stresses associated with such a continuous loss. In addition, most beam tuning and collimating will be done at low energies and with low intensities.

Wall and ceiling shielding requirements are based on the radiation levels produced by secondary particles at 90°. Shielding requirements around the beam dumps are based on a continuous 100% loss (600 kW, 55 MeV).

Shielding analyses were based upon the work of Jenkins [1979]. Calculations were performed with a computer program from the Stanford Linear Accelerator Center (SLAC), which incorporates these analytical models. The expressions for determining the dose equivalents from photons and neutrons are as follows:

$$H_\gamma = 10^{-11}\, E \left(\frac{\sin\theta}{R}\right)^2 \times \left[\frac{133 \exp\left(-\frac{\mu}{\rho}\frac{\rho d}{\sin\theta}\right)}{\left(1-0.98\cos\theta\right)^{1.2}} + \frac{0.27 \exp\left(-\frac{\rho d}{\lambda_1 \sin\theta}\right)}{\left(1-0.72\cos\theta\right)^2}\right] [\text{rem}\cdot\text{cm}^2\cdot\text{GeV}^{-1}] \qquad (3\text{-}18)$$

where

H_γ = dose equivalent (in rem) due to photons, per GeV-electron, normalized to a distance of 1 cm

E = electron energy, in GeV

R = distance normal to the beamline to outer shield surface, in cm

μ/ρ = 0.0243 $\text{cm}^2\cdot\text{g}^{-1}$, the mass attenuation coefficient for the Compton minimum in the target material (8 MeV for iron)

d = shield thickness at 90° to the beam direction, in cm

λ_1 = 120 $\text{g}\cdot\text{cm}^{-2}$, the attenuation length of high-energy neutrons in concrete

ρ = 2.25 $\text{g}\cdot\text{cm}^{-3}$, the density of ordinary concrete

θ = angle with respect to the beam direction

and

$$H_n = 10^{-11}\, E \left(\frac{\sin\theta}{R}\right)^2 \left[\frac{13.7 \exp\left(-\frac{\mu}{\lambda_1}\frac{\rho d}{\sin\theta}\right)}{A^{0.65}\left(1-0.72\cos\theta\right)^2} + \frac{10 \exp\left(-\frac{\rho d}{\lambda_2 \sin\theta}\right)}{\left(1-0.75\cos\theta\right)} + 4.94\, Z^{0.66} \exp\left(-\frac{\rho d}{\lambda_3 \sin\theta}\right)\right] [\text{rem}\cdot\text{cm}^2\cdot\text{GeV}^{-1}] \qquad (3\text{-}19)$$

where

λ_2 = 55 g·cm^{-2} for the mid-energy neutrons (1 tenth-value layer = 50 cm)

λ_3 = 30 g·cm^{-2} for giant resonance neutrons (1 tenth-value layer = 29 cm)

A = atomic weight of the target material

Z = atomic number of the target material

Since the maximum energy of the IRFEL is 55 MeV, the terms representing the contributions from mid- and high-energy neutrons were neglected and only giant resonance neutrons were considered [Jenkins, personal communication].

Figure 3-23 shows the dose rate as a function of concrete thickness. The three curves represent different thicknesses of local lead shielding. The top curve is dominated by bremsstrahlung photons that can be effectively reduced by adding lead shielding around points of local continuous loss. However, a point of diminishing returns is reached at about four inches of additional lead, at which thickness the dose equivalent rate is due largely to giant resonance neutrons. To achieve the criterion of 100 mrem per 2000 hr, a level less than or equal to

$$\frac{100\ \text{mrem}}{2000\ \text{hr}} \cdot \frac{1}{60\ \text{kW}} \cdot \frac{1\ \text{rem}}{1000\ \text{mrem}} = 8.3 \times 10^{-7}\ \text{rem}\cdot\text{kW}^{-1}\cdot\text{hr}^{-1} \qquad (3\text{-}20)$$

is needed. From Fig. 3-23, we find that this corresponds to about 10 feet of concrete. The shield walls and the ceiling will therefore consist of 10 feet of ordinary concrete (ρ = 2.25 g·cm^{-3}), and 4 inches of additional lead will surround local loss points such as the collimators. Additional loss points will be identified during commissioning.

3.7.3 Beam Dumps

The dumps and associated systems were designed to absorb and dissipate a 600-kW, 55-MeV, cw electron beam. Ample precedent exists for such a design. SLAC has successfully operated high-power beam dumps of 600 kW and 2.2 MW for an electron energy of 20 GeV [Waltz and Lucas, 1969; Waltz et al., 1965], and LLNL has considered the design of a 225-MW, 150- to 300-MeV electron beam dump [Van Sant et al., 1989].

For high-average-power, low-energy electron beams, only aluminum or other materials of low atomic number (Z) are suitable as beam absorbers. Power deposition increases with Z and may cause melting or vaporization in high-Z absorbers. For the IRFEL, only water is suitable to absorb the majority of the electron beam power. A 55-MeV electron in water has a minimum collision stopping power of 1.82 MeV·cm^2·g^{-1} [Berger and Seltzer, 1983]. This corresponds to a maximum range of about 27 cm, or about 1 foot. An electron loses energy by two major processes: collisional losses and radiative losses, the latter becoming more important at high energies. The ratio of radiative to collisional losses is about 0.5 [Berger and Seltzer, 1983]. Therefore, about one-third of the power at 55 MeV in water is converted to radiation, that is, bremsstrahlung x-rays. The bremsstrahlung energy spectrum can be characterized as having a preponderance of low-energy photons, asymptotically decreasing to near zero at

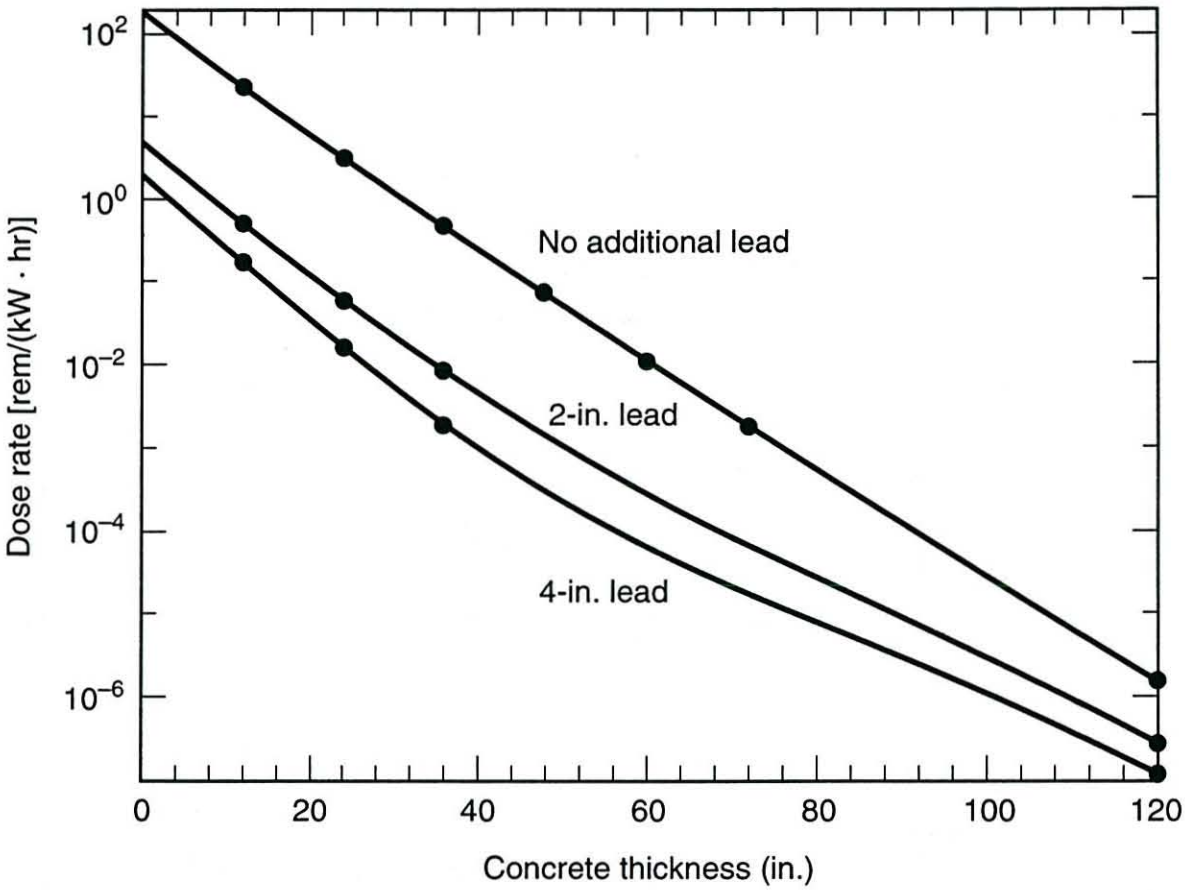


Figure 3-23. Calculated dose rate from the IRFEL, as a function of concrete thickness, for the cases of 0, 2, and 4 inches of additional lead. [XBL 921-5567]

the incident electron energy. Therefore, the length of the dump can be minimized by using high-Z materials at the appropriate depth.

Each beam dump will therefore consist of (i) about two feet of water to range out the incident electrons, absorb a large fraction of the soft bremsstrahlung x-rays, and provide a large coolant reservoir, (ii) a six- to twelve-inch water-cooled aluminum block to absorb a large fraction of the intermediate- and high-energy x-rays, and (iii) a high-Z backstop consisting of two to four inches of tungsten (or other high-Z material) to attenuate the remaining high-energy bremsstrahlung x-rays. (A detailed design must await the results of Monte Carlo calculations to determine energy deposition profiles.) A schematic of the complete system is shown in Fig. 3-24. One dump is located downstream of the FEL and will be in continuous use during routine operation. A second dump, sharing the same surge tank, hydrogen recombiner, heat exchanger, and ion exchange system, is located at the end of the RF linac (see Fig. 1-1). This second dump will be used primarily during commissioning and tune-up.

The primary, or radioactive, loop of the dump is isolated from the secondary, or plant water, loop. In addition, a demineralizer loop provides that some fraction of the cooling

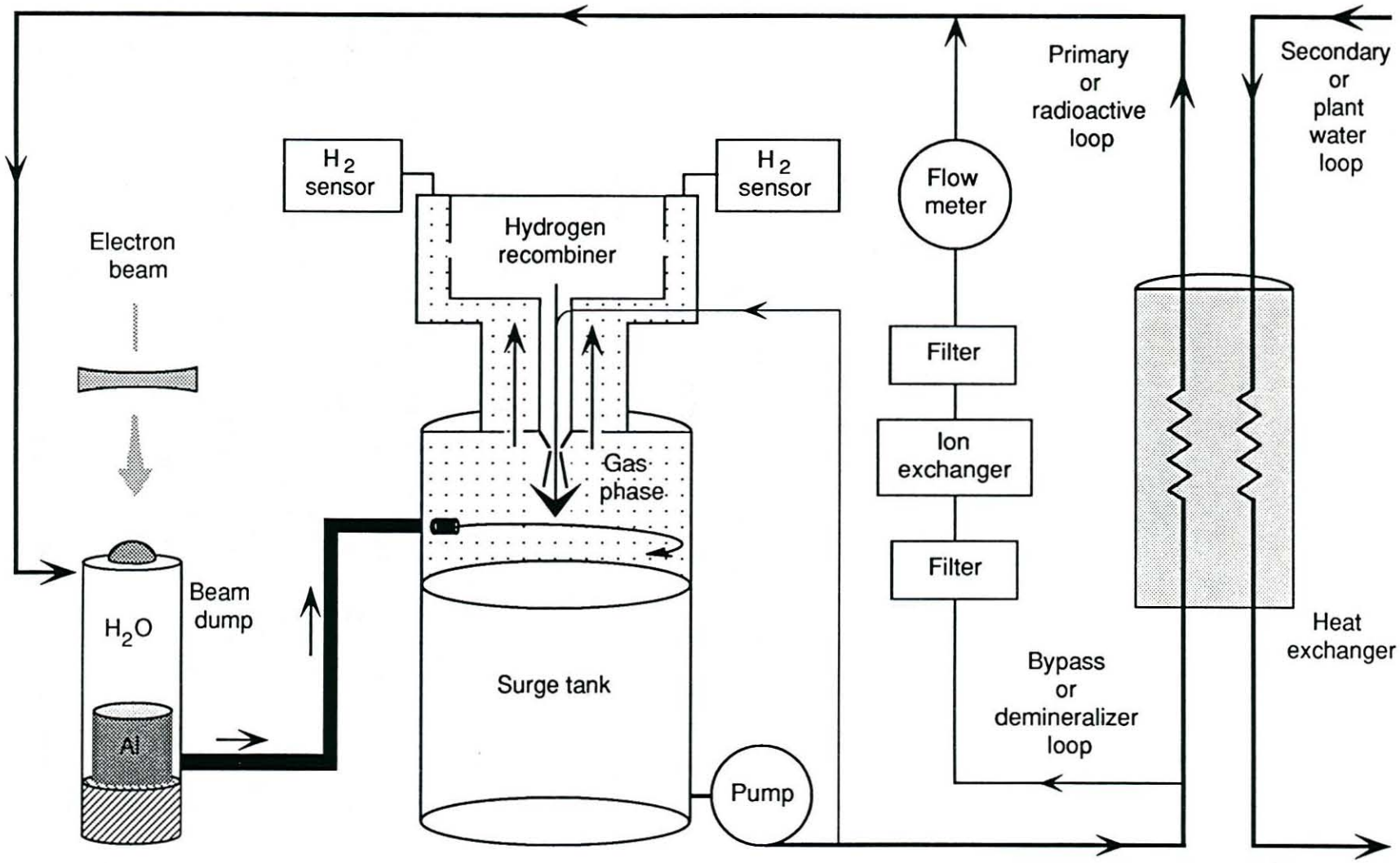


Figure 3-24. Schematic of the beam dump design for the IRFEL.

water is continuously purified in the ion exchange bed. The surge tank capacity is about 100 gal (75 gal liquid and 25 gal gas) and is sized to accommodate about 25% of the primary-loop water volume. Aluminum-copper electrolysis will be avoided by using stainless-steel plumbing. All welds will be radiographed, and the plumbing will be buried in the floor or wall. Buried plumbing will reduce radiation exposure during routine and unscheduled maintenance.

Figure 3-25 shows the layout of one of the beam dump systems within the accelerator wall. The beam dump and its associated water systems are isolated from the vault, as well as from each other, to ensure that radiation exposures are kept as low as reasonably achievable (ALARA). The vault will contain all water spills in a sump/hold-up tank to ensure that radioactive water is not released to the sanitary sewer or storm drain.

Window Design. A critical element of the beam dump system is the vacuum window into the beam dump. The window must be strong enough (that is, thick enough) to withstand stresses created by the difference in pressure, but thin enough that energy deposition, and hence thermal stresses, are minimized. We chose a 2-mm-thick aluminum window, which will be curved to reduce the stresses caused by pressure differences between the beam dump and the accelerator vacuum.

As the beam penetrates the window, volumetric heating occurs. This heat is removed by the coolant water behind the window. Assuming only convective heat transfer from the back of the window, the heat flux can be determined from

$$\frac{q}{A} = t_w \frac{I_{\text{avg}}}{A_b} \rho_w \left.\frac{dE}{dx}\right|_{\min} = h\,(T_w - T_\infty) \ \ [\text{W}\cdot\text{cm}^{-2}] \tag{3-21}$$

where

t_w = 2 mm, the window thickness

I_{avg} = 12 mA, the average current

A_b = beam area, in cm^2

ρ_w = 27 $\text{g}\cdot\text{cm}^{-3}$, the window density

$\left.\frac{dE}{dx}\right|_{\min}$ = 1.8 $\text{MeV}\cdot\text{cm}^2\cdot\text{g}^{-1}$, the minimum collision stopping power

h = convective heat transfer coefficient, in $\text{W}\cdot\text{cm}^{-2}\cdot{}^\circ\text{C}^{-1}$

T_w, T_∞ = window and water temperatures, in °C

To minimize thermal stresses and ensure long life, the temperature difference between window and coolant water ($\Delta T = T_w - T_\infty$) will be limited to about 100°C. Assuming a reasonable convective heat transfer coefficient of 1.5 $\text{W}\cdot\text{cm}^{-2}\cdot{}^\circ\text{C}^{-1}$, this ΔT can only be achieved by reducing the electron current density, that is, by increasing the area of the beam. The minimum allowable beam area can be determined by solving for A_b in Eq. 3-20:

$$A_b \geq \frac{t_w\, I_{\text{avg}}\, \rho_w}{h\, \Delta T} \cdot \left.\frac{dE}{dx}\right|_{\min} \tag{3-22}$$

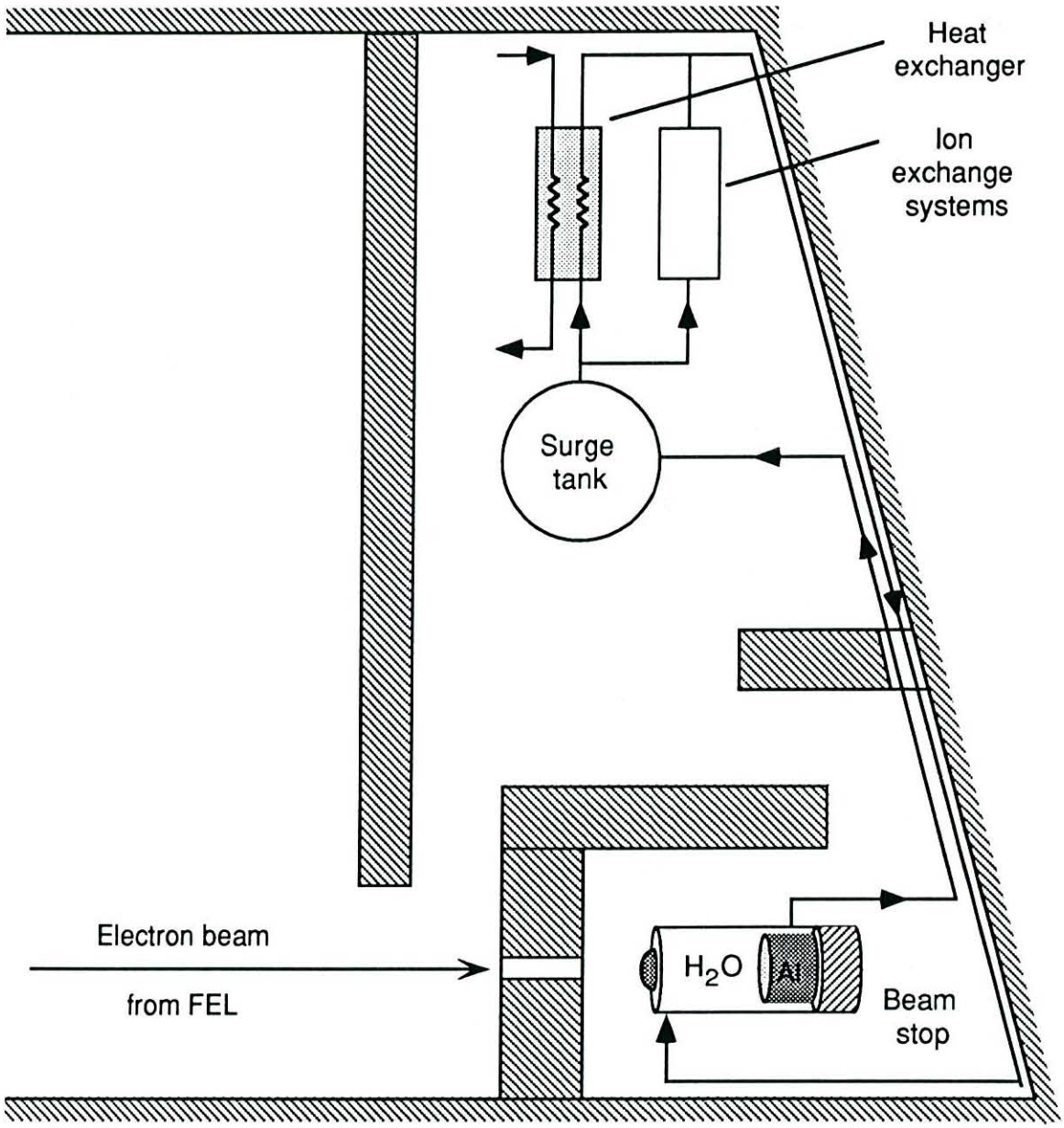


Figure 3-25. Layout of the main beam dump system inside the FEL vault. A second beam dump, sharing the same surge tank, hydrogen recombiner, heat exchanger, and ion exchange system, will be located at the end of the RF linac (see Fig. 1-1). [XBL 922-5610]

Using values given previously yields a minimum area of 80 cm^2. To be conservative, we adopted a minimum of 100 cm^2, or a minimum diameter of 10 cm. The heat flux calculated from Eq. 3-21 is therefore only 150 $W \cdot cm^{-2}$.

A series of parallel tubes will be directed toward the back of the window to sweep it with cool water and thus ensure uniform heat convection.

Hydrogen Recombination. Another major design feature of the beam dump system is the hydrogen recombiner. Hydrogen gas is produced in the dumps by radiolysis, because the energy of the incident radiation is greater than the ionization potential of water. After the resulting H_2 saturates the water, it appears as a potentially explosive gas, at a rate of 0.3 liters·MW^{-1}·s^{-1} [Waltz and Seppi, 1967]. Hydrogen gas has a lower explosive limit (LEL) of only 4%. When formed in an air environment, it concentrates and can quickly reach explosive levels. Radioactive gases produced in the water system prohibit the venting of this hydrogen. The most common solution in such situations is to catalytically recombine the hydrogen with oxygen to form water. This process has been described in detail [Waltz and Lucas, 1969] and is the basis of our design. An isometric view of the SLAC hydrogen recombiner is shown in Fig. 3-26.

This dump has been operating successfully since the mid-1960s. Cooling water from the beam dump enters from the bottom left. Hydrogen gas collects in the gas space and is drawn into the recombiner, where it is heated to the optimum temperature, then over the catalyst bed, where it is mixed with oxygen to form water. Redundant H_2 sensors ensure that the recombiner is working properly at all times.

Future Work. The following areas have been identified as meriting further attention during detailed design work:

- Thermal and stress analyses to determine the fatigue life of the window.
- Detailed Monte Carlo radiation transport calculations to determine energy deposition profiles inside the dump.
- Appraisal of alternative designs for a safe, reliable means of protecting/interlocking the integrity of the vacuum window.

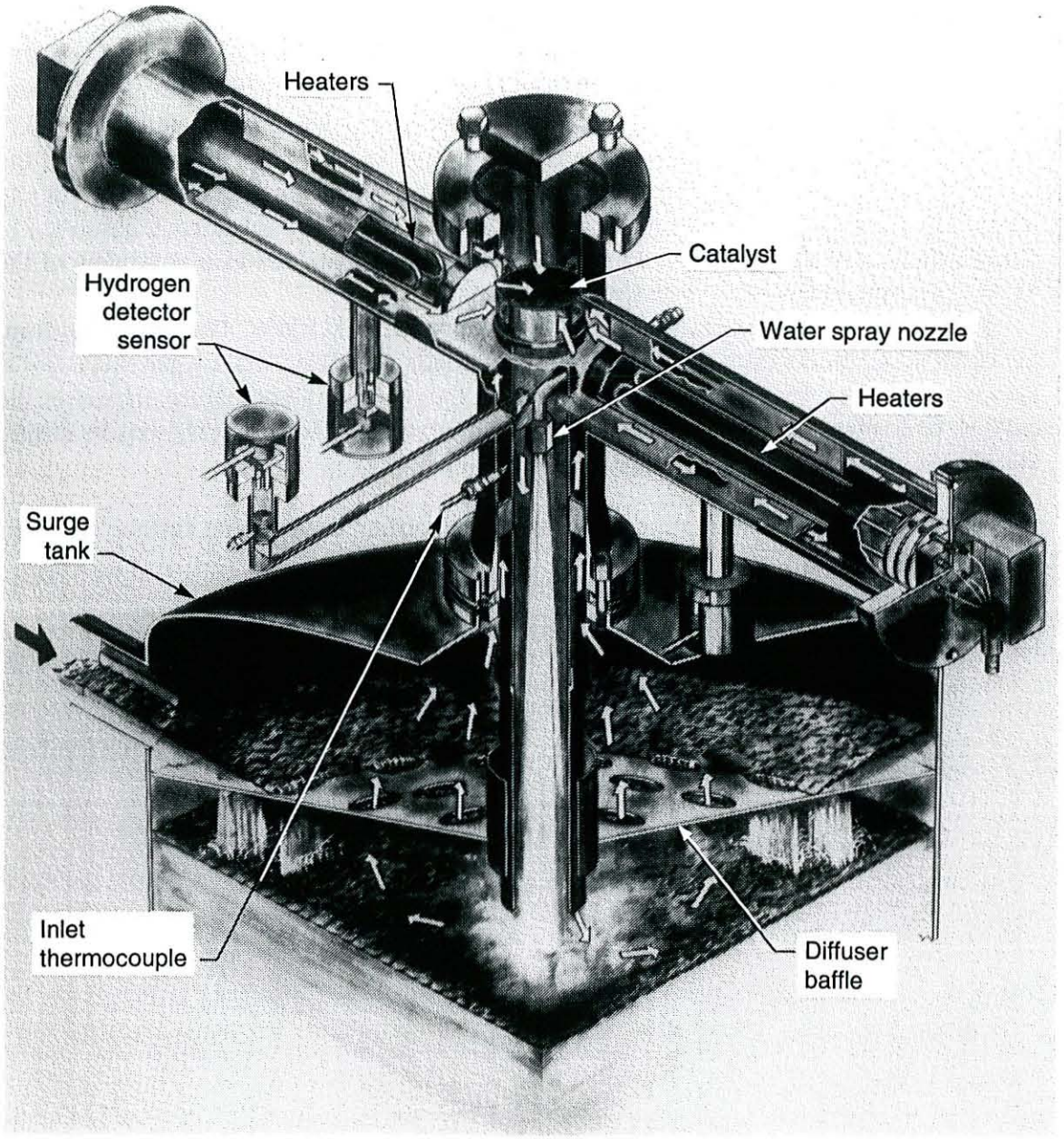


Figure 3-26. Artist's drawing of the catalytic hydrogen recombiner used at SLAC.

4.

FEL SYSTEMS

PREVIOUS sections described the accelerator and the transport optics necessary to produce an electron beam suitable for a free-electron laser. The sections that follow focus on the physical components that constitute the FEL itself—the undulator and the elements of the optical cavity. An introductory section provides a brief overview of FEL physics, concentrating especially on design and modeling issues pertinent to the performance of an IRFEL for chemical dynamics research. Section 4.2 then follows with a description of the undulator design, which draws heavily on the design, engineering, and construction experience gained at the Advanced Light Source. A final central design issue, the choice of a practical outcoupling scheme, is discussed in detail in section 4.3, as an introduction to the description in section 4.4 of the elements of the optical cavity, including the optical diagnostics systems. Finally, section 4.4 also describes the optics design for the transport system that will deliver infrared radiation from the FEL to the users.

4.1 FEL MODELING AND DESIGN ISSUES

In a free-electron laser, electron beams receive a periodic transverse kick in the magnetic field of the undulator so that the electrons' kinetic energy is transferred to the radiation field. The radiation is trapped in an optical cavity and amplified by interacting with the electron beam during successive traversals. A portion of the optical energy in the optical cavity is then coupled out and transported to experimental stations. In this section, we consider the issue of modeling the basic FEL interactions.

4.1.1 Basic Considerations

The FEL wavelength is given by

$$\lambda = \frac{\lambda_u\left(1 + K^2/2\right)}{2\gamma^2} \tag{4-1}$$

where λ_u is the period length of the undulator magnet, γ is the electron's relativistic energy E divided by its rest energy m_0c^2, and K is the dimensionless deflection parameter, related to the peak magnetic field B_0 in the undulator and the electron charge e as follows:

$$K = \frac{eB_0\lambda_u}{2\pi m_0 c} = 0.934\ B_0\,[\mathrm{T}]\ \lambda_u\,[\mathrm{cm}] \tag{4-2}$$

From these equations, it is clear that the FEL wavelength can be changed either by changing the electron beam energy or by changing the undulator magnet gap (thereby changing K). We shall employ both methods of tuning, changing the undulator gap for broad tuning within each of four ranges established by the choice of electron beam energy and, at a fixed gap, changing the electron beam energy for rapid tuning over a narrow range.

The FEL gain in the small-signal regime is given by (see, for example, Brau [1990])

$$g = 16\sqrt{2}\,\frac{\lambda^{3/2}\,\lambda_u^{1/2}}{\Sigma}\,\frac{K^2\,[JJ]^2}{\left(1+K^2/2\right)^{2/3}}\,\frac{I}{I_A}\,N^3 f \tag{4-3}$$

Here N is the number of undulator periods, Σ is the combined transverse area of the mode and the electron beam, I is the peak electron current, I_A is the Alfven current (17,000 A), and

$$[JJ] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right) \tag{4-4}$$

where the J's are the Bessel functions. The factor f describes the frequency dependence of the gain, with the maximum value $f_{\max} = 0.0675$. If the radiation intensity is to build up in the cavity, the gain must be at least as large as the round-trip loss in the cavity. Indeed, it is desirable to design FELs so that the single-pass gain is as large as possible.

For the electron micropulses to continue to overlap with the optical pulses, the round-trip time of the optical pulses in the cavity must be an integral multiple of the time interval T between the electron micropulses. Thus,

$$nT = 2L_c/c \tag{4-5}$$

where L_c is the length of the optical cavity. The integer n is the number of optical pulses simultaneously present in the optical cavity; in our case, $n = 1$ or 2. The timing between the pulses is arranged so that some of the FEL pulses can overlap with ALS pulses.

The Rayleigh length of the optical cavity, z_R, is determined by two considerations, namely, the desirability of minimizing the transverse mode size Σ in the interaction region, as well as the loss in the undulator bore. The optimum value of z_R is

$$z_R \cong L_u/2 \tag{4-6}$$

where $L_u = N\lambda_u$ is the length of the undulator.

To avoid gain degradation, the energy spread $\Delta\gamma$ of the electron beam should satisfy

$$\frac{\Delta\gamma}{\gamma} < \frac{1}{2N} \tag{4-7}$$

Effective lasing also requires a good overlap of the optical pulse and the electron beam in transverse phase space. This condition can be written (for the beam waist) as

$$\sigma_x \sigma_{x'} < \frac{\lambda}{4\pi}, \ \sigma_y \sigma_{y'} < \frac{\lambda}{4\pi} \tag{4-8}$$

where σ_x (σ_y) and $\sigma_{x'}$ ($\sigma_{y'}$) are the rms size and angle, respectively, of the electron beam in the x (y) direction. The product $\sigma_x\sigma_{x'}$ ($\sigma_y\sigma_{y'}$) is the rms beam emittance in the x (y) direction.

Given the beam emittance, the maximum overlap occurs when the envelopes of the electron beam and the radiation beam are similar to one another. This condition is achieved by arranging that the horizontal betatron function β_x is at a minimum at the undulator center, having a value

$$\beta_x = z_R = L_u/2 \tag{4-9}$$

In the vertical direction, however, there is a constant focusing produced by the undulator magnetic field, given by

$$\beta_y = \frac{\gamma\lambda_u}{K\pi\sqrt{2}} \tag{4-10}$$

Therefore, the external focusing must be arranged to match this value. Otherwise, the beam envelope develops a modulation and the FEL gain is reduced.

4.1.2 Spectrum and Intensity

When the FEL signal begins to develop, the optical pulse is dominated by the spontaneous radiation, for which the bandwidth is given by

$$\frac{\Delta\lambda}{\lambda} \cong \frac{1}{N} \tag{4-11}$$

As the signal is repeatedly amplified by the FEL gain process, the spectrum becomes narrower:

$$\frac{\Delta\lambda}{\lambda} \cong \frac{1}{N\sqrt{n}} \tag{4-12}$$

where n is the number of round-trips. Eventually, the bandwidth reaches a value corresponding to a coherent optical pulse extending the length $c\tau$ of the electron beam micropulse:

$$\frac{\Delta\lambda}{\lambda} \cong \frac{\lambda}{c\tau} \tag{4-13}$$

Equation 4-13 is usually known as the (Fourier) transform-limited bandwidth. The condition for obtaining this bandwidth is that FEL saturation take place at a strong field, where the intensity-dependent gain reduction becomes significant [Kim, 1991].

We have observed that the optical pulses can, in some cases, develop an exponential tail at the front end. This phenomenon, which occurs when the gain is sufficiently high and the detuning is properly chosen, is caused by the spilling of optical energy through the front end of the electron pulse. The existence of the tail means that the spectral bandwidth can be narrower than that given by Eq. 4-13. Note, however, that the spectral shape due to an exponential tail is Lorentzian; it thus has a long tail in the frequency domain and may be undesirable for certain applications.

In practice, the length of the optical cavity should be slightly shorter, by an amount δL (usually referred to as the cavity detuning), than that implied by Eq. 4-5. The cavity detuning proves to be an important parameter that can be adjusted to control FEL performance. For a small detuning, the approach to saturation is slow and the spectrum exhibits sidebands and sometimes even chaotic modes. The appearance of the sidebands and chaotic modes is a high-intensity phenomenon and is related to the synchrotron oscillation in the ponderomotive potential [Kroll et al., 1981; Goldstein, 1984]. These undesirable effects can be avoided by adjusting the amount of the cavity detuning [Warren et al., 1986; Warren and Goldstein, 1988].

The fraction η of the electron beam's kinetic power P_{el} that is converted into the optical power P_{opt} generated by the FEL interaction is called the efficiency. Thus,

$$P_{opt} = \eta\, P_{el} \tag{4-14}$$

A simple argument shows that the efficiency is about $1/2N$. However, numerical simulations indicate that, when sideband development is suppressed for higher spectral purity, the efficiency is about $1/4N$ or less.

Numerical simulation and analytic calculation of FEL performance [Kim and Xie, 1991] reveal that FEL behavior can be divided into three distinct regions, each characterized by a range of values for the detuning δL:

- Region I, where $\delta L \leq 0.1 g\lambda N$, characterized by the appearance of sidebands and a chaotic spectrum, but with high efficiency, $\eta \geq 1/4N$.
- Region II, where $0.1 g\lambda N \leq \delta L \leq 0.2 g\lambda N$, characterized by a good spectrum and a reasonable efficiency, $1/5N \leq \eta \leq 1/4N$.
- Region III, where $\delta L \geq 0.2 g\lambda N$, characterized by a good spectrum but low efficiency, $\eta \leq 1/5N$.

A curve showing the FEL efficiency as a function of the cavity detuning δL is called the detuning curve. In Fig. 4-1, we show a typical such curve, in which efficiency is plotted in units of $1/2N$. The FEL spectra corresponding to points A and B are shown in Figs. 4-2a and 4-2b, respectively. These figures clearly illustrate the distinct regions discussed

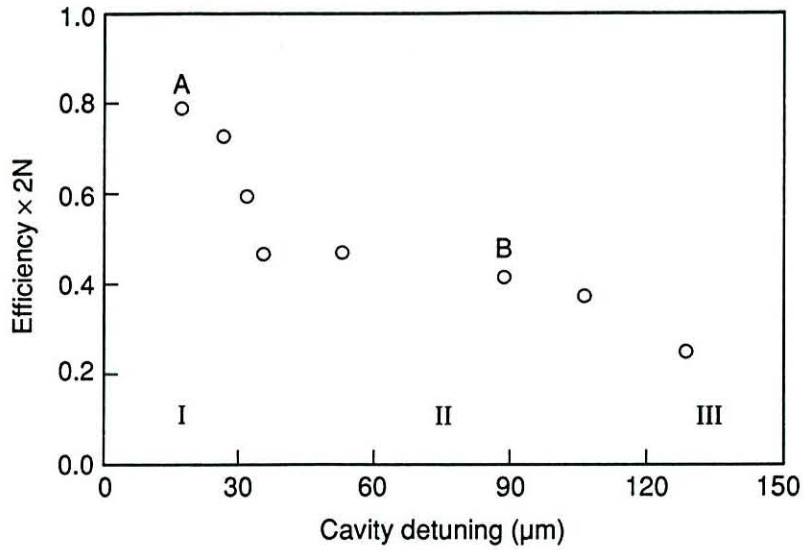


Figure 4-1. Plot of extraction efficiency η as a function of cavity detuning, for $\lambda = 10\ \mu m$. Three different regions are denoted with capital Roman numerals. The FEL spectra at the detunings marked by A and B are shown in Fig. 4-2. [XBL 922-5576]

above. (These figures were obtained using the parameters of an earlier FEL design, based on a room-temperature linac [Conceptual Design Report: Chemical Dynamics Research Laboratory, 1991; Kim et al., 1991]).

For the current IRFEL design, a good spectrum is important. Thus, the detuning was chosen to be $\delta L \geq 0.1 g\lambda N$. Accordingly, the efficiency η will be equal to about $1/5N$.

If we denote the total round-trip loss by α, the intracavity power is given by

$$P_{\text{cav}} = \frac{P_{\text{opt}}}{\alpha} = \frac{\eta}{\alpha} P_{\text{el}} \tag{4-15}$$

The intracavity optical elements must be designed to withstand the power level given by P_{cav}. The total loss α consists of the useful loss α_c due to outcoupling and other losses α':

$$\alpha = \alpha_c + \alpha' \tag{4-16}$$

Thus, the useful output power is given by

$$P_{\text{out}} = \left(\frac{\alpha_c}{\alpha}\right) \eta P_{\text{el}} \tag{4-17}$$

The ratio α_c/α, the coupling efficiency, depends on the details of the outcoupling. For the hole-coupling scheme discussed in section 4.3, this ratio is about 0.5.

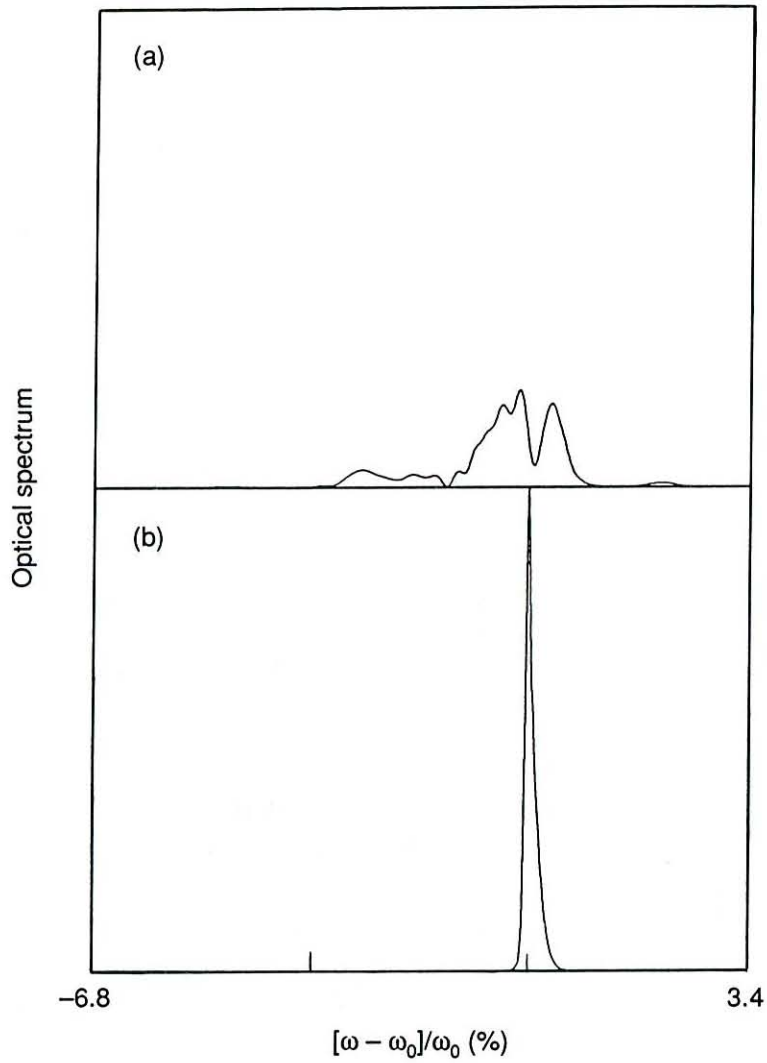


Figure 4-2. The FEL spectra for different cavity detunings, as a function of the relative frequency, for $\lambda = 10\ \mu m$, $\tau = 33$ ps, and pulse charge = 1 nC: (a) $\delta L = 18\ \mu m$, corresponding to point A in Fig. 4-1; (b) $\delta L = 89\ \mu m$, corresponding to point B. [XBL 922-5577]

Finally, the optical power delivered to the experimental station, P_{exp}, is obtained by multiplying the output power by the transport efficiency η_{trans}:

$$P_{exp} = (\alpha_c/\alpha)\ \eta_{trans}\eta P_{el} \tag{4-18}$$

Typically, $\eta_{trans} \cong 0.75$.

Denoting the electron kinetic energy, the generated optical energy, and the transported optical energy in a micropulse by W_{el}, W_{opt}, and W_{exp}, respectively, we have

$$\begin{aligned} W_{opt} &= \eta\ W_{el} \\ W_{exp} &= (\alpha_c/\alpha)\ \eta_{trans}\ \eta\ W_{el} \end{aligned} \tag{4-19}$$

4.1.3 IRFEL Performance Calculation

Our FEL modeling is based on several numerical simulation codes. The workhorse of the calculation is a code named PLS PRPLP, developed originally by S. Benson [1985]. The code is based on the one-dimensional FEL equations, three-dimensional effects being taken into account by means of a suitable filling factor. PLS PRPLP takes into account the effects of the finite length of electron micropulses, spontaneous radiation, and the electron beam energy spread. The code calculates the evolution of the temporal and spectral profiles of the optical pulses in the cavity.

Table 4-1 summarizes the performance of the IRFEL, as obtained from a simulation calculation using PLS PRPLP. The electron beam parameters used for this calculation are listed in Table 4-2. The magnet parameters and wavelength tuning are discussed in section 4.2.

The net gain shown in Table 4-1 is the total gain g minus the loss α (10% in this case) at the beginning of FEL evolution. The output characteristics represent the optimized performance with respect to cavity detuning. The optimization was achieved by comparing the output at several values of the cavity detuning at the lower end of region II (see Fig. 4-1), and then choosing the one with the maximum output energy (or efficiency) showing no sideband development. The values of δL corresponding to the optimum performance are shown in Table 4-1; they agree with the formula $\delta L \cong 0.1 g \lambda N$, except in the long-wavelength cases.

The spectral bandwidths in Table 4-1 are consistent with the electron beam transform-limited values given by Eq. 4-13 for short wavelengths ($\lambda \leq 10\ \mu$m). For longer wavelengths near 50 μm, the bandwidth is smaller than that expected from Eq. 4-13, owing to the spilling phenomenon and front tail development discussed above.

Table 4-1. FEL performance predicted on the basis of a simulation using the computer code PLS PRPLP. The total round-trip loss was taken to be 10%; the output coupling, 5%.

λ (μm)	E (MeV)	Net gain (%)	δL (μm)	$\Delta\lambda/\lambda$ (%)	Pulse energy (μJ)
3	55.3	17	4.6	0.04	99
6.8	55.3	51	15	0.08	170
6	39.1	44	15	0.06	134
13.7	39.1	116	60	0.13	169
12	27.7	105	40	0.13	176
27.4	27.7	227	150	0.38	154
24	19.6	119	100	0.24	113
54.7	19.6	260	300	0.32	108

Table 4-2. Electron beam parameters used for the simulation of Table 4-2. The pulse length (FWHM) was taken to be 33 ps.

E (MeV)	q (nC)	Normalized rms emittance (mm·mrad)	Energy spread, FWHM (%)
55.29	1	7.0	0.35
39.1	1.414	8.7	0.48
27.65	2	11.1	0.66
19.55	2	11.1	0.93

It has been pointed out that FEL micropulses can develop chirping [Moore, 1988; Szarmes et al., 1990]. A fraction of the bandwidth in Table 4-1 in the short-wavelength cases might be due to this "natural" chirping phenomenon. If so, a narrower bandwidth can be achieved by accelerating the electron beam slightly away from the peak of the RF crest. Note that Eq. 4-13 yields a bandwidth about twice as wide as that expected from a coherent Gaussian pulse.

From the values of the generated optical micropulse energy W_{opt} given in Table 4-1, we find that the FEL efficiency η is consistent with our expectation that it be larger than about $1/5N$. The final transported optical energy W_{exp} can be estimated from Eq. 4-19, assuming $\alpha_c/\alpha = 0.5$ and $\eta_{trans} = 0.75$.

It is possible to increase the FEL efficiency by tapering the undulator magnetic field [Kroll et al., 1981]. For this scheme to work, the intracavity optical intensity must be high, so that the required fraction of the electron beam is trapped in the ponderomotive "bucket." Thus, it might be necessary to reduce the cavity loss while maintaining the coupling efficiency α_c/α at a reasonable value. Tapered operation of the CDRL IRFEL is currently being evaluated.

We have also calculated the variations in the FEL spectrum and power caused by sinusoidal modulation of the electron beam energy and of the timing between the micropulses under different operating conditions. Figure 4-3 is an example of such a calculation. The results are in general agreement with the analysis in section 3.1.1.

4.1.4 Intracavity Gratings

Intracavity dispersive elements such as gratings can be useful for sideband suppression and for wavelength stabilization beyond the level made possible by electron beam control alone. A schematic of the optical cavity with a grating in a Littrow configuration is shown in Fig. 4-4. Here, the light diffracted in the first order remains in the cavity, whereas the zeroth or second order provides a convenient outcoupling mechanism. A proof-of-principle experiment using gratings in an FEL for sideband suppression [Sollid et al., 1989a, 1989b] and for wavelength stabilization [D.W. Feldman, private communication] has been carried out at LANL.

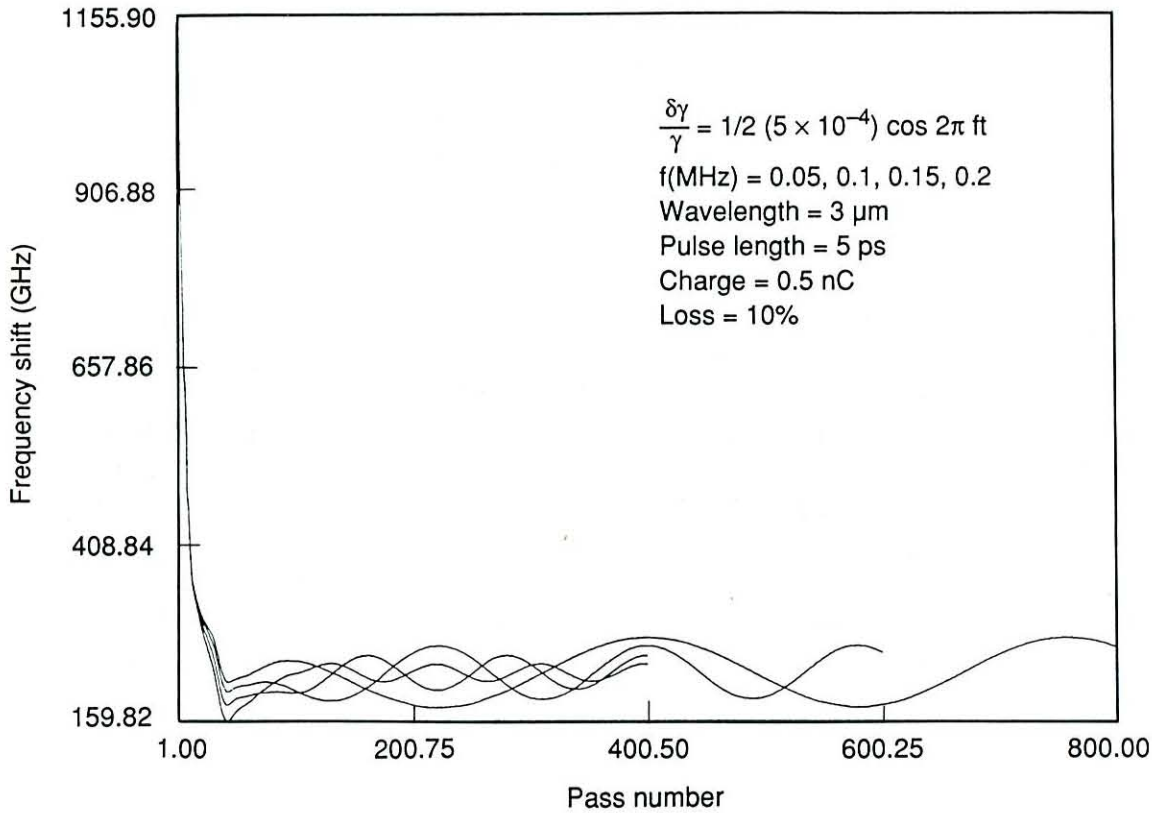


Figure 4-3. Plot of the FEL frequency shift as a function of pass number, showing the frequency modulation caused by modulation in the electron energy. The conditions assumed for the four curves are described in the figure. [XBL 922-5578]

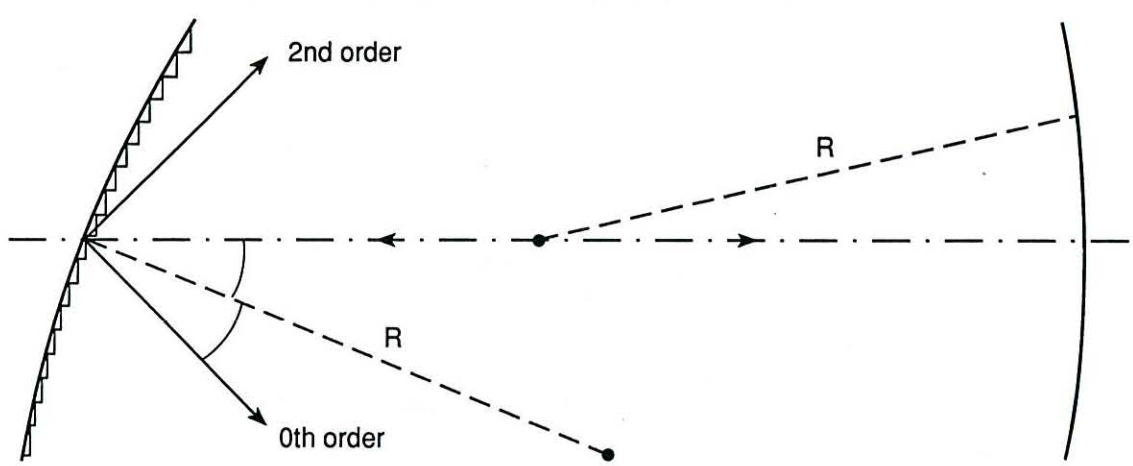


Figure 4-4. Schematic of the FEL optical cavity with a grating in a Littrow configuration. [XBL 922-5579]

The wavelength fluctuation in the presence of an intracavity grating is related to the fluctuation in the absence of a grating, $\delta\omega_0/\omega_0$, by

$$\frac{\delta\lambda}{\lambda} = \frac{g\left(\sigma_g/\sigma_0\right)^2}{1+g\left(\sigma_g/\sigma_0\right)^2}\frac{\delta\omega_0}{\omega_0} \tag{4-20}$$

where σ_0 is the gain bandwidth (~$1/2N$) and σ_g is the grating bandwidth. At saturation, the gain g in Eq. 4-20 can be replaced by the loss α, which is typically 0.1 for the IRFEL described here. Thus, the wavelength fluctuations can be reduced by a factor of 10 or more below that possible with electron beam control alone, when $\sigma_g < \sigma_0$.

We have calculated the wavelength fluctuations caused by the electron beam modulation in the presence of an intracavity grating by modeling the grating as a frequency filter in PLS PRPLP. The result agrees qualitatively with the behavior predicted by Eq. 4-20.

Gratings with narrower bandwidths, or with finer grooves, will be better in terms of stability. However, excessive pulse stretching, caused by a finer grating, could lead to an unacceptable reduction in the FEL gain [Sollid et al., 1989a, 1989b]. For a Littrow grating configuration, the rms pulse stretching per grating reflection is calculated to be

$$\sigma_{\Delta z} \cong \lambda\sigma_x/d \tag{4-21}$$

where σ_x is the rms beam size at the grating and d is the groove spacing. To avoid a significant gain reduction, $\sigma_{\Delta z}$ should be small compared with the electron pulse length. For the CDRL FEL, this requirement leads to a coarse grating with $d \cong 0.1$ mm for $\lambda \leq 10$ μm, and to even coarser gratings for longer wavelengths.

For a coarse grating with a shallow groove, the grating efficiency can be calculated in a closed form by using an asymptotic form of the Rayleigh expansion [Loewen et al., 1978]. The result for the first order efficiency $|E_1|^2$ near the blaze frequency ω_g is

$$|E_1|^2 = [(\sin\varepsilon)/\varepsilon]^2 \tag{4-22}$$

where $\varepsilon = \pi\,(\omega - \omega_g)/\omega_g$. If we require the efficiency to be larger than 90%, a single grating can cover the wavelength range

$$-0.17 \leq \frac{\omega-\omega_g}{\omega_g} \leq 0.17 \tag{4-23}$$

Thus, the total tuning range is about 34%.

The efficiency into the zeroth- or second-order reflection is given by

$$|E_0|^2 = |E_2|^2 = \left(\frac{\varepsilon}{\pi}\right)^2 = \left(\frac{\omega-\omega_g}{\omega_g}\right)^2 \tag{4-24}$$

Therefore, up to about 3% of the FEL intensity can be coupled out in each order for external use. However, according to Eq. 4-24, the efficiency vanishes quadratically as ω approaches ω_g.

Three-dimensional effects could be important for FEL operation with intracavity gratings. For example, for a fixed grating, the optical axis corresponding to a wavelength $\lambda \neq \lambda_g$ (where λ_g is the wavelength corresponding to ω_g) is rotated by an angle θ with respect to the original axis, where θ is given by[1]

$$\theta = \frac{L}{4(2R - L)}\left(\frac{\lambda - \lambda_g}{d}\right) \tag{4-25}$$

in which R is the radius of curvature for the grating. The rotation of the optical axis can excite a walking mode around the new axis [Grossman and Quimby, 1984; Warren and McVey, 1987] and should be limited to a value smaller than, for example, the mode divergence angle.

4.2 FEL UNDULATOR

The heart of the IRFEL is a steel–permanent magnet hybrid undulator, consisting of a magnetic structure, a support and drive system, a control system, and a vacuum system. As shown in Fig. 4-5, the magnetic structure is outside the vacuum chamber, which is a small cylindrical pipe extending the length of the undulator. The magnet gap is varied mechanically for wavelength tuning.

4.2.1 Parameter Selection and Tuning

The undulator period length, the wavelength tuning ranges, and the vacuum chamber dimensions are closely related parameters that must be chosen carefully. The diameter of the pipe must be neither too large (to ensure a sufficiently strong magnetic field) nor too small (to avoid excessive diffraction loss). To balance these considerations, we chose the inner diameter of the vacuum chamber to be 21 mm. Allowing for a 1-mm chamber thickness yields a minimum magnet gap $g_{\min}$ = 23 mm. The corresponding peak magnetic field on the undulator axis, B_0, is 0.45 T. Thus, for the chosen undulator magnet period length λ_u = 5 cm, the maximum value of the deflection parameter K is, from Eq. 4-2,

$$K_{\max} = 2.1 \tag{4-26}$$

To insure a sufficient FEL gain, the minimum value of K, obtained by opening the gap, was chosen as

$$K_{\min} = 0.9 \tag{4-27}$$

[1]We thank R. W. Warren for his help in deriving Eq. 4-25.

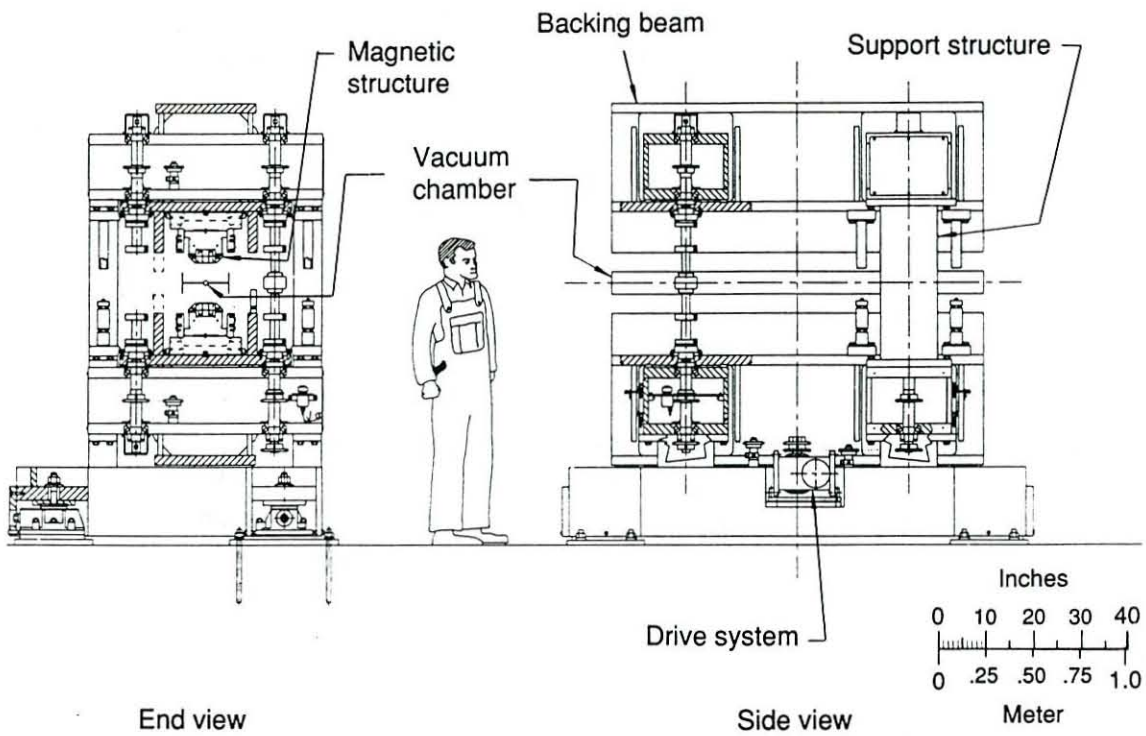


Figure 4-5. Cross-sectional end and side views of the IRFEL undulator. [XBL 922-5580]

Thus, at a fixed electron energy E, the wavelength can be varied between λ_{min} and λ_{max}, where

$$\frac{\lambda_{max}}{\lambda_{min}} = \frac{1 + K_{max}^2/2}{1 + K_{min}^2/2} = 2.28 \tag{4-28}$$

The entire wavelength range 3–50 μm can therefore be covered by operating the FEL at four energies, as shown in Table 4-3. Ease of wavelength tuning is crucial for the

Table 4-3. Wavelength tuning ranges for four selected electron beam energies.

Electron energy (MeV)	Wavelength tuning range
55.3	$3\ \mu m \le \lambda \le 6.84\ \mu m$
39.1	$6\ \mu m \le \lambda \le 13.7\ \mu m$
27.7	$12\ \mu m \le \lambda \le 27.4\ \mu m$
19.6	$24\ \mu m \le \lambda \le 54.7\ \mu m$

successful operation of a user facility. Accordingly, changes in the undulator gap that are required to satisfy user needs will be carried out under automated computer control. The full undulator scan at a given electron energy will take about one minute.

The dependence of the deflection parameter on the magnet gap is given approximately by

$$K = K_{\max} \exp\left[-\frac{\pi(g - g_{\min})}{\lambda_u}\right] \tag{4-29}$$

Thus, the maximum gap corresponding to $K_{\min} = 0.9$ is $g_{\max} = 36.5$ mm.

4.2.2 Tolerance Requirements

Gap Motion. The change $\Delta\lambda$ in FEL wavelength due to a gap change Δg is, from Eqs. 4-1 and 4-29

$$\frac{\Delta\lambda}{\lambda} = \left(\frac{K^2}{1 + K^2/2}\right)\left[\frac{\pi(\Delta g)}{\lambda_u}\right] \tag{4-30}$$

We require the wavelength change per step to be about one-tenth of the bandwidth (which is 10^{-3}); thus, the gap change per step must be no larger than about 1 μm.

Random Field Errors. We require that the intensity reduction due to random field errors be less than 10%. This leads to the condition [Kincaid, 1985]

$$q = \frac{n\sigma^2 N^2 K^2}{2\left(1 + K^2/2\right)} \leq 0.1 \tag{4-31}$$

where σ is the rms error, n is the harmonic number, and N is the number of undulator periods. Setting $n = 1$, $N = 40$, and $K = 2.01$, we find that the requirement is satisfied by $\sigma \leq 0.9\%$. We chose to set the tolerance at $\sigma \leq 0.5\%$, in case operation at the third harmonic is required. This requirement on random errors is less stringent than that for the U5.0 undulator for the ALS.

Variations in the Undulator Gap. Variations in the undulator gap, such as those caused by weight, will cause a broadening of the homogeneous gain bandwidth. We require this broadening to be less than $1/4N$. Using Eq. 4-30, this requirement demands that $|\Delta g| \leq 35$ μm along the undulator.

Field integral. The first field integral is

$$\int B_y \, dz \tag{4-32}$$

where y is the vertical direction and B_y accounts for the deflection of the electron beam. We require the deflection angle to be less than one-tenth of the angular divergence of the electron beam ($\sigma_{x'} \leq 450$ mrad). This leads to the requirement

$$\int B_y \, dz \leq 10 \text{ G·cm} \tag{4-33}$$

4.2.3 Mechanical Description

The proposed IRFEL undulator is a shortened version of the ALS U5.0 undulator. Table 4-4 summarizes the proposed engineering design parameters. The major subsystems are

- The magnetic structure, which includes the hybrid pole assemblies mounted on pole mounts that are attached to the backing beams.
- The support and drive system, which includes the framework for supporting the magnetic structure and the mechanism for closing and opening the magnetic gap.

Table 4-4. Engineering design parameters for the IRFEL undulator, based on the design of the ALS U5.0 undulator.

Maximum peak field, at 23-mm magnetic gap [T]	0.475
First harmonic peak field, at 23-mm magnetic gap [T]	0.450
Period length [cm]	5
Number of periods	40
Number of full-field poles	81
Nominal entrance/exit sequence	0, +1/2, –1, +1
Magnetic structure length [cm]	210.8
Pole width [cm]	8
Pole height [cm]	6
Pole thickness [cm]	0.8
Number of blocks per half-period pole	6
End correction range, B_y [G·cm]	1500
End correction range, B_x	None
Steering coil length, if required (short) [cm]	~25
Dipole trim coil length, if required (long) [m]	1.95
Steering and trim field strength [G]	±5
Systematic gap variation tolerance [μm]	35

- The control system, which provides for remote, precise control of the magnetic gap.
- The vacuum system, which includes a small-bore vacuum chamber and its associated vacuum pumping system.

The magnetic structure consists of samarium-cobalt and vanadium permendur poles, arranged in a hybrid configuration similar to that used successfully in the wigglers constructed for the Stanford Synchrotron Radiation Laboratory Beamlines VI and X, as well as that being used for the ALS undulators. Figure 4-6, an ALS U5.0 undulator assembly section, shows the mechanical configuration of the half-period pole assemblies, pole mount, and mount adjusters. All pole surfaces are located in a plane, with a tolerance of ±0.001 in. (25 μm).

A plot of the estimated peak field is shown in Fig. 4-7 as a function of gap. The peak field at the minimum operating gap is 0.475 T, and the peak field of the fundamental at this gap is 0.450 T. To achieve the required field tolerances, the permanent magnet

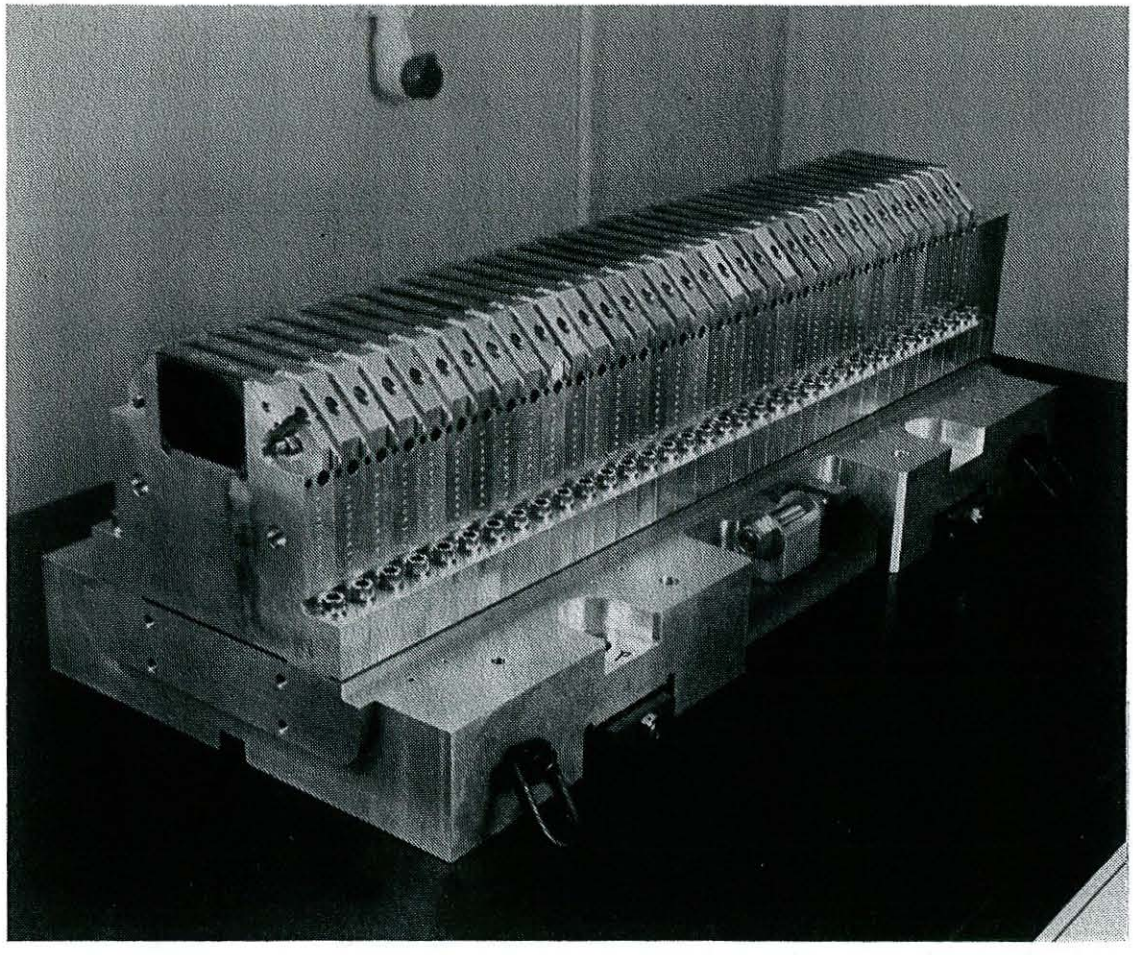


Figure 4-6. An assembly section for the first ALS U5.0 undulator; the IRFEL undulator is expected to be essentially identical. [CBB 910-8311]

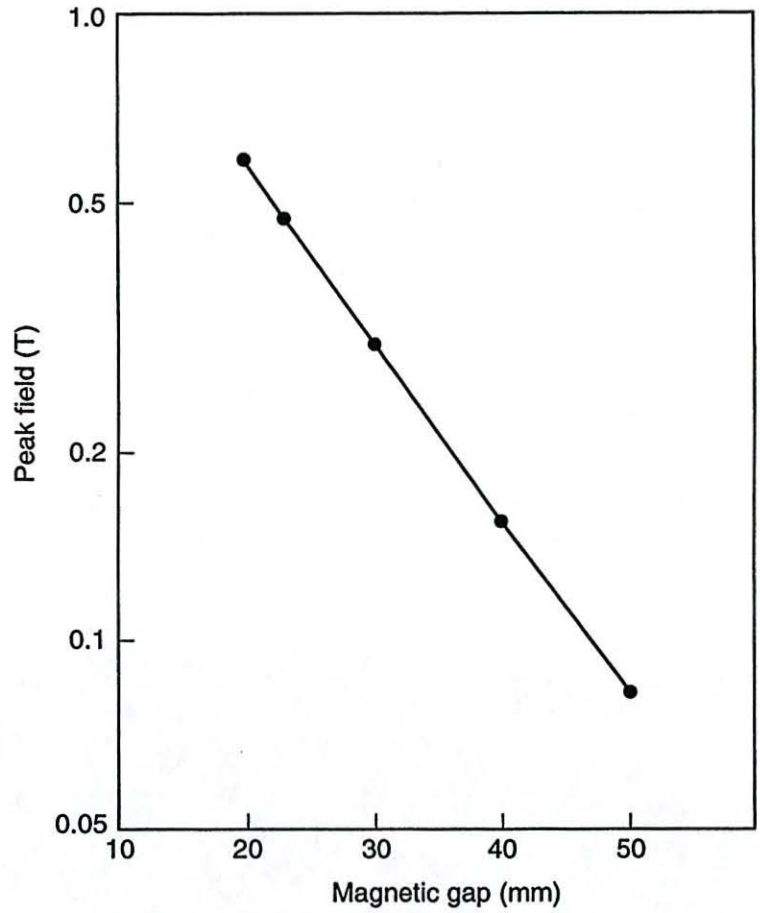


Figure 4-7. Plot of predicted undulator peak field as a function of gap. [XBL 922-5581]

blocks will be measured and sorted, and provisions have been made to correct the fields with pole adjustment and auxiliary coils, if necessary. To date, measurements on the first ALS U5.0 undulator assembly section have shown good control of field errors, and no field corrections have been required. The uncorrelated field errors are only 0.22%.

The 2.15-meter-long backing beams are sized to minimize the gap variation due to magnetic loading. To null the undulator vertical field integral, the IRFEL undulator design includes permanent-magnet end rotators, above and below the midplane at each end of the undulator; each of the four assemblies comprises two permanent-magnet rotators.

The support structure is a shortened version of the 4-post configuration adopted for the ALS insertion devices, as shown in Fig. 4-8. The support structure consists of a base, two lower horizontal beams, four vertical posts, and two upper horizontal beams. Prior to assembly, the four horizontal beams will be inserted through the webbing of the two backing beams that carry the magnetic structure. A magnetic load–compensating spring system is incorporated to buck the gap-dependent magnetic load.

The drive system changes the magnetic gap by rotating right- and left-handed Transrol roller screw/nuts, located in the upper and lower sections of the device,

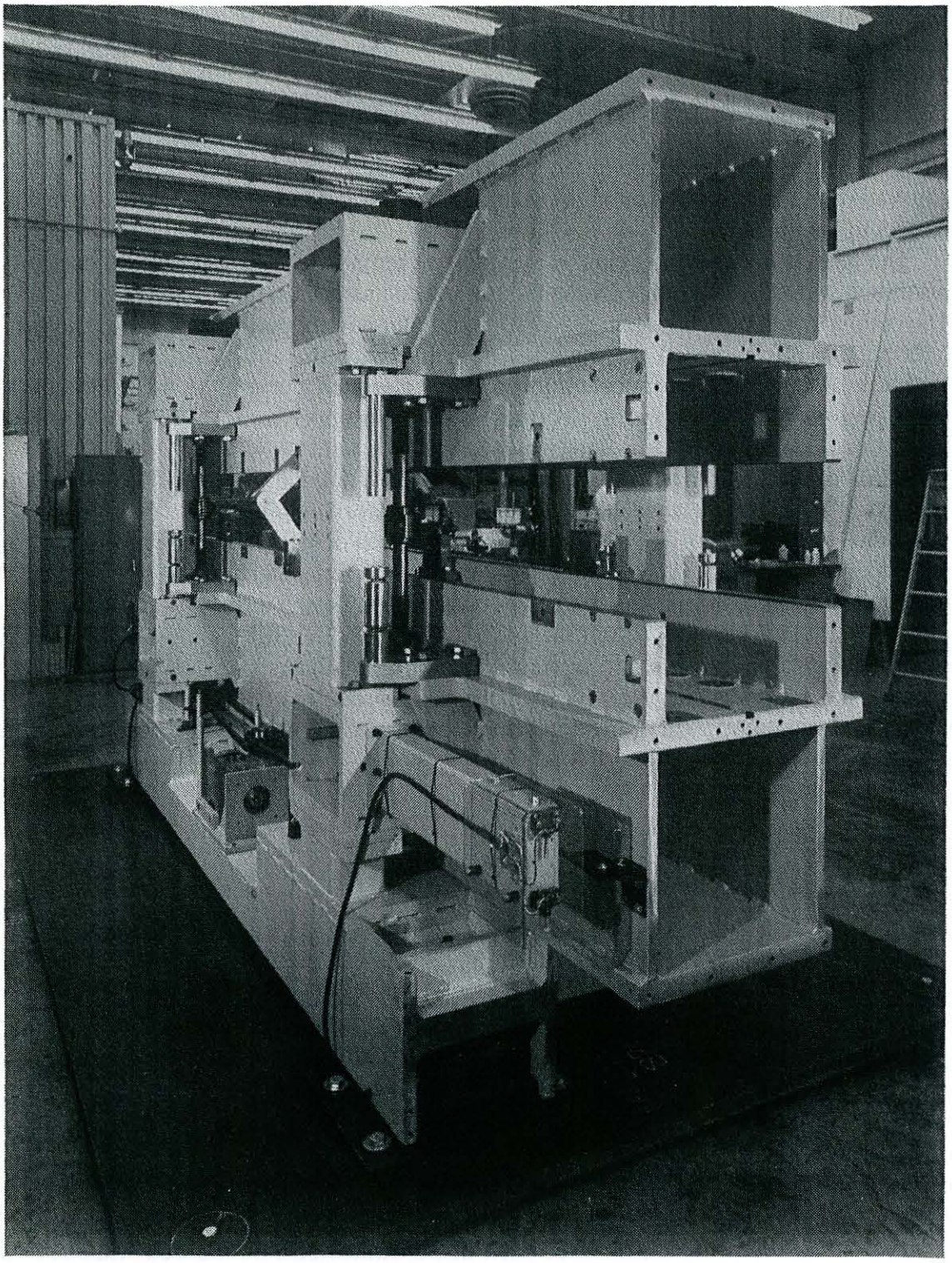


Figure 4-8. The support structure/drive system for an ALS undulator; a shortened version is proposed for the IRFEL undulator. [CBB 910-8205]

respectively. These roller screws are, in turn, interconnected with a system of roller chains, sprocket wheels, couplings, and loaded idler sprocket wheels. A gearbox and stepper motor drives the system. An absolute rotary encoder, with a resolution of better than 0.1 μm, is coupled to one of the roller screws to read the absolute position of the magnet gap.

If it is found to be desirable to taper the undulator magnetic field, a differential drive between the upstream and downstream drive shafts can be readily implemented. A 2% taper of the magnetic field along the length of the insertion device requires a maximum gap variation of about 0.4 mm, equal to about a 40° rotation of one drive shaft with respect to the other.

The goal of the undulator control system is to provide sufficient positional accuracy, resolution, velocity, and range for the motors and encoders used to vary the magnetic gap. The computer-controlled system uses a Compumotor control package, and provisions for interfacing limit switches are included, together with the ability to compensate for backlash and to program acceleration and deceleration curves. A selection of 10 microsteps/step by the control electronics for the stepper motor will provide 2000 steps/revolution, thus ensuring a gap resolution of 0.07 μm.

Initial measurements with the control system operating the first ALS U5.0 undulator support structure/drive system in a open-loop motor-stepping mode have shown a positional reproducibility of 4 μm or less in all tests. To achieve 1-μm gap reproducibility with the IRFEL undulator, a laser interferometer will be provided as an integral part of the control system, to monitor the magnetic gap directly.

The undulator vacuum system includes a small-diameter 321 stainless-steel vacuum chamber, transition sections, and associated pumping and diagnostics—all supported by a stainless-steel framework. Ports for diagnostics are provided at the entrance, center, and end of the undulator. The transition sections include bellows sections, beam position monitors, and vacuum pumping. If required, pumping can also be installed at the center of the undulator vacuum chamber.

4.3 OUTCOUPLING STUDIES

Ease of tuning is a high priority for the CDRL IRFEL. An essential feature of the design, therefore, is an outcoupling scheme that covers the widest possible range of wavelengths. We adopted a hole-coupling approach after an extensive study of its performance, in which we found that it fully meets our requirements [Xie and Kim, 1991a, 1991b]. Here we discuss the results of that study; in section 4.4, we describe the optical cavity itself.

The outcoupling schemes applicable to FELs can be broadly classified as relying on either dielectric materials or metal optics. Among the first class are those based on dielectric mirrors and those using deflection from Brewster plates. Belonging to the second class are schemes based on hole coupling, edge coupling in stable and unstable cavities, and diffraction from intracavity gratings.

The use of dielectric mirrors has been demonstrated at both the Los Alamos FEL project and the Mark III project at Stanford. For this approach to work well, both the coating materials and the substrate material must be compatible with the IRFEL power density in the cavity, and the materials must survive the intense flux of x-rays that is

emitted concurrently with the undulator radiation. This severely limits the choice of materials. In addition, the bandwidth of the dielectric coating is typically about 10% of the central wavelength of the coating. For broad tuning, this means that mirrors must be changed frequently.

The Stanford Mark III FEL (now at Duke University) used an intracavity CaF_2 plate tilted slightly off the Brewster's angle as an output coupler [Benson, 1991]. It worked well between 3 and 8 μm, which was the primary tuning range of the FEL. The drawbacks of this scheme were a tuning range limited by the long- and short-wavelength cutoffs of the CaF_2 and an output that consisted of two to four parallel beams. A future alternative to CaF_2 may be thin-film diamond, which has a unique transparency range and should have good optical properties, as well as being resistant to radiation damage. However, further development of this material is necessary before it can be relied on for practical applications.

Notwithstanding the promise of approaches using dielectric materials, outcoupling schemes based on all-metal optics appear to be the best-suited for FEL applications, because they allow broad tuning and because of their power-handling capabilities. As discussed below, the hole-coupling approach fully satisfies our design requirements, and edge-coupling schemes in stable and unstable resonators also appear promising. The use of intracavity gratings was discussed in section 4.1.4.

4.3.1 Hole Coupling

Basic Considerations. The resonator configuration used to study the performance of hole coupling is shown in Fig. 4-9. The effect of the undulator bore is taken into account approximately by the two apertures shown in the figure. The right-hand mirror has a circular hole for outcoupling. The effective radius of the left-hand mirror can be varied by means of an adjustable aperture, whose role is to control the intracavity mode profile.

A wave profile that reproduces itself after one round-trip in the cavity, except for a multiplicative constant, is called a mode. Modes for a cylindrically symmetric resonator are denoted by the designation TEM_{mn}, where m and n are the azimuthal and radial mode numbers, respectively. For each mode, we define the total round-trip loss α and the loss through the hole α_c [Xie and Kim, 1991b]. The coupling efficiency of the mode is then defined as

$$\eta_c = \frac{\alpha_c}{\alpha} \tag{4-34}$$

When a random electromagnetic field is injected into a cavity, the profile converges, after some number of cavity round-trips, to the dominant mode with the lowest loss. Two modes are said to be degenerate when their losses are the same. Even if degenerate, however, their round-trip phase advances are in general distinct. Mode degeneracy should therefore be avoided, because the beating of the two degenerate modes causes the field distribution to oscillate rapidly, leading to a corresponding modulation in FEL output.

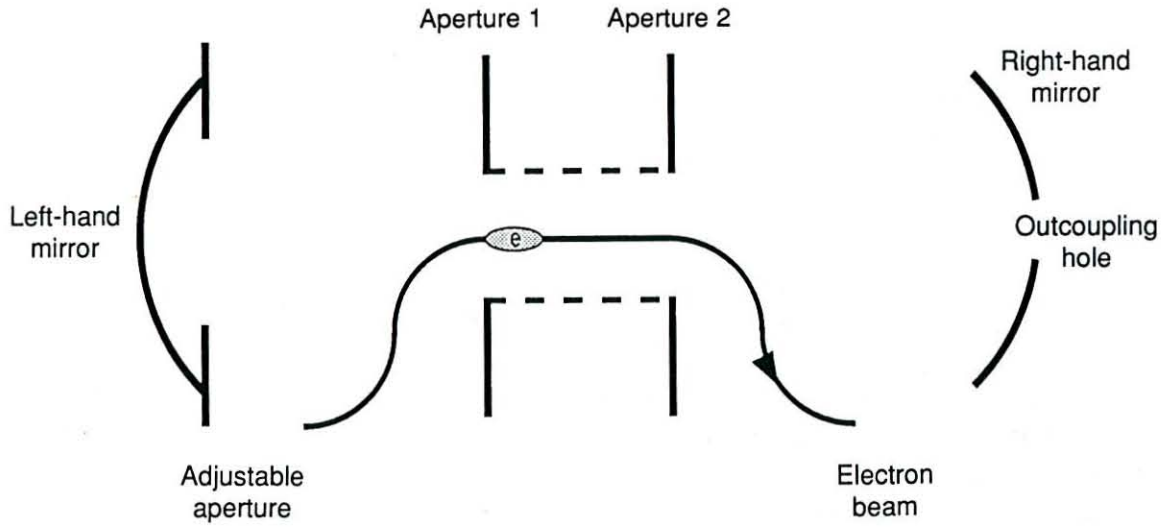


Figure 4-9. Cross-sectional view of a cylindrical IRFEL resonator, as modeled for the simulation code HOLD. The resonator consists of two mirrors and two intracavity apertures. A circular hole is located at the center of the right-hand mirror, and an adjustable aperture is placed in front of the left-hand mirror for mode control. The dashed lines indicate the boundary of an undulator bore simulated by the two fixed apertures. An electron beam traverses the FEL interaction region from aperture 1 to aperture 2. [XBL 922-5606]

Several considerations enter into the optimization of a hole-coupling resonator for the CDRL IRFEL. First, the coupling efficiency should be high enough to allow efficient utilization of the FEL output. Here, we aim for an efficiency in the neighborhood of 50%. Second, the mode profile in the interaction region should be a smooth, Gaussian-like shape for optimum overlap with the electron beam. The fundamental mode TEM_{00} satisfies this requirement. Third, mode degeneracy should be avoided. This can be done by increasing the losses for the unwanted higher-order modes (HOMs) by choosing an appropriate radius for the adjustable aperture.

Whether the outcoupled beam can be efficiently transported to a user station is another important issue in the design of an outcoupling scheme. Since the fundamental Gaussian mode in free space can usually be transported efficiently, it is of interest to know what fraction of the outcoupled optical energy is contained in the fundamental Gaussian mode in the Laguerre-Gaussian expansion. (This expansion contains two free parameters, the mode waist and the Rayleigh length. These parameters are chosen so that the power in the fundamental Gaussian mode is maximized.) With this in mind, we define the Gaussian quality factor for the outcoupled mode as the ratio of the power in the fundamental Gaussian mode to the total power. In the special case where the field distribution is uniform over the hole area (the far-field diffraction pattern in that case is known as the Airy pattern), the Gaussian quality factor is 81%. We find that the Gaussian quality factor is close to this value when the hole radius is below the mode degeneracy point.

Empty-Cavity Simulation. We developed a Fox-Li–type [Fox and Li, 1961] simulation code called HOLD (*HOL*e and *D*iffraction) to evaluate hole coupling and other resonator configurations. For an arbitrary resonator configuration involving apertures and mirrors (with or without holes), the code calculates the dominant mode by iteratively simulating round-trip propagations, starting from a random distribution. When first written, the code neglected the FEL interaction [Xie and Kim, 1991a]; we refer to this as the empty-cavity simulation. Each round-trip propagation in this case consists of a sequence of Fresnel-Kirchhoff integral transforms. FEL gain at saturation is equal to the total loss, which is about 10%. Therefore, neglecting the FEL interaction is expected to be a valid approximation in estimating the resonator performance. Simulations using the empty-cavity HOLD code demonstrate very clearly the phenomenon of degeneracy and the role of adjustable apertures in removing the degeneracy, hence widening the wavelength tuning range.

Figure 4-10 illustrates the wavelength dependence of the performance of hole coupling with an adjustable aperture. The right-hand mirror size was chosen to be sufficiently large to have no effect on performance, whereas the effective size of the left-hand mirror was increased linearly from 6.7 to 10 mm by varying the adjustable aperture,

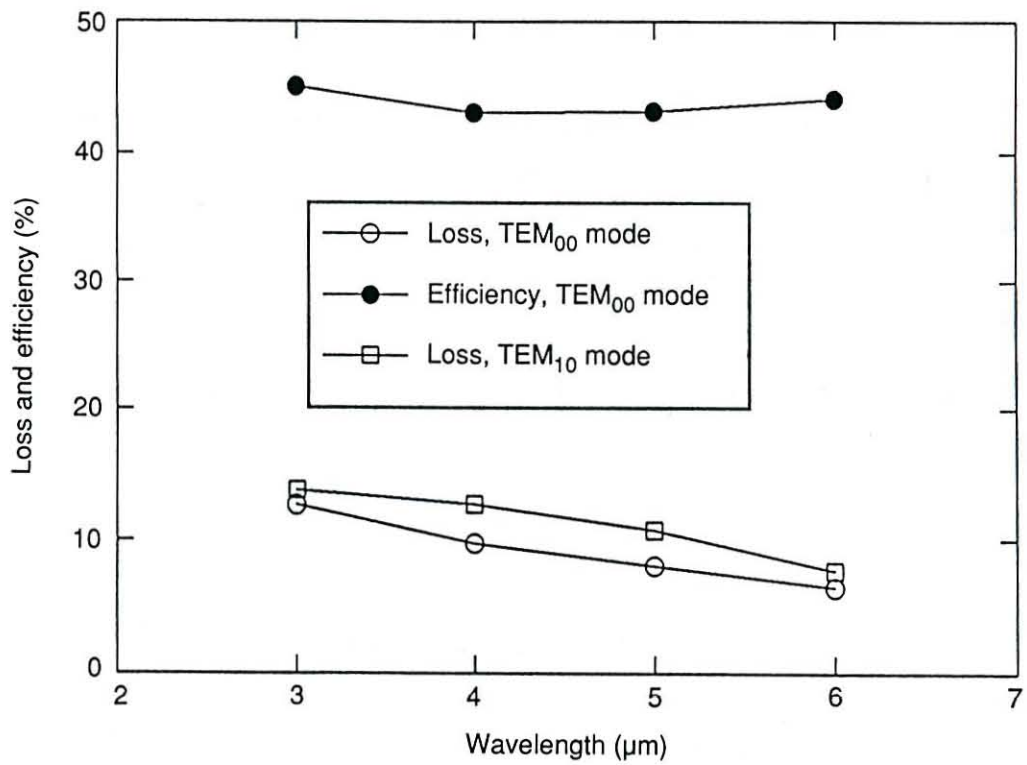


Figure 4-10. Hole-coupling efficiency for the TEM_{00} mode and loss for the TEM_{00} and TEM_{10} modes, at different wavelengths. The radius of the left-hand mirror was increased linearly from 6.7 to 10 mm as the wavelength was varied from 3 to 6 μm. The FEL interaction was neglected in this simulation. [XBL 922-5605]

as the wavelength was tuned from 3 to 6 μm. Note that the coupling efficiency and the loss remain close to 45% and 10%, respectively, varying little over the tuning range. Also, the loss of the TEM_{10} mode is kept higher than that of the TEM_{00}. Although not shown, the losses for other HOMs are higher, given our choice of left-hand mirror size. For comparison, Fig. 4-11 shows the corresponding curves for the case where the left-hand mirror size is fixed at the midpoint value of 8.35 mm. The performance is unacceptable: At the short-wavelength end, the mirror is large enough to allow the TEM_{10} mode to dominate. This mode becomes degenerate with the fundamental mode at $\lambda = 4.3$ μm. On the other hand, the mirror is too small at the longest wavelengths, thus reducing coupling efficiency.

Simulations Including the FEL Interaction. The HOLD code was subsequently modified to include the FEL interaction [Xie and Kim, 1991b]. This was done by replacing the Fresnel-Kirchhoff transportation in the interaction region, in the direction from aperture 1 to aperture 2, by a new map constructed from an FEL integral equation. The map is valid in the small-signal regime.

The most striking result of this modification is the fact that the gain, even if small, can be very effective in suppressing the HOMs among the azimuthally symmetric ($m = 0$) modes when the electron-beam Fresnel number is not too small. This suppression occurs because the overlap with the electron beam is optimal for the fundamental mode. Figures

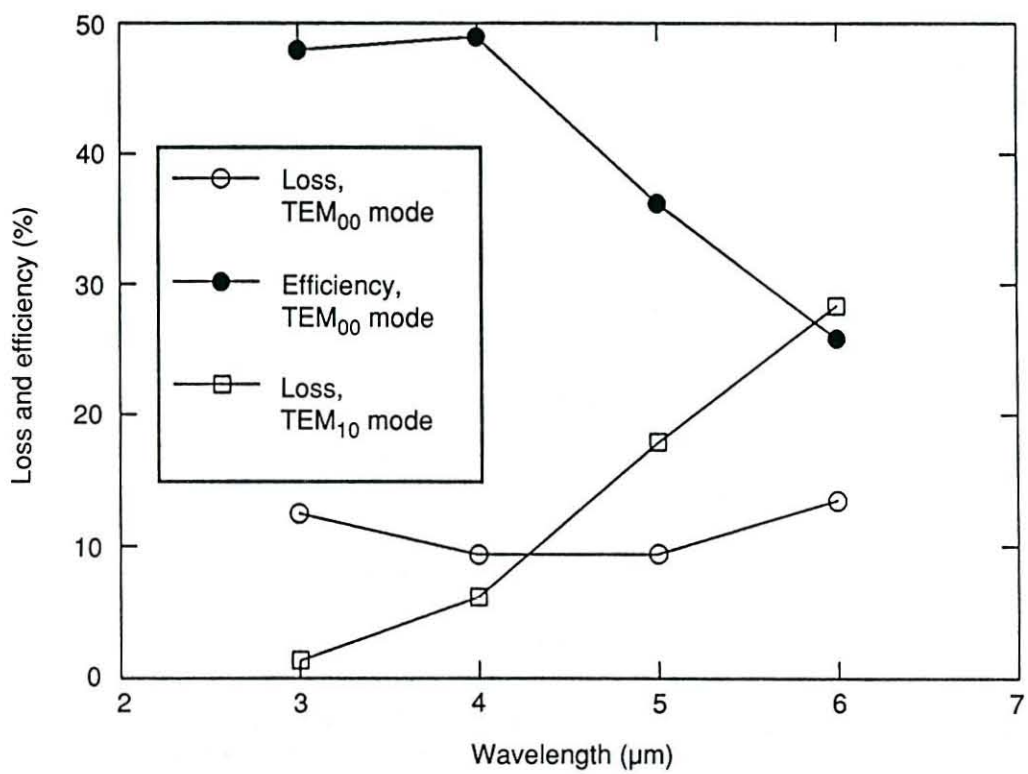


Figure 4-11. Same as Fig. 4-10, except that the radius of the left-hand mirror remained fixed at 8.35 mm for all wavelengths. [XBL 922-5604]

4-12 through 4-14 illustrate the intracavity mode profiles for single-pass gains of 0%, 2%, and 55%, respectively. The resonator configuration is such that the dominant symmetric mode for 0% gain has a large mode number $n = 4$. However, for a gain as small as 2%, the fundamental mode becomes dominant. Comparing Figs. 4-13 and 4-14, we also find that the mode profile changes little when the gain increases from 2% to 55%. The performance of hole coupling is therefore insensitive to the gain, except for the desirable effect of suppressing the symmetric HOMs.

As the electron beam size becomes smaller, the symmetric HOMs can become dominant. In principle, operation with such a mode can provide satisfactory performance, since the mode has a narrow central peak and thus a good hole-coupling efficiency; however, in practice, it will usually be necessary to suppress such modes, since a single resonator mode should remain dominant while the FEL wavelength is being scanned. This suppression can be accomplished by introducing intracavity apertures.

We expect that the asymmetric modes ($m \neq 0$) will not be perturbed significantly by the FEL interaction, because their intensities vanish on axis at the location of the electron beam. The asymmetric HOMs are also suppressed by means of adjustable intracavity apertures.

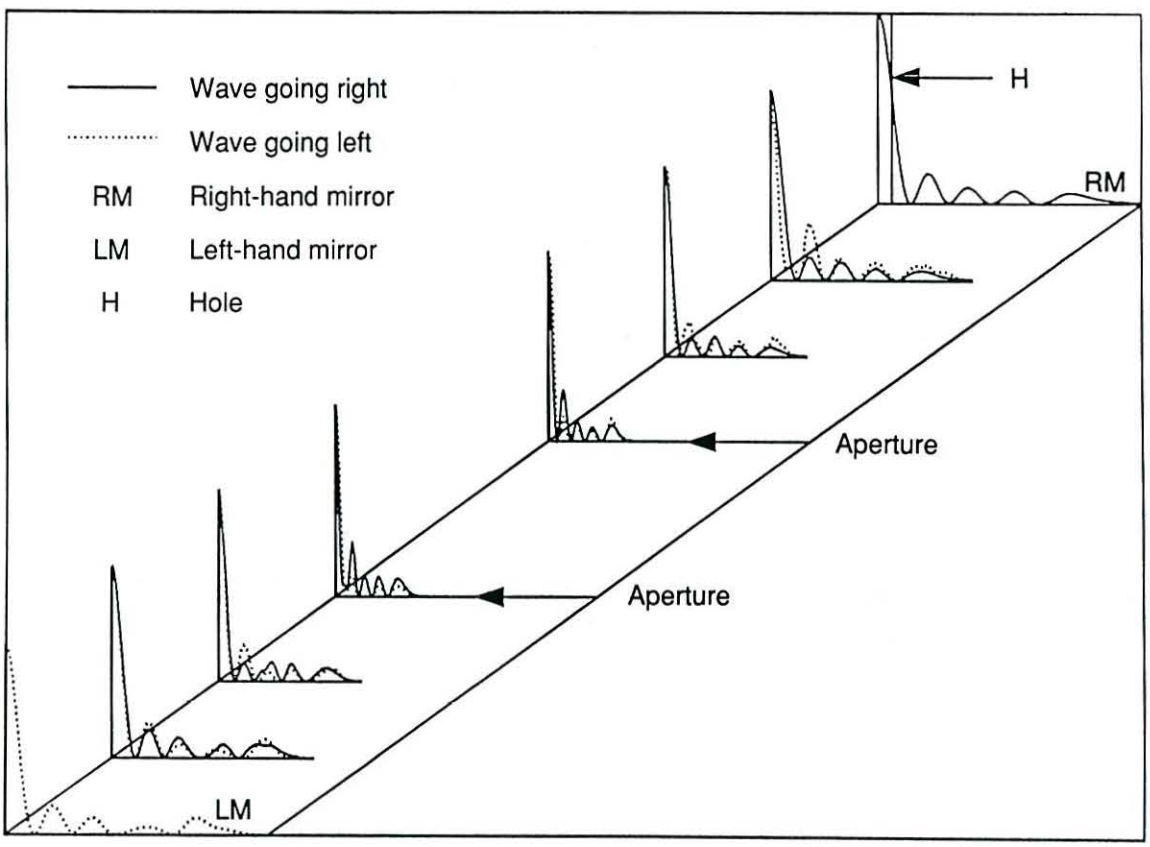


Figure 4-12. Intracavity intensity profiles of the dominant mode at a wavelength of 3 μm, for a gain of 0%. [XBL 922-5603]

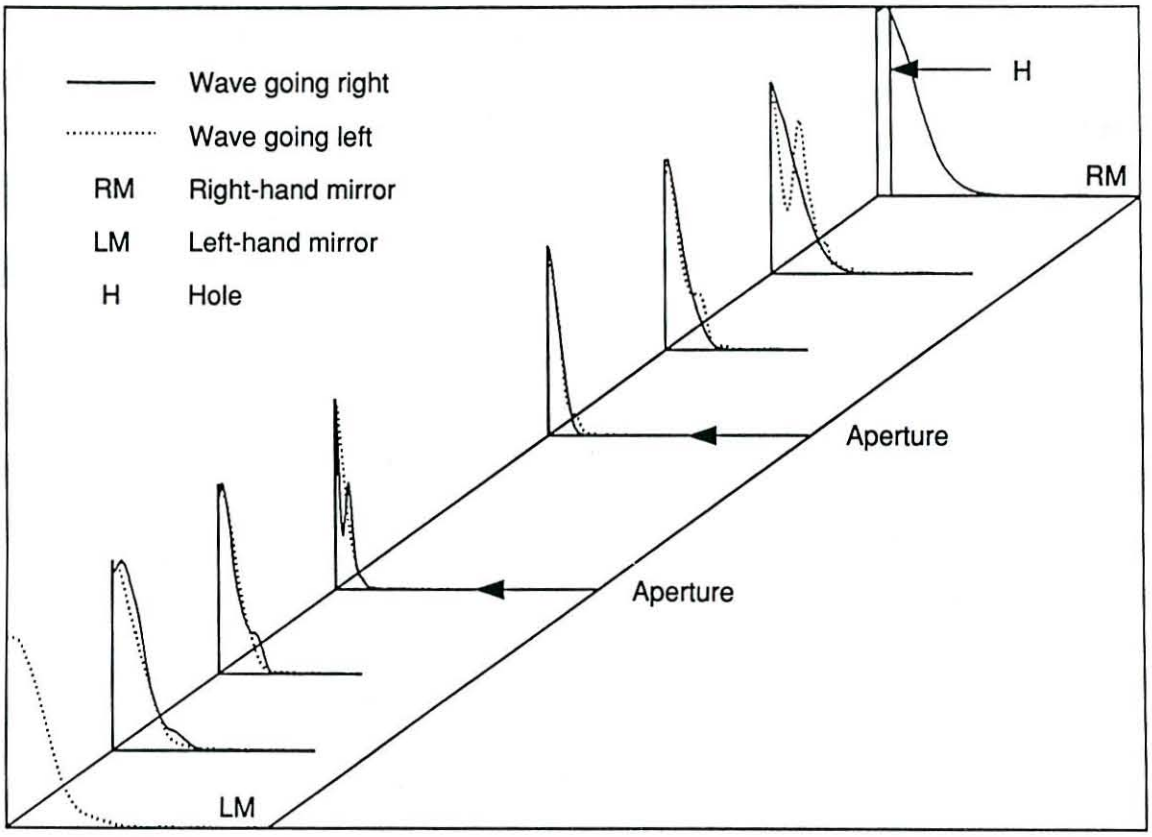


Figure 4-13. Intracavity intensity profiles of the dominant mode at a wavelength of 3 μm, for a gain of 2%. [XBL 922-5602]

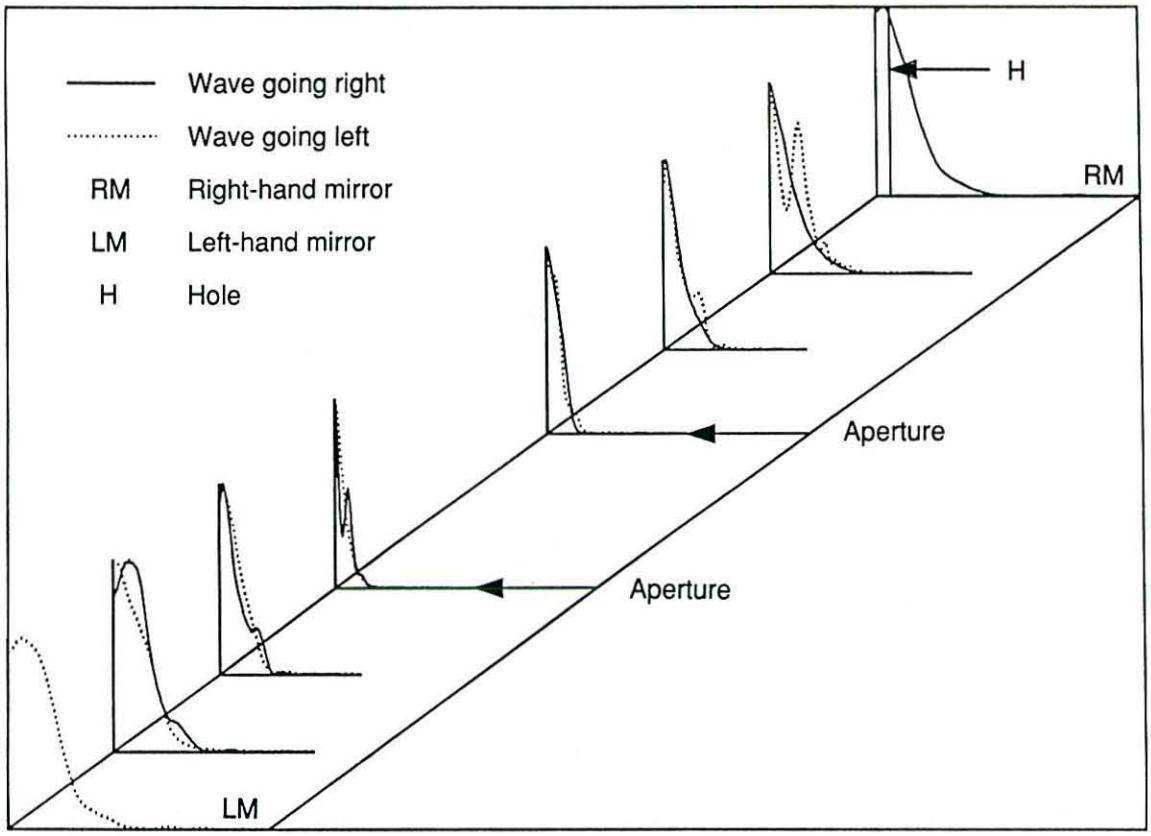


Figure 4-14. Intracavity intensity profiles of the dominant mode at a wavelength of 3 μm, for a gain of 55%. [XBL 922-5601]

As the intensity increases in the oscillator, the gain decreases from pass to pass. The saturated value of the gain at steady state, g_s, is given by

$$(1 - \alpha)\,(1 + g_s) = 1 \tag{4-35}$$

The mode profile and the resonator performance at saturation can therefore be obtained by computing the dominant mode for a sequence of cases obtained by decreasing the magnitude of the gain parameter until Eq. 4-35 is satisfied. The results of such a calculation were compared with those obtained from the oscillator version [Krishnagopal et al., 1991] of the three-dimensional FEL simulation code TDA [Tran and Wurtele, 1989]. The agreement is excellent when the saturated gain is low. Thus, our use of the linear FEL map to calculate the dominant resonator mode is also justified in the strong-signal regime.

In Fig. 4-15, we show an example of the hole-coupling performance for an FEL at saturation. The resonator configuration for this calculation was same as that for the empty-cavity results shown in Fig. 4-10, except that the left-hand mirror size is allowed to be somewhat larger to take advantage of the FEL gain. Figure 4-15 shows the loss and efficiency for the fundamental mode. We see that the hole-coupling efficiency, about

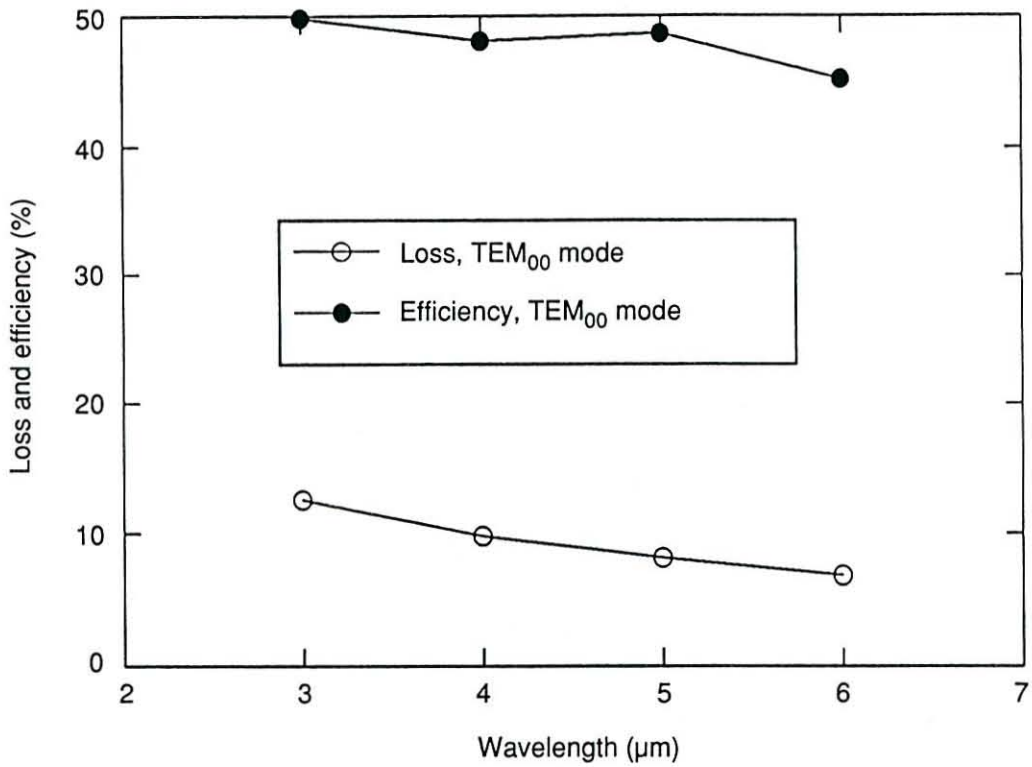


Figure 4-15. Hole-coupling efficiency and loss for the TEM_{00} mode, with intracavity FEL gain, at different wavelengths. The radii of the left-hand mirror were 7, 8.3, 9.4, and 10.3 mm at wavelengths of 3, 4, 5, and 6 μm, respectively. [XBL 922-5600]

50%, is somewhat higher than in the empty-cavity case, whereas the round-trip loss is practically the same over the entire tuning range from 3 to 6 μm.

To make sure that the TEM_{00} mode remained dominant, we checked the net gain of both the TEM_{00} and the TEM_{10} mode in the small-signal regime and at saturation. The results are shown in Fig. 4-16. At small signal, both modes are above threshold (net gain > 0); however, the TEM_{00} mode has a larger net gain. At saturation, where the net gain for the TEM_{00} mode is zero by definition (indicated in Fig. 4-16 by the horizontal line), the TEM_{10} mode is below threshold. Thus, we conclude that the fundamental mode is dominant.

Design of a Hole-Coupled Resonator for the IRFEL. Table 4-5 gives the basic resonator parameters for the CDRL IRFEL. The radius of mirror curvature is determined by the requirement that the Rayleigh length be 1 meter. The radius of the undulator bore determines the radius of the fixed apertures 1 and 2.

As discussed in section 4.2.1, the full wavelength range of the FEL is divided into four subranges, each spanning a wavelength region from λ_{min} to $\lambda_{max} \cong 2.28\ \lambda_{min}$. Each subrange is covered by changing the undulator gap at a fixed electron energy. It is obviously convenient to design the resonator configuration so that the size of the mirror

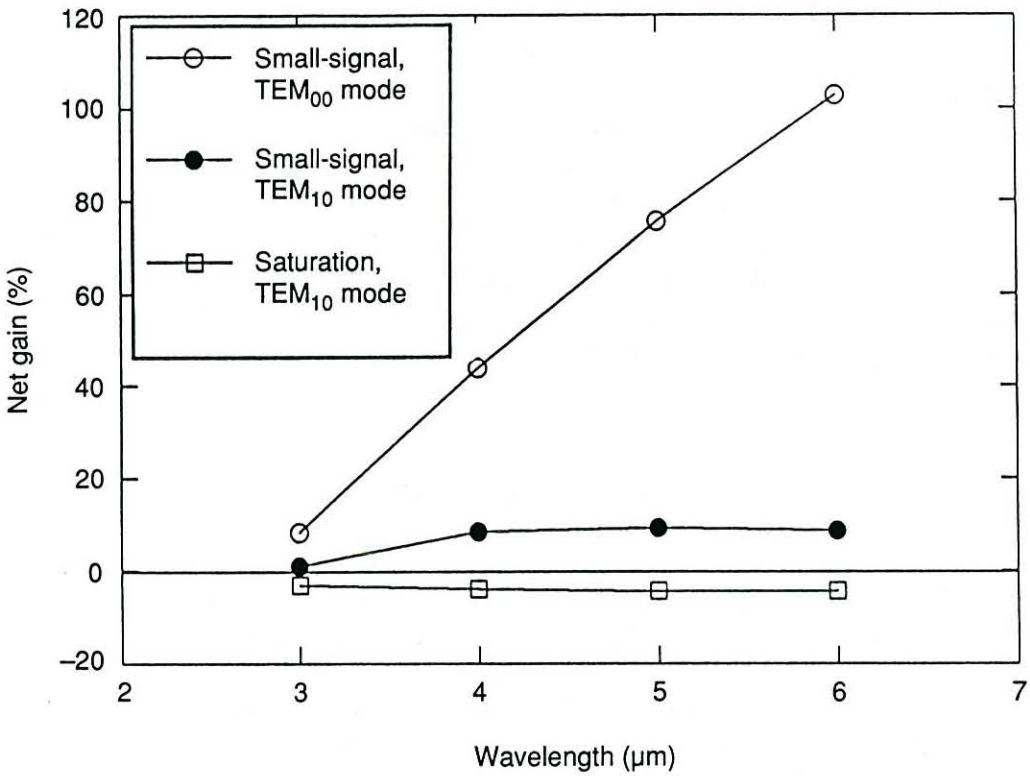


Figure 4-16. The net gains of the TEM_{00} and TEM_{10} modes in the small-signal regime and at saturation, for the same conditions described for Fig. 4-15. By definition, the horizontal line at 0% reflects the net gain of the dominant TEM_{00} mode at saturation. [XBL 922-5599]

Table 4-5. Basic resonator parameters for the CDRL IRFEL.

Cavity length [m]	24.6
Mirror radius of curvature [m]	12.38
Stability parameter, g	–0.987
Rayleigh length, z_R [m]	1
Undulator length [m]	2
Radius of undulator bore [mm]	10.5

coupling hole need not change during the wavelength scan within a given subrange. Thus, the right-hand mirror in Fig. 4-9 need not be changed during the scan. On the other hand, the radius of the adjustable aperture varies continuously during the scan.

The hole-coupling parameters for the CDRL IRFEL are given in Table 4-6. The performance of the hole-coupling resonator is summarized in Figs. 4-17 and 4-18. Figure 4-17 shows the hole-coupling efficiency η_c and the total loss α as functions of the wavelength. Over the entire wavelength range, $40\% \leq \eta_c \leq 60\%$ and $5\% \leq \alpha \leq 15\%$. The resonator parameters were chosen so that degeneracies do not occur during a wavelength scan within a given subrange. Figure 4-18 shows the small-signal gain (the gain at the beginning of the FEL start-up) and loss α as functions of the wavelength. At all wavelengths, the gain is larger than the loss by a margin sufficient to ensure efficient FEL operation.

4.3.2 Additional Outcoupling Schemes Based on All-Metal Optics

For finite-radius mirrors, some radiation energy must spill over the mirror edges. Outcoupling approaches based on this phenomenon are referred to as edge-coupling schemes. Edge coupling can be used in either a stable or an unstable resonator.

Edge Coupling in a Stable Resonator. The case of a stable resonator is illustrated in Fig. 4-19. The radius of the left-hand mirror is taken to be sufficiently large that the loss at the mirror edge is negligible. The radius of the right-hand mirror is chosen to maximize the coupling efficiency, while maintaining the total loss at the desired level.

The parameters for an edge-coupling scheme optimized for the CDRL IRFEL are given in Table 4-7. The radius of curvature for both mirrors is the same as that given in Table 4-5. The coupling performance is shown in Fig. 4-20. As expected, the loss for a fixed mirror size increases as a function of the wavelength, in contrast to the case of hole coupling. Such behavior is desirable, because it is similar to the behavior shown in Fig. 4-18 for the small-signal gain. The efficiency is significantly higher than that in the hole-coupling case, especially at short wavelengths. At long wavelengths, the loss at the fixed apertures (the undulator bore) becomes the limiting factor in the efficiency. For the edge-coupling scheme described here, the wavelength scans encounter no mode degeneracies. Thus, it is unnecessary to introduce adjustable apertures.

Table 4-6. Hole-coupling parameters for the IRFEL.

Wavelength range (μm)	Hole radius (mm)	Adjustable aperture radius (mm)
3–6.84	2	19–35
6–13.7	2.8	30–50
12–27.4	4.4	45–65
24–54.7	6	60–100

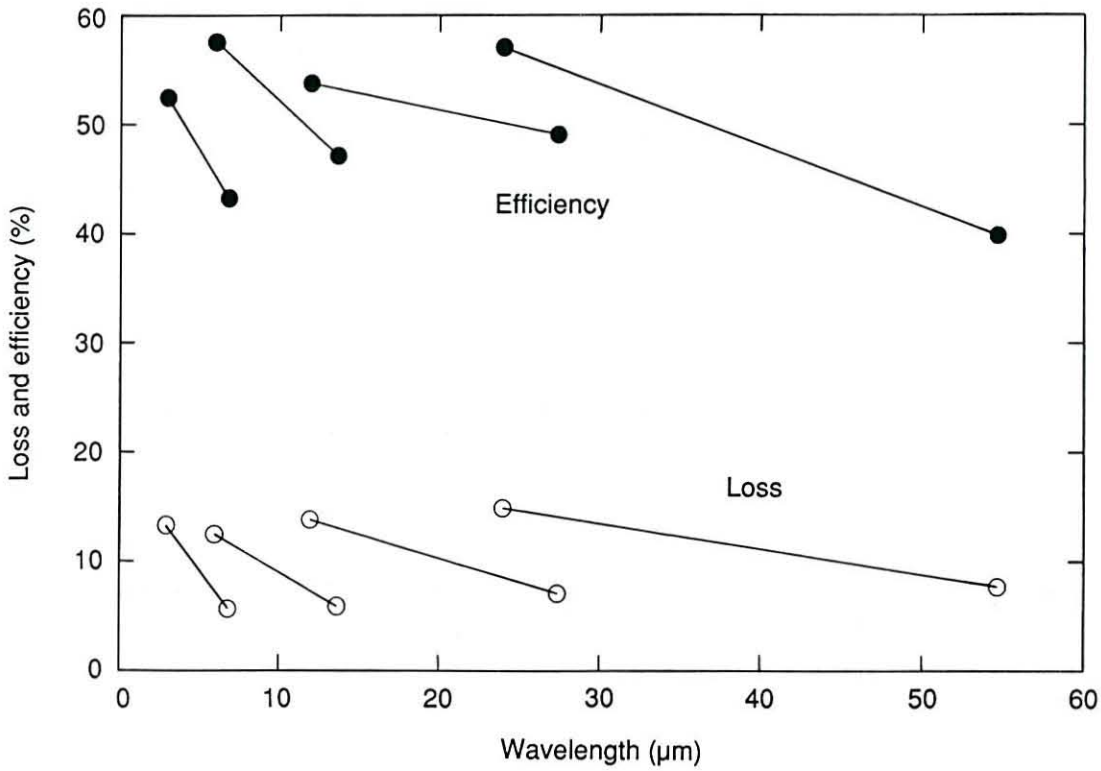


Figure 4-17. Hole-coupling performance parameters (loss and efficiency) for the CDRL IRFEL, as functions of wavelength. Each line segment represents the wavelength scanning range for a fixed electron beam energy. [XBL 922-5598]

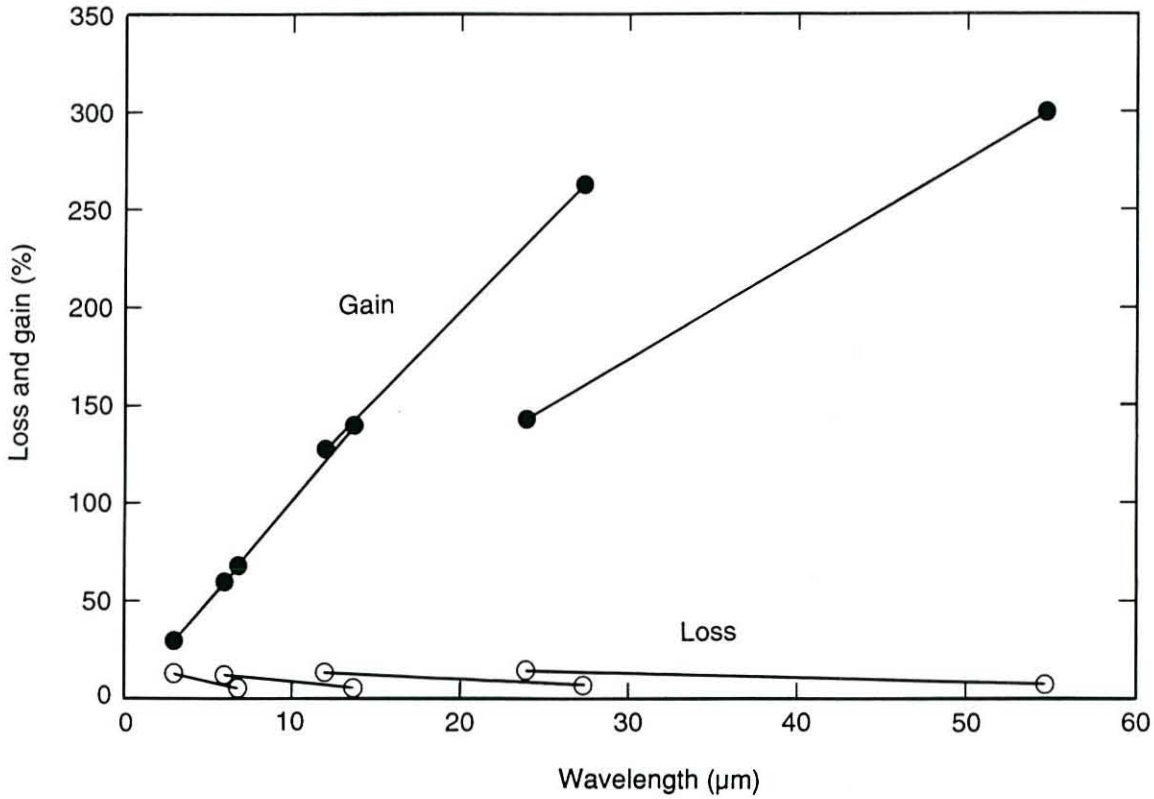


Figure 4-18. Small-signal FEL gain and the loss of a hole-coupling resonator, as functions of wavelength. [XBL 922-5597]

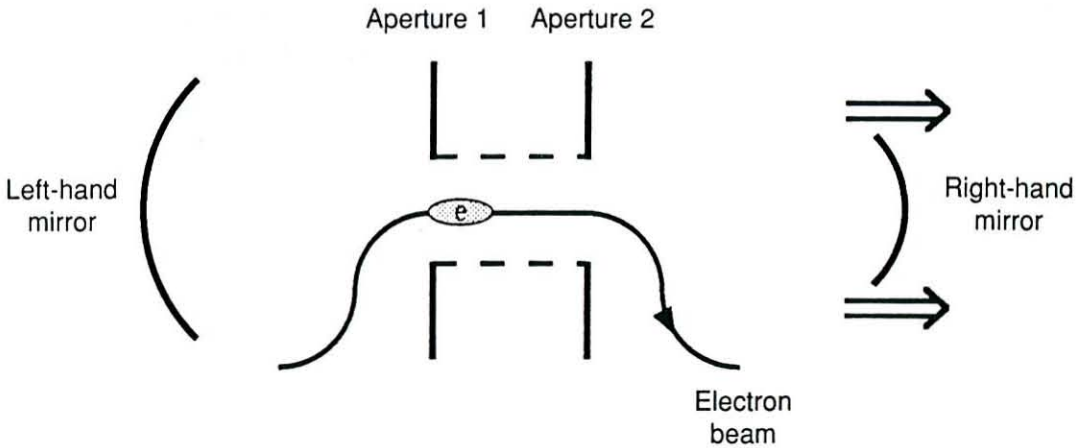


Figure 4-19. Schematic of an edge-coupling arrangement in a stable resonator. [XBL 922-5595]

Table 4-7. Parameters for edge coupling in a stable resonator, optimized for the CDRL IRFEL.

Wavelength range (μm)	Radius of coupling mirror (mm)
3–6.84	14
6–13.7	19
12–27.4	26
24–54.7	36

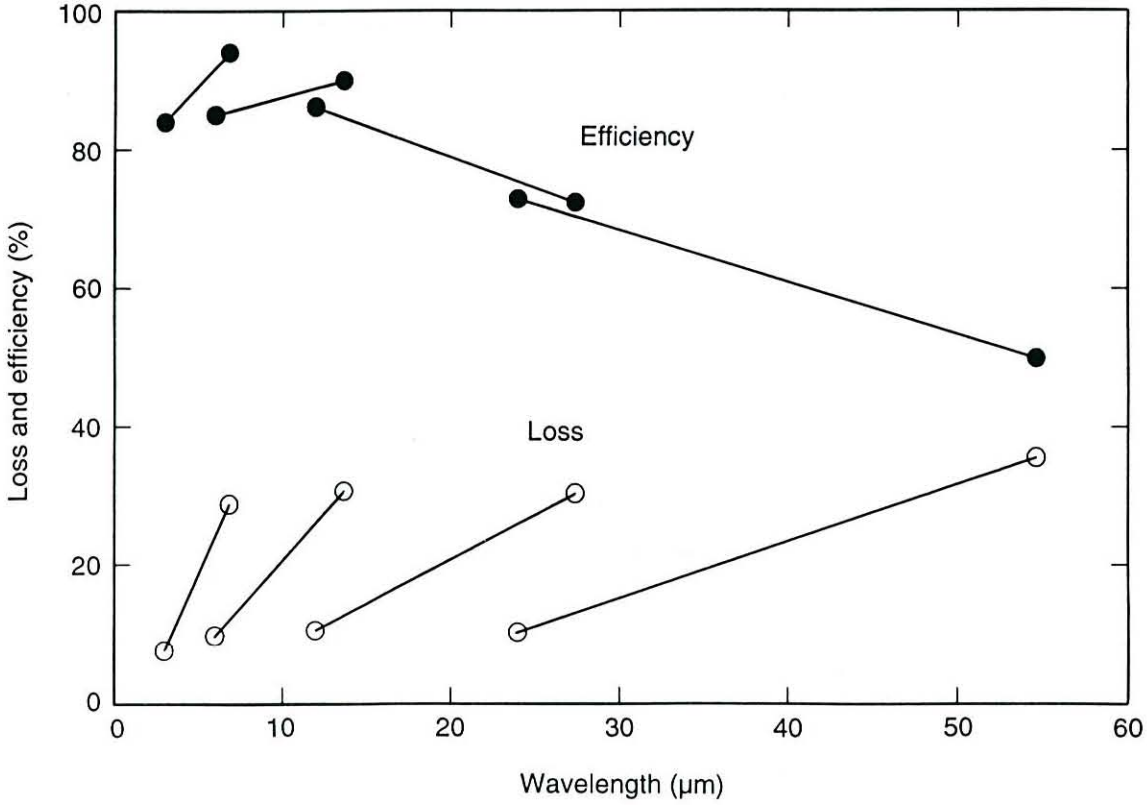


Figure 4-20. Edge-coupling performance parameters as functions of wavelength. [XBL 922-5594]

The intracavity mode profile is smooth and Gaussian-like, as shown in Fig. 4-21. Such a profile matches well to the electron beam profile.

A drawback of the edge-coupling scheme is the fact that the mode profile immediately beyond the coupling mirror has the shape of a ring, with a poor Gaussian quality factor. However, it is possible to transform the ring profile into a solid profile by using an exotic optical element known as an axicon (Fig. 4-22). Whether the use of an axicon is consistent with the broad tuning requirement of the CDRL IRFEL is an issue that merits careful study.

Edge Coupling in an Unstable Resonator. Unstable resonators have been used in many high-power lasers [Siegman, 1986]. Recently, Siegman [1991] has studied a negative-branch stable-unstable resonator for FEL applications, as shown schematically in Fig. 4-23. The mirrors are toroidal, so that the mode characteristics are different in the horizontal and vertical planes. In the vertical plane (the plane perpendicular to the page in Fig. 4-23), the resonator is stable and has a lowest-order Gaussian mode. In the horizontal plane, which is also the oscillation plane for the undulator, the cavity is a one-sided, low-magnification, confocal, negative-branch unstable resonator, with the internal focal region of the negative-branch resonator providing the focused interaction region with the electron beam.

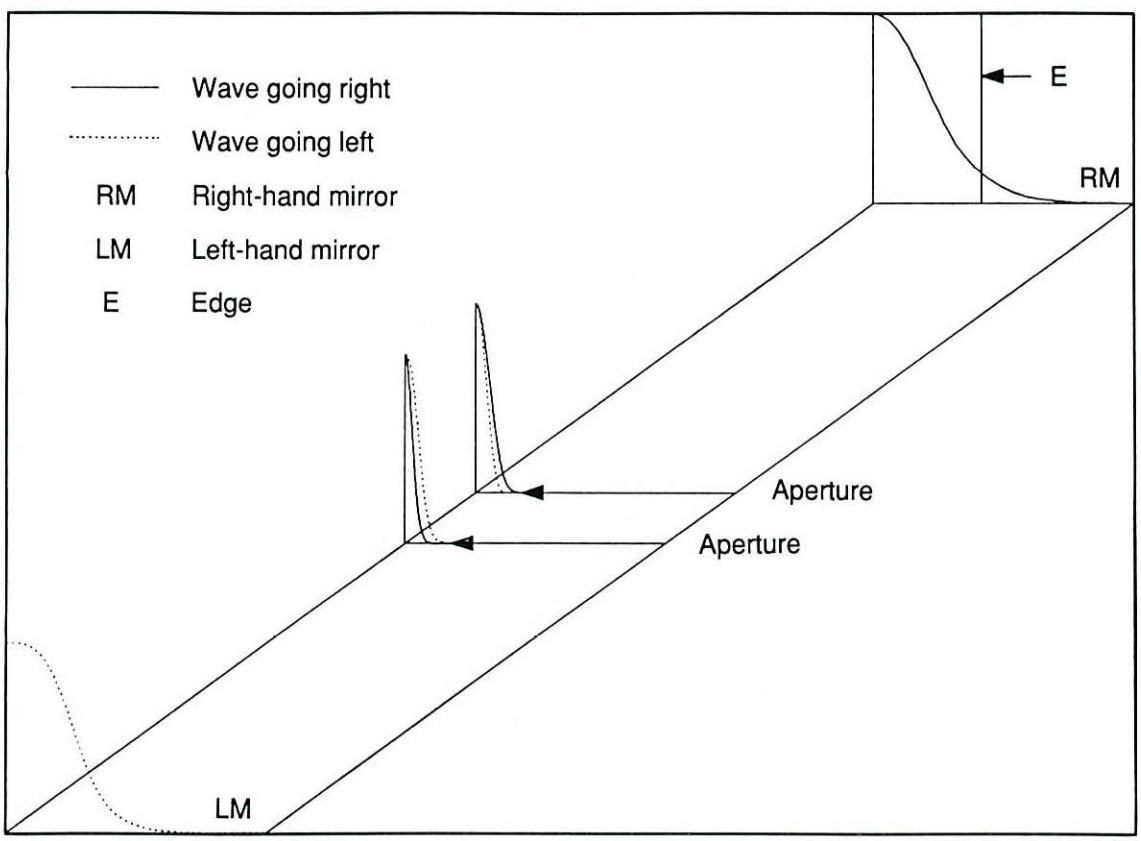


Figure 4-21. Intracavity mode profile at a wavelength of 21.5 μm, for an edge-coupled resonator. [XBL 922-5593]

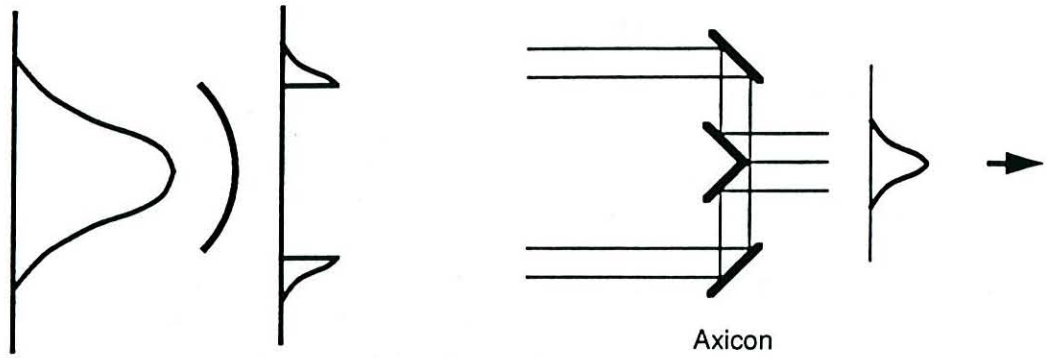


Figure 4-22. Schematic illustration of a axicon, used to improve the mode quality of an edge-coupled beam. [XBL 922-5596]

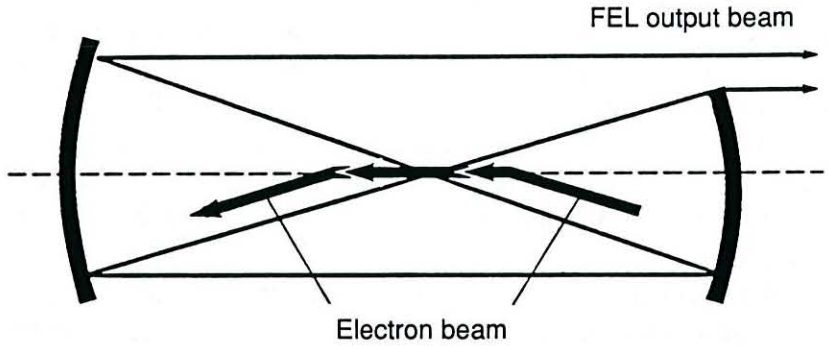


Figure 4-23. Schematic top view of an unstable resonator. By using toroidal mirrors, the cavity can be made geometrically stable, with low loss, in a direction perpendicular to the page, while operating as a one-sided, confocal, negative-branch unstable resonator in the plane of the page. [XBL 922-5592]

Preliminary calculations [Siegman, 1991] indicate that this type of resonator has attractive features for long-wavelength, widely tunable IRFELs, such as the one described here. We intend to carry out a more extensive study in the future to compare the performance of such a resonator with that of the hole-coupling scheme.

4.4 Optical Cavity and Diagnostics

In this section, we first describe the optical cavity, explicitly outlining the engineering requirements imposed on the various optical elements and their supports. Next, we describe the diagnostics that will allow us to evaluate FEL performance and that will serve as the front end of a feedback-controlled cavity alignment and stabilization system. Section 4.3.3 then outlines the underlying principles and design of semiconductor switch–controlled pulse slicers and pulse pickers, which will be used to further tailor the FEL output to user requirements. Finally, we briefly describe the beam transport system that will deliver infrared radiation to CDRL researchers.

4.4.1 Specifications for the Cavity Optics

The basic optical cavity layout is shown schematically in Fig. 4-24, and the basic cavity parameters are given in Table 4-8. Of particular importance, the cavity optics can suffer only low losses, and good surface quality is necessary. To ensure a clean optical mode pattern, we require a maximum tolerance of $\lambda/20$, peak-to-peak at 10 μm, for surface flatness, coma, astigmatism, and spherical aberrations. These specifications, however, can currently be met by commercial manufacturers. The maximum spot size on the mirror surface occurs during operation at 50 μm. Gaussian optics predicts a spot size $w_M \cong 5$ cm, which would require 15-cm optics to minimize diffraction losses; however, the simulations described in section 4.3 indicate that diffraction at the exit plane of the undulator bore will increase the spot size and thus require 25-cm optics. Transverse mode control will be handled using intracavity apertures.

For the FEL to operate efficiently, the Rayleigh length z_R should be matched to the undulator length to provide a good overlap between the electron beam and the optical beam. From simulations (again, see section 4.3), we have determined for different wavelength ranges a ratio of the spot size on the mirror to the mirror hole size that maximizes the outcoupled power. As shown in Fig. 4-25, a small deviation ΔR from the design value for the radius of curvature leads to a large deviation in both z_R and the spot size on the mirror (and therefore the fraction of outcoupled power). We therefore require a 0.04% tolerance on the 12.38-meter radius of curvature, which can again be met by commercial manufacturers.

The mirror must also handle high peak and high average intracavity power densities. When the FEL operates in a high-efficiency (1/2N) sideband mode, the intracavity power levels are given by

$$P_{\text{cw}} = \frac{\text{efficiency}}{\text{loss}} P_{\text{cw}}^{\text{beam}} \cong \frac{1.25\%}{10\%} 370 \text{ kW} = 46 \text{ kW} \tag{4-36}$$

$$P_{\text{peak}} = 107 \text{ MW}\left(\sim 10\% \text{ of } P_{\text{peak}}^{\text{beam}} = 1 \text{ GW}\right) \tag{4-37}$$

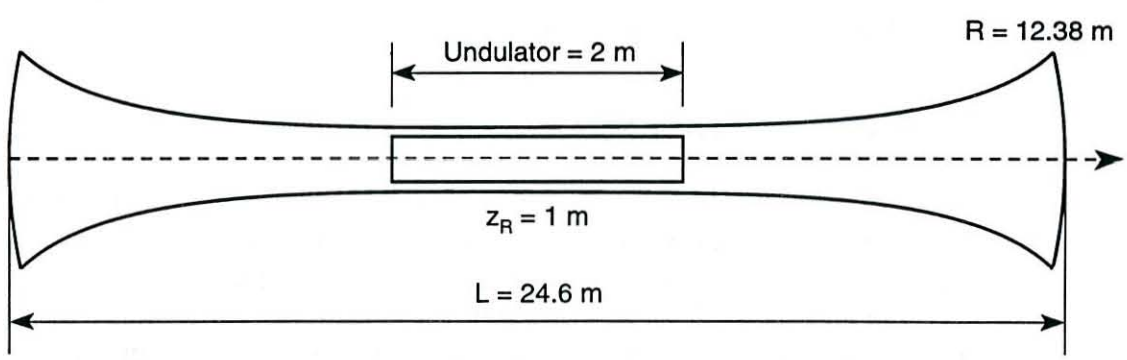


Figure 4-24. Schematic of the basic cavity layout. R = mirror radius of curvature; z_R = Rayleigh length. [XBL 922-5613]

Table 4-8. Cavity dimensions and output parameters.

Wavelength range [μm]	3–50
Cavity length, L [m]	24.6
Undulator length, L_u [m]	2.0
Rayleigh length, z_R [m]	1.0
Radius of mirror curvature, R [m]	12.38
Stability parameter, g	–0.987
Micropulse duration, τ_p [ps]	35
Intracavity cw power, P_{cw} [kW]	46
Intracavity peak power, P_{peak} [MW]	107
Micropulse energy E_{pulse} [μJ]	
at 10 μm and 12.2 MHz	50
at 10 μm and 6.1 MHz	100
Peak output power, P_{peak}^{out} [MW]	2
Repetition rate [MHz]	12.2 or 6.1
CW output power, P_{cw}^{out} [kW]	0.6
Spectral bandwidth at 10 μm, $\Delta\lambda/\lambda$	$\leq 10^{-3}$

and the intracavity power densities on the mirror surface are then given by

$$\left.\frac{dP}{dA}\right|_{cw} = 6.1 \text{ kW/cm}^2 \tag{4-38}$$

$$\left.\frac{dP}{dA}\right|_{peak} = 14 \text{ MW/cm}^2 \tag{4-39}$$

The surface quality we demand can be maintained without active cooling only for average power densities below 200 W/cm^2. We therefore require actively cooled mirrors. The peak power density is well below the single-pulse damage threshold for uncoated OFCH-copper, but the cumulative effect of a 12-MHz pulse train is unclear. Fortunately, the high vacuum that must be maintained in the optical cavity will greatly reduce surface contamination, which is the main source of surface damage.

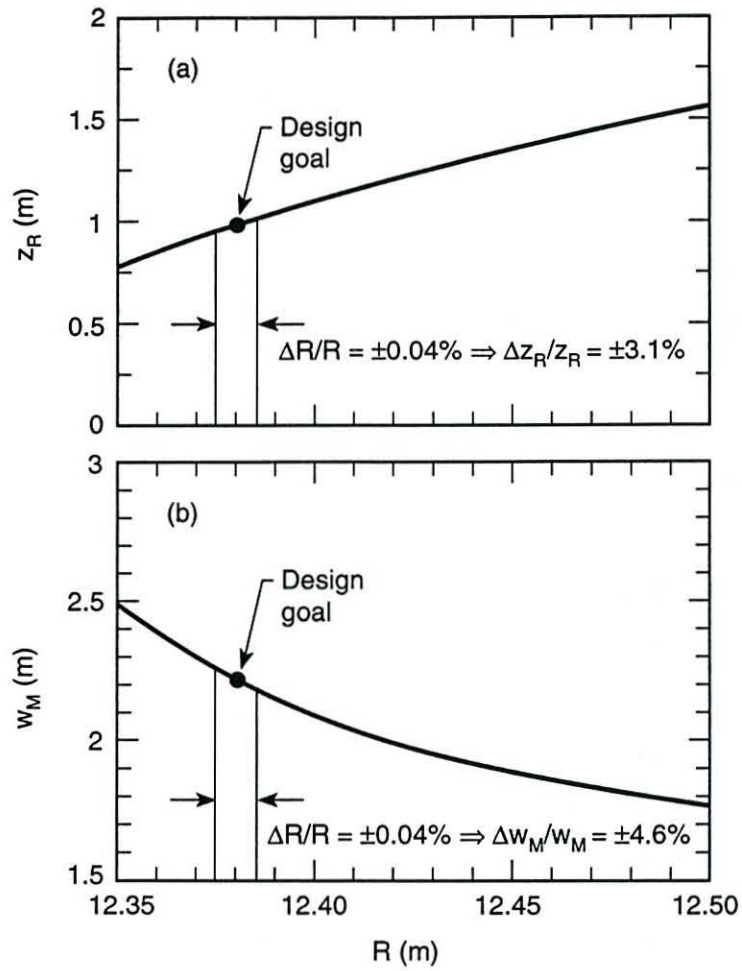


Figure 4-25. (a) The Rayleigh length z_R and (b) the laser spot size on the mirror, w_M, as functions of the radius of mirror curvature, R. The vertical lines indicate a 0.04% tolerance around the design value of 12.38 meters. [XBL 922-5612]

The mirror mounts must allow accurate alignment . As shown in Fig. 4-26, mirror misalignment by an angle θ_M leads to a change in the angle of the optical axis, θ_{OA}, given by

$$\Delta\theta_{OA} \cong \frac{R}{2R - L}\Delta\theta_M \tag{4-40}$$

To keep the optical axis within 1/10 of the mode rms angle

$$\sigma = \left(\frac{\lambda}{4\pi z_R}\right)^{1/2} = 890\ \mu\text{rad} \tag{4-41}$$

we demand a pointing accuracy of $\Delta\theta_M < 1.0\ \mu$rad . (Off-the-shelf mounts are available with a pointing accuracy better than 0.4 μrad.) In addition, the mirror mount must have a true gimbal design and must be able to accommodate large 25-cm water-cooled optics.

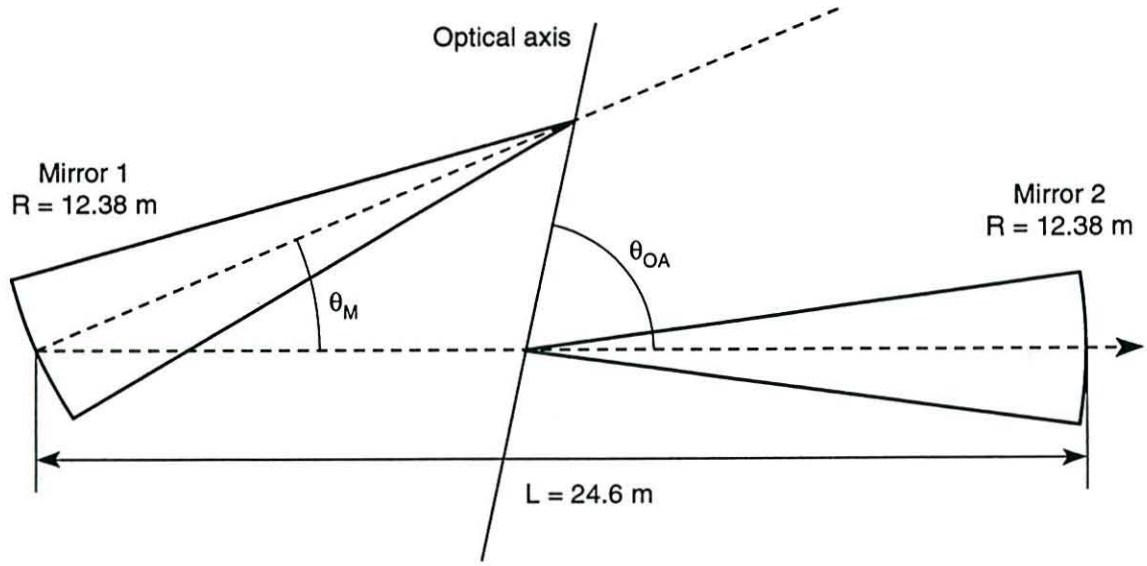
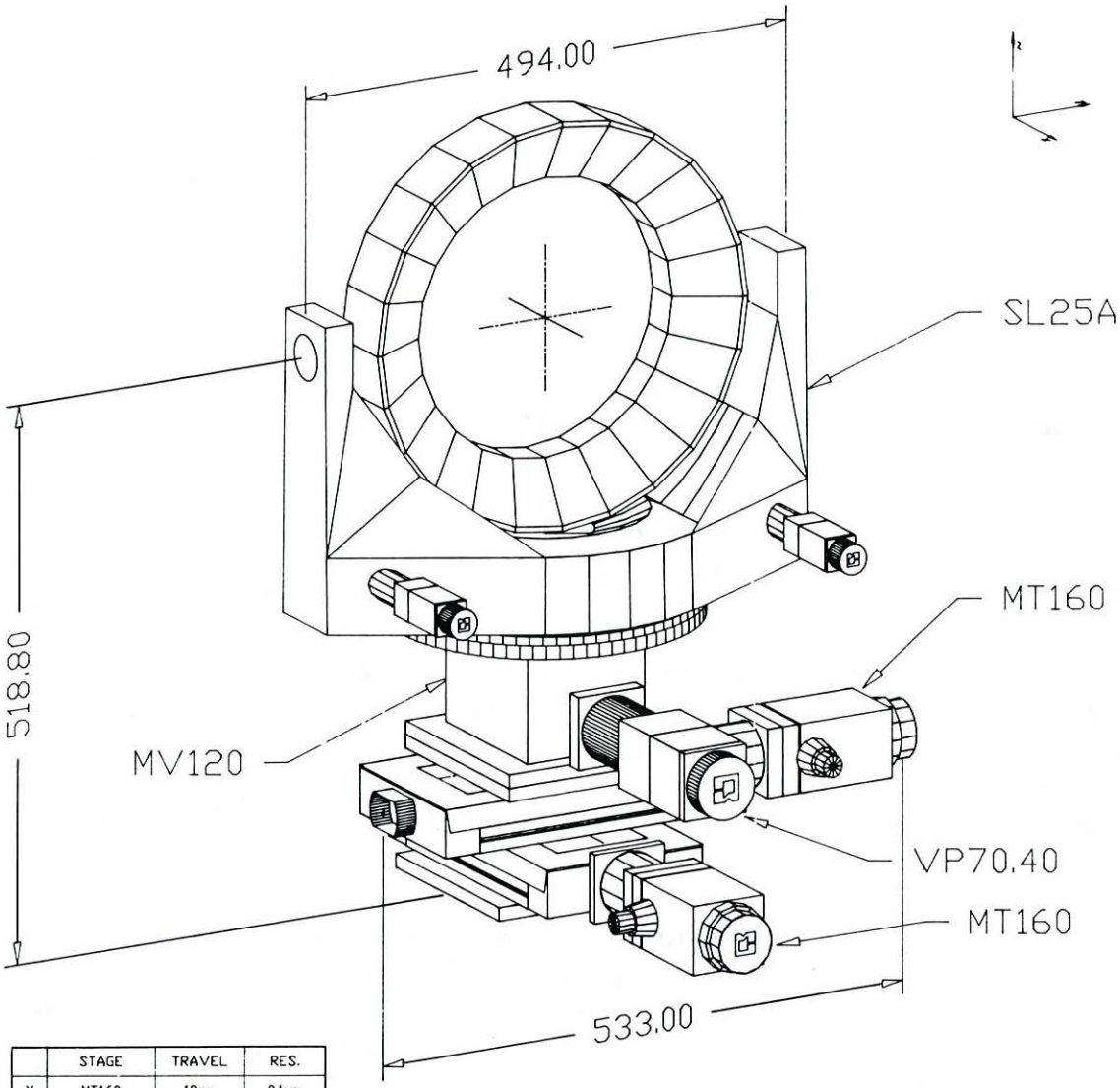


Figure 4-26. Depiction of the effect of an angular mirror misalignment, θ_M, on the position of the optical axis. [XBL 922-5614]

Angular adjustments must have a resolution better than 1 μrad. The mount should allow remotely controllable, trackable translations in the *x, y,* and *z* directions and two orthogonal rotations. (Here, the laser propagates in the *x* direction and *yz* defines the transverse plane.) Resolution must be 0.1 μm in the *x* direction and 1 μm in the transverse plane. An interferometric measuring unit will be used to measure cavity length changes with a resolution of 0.2–0.3 μm and can also be used to monitor pitch, roll, and yaw of the mirror mount. The motion control system must allow for a feedback control system based on the interferometric measurements. A large-aperture (~22-cm), pin-actuated iris diaphragm will be used for transverse mode control. Finally, all electromechanical and electro-optical components must be compatible with the radiation and vacuum environment of the optical cavity. Commercially available mounts, translation stages, and motion-control modules that interface with personal computers meet the above specifications. One such assembly is shown in Fig. 4-27.

Two options are available for the support system. The option selected for the conceptual design involves mounting the mirror mount and stages directly to the vacuum chamber, then supporting the vacuum chamber with a pneumatically isolated table. The alternative consists of an electronic vibration-isolation system that supports both the mirror mount and the translation stages and dynamically damps out system vibrations inside the vacuum housing. The vacuum housing is then bolted to a concrete block, which provides static inertial isolation. In both options, the vacuum housing of the mirrors is isolated from the beam pipe using flexible bellows. A final engineering design will be based on the adequacy of these two options in damping out vibrations, after we have measured the actual frequency spectrum and levels of vibrations in the accelerator vault. A conceptual layout of the first design alternative is shown in Fig. 4-28.



	STAGE	TRAVEL	RES.
X	MT160	10mm	0.1um
Y	MT160	10mm	0.1um
Z	MV120	10mm	1um
θx			
θy	SL25A	360°	5/0.5urad
θz	SL25A	360°	5/0.5urad

Figure 4-27. A mirror mount, available commercially from Klinger Scientific, that meets the specification for the IRFEL optical cavity end mirrors. [XBL 922-5608]

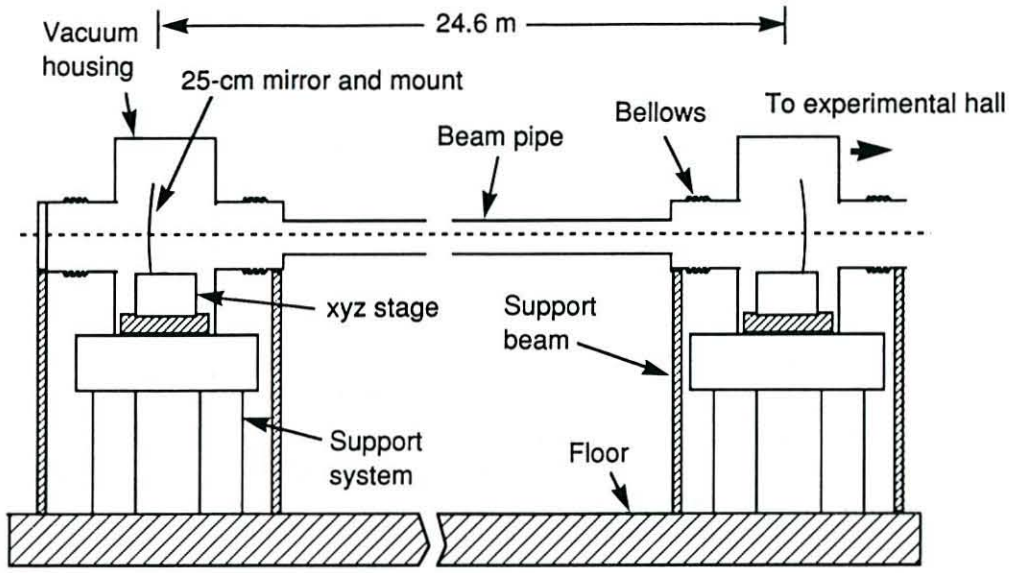


Figure 4-28. Conceptual layout of the mirror mount and support system. [XBL 922-5590]

4.4.2 Optical Alignment and Diagnostics

The basic layout for the optical alignment and diagnostics system is shown in Fig. 4-29. The FEL will be aligned as follows. An optical axis is defined by aligning a cw He-Ne laser and a pulsed or cw CO_2 laser on the undulator axis. (All the radiation diagnostics will be aligned on this axis.) The initial electron beam is then aligned by making the electron beam (at low duty cycle) overlap the He-Ne laser beam on alignment screens. Fine tuning at full electron beam power is then done by maximizing the intensity of the on-axis spontaneous emission. Finally, the optical cavity is aligned, first with a cw visible and/or infrared laser and then by maximizing the FEL output.

Optimizing the performance of the FEL (both during the start-up phase and during normal operation), as well as providing the user with all pertinent FEL output parameters, requires measuring peak and average output power levels, macropulse and micropulse durations, wavelength, time-averaged and instantaneous line widths, and the output beam mode quality. Average output power will be measured with thermopiles, and peak power will be estimated from the average power, once the pulse duration is known. The time evolution of the pulse train will be monitored using room-temperature or cooled intrinsic photoconductors, such as HgCdTe, Ge:Cu, or Ge:B. The signal from these detectors will also be used as the basis for feedback-controlled cavity alignment.

Average wavelength and line width will be measured using a 1-meter spectrograph, with suitable gratings and a one-dimensional pyro-array detector. Resolution for the wavelength measurement ($\Delta\lambda/\lambda$) will be about 10^{-4}. Stabilizing the wavelength at which the FEL operates will require tracking the spectral peak, which can be done with a resolution of 10^{-5}. We plan to measure the spectral properties of each micropulse by

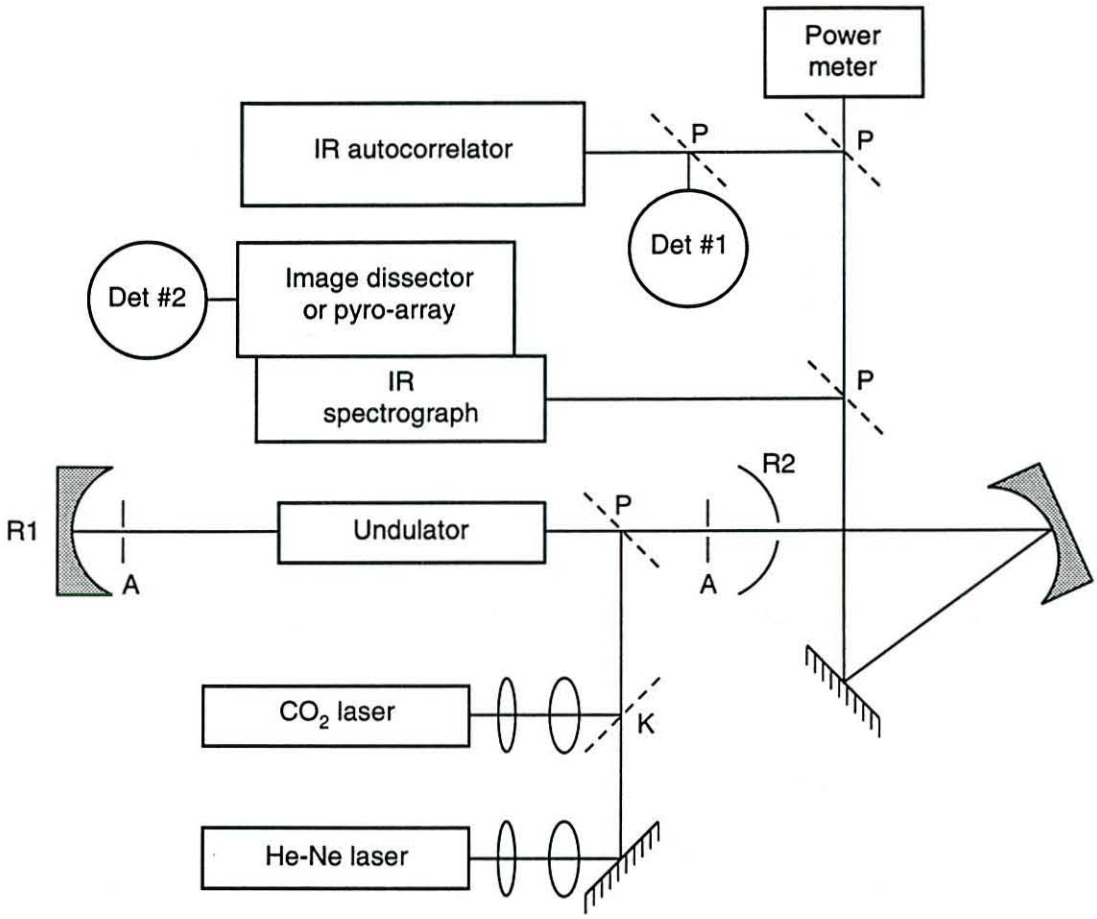


Figure 4-29. Schematic layout of the optical diagnostics. R1 and R2 are the cavity mirrors; the P's are partially reflecting mirrors; K is a kinematic mirror; the A's are transverse apertures; and Det. #1 is an intrinsic photoconductor detector that monitors the pulse train. The spectrograph–pyro-array combination is used to record average spectral information. An image dissector replaces the pyro-array to obtain single-pulse spectral information on a fast single-element detector, Det. #2. [XBL 922-5615]

replacing the pyro-array with an image dissector, set up as shown in Fig. 4-30 [Baldis et al., 1977]. An image dissector switches slices of arbitrary width from a linear infrared image (in this case, a single pulse spectrum) onto a single-element detector, with a time delay between successive slices that depends on the round-trip time within the instrument. The round-trip time thus determines the time resolution, which can be better than 5 ns.

The micropulse duration will be measured using an infrared autocorrelator. The underlying idea in autocorrelation is to split an incident pulse into two half-intensity pulses and then to recombine then in a nonlinear medium. Only when the intensity is high enough (requiring good overlap between the two pulses) will a second-harmonic signal be generated. Two different types of autocorrelators will be constructed: a scanning autocorrelator that employs a time-varying delay unit [Ippen and Shank, 1975]

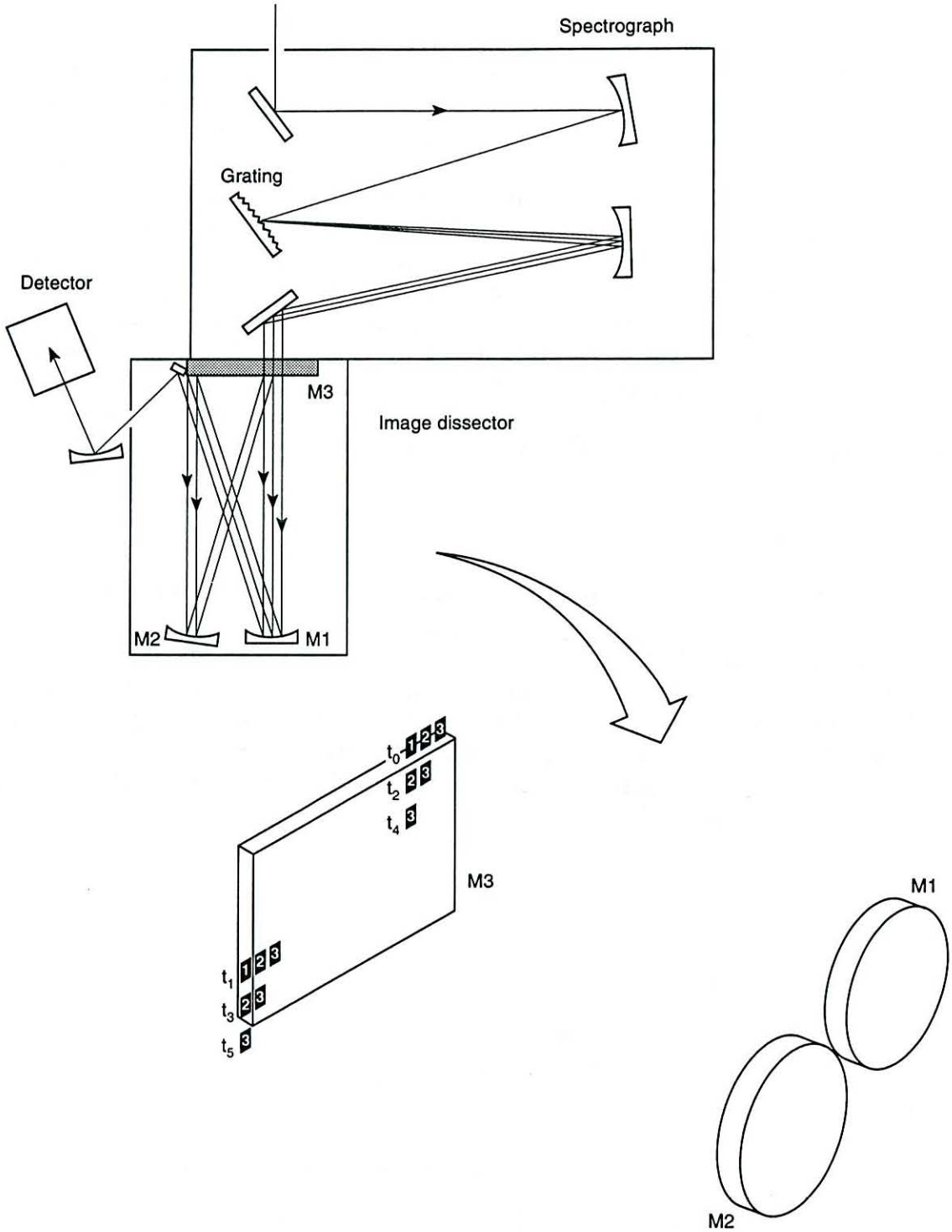


Figure 4-30. Schematic of a single-pulse measurement setup using an image dissector. Slices from a spectral image are sent sequentially to the detector, with a time delay between slices equal to the round-trip time within the instrument. The figure depicts the optical paths of three slices from an infrared spectrum. Slice 1 exits the image dissector at t_1, following a single reflection from mirror M1; slices 2 and 3 are further reflected from mirrors M3, M2, M3, and M1, before slice 2 exits at t_3. Slice 3 requires another round-trip before exiting at t_5. [XBL 922-5616]

and a single-pulse autocorrelator based on non-collinear optical mixing [Kolmeder et al., 1979]. The former requires many pulses to construct the autocorrelation; the two halves of each split pulse receive different time delays, and the relative time delay for succeeding pulses is varied slowly by slowly changing the path lengths the pulses travel (by means of rotating glass blocks, for example). By measuring the second-harmonic intensity as a function of delay, we obtain the pulse width. Typically, one scanning autocorrelation trace can be obtained in 1–10 μs; however, this time scale is comparable to the optical cavity decay time. In a single-pulse autocorrelator, it is the physical length of the region in which the second harmonic is generated that is measured and that yields the pulse length. To truly qualify as a single-shot device again requires the use of an image dissector and a fast single-element detector. Commercially available nonlinear crystals allow frequency doubling of wavelengths up to 12.6 μm (for example, $AgGaSe_2$ can be used in the 3- to 12.6-μm range). Further, recent experiments suggest that CdMnTe could be used to extend the wavelength range to 40 μm [Becla et al., 1992].

4.4.3 Pulse Control

In some experiments, a single pulse, shorter than the nominal infrared micropulse, may be required. Semiconductor switching offers a practical means for providing such pulses [Alcock and Corkum, 1979]. The idea is to create free-carrier pairs in a semiconductor, on a time scale that is short compared with the incident infrared pulse duration, using a visible control pulse (see Fig. 4-31). When the visible photon energy is higher than the band-gap energy, free-carrier absorption terminates transmission; when the plasma density of free carriers reaches the critical density for the infrared radiation, the semiconductor becomes highly reflective.

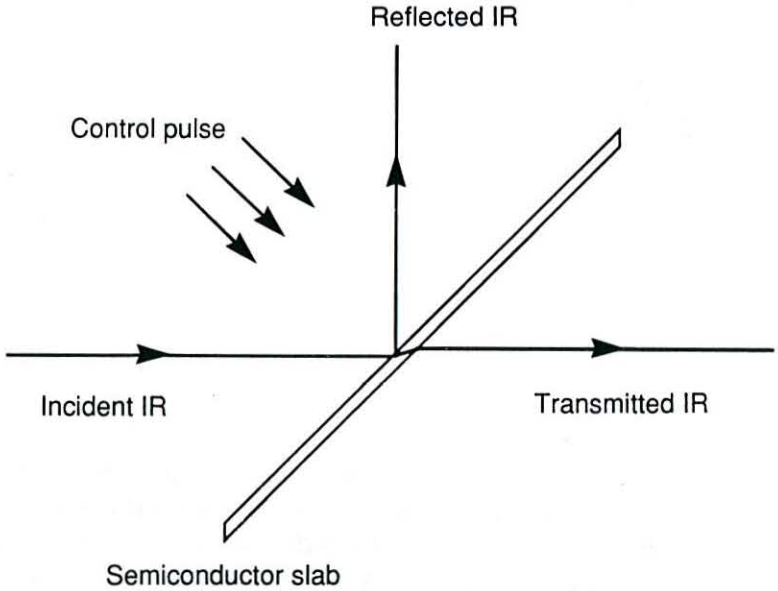


Figure 4-31. Schematic of a semiconductor switch used to provide output pulses shorter than the nominal infrared pulse duration. [XBL 922-5591]

The control pulse should have a power density of 10–50 MW/cm^2 at visible wavelengths. For example, a 1- to 10-ps pulse at 532 nm, containing a few tens of microjoules in a 1-mm spot, is sufficient to create a fast switch [Corkum, 1983]. The time scales for which switching is practical can be inferred from Fig. 4-32 [Alcock and Corkum, 1979]. Typically, total reflection occurs in about 5 ps and significant attenuation occurs on a 1- to 2-ps time scale.

To produce pulses shorter than the infrared micropulse, two semiconductor switches will be configured as a pulse slicer, as shown in Fig. 4-33. A short pulse is sliced from a longer pulse by using one semiconductor to remove the leading tail of the micropulse (by transmission), and a second to remove the trailing tail (by reflection). This method has been used successfully in generating 1- to 2-ps pulses from 50-ns CO_2 laser pulses at 10.6 μm [Corkum, 1983].

As Fig. 4-32a demonstrates, the surface density of free carriers can remain high for tens of picoseconds, a phenomenon that we will use to our advantage for a pulse picker. As shown schematically in Fig. 4-34, a pulse picker selects one pulse from the infrared pulse train. A single suitable semiconductor in reflection mode serves well as such a device. Since the free-carrier density remains high for tens of picoseconds, the control pulse can be fired onto the semiconductor well before the arrival of the infrared pulse.

According to Alcock and Corkum [1979], faster fall times for the surface density of free carriers may be achieved by choosing semiconductors with a high electron-hole recombination rate or by enhancing the rate (for example, by using a highly polished surface). Such a fast-closing semiconductor switch may be useful as single-element pulse slicers. The availability of such semiconductors would also allow a micropulse duration measurement, based on correlating a short visible-light pulse with the infrared pulse. The

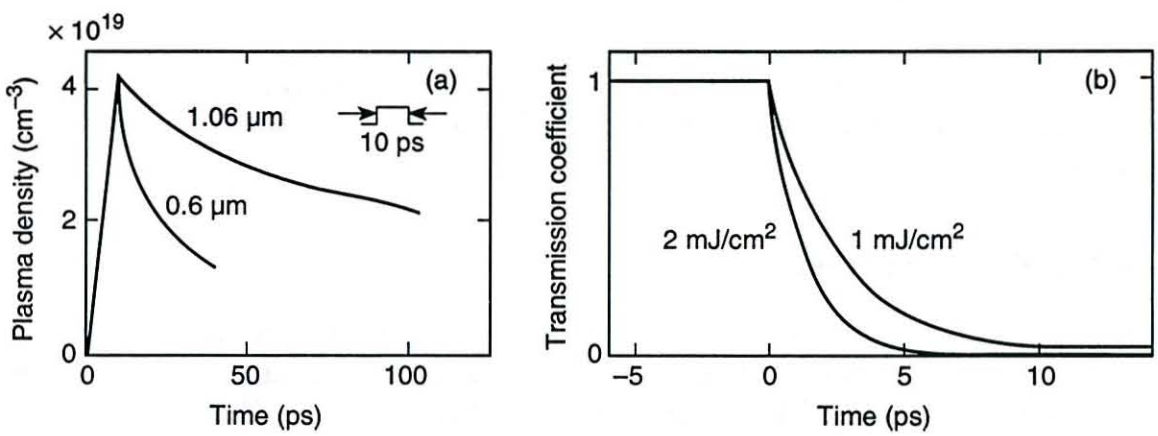


Figure 4-32. (a) Surface density of free-carrier pairs in germanium, plotted as a function of time for a 10-ps, 1-mJ/cm^2 (absorbed energy), 1.06-μm pulse (upper curve) and for a 10-ps, 0.5-mJ/cm^2 (absorbed energy), 0.6-μm pulse (lower curve). (b) Transmission coefficient of germanium as a function of time, showing the attenuation of 10-μm radiation due to an intravalence band transition induced by a 10-ps pulse of 1-μm radiation at t = 0. The absorbed energy density was 1 mJ/cm^2 (upper curve) and 2 mJ/cm^2 (lower curve). [XBL 922-5617]

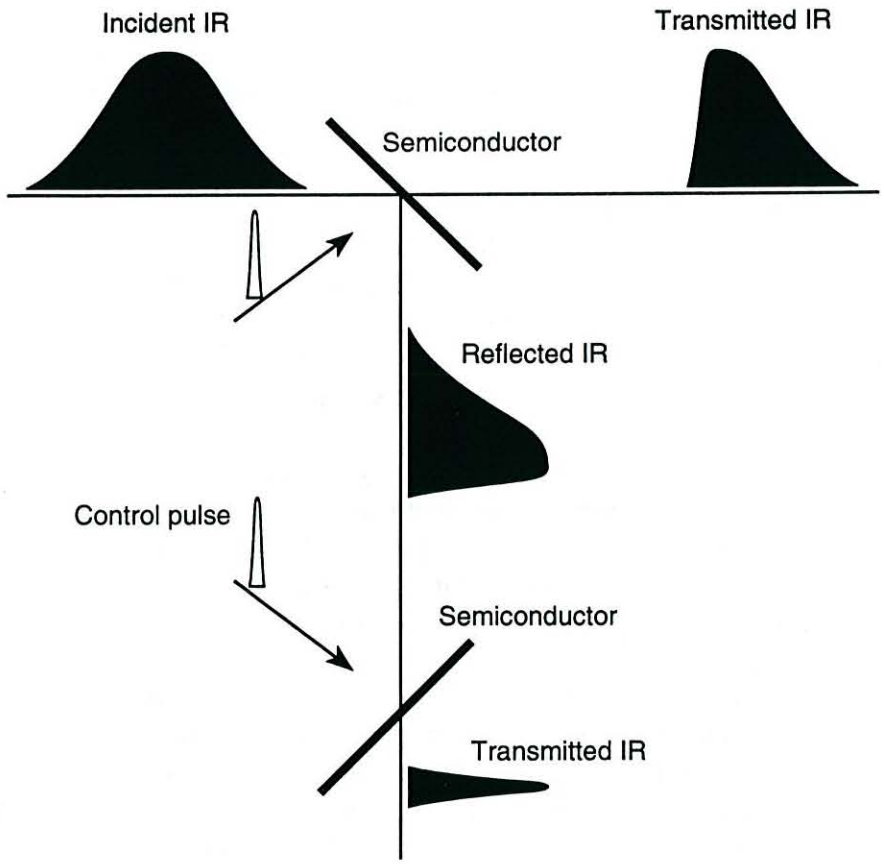


Figure 4-33. Schematic layout of a pulse slicer based on a pair of semiconductor switches arranged in series. [XBL 922-5618]

semiconductor would be used as a gate that could be swept across the infrared pulse by changing the delay time between visible and infrared pulses. Semiconductor switching may also be useful as a technique for cavity dumping.

4.4.4 Optical Beam Transport

The IRFEL output must propagate at least 30 meters to reach the experimental hall; then, depending on the location of the experiment, it must travel an additional 10–20 meters within the hall. To reach laboratories on the second level of the CDRL, the beam must cover yet another 50 meters. Since infrared beams are prone to significant diffraction, a suitable beam transport system must be provided to guide the beam for distances up to 100 meters, at the same time maintaining it at a reasonable size.

Since the diameter of the output-coupling hole is small compared with the mode size, the output can be approximated by an Airy pattern. This output will first be collimated. An image-relay system will then be used to transport the beam to the experimental hall.

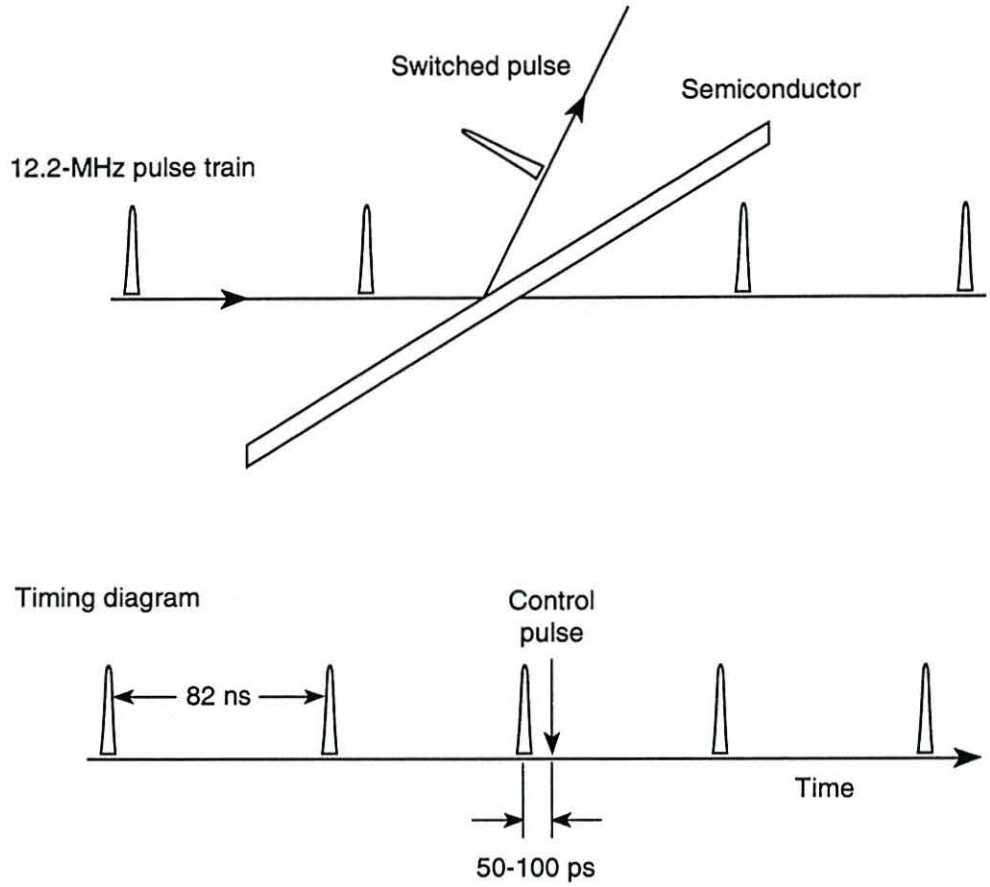
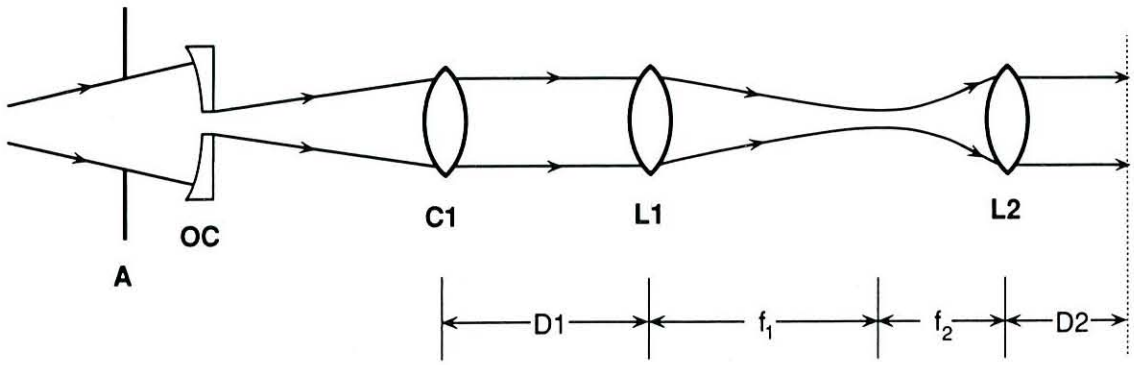


Figure 4-34. Schematic layout of a pulse picker based on a semiconductor switch. [XBL 922-5619]

Figure 4-35 shows the optical arrangement of the transport system. Because of the fast divergence of beams at infrared wavelengths, image relaying is necessary to maintain the beam at a practical size. Two stages of relay imaging are required to cover 30 meters. From the entrance port in the experimental hall, another image relay system will be used to adjust the beam size and bring it to the experiment. Additional optics will relay the beam to the second level of the building.

For maximum flexibility, all transport optics are high-reflectivity, overcoated copper mirrors, similar in their specifications to the optical cavity mirrors. Reflective optics are used for the lens systems, shown in Fig. 4-36. Each system consists of two matched copper mirrors, separated such that the angle θ is less than 10°, to minimize astigmatism. In this arrangement, the effective focal length of the system is given by $f_{\mathrm{eff}} \cong R/4$, where R is the radius of mirror curvature.

Many applications require that the beam-pointing fluctuations be less than 10% of the beam diameter. This dictates the overall stability requirement for the transport system. Angular stability (mechanical and temperature induced) must be better than 5″. Position sensors will be used to guide alignment of the beam through the transport system and to provide occasional long-term directional adjustments.

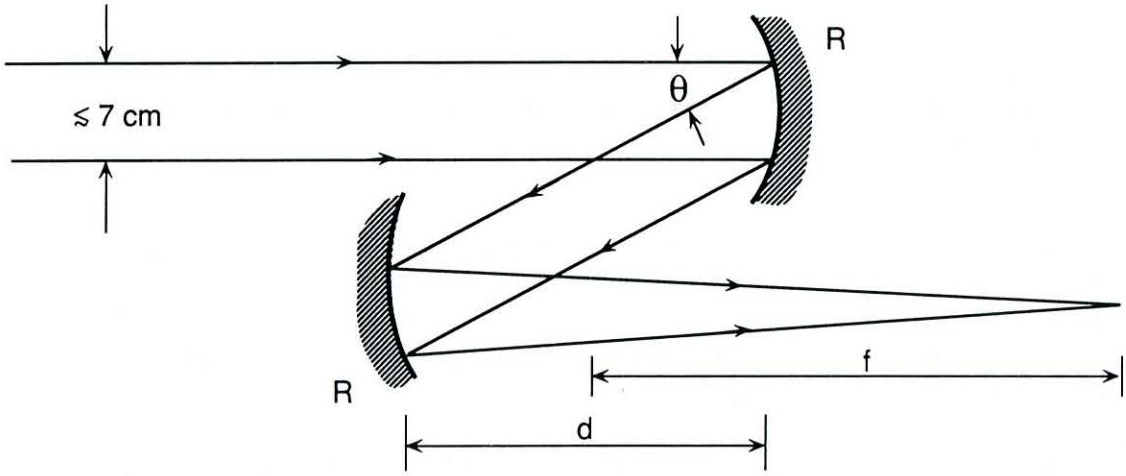


$D2 = M(f_1 + f_2) - M^2 D1$

$M = f_2 / f_1$

A = Aperture
OC = Output coupler
C1 = Collimator
L1 , L2 = Lens of focal length f_1 , f_2

Figure 4-35. Optical arrangement for the infrared beam transport system. [XCG 8912-4753]



For f >> d, f ≅ R/4

Figure 4-36. Optical arrangement for the infrared beam lens system. [XCG 8912-4754]

The entire beam path will be evacuated to $<10^{-6}$ Torr to minimize absorption losses. A Brewster-angle exit window of an appropriate material (ZnSe for short wavelengths, KrS_5 or CsI for longer wavelengths) separates the transport system vacuum from the experimental apparatus.

5.

CONTROL SYSTEM

THE design of the computerized control system for the IRFEL, which is patterned closely after that of the ALS, provides a means of accessing all machine components so that their values can be set and monitored remotely. This is done by the operator through a console equipped with video displays and data input devices. To allow flexible control, a number of computer programs are provided to the operator. The status of machine devices is displayed, with graphics where appropriate, and software is provided for archival and subsequent retrieval of machine parameters. A typical start-up sequence for machine operation will involve recalling a set of machine parameters from the archives, making a few corrections to it (either by direct operator input or under program control), and sending it to the hardware devices.

The operator interface, comprising the console displays and controls, is structured to permit efficient operation. This requires that a number of different operational scenarios be accommodated. The experienced operator will require instant access, with a minimum of advice from the programs; for the beginning operator, a programmed path will be provided to ease the learning process. A number of programs are available that will provide computer models of the machine (for example, a program that calculates the behavior of a beam through a series of steering and focusing magnets). These make it possible to implement computer tuning, that is, tuning under program control, to make the beam parameters more closely approach the idealized model.

Normal day-to-day operation will require that a set of machine settings be given to the control system as a reference and that a set of tolerances be established on these data. The control system will then advise the operator of any values out of tolerance.

The control system design is based on a highly distributed, microprocessor-based architecture. In the days before the ALS, this approach was pioneered at LBL on the Uranium Beams Project at the Bevalac accelerator complex, and many of its underlying ideas (parallel processing, completely microprocessor-based architectures, distributed data base, bus-based systems, etc.) are now widely used—for example, in the control system of the LEP collider at CERN. The major benefits of such decentralized systems are improvement in system response, substantial simplification in programming, lower maintenance cost over the life of the accelerator, and the ability to adapt to future developments, both in hardware (processors, etc.) and in network technologies and topologies (Ethernet, Fiber Distributed Data Interface or FDDI, etc.).

The design philosophy for the control system is to have a reliable, fast, and user-friendly system, with complete capability for reporting all operating parameters, from initial commissioning through routine, day-to-day operation. All aspects of the linac and undulator will be controlled through a distributed system based on many high-performance microcomputers (using the Intel 80186, 80386, and 80486 microprocessors) operating in parallel. With this very flexible architecture, we can make careful trade-offs between hardware and software, thereby using technology effectively and holding software costs down. In addition, using a compatible family of processors will simplify the interface among the many parts of the system, further reducing software cost and complexity.

To facilitate the development of specialized auto-tuning or modeling applications software, workstations (the IBM PC/AT family and others familiar to accelerator physicists and operators) can be connected to the control system. This is assured by providing for an industry-standard network interface with high-speed access to the accelerator data base. Since these programs will be written mostly in high-level languages (BASIC, FORTRAN, PLM, C, and Pascal), they will be easy to integrate into the main part of the control system if even faster access and higher performance should be desired.

This transition is particularly simple if the workstations utilize Intel-based processors, as does the IBM PC family, since the processor used in the main part of the control system will be an Intel 80486. This microprocessor has the hardware-supported capability to run multiple operating systems simultaneously [MS DOS, UNIX (Xenix), or RMX, a real-time operating system]. Additional features carried forward include

- Local debugging capability
- High-level programming languages
- Homogeneous processor architecture throughout the system
- Ease of maintenance and repair
- Use of workstations
- Data-driven software capability
- Built-in help functions

Furthermore, it will be possible to utilize a substantial amount of existing software to minimize software development costs. The understanding of the processors, architectural features, and computer languages attained in the course of ALS commissioning and prior projects will lead to considerable cost savings and rapid commissioning.

5.1 SYSTEM ARCHITECTURE

The overall system architecture, shown in Fig. 5-1, consists of

- A large number of single-processor units (Intelligent Local Controllers, or ILCs, illustrated in Fig. 5-2).
- A central data base storage/collector (Collector Micro Module, or CMM, Fig. 5-3).
- The operator display driver (Display Micro Module, or DMM, Fig. 5-4).

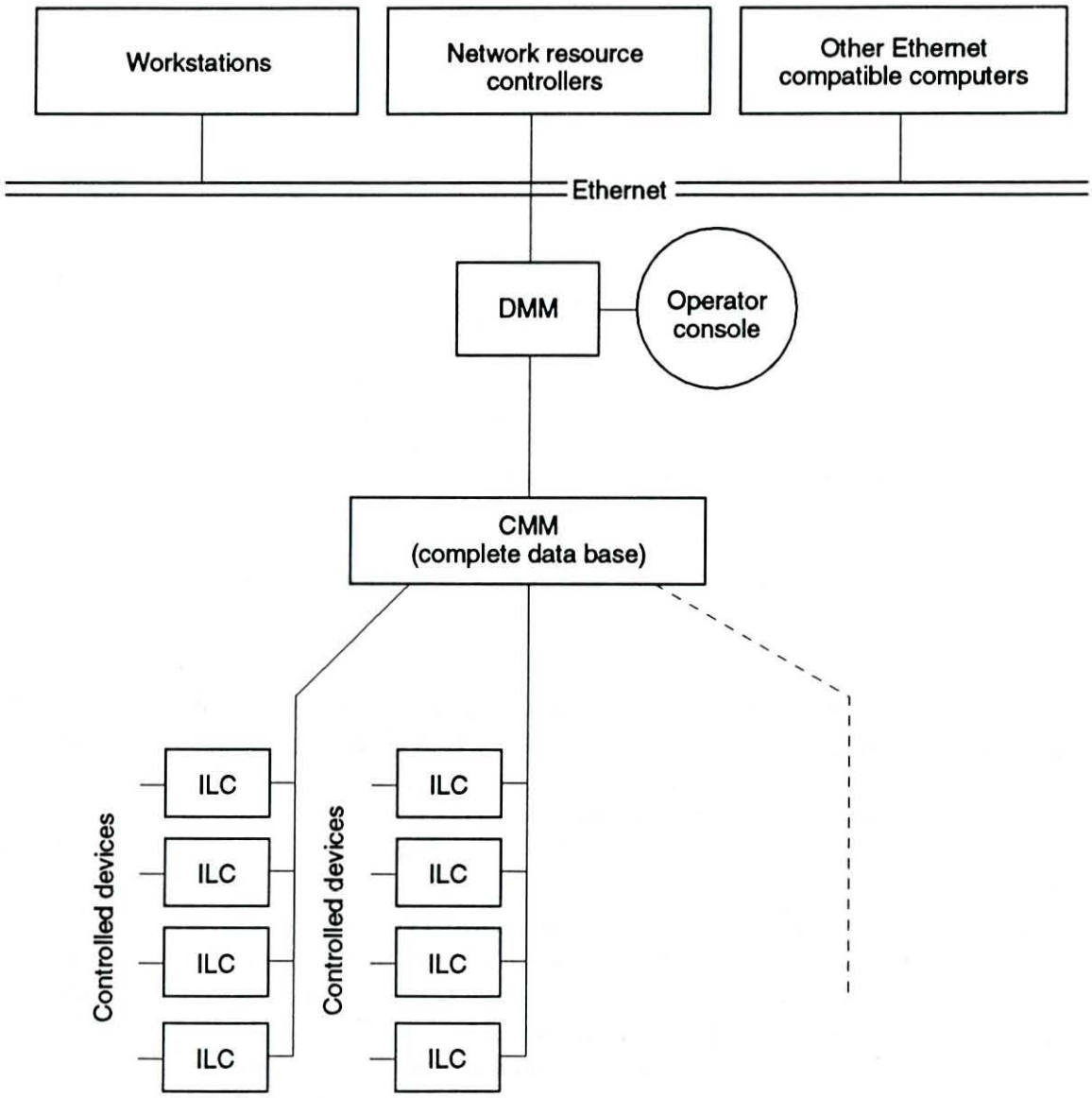


Figure 5-1. Block diagram of the overall control-system architecture. [XBL 902-5416]

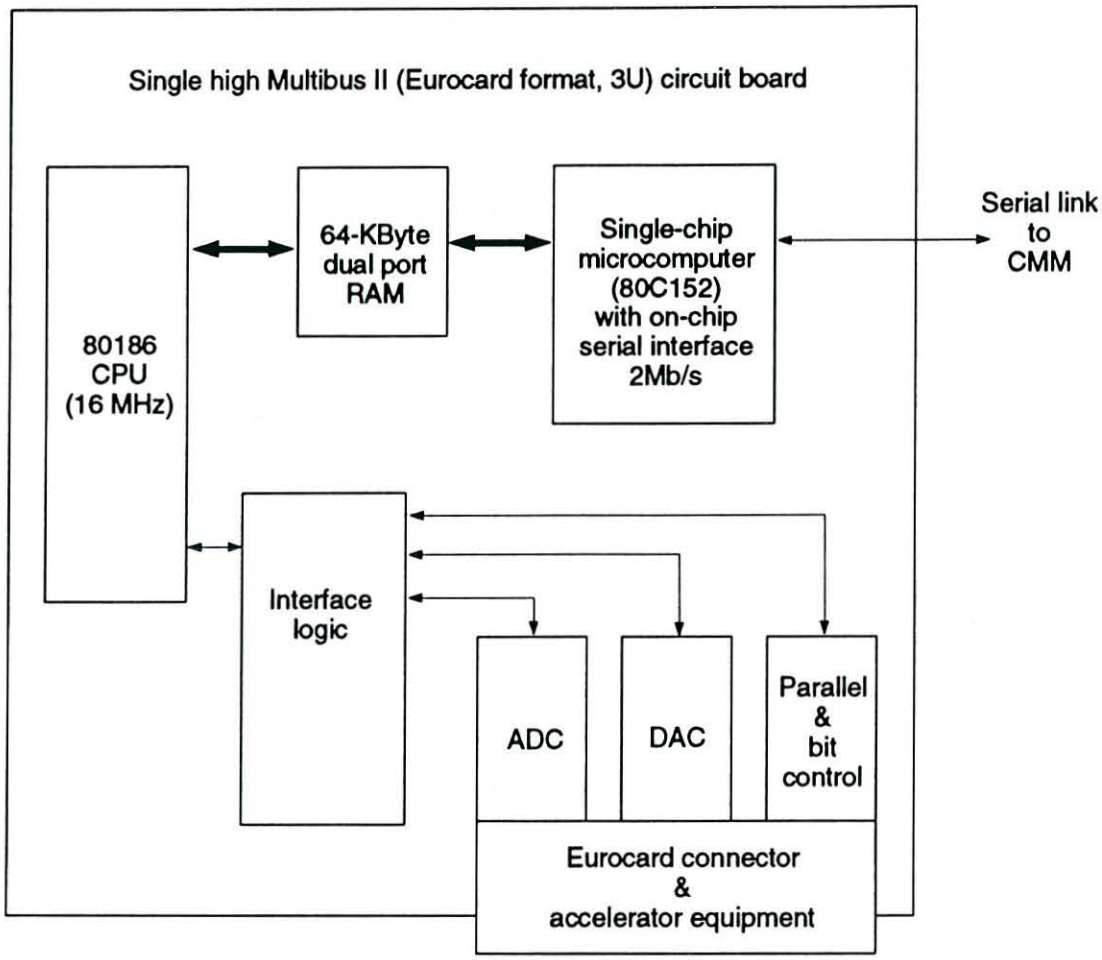


Figure 5-2. Block diagram of an Intelligent Local Controller (ILC). [XBL 902-5415]

The ILCs provide an interface to the accelerator equipment by collecting data and transmitting control instructions. They contain a local data base and reside near the accelerator hardware. A primary function of these units is to continually refresh the data stored in the central data base at the CMM.

The CMM collects the data from all the ILCs. Data are sent to and from the CMM over fiber-optic serial links at a rate of 2 Mb/s. These data are stored in dual-ported memory, so that a fresh copy of the local data bases resides at all times in the CMM.

The DMM services the operator console. Access to the accelerator data base that resides in the CMM is provided via a commercial Multibus-II to Multibus-I extension board. A word of data can be fetched in less than 1 μs. There is one DMM per operator console; each console consists of four operator stations.

An Ethernet or FDDI link connects the workstations, the network resource manager, and the DMMs. Commercial hardware is used to provide communications to and from a

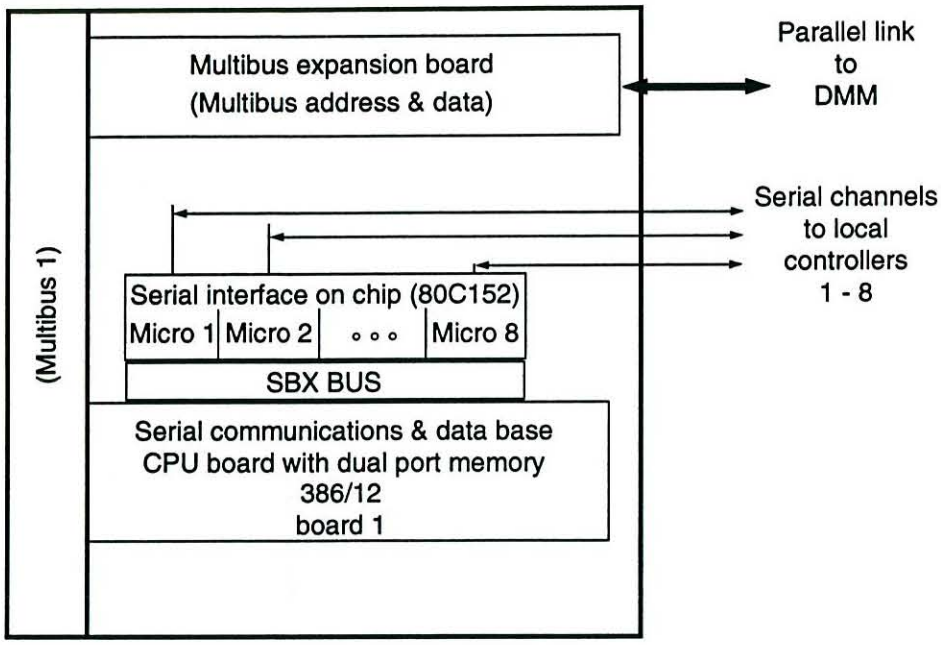


Figure 5-3. Block diagram of a Collector Micro Module (CMM). [XBL 902-5414]

file server/spooler, as well as data base entry and retrieval service between the accelerator and the various workstations and personal computers. The file server/spooler is used to record accelerator data, to log errors, to hold output data, to store applications software and the appropriate tools to aid in its development, and in general, to perform system file management. The workstations and personal computers are used for program development and problem diagnosis. The philosophy is to develop and test programs such as auto-tuning and modeling, with full access to the accelerator data base. Completed and debugged programs can then be installed for use by the operator.

The board-level computers in the control system are very powerful and can easily be augmented by board-level array processors for special functions (such as fast Fourier transforms). The Ethernet or MAP network also provides controlled experimenter access to appropriate control system parameters (such as undulator gap control) or beam-status information.

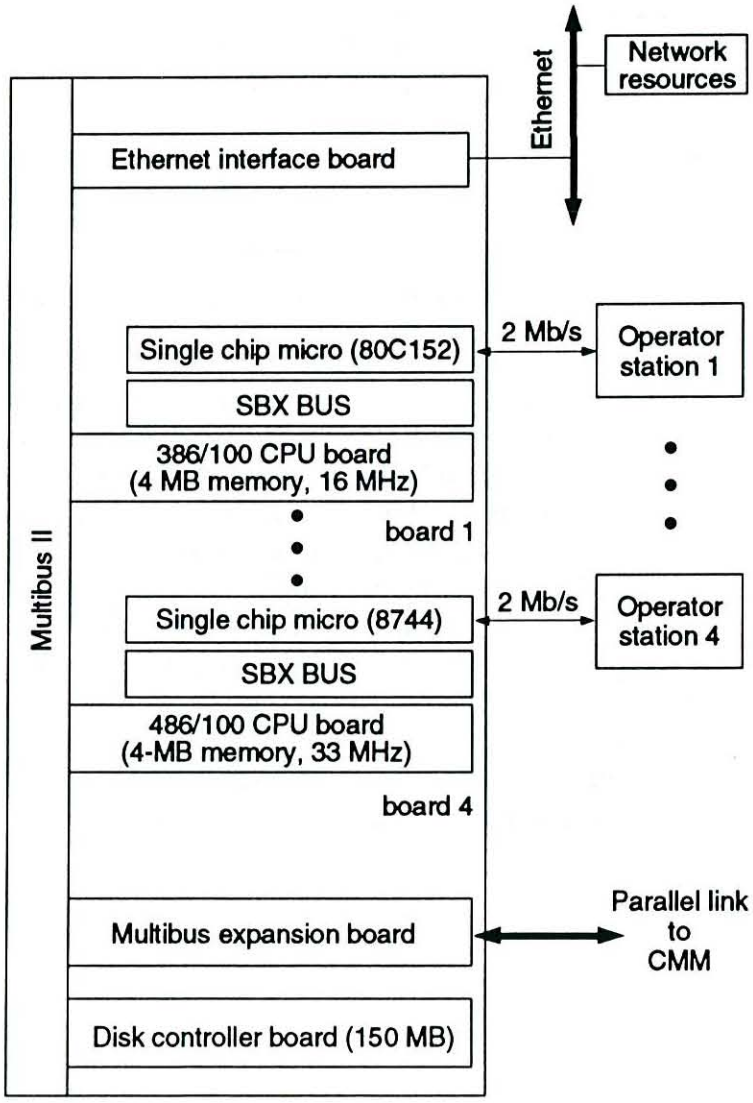


Figure 5-4. Block diagram of a Display Micro Module (DMM). [XBL 902-5417]

5.2 OPERATOR INTERFACE

Operator stations (see Fig. 5-5) provide the human interface to the control system. Each operator station is an 80486-based IBM PC with a high-resolution (1280 × 1024) 19-inch color monitor. For input there will be knob panels, keypads, and mice. The knob panel will have an LED display for each of the knobs (for labeling or display of values), and these displays can be updated under program control when scrolling or using the mouse. A console, made up of four operator stations, will also have space for oscilloscopes, network analyzers, and other instruments.

Operator stations are connected to the DMM by high-speed (2-Mb/s) serial lines; this unique feature of the system allows the placement of such stations almost anywhere in the vicinity of the machine (for instance, as a local control station for any of the major subsystems of the accelerator). The DMM incorporates one high-performance, 80486-based single-board computer (SBC) per station, thereby providing extremely fast (less than 0.1 s) response to operator input. The four SBCs (per DMM) share data and communicate via a commercial Multibus-II–based chassis. These microprocessors,

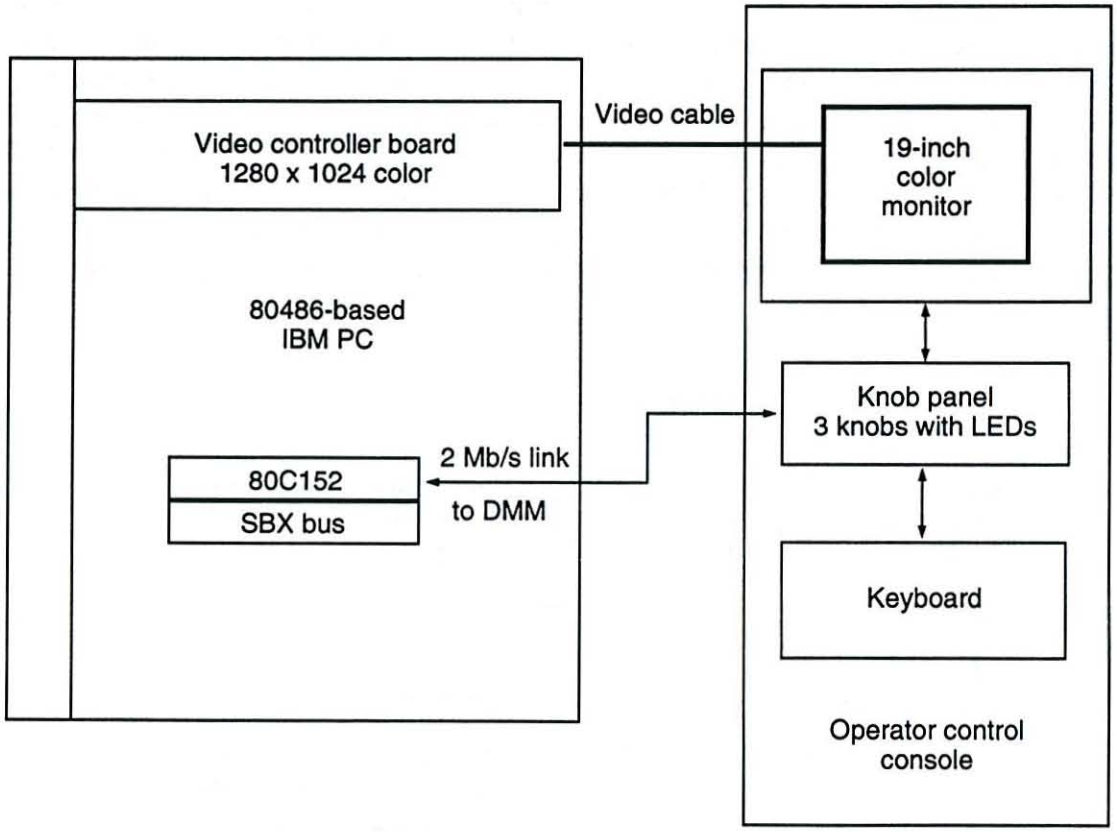


Figure 5-5. Block diagram of an operator control station. [XBL 902-5418]

operating in parallel, provide performance exceeding that of many super-minicomputers, at a very modest price. Each operator station PC contains a video board and an SBC; the latter does the serial communication with the DMM. The knob panel electronics (shown in Fig. 5-6) also contain single-chip microcomputers, so they, in turn, present only relatively high-level information to the operator station PC.

5.3 SUBSYSTEMS

The DMM has access to the data that describe the status of the machine via a Multibus-II to Multibus-l extension into the CMM. The CMM collects data from the various ILCs and stores them in memory accessible to the DMM. The CMM sends to the ILCs any messages (new set points, etc.) generated by the DMM or the operator stations.

The ILCs monitor and control the operation of the machine. They are directly interfaced to the various components, and because they possess the computing power of a 16-bit minicomputer, they are capable of many control functions, such as monitoring interlocks, data acquisition, closed-loop control, data analysis, and error checking. Only data processed by these ILCs are sent to the CMM. The DMM, therefore, is not burdened with low-level signal-processing tasks. The ILCs control a single, or at the most a few, devices. A modified operator station or laptop computer can interface directly to the ILC links, thereby providing local control and testing. This is particularly useful during machine commissioning and for failure diagnosis (to isolate one chassis from another).

The justification for using many ILCs lies primarily in the complexity of the system. Each ILC deals mainly with one device (or one type of device), making it easy to provide additional computing and network capacity. This kind of power may be desirable during simultaneous ramping of a number of elements. Furthermore, it simplifies the programming task and can shift the software (for example, floating-point conversion,

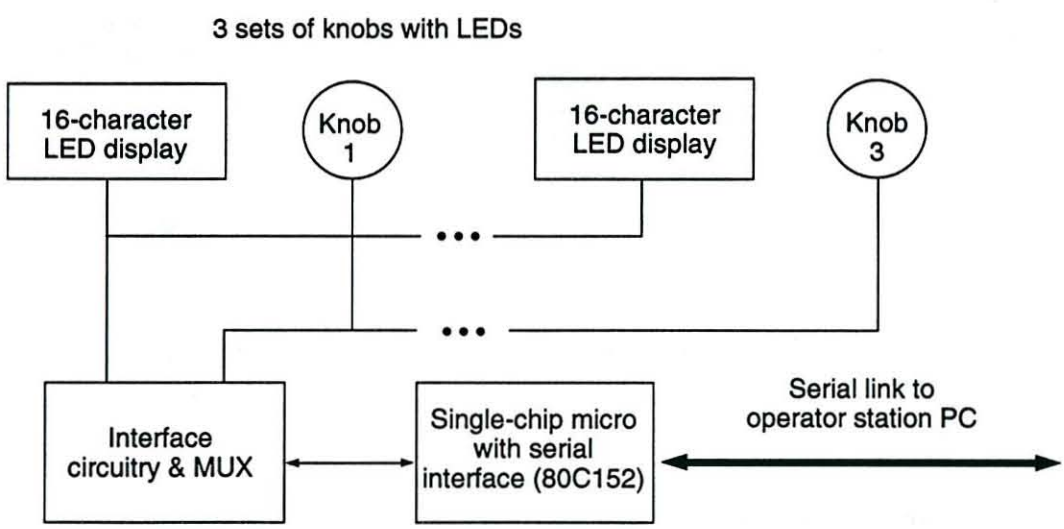


Figure 5-6. Block diagram of an intelligent knob panel. [XBL 902-5419]

error checking, or ADC/DAC processing) from the DMM to the ILC. The results are a reduction of DMM software, improved response to the operator, and simplified hardware maintenance.

The simplified system design allowed by the use of ILCs will be especially important during routine machine operation, when experts who built the control system may become less readily available. The use of ILCs also provides considerable flexibility for future expansion. If the data refresh rate needs to be increased, the number of ILCs on a link can be decreased to accommodate this improvement. Use of the ILC means that only relatively simple boards must be added to provide control functions, and that only a modest amount of software development effort would be required for such expansion.

6.

SAFETY AND QUALITY ASSURANCE

FROM a safety standpoint, the IRFEL presents no significant new problems. All of the potential hazards are ones that have been faced and solved during previous construction projects or experimental activities, at LBL or elsewhere. In all cases, measures have already been developed to protect the health and safety of workers and others, and to guarantee no adverse effects on the environment. In particular, the close association of the IRFEL with the ALS will allow us to take advantage of a number of safety systems that already exist.

6.1 RADIATION SAFETY

The design and operation of all facilities at LBL are governed by the ALARA (as low as reasonably achievable) policy. LBL has always maintained radiation dose limits well below those allowed by regulation.

The most important elements of radiation safety—well-designed radiation shielding, adequate beam dumps, and redundant beam-containment measures—have already been described. The shielding and the beam dumps are discussed in detail in section 3.7, and the diagnostics and interlock systems that serve to ensure adequate beam containment are described in section 3.4.

6.1.1 Personnel Protection System

The design philosophy behind the personnel protection system is that it must protect personnel from all plausible hazards related to the operation of the IRFEL. The primary hazards addressed are those associated with radiation, high voltage, high-stored-energy devices, and moving mechanical parts or assemblies. To achieve its aim, such a system must be fail-safe, redundant, self-checking, reliable, and simple.

Redundancy requires more than one level of checking and protection. The long history of safe operation at facilities with two levels of redundancy led us to adopt such a system for the IRFEL.

Self-checking means that any single system error or failure must be detected before other failures occur that might produce a hazardous situation. This requires that all individual circuits and chains be checked to determine whether they are reporting the same status. On the basis of this criterion, a simple, hard-wired electromechanical system was selected. The safety system uses the industry-standard 24-V dc control voltage and electromechanical relay logic, with complete redundancy (independently wired relay systems with parallel functions) and fail-safe features throughout. Microswitches are used to sense position (open or closed). When semiconductors are used in applications where a failure could render the system inoperative or result in a hazardous situation, the system is designed to fail in a safe condition.

Operational safety procedures specifying, in detail, the steps required for entry into controlled-access zones and the search sequence required for restarting the IRFEL will be prepared prior to operation. Appropriate review and approval procedures will be followed. Procedures for personnel access, interlock bypass, interlock testing, and calibration of radiation detectors will be similar to those used at the ALS, which served as the basis for the descriptions below.

Personnel Access. The radiation safety enclosure for the IRFEL is designed with one main access gate and one emergency exit gate. Each gate's position is sensed by redundant microswitches. During normal operation, access to the IRFEL vault is controlled by the control room. A two-way audio communications system, closed-circuit television camera system, "key tree," and lighted status sign are located adjacent to the main access gate. Access to the vault requires communications with and surveillance by the control room operator. Controlled access requires the following sequence of events:

1. The control room operator relinquishes control of the IRFEL by switching it to the safe mode.
2. Each person entering takes a key from the key tree.
3. The control room operator logs the access and releases the gate for entry.
4. As each person leaves the vault, his or her key is returned to the key tree. Once all personnel have left the vault and returned their keys, the control room operator may return the IRFEL to operational status.

"Crash-off/search" reset boxes are located inside the IRFEL vault, and the main access and emergency exit gates have emergency "crash-out/in" release mechanisms. Activation of a crash-off box or crash-out/in gate release inhibits operation of the IRFEL and requires a search of the IRFEL vault. The search procedure requires that a key from the control room be used in a prescribed manner, thus ensuring that a complete and thorough search-and-secure procedure is followed. The IRFEL can be operated only after the search is completed and the key returned to its key-switch cache in the control room.

Active radiation monitoring outside the IRFEL vault consists of x-ray and neutron detectors. Radiation detected above the allowable limits inhibits operation of the IRFEL.

Interlock Bypass Procedures. Procedures for bypassing radiation interlocks will be prepared in accordance with Chapter 21 ("Radiation Safety—Ionizing and Nonionizing") of the LBL *Health and Safety Manual* [1990]. Interlock bypass procedures will be

defined in the *IRFEL Operational Safety Procedures Manual* (OSP). Modifications made to a radiation interlock system (such as temporary defeat for testing) will be carefully documented, approved by authorized personnel, and removed when no longer needed. An interlock bypass must be approved by the second level of supervision. Only properly trained personnel will be allowed to install an interlock bypass. An interlock bypass will be documented on appropriate drawings and logged, and a notice of the installed bypass will be displayed in the control room. A notice of an installed bypass will also be displayed so that any person who normally relies on the bypassed interlock will be informed that a safety device has been disabled. Current LBL policy and practice require that all interlock bypasses be removed when no longer needed; if more than three days are needed to complete the task for which the bypass is installed, a permanent solution must be devised and implemented.

Interlock Testing. All radiation interlocks will be tested at intervals of not more than six months. The testing and maintenance schedule will be incorporated into the IRFEL OSP. Records of all testing will be maintained by the IRFEL Safety Officer. Failures will be reviewed by a safety committee, and any hazards that personnel may have been subjected to during the failure will be evaluated. All installations and alterations will be reviewed by a safety committee composed of qualified personnel. Access to system components will be restricted to personnel authorized to maintain the system.

Calibration of Radiation Monitoring Equipment. Calibration procedures for all radiation monitoring devices will be incorporated into the IRFEL OSP. All radiation monitoring equipment will be tested for calibration at intervals of three months by the IRFEL Safety Officer. Radiation monitoring devices not meeting specifications will be tagged and removed from service. Radiation monitoring equipment will be maintained by trained personnel. The IRFEL Safety Officer will retest and calibrate repaired radiation monitoring devices before returning them to service. Active test sources used for calibration will be handled and stored in accordance with current DOE regulations.

6.1.2 Radiation Safety Training

In accordance with the LBL *Health and Safety Manual* [1990], the implementation plan for DOE Order 5480.11 (Radiation Protection for Occupational Workers) includes appropriate radiation safety training for all regular LBL employees, participating guests, and visitors. All new employees must attend a health and safety orientation program within one month of employment; this program covers the fundamentals of radiation safety. In addition, those workers who might potentially receive a total occupational radiation dose greater than 100 mrem in one year are classified as radiation workers; as such, they are required to take additional radiation safety training and to demonstrate proficiency by passing an examination. Radiation workers are retrained every two years.

6.2 OTHER SAFETY ISSUES

6.2.1 Nonionizing Radiation

The IRFEL will generate radio-frequency radiation at several frequencies, including 499.65 MHz and its harmonics. Areas of potential exposure include the IRFEL vault, the room housing the klystrons, and adjacent areas. Personnel will not be allowed in the vault during operation, and the klystron room and adjacent areas will be surveyed for electric and magnetic fields during IRFEL operation. The American Conference of Governmental Industrial Hygienists threshold limit values (TLVs) will be adopted as the limits for personnel exposure. Engineering and administrative controls will be implemented as necessary to ensure that the TLVs are not exceeded. Periodic measurements will be made to confirm the adequacy of controls.

6.2.2 Confined Space

Areas identified by LBL's Environment, Health, and Safety Division as confined spaces will be governed by LBL Confined Space Entry Procedures. These existing measures ensure the safety of personnel working in confined areas.

6.2.3 Oxygen-Deficient Atmosphere

The superconducting cavities of the IRFEL require significant quantities of liquid nitrogen and helium. Oxygen-deficiency sensors and alarms will be installed in areas where a gas leak might decrease the atmospheric oxygen level to less than 19.5%. Oxygen-deficiency hazard (ODH) training will be provided for all personnel working in ODH areas. Access to such areas will be limited to ODH-trained personnel (or persons accompanied by such personnel).

6.2.4 Toxic Gases

Ozone and oxides of nitrogen are likely to be generated during IRFEL operation. Airborne concentrations of these gases will be measured in areas adjacent to the accelerator vault during operation and in the vault immediately after any shutdown. We anticipate that ozone levels within the vault will decrease to safe levels within five minutes. The American Conference of Governmental Industrial Hygienists TLVs will be adopted as the limits for personnel exposure. Engineering and administrative controls will be implemented if TLVs for toxic gases are exceeded.

6.2.5 Electrical Hazards

Electrical protection is achieved by scrupulous adherence to applicable standards, codes, and directives governing design, operation, and maintenance of electrical equipment,

including the *National Electric Code 1990* [NFPA, 1990] and the *Electrical Safety Requirements for Employee Workplaces* [NFPA, 1988]. All installation and maintenance of electrical equipment is checked by LBL Construction and Maintenance (C&M) supervisory personnel or electronic-maintenance-shop personnel. In addition, all installations and operations must be carried out in accordance with the latest edition of Chapter 8 of the LBL *Health and Safety Manual* [1990], which defines responsibilities of personnel, principles of safety procedure implementation, requirements for design and construction of equipment, and means of accident prevention.

Cabinet doors to high-voltage equipment will be interlocked to turn off circuits when doors are opened. Enclosures containing high-voltage equipment (600 V or higher) will be marked in accordance with *National Electric Code 1990* [NFPA, 1990], paragraph 370-52(e), "Danger High Voltage Keep Out." Enclosures containing lower-voltage equipment will have warning signs of a similar nature. Stored-energy devices such as capacitors will have automatic discharging devices. Grounding and bonding of electrical equipment cabinets and electromechanical devices, including magnet iron, and girder support assemblies, will be in accordance with the National Electric Code.

6.2.6 Fire and Earthquake Safety

Fire safety measures for the IRFEL and its associated systems have been incorporated into the design of the CDRL building itself, which has been classified within ordinary hazard group 3. In particular, the IRFEL control room, power supply room, and FEL vault will be protected by double-interlocked, preaction sprinkler systems.

Facilities associated with the IRFEL, as well as all shielding, will be designed to withstand a site-specific maximum credible earthquake on the nearby Hayward Fault, in accordance with special seismic criteria included in the LBL *Health and Safety Manual* [1990]. A third-party design review of the entire CDRL building will be carried out by a consulting structural engineer experienced in earthquake engineering.

6.3 CONSTRUCTION

Responsibility for monitoring various construction activities at LBL is delegated by line management to several organizations. Project line management will also designate Safety and Quality Assurance Officers who will oversee all aspects of the project. The Purchasing Department is responsible for business matters and thus ensures contractor compliance with administrative contractual requirements. For matters pertaining to conventional construction, Plant Engineering is responsible for quality assurance and for ensuring contractor compliance with contractual terms and conditions related to performance, schedule, and budget. Plant Engineering personnel serve as LBL management representatives for conventional construction activities and the Laboratory's primary contact with the contractor.

LBL's Environment, Health, and Safety (EH&S) Division has primary responsibility for monitoring safety compliance by the construction contractor. The Construction Safety Engineer assigned to EH&S's Occupational Safety Department ensures compliance with LBL, DOE, CAL/OSHA, OSHA, and other applicable safety

requirements. This individual's safety responsibilities are carried out in concert with LBL Plant Engineering, Purchasing, and line management; they include

- Apprising contractors of LBL and DOE safety criteria pertaining to the construction project.
- Requiring the contractor to submit a written Safety Plan.
- Conducting periodic inspections of contractor areas to evaluate the quality of the contractor's safety compliance program.
- Stopping contractor work when situations are noted that pose imminent danger.
- Obtaining contractor accident reports and compiling such information for reporting to DOE.

6.4 EMERGENCY PREPAREDNESS

LBL has developed a Master Emergency Plan and site-specific Building Emergency Plans, which, together, establish emergency procedures to be followed in the event of an earthquake, fire, chemical release, or other potentially hazardous occurrence. The emergency plans conform to DOE Orders and other health and safety code requirements. The CDRL building will have such a Building Emergency Plan that will address site-specific emergencies, the duties of Building Managers and the Building Emergency Team, utility shutdown procedures, evacuation routes, assembly areas, and the location of fire and first-aid equipment. Building Emergency Plans are tested at least annually.

6.5 ENVIRONMENTAL PROTECTION

Protection of the environment, employees, and the public is of paramount concern in all activities at LBL. Accordingly, the OSP for the CDRL will address all pertinent environmental protection laws, regulations, and standards, and all requirements in the LBL *Health and Safety Manual* [1990] relevant to environmental protection will be met, during both construction and operation of the IRFEL.

6.6 QUALITY ASSURANCE

LBL facility operations and research programs are governed by the quality assurance (QA) provisions of the *LBL Institutional Quality Assurance Program Plan* [LBL, 1988] . This plan requires each LBL programmatic division to develop plans and procedures to carry out LBL QA requirements. The Accelerator and Fusion Research Division (AFRD) has developed a divisional QA plan that describes how quality is assured in the conduct of its accelerator operations and research activities.

Typical QA procedures required by the AFRD plan for accelerator operations include

- Operator training.
- Operational checklists.
- Maintenance and periodic reviews of downtime logs to help identify causes of ineffective operation.
- Relevant documentation maintained and accessible at the site of the facility.
- Periodic updates and reviews of operator training procedures, operational checklists, and relevant documentation.
- Maintenance and periodic checks and recalibration of instrumentation to indicate clearly the status of the facility and the permissible range of critical operating parameters.
- Meetings to update operations schedules and to provide periodic emphasis on facility performance and efficiency.

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