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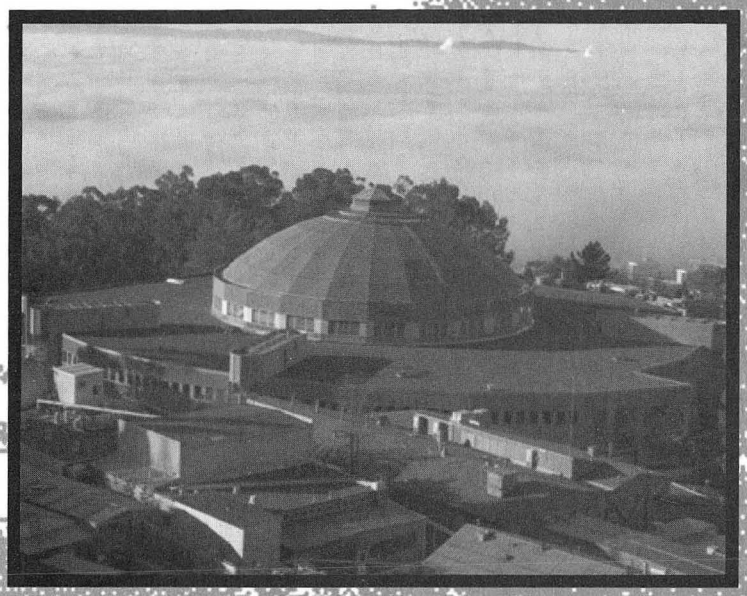

Accelerator & Fusion Research Division

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SUMMARY of ACTIVITIES

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

April 1994

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Accelerator and Fusion Research Division

1993 Summary of Activities

Lawrence Berkeley Laboratory
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April 1994

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Table of Contents

Accelerator and Fusion Research Division i

Table of Contents iii

Foreword v

Accelerator and Fusion Research Division Staff vii

AFRD: Diversity with a Common Theme ix
- Fusion Energy: Exploring a New Frontier ix
- Advanced Light Source: Seeing the Future in a New Light xii
- Magnets for the Accelerators of the Future xiv
- Center for Beam Physics: "Nothing Happens Unless First a Dream" xvi
- Ion Beams for Science and Commerce xviii

Fusion Energy Research 1-1
- Heavy-Ion Inertial Fusion Accelerator Research: Developing a Promising Approach to Inertial Fusion Energy 1-2
  - The HIFAR Program in AFRD 1-4
- HIFAR Physics and Technology R&D: Progress Toward Driver-Scale Systems 1-6
  - Injector-Related R&D 1-6
  - ILSE-Scale and Driver-Scale Technology Development 1-8
- HIFAR Research in Beam Transport: Theoretical Studies and Technology Development 1-9
  - Aperture Ratio Studies 1-10
- HIFAR Pland for 1994 and Beyond: Continuing Driver-Oriented R&D 1-11
  - Experimental Plans 1-11
- MFE R&D Progress: Neutral-Beam Injection Options for ITER 1-12
  - ITER Beamline Studies: Options for the Detailed Design 1-12
  - Merging Beams: A Joint Experiment with JAERI 1-16
- Ion Sources for MFE: Technology, Tools, and Spinoffs 1-17
  - An RF-Driven H^- Source for High Power and Long Pulses 1-18
- Plasma Theory and Nonlinear Dynamics 1-19
  - Wave Dynamics and Gyroresonant Energy Absorption 1-19
- Publications and Presentations 1-21

Advanced Light Source 2-1
- Commissioning Progress 2-3
  - Storage Ring Commissioning 2-3
- Experimental Systems 2-5
  - Beamlines 7.0 and 8.0: The First Undulator Beamlines 2-6
  - Beamline 9.0: The Next Step 2-8
  - Bend-Magnet Beamlines: 10.3, 9.3.2, and 9.3.1 2-8
  - Diagnostics: Assuring Quality of Electron and Photon Beams 2-10
  - Charting a Course for Progress: The ALS Beamlines Initiative and Other Plans 2-13
  - Characterizing Optical Components: Award-Winning Innovations 2-13
- Serevice to the User Community 2-14
  - Availability to Researchers 2-15
  - User Services 2-15
  - Workshops and ALS Science 2-15
  - ALS Advisory Panels 2-16
  - ALS Users' Association 2-17
- Publications and Presentations 2-18

Center for Beam Physics **3-1**
PEP-II: Refining the Design and Preparing for Construction 3-2
Conceptual Design Overview 3-4
Lattice Design Progress 3-6
Beam-Beam Interaction Studies 3-7
Beam Test Facility: Commissioning Progress and Experimental Plans 3-8
Plasma-Focus Experiments 3-9
Sub-Picosecond X-ray Pulses 3-9
Laser-Optics Laboratory 3-11
Advanced Optical Diagnostics for FELs 3-11
Beam Electrodynamics 3-13
Progress in PEP-II RF Systems 3-13
Support for the Advanced Light Source 3-14
Fermilab Antiproton Cooling System 3-15
Heavy Ion Beam Cooling for RHIC 3-15
Free-Electron Lasers and Other Radiation Sources 3-16
Single-Pass Amplification: The Key to Short-Wavelength FELs 3-17
Optical Resonator R&D 3-18
High-Energy Collider Physics 3-18
Transversely Modulated RK 3-19
Standing-Wave and Multicavity FELs 3-20
Beam Conditioning 3-21
Exotic Colliders 3-21
Publications and Presentations 3-23

Superconducting Magnets **4-1**
Advanced Lattice Magnets: Higher Fields, Lower Cost 4-4
D19B and -C: The Next Steps for a Record-Setting Magnet 4-4
D20: The Push Beyond 10 T 4-6
Beyond D20: Speculations on the 16-T Regime 4-7
Other Advanced Magnets for Accelerators 4-7
Spinoff Applications 4-8
Advanced Materials and R&D Techniques 4-9
APC Materials Development 4-9
Cable and Cabling-Machine Development 4-12
High-T_c Superconductor at Low Temperature 4-13
Publications and Presentations 4-14

Ion Beam Technology **5-1**
Accelerator Technology for Nuclear Physics: Leveraging the Benefits of AFRD Expertise 5-3
Stochastic Heavy-Ion-Beam Cooling for RHIC 5-3
High-Efficiency, Low-q/A, Low-Beta Acceleration 5-4
Future Directions 5-6
Biomedical Accelerators: Proton Therapy for Cost-Effective Health Care 5-8
Progress in Facility Design and Construction 5-9
Plasma Applications: Using Accelerator Technology for Materials Modification and Synthesis 5-10
Metallic Thin Films and Multilayers 5-10
Vacuum Arc Ion Source Development and Applications 5-10
Metal Plasma Immersion (MPI) Surface Modification 5-11
Diamond Synthesis 5-12
Publications and Presentations 5-13

Foreword

Some of the brightest news for AFRD in 1993 came from the Advanced Light Source, which met or bettered a succession of major goals and is now officially "open for business." A beam was stored on March 16, the first day that rf power was applied to the storage ring, and on April 9, the ALS exceeded its design specification of 400 milliamperes of stored beam current. Formally dedicated as a national user facility in a ceremony on October 17, the ALS will serve at the forefront of synchrotron-radiation research well into the 21st century. The availability of high-brightness ultraviolet and x-ray beams from the ALS is anticipated eagerly in a broad variety of research communities, including materials science, chemical dynamics, and structural biology.

The Center for Beam Physics also brought welcome news. The proposed PEP-II collider, a "B factory" at the Stanford Linear Accelerator Center in which LBL plays a major role, was approved for construction by the Department of Energy. The Beam Test Facility was completed and commissioning began; this facility will use the high-quality 50-MeV electron beam from the ALS injection linac for a diverse experimental program during the periods when the storage ring is full and the injector would otherwise be idle. Of the many possible experiments, the first two will be a plasma focus and a scheme for generating femtosecond X-ray pulses via Thomson scattering against a laser beam.

Nineteen ninety-three found AFRD, like most research organizations, assessing its competitive position and plotting a course. To ensure the continued vitality of accelerator-based physics at LBL, our scientific leaders, along with guests from other divisions, began a series of retreats designed to plan our future directions and coordinate our efforts with those of others.

During this time, our 35-year-old program in magnetic fusion energy effectively came to an end with the termination of neutral-beam development. The remaining efforts that were directly related to fusion were consolidated with those of the Heavy-Ion Fusion Accelerator Research (HIFAR) program. The new Fusion Energy Research Program is thus retaining some capability for designing neutral-beam systems, and meanwhile is in an even stronger position to begin the proposed Induction Linac Systems Experiments, the logical next step on the road to a heavy-ion "driver" for inertial fusion energy, when approval is received.

Other former MFE efforts that emphasize industrial spinoff applications of ion beams and plasmas have been added to our new Ion Beam Technologies Program. The centerpiece of that program has gotten an encouraging reception at DOE: the development of challenging acceleration and beam-control technologies needed for future advances in nuclear-physics facilities. The Ion Beam Technologies Program also oversees the "stand-down and secure" effort at the Bevalac as we ensure the environmental, safety, and health quality of the decommissioning process and maximize the future scientific benefits of the still-valuable equipment and facilities.

An R&D 100 Award, given annually by Research and Development Magazine in honor of the year's 100 most-significant innovations, was given jointly to Steve Irick of the Advanced Light Source and colleagues from Brookhaven National Laboratory. The award honored the design and implementation of the Long Trace Surface Profiler for characterizing metal optics, such as those used at synchrotron light sources. (AFRD researchers have been given at least one R&D 100 award each year since 1985.) And a multidivisional team including Jose Alonso and John Staples of AFRD won a Federal Laboratory Consortium Technology Transfer Certificate of Merit for their conceptual demonstrations and technology innovations in heavy-charged-particle radiotherapy.

Underlying all these accomplishments are the skill, creativity, and hard work of the people of AFRD. These qualities have made me proud to take on the leadership of this organization.

William A. Barletta, Director
Accelerator and Fusion Research Division
March 1994

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AFRD: Diversity with a Common Theme

The Accelerator and Fusion Research Division is not only one of the largest scientific divisions at LBL, but also one of the most diverse. Major efforts include:

- Investigations in both inertial and magnetic fusion energy.
- Operation of the Advanced Light Source, a state-of-the-art synchrotron-radiation facility.
- Exploratory investigations of novel radiation sources and colliders.
- Research and development in superconducting magnets for accelerators and other scientific and industrial applications.
- Ion beam technology development for nuclear physics and for industrial and biomedical applications.

These efforts share a foundation in the physics and technology of beams of ions, electrons, and photons. This introductory section gives an overview of AFRD's fields of inquiry and their relevance to current issues in science and technology. Later chapters go into greater detail on each topic.

An important goal of every program—and one that builds on the traditions and values of AFRD—is the education of graduate and undergraduate students. We are strengthening and diversifying our ties to the University of California system and other academic institutions, both for scientific collaboration and for the education of our intellectual heirs. Industrial interaction and technology transfer also receive great emphasis so that the private sector can take advantage of the public investment in our expertise.

Fusion Energy: Exploring a New Frontier

As the world contemplates its dwindling fossil-fuel supplies and the environmental costs of energy production, nuclear fusion looks ever more appealing. Potentially one of the most efficient of all physical processes that release energy, it is also attractive from a pragmatic viewpoint. The fuel (the hydrogen isotopes deuterium and tritium) could be readily obtained, and the reactions would not leave the long-lived, highly radioactive waste products associated with fission. But controlled, self-sustaining fusion on a power-plant scale will require some years of further development; typical estimates call for a demonstration power plant in 2025.

The work being done today addresses two fundamental problems. One is how best to get the reaction started; a temperature of about 100 million degrees Celsius is required before random thermal interactions force the nuclei close enough to each other to fuse. (The nuclei are all positively charged and therefore repel each other; to make them fuse when they meet, the temperature must be kept high, a condition that causes them to move fast and collide with high impact.) The other problem is how to make the product of density and confinement time reach a very high value known as the Lawson criterion. The Fusion Energy Research Program in AFRD has worked on both of the basic approaches to these problems.

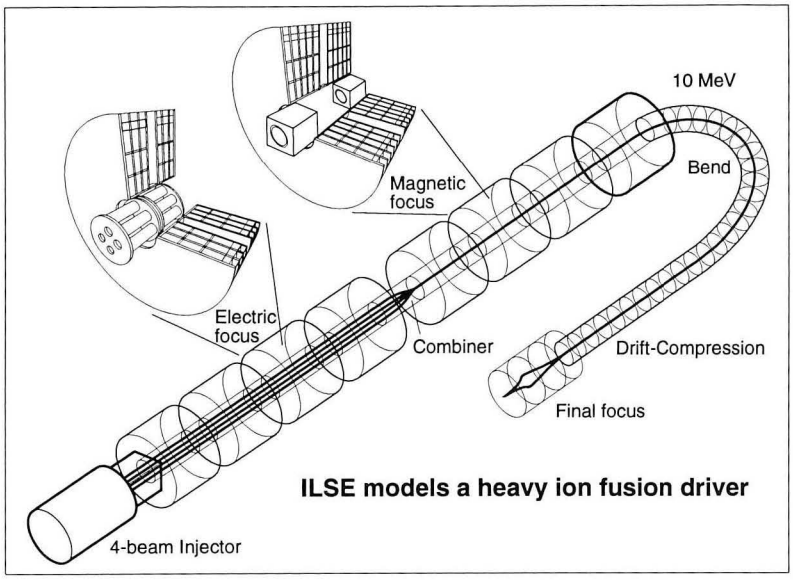
Magnetic fusion, the more familiar scheme, uses a magnetic field of great strength and rigorously maintained geometry to confine a continuously reacting plasma and keep it away from the reactor walls. In the largest of today's tokamak reactors, magnetically confined deuterium plasmas (and, at the Joint European Torus and the Tokamak Fusion Test Reactor, a deuterium-tritium plasma) have been heated to temperatures at which fusion reactions took place. The best of these brief "shots" have released about 80% as much energy as was required to heat the plasma, or about 10% of the energy that would be needed for ignition (self-sustaining fusion). In the tokamak projects, which tend to be very large and increasingly international, Lawrence Berkeley Laboratory has played a major supporting role. The effort focused on development of neutral-beam injector systems that pump large quantities of energetic hydrogen or deuterium atoms into a tokamak, thereby helping to heat the already hot plasma to thermonuclear temperatures.

The injection of intense neutral beams presents interesting scientific and engineering challenges: the atoms must initially be ionized, or given a charge, so they can be accelerated, but then they must be neutralized so they can penetrate the tokamak's magnetic field. While further neutral-beams development is no longer being supported in the US, the Fusion Energy Research Program should remain in a position to support future magnetic-fusion experiments, as it has supported the current generation, by developing ion sources, accelerators, and neutralizers. This work—in particular the ion-source technology—also has much in common with the other approach, inertial fusion energy.

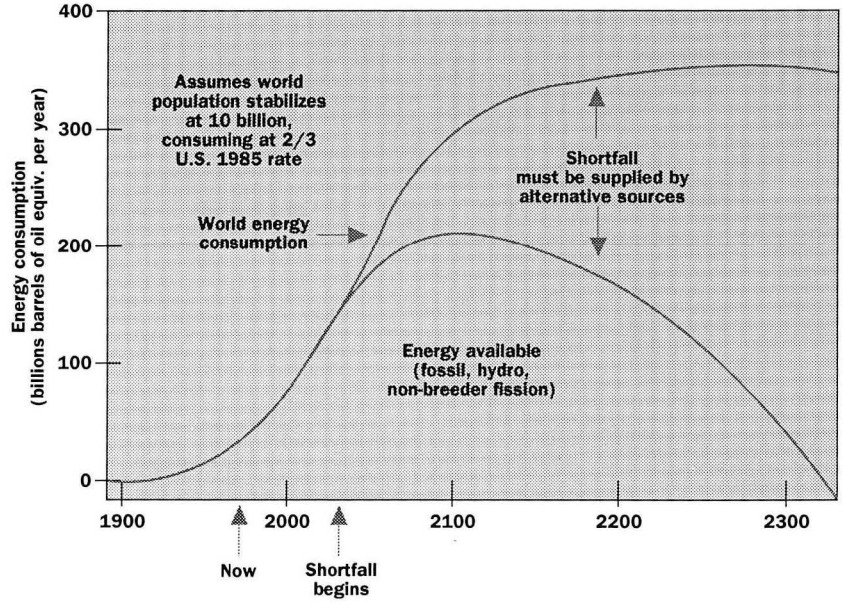
Inertial fusion energy begins not with a plasma but with a spherical target of deuterium-tritium fuel. The target is hit from many directions at once with beams of laser light or energetic particles. This energy bombardment heats and compresses the target enough to induce fusion; the reaction is over so quickly that the balance of forces from all sides is enough to provide containment and satisfy the Lawson criterion. The process would be repeated several times per second in a power plant.

Heavy ions (as opposed to lasers or lighter ions) appear to be the best candidates for the repetition rate, reliability, and efficiency that would be needed in a power plant. Much of the Fusion Energy Research Program in AFRD theoretically and experimentally evaluates the possibilities for using heavy-ion beams as drivers for inertial-confinement fusion.

Since 1982, the program's researchers have been progressively scaling up systems that transport and accelerate beams of heavy ions. They are now making detailed preparations for the next step: ILSE, the proposed Induction Linac Systems Experiments. ILSE will contribute further knowledge toward the goal of a full-scale driver by modeling many beam manipulations and characteristics at full or partial driver scale.



The population of the world and the per-capita energy demand are both growing, so a shortfall is expected sometime in the next century. New sources of energy, such as fusion, will be needed to fill the gap. It will take time to meet the technical challenges of developing these new sources; the National Energy Strategy calls for a fusion demonstration in the 2025 time frame. Early and vigorous R&D would be prudent, especially for inertial fusion energy, a young program in which small delays or funding shortfalls could have disproportionate effects on the schedule. ILSE and various options for neutral-beam injection in the proposed International Thermonuclear Experimental Reactor are among AFRD's proposed contributions to the attempt to harness fusion power. (Energy-shortfall graph courtesy LLNL.)



Advanced Light Source: Seeing the Future in a New Light

The discovery of the x-ray in 1895 revolutionized not only the work of physicians, but also that of physicists. In two decades of excitement that helped set the stage for today's knowledge of the atom, they studied the interaction of x-rays and matter. The investigators—Roentgen, Compton, Laue, the Braggs—and the results are familiar from freshman physics and from the roll of Nobel laureates.

After that heady beginning, the scientific and industrial uses of x-rays continued to progress, growing very subtle and sophisticated. Nonetheless, a backlog of interesting and potentially useful x-ray work began to accumulate, including studies of processes at interfaces and surfaces; microscopy and holography; and the probing of chemical reactions. The conventional means of producing x-rays, which involves striking a material with a beam of electrons, could generate tremendous power, but the backlogged ideas needed qualities other than sheer power: tiny, intense beams, perhaps of just one precise "color," perhaps coherent, almost like a laser beam.

The solution was found in the late 1940s in what seemed to be a completely unrelated realm: the electron synchrotron. When a magnetic field causes an electron beam to change direction, photons are given off. This effect was at first considered a nuisance for robbing power from the beam and heating the accelerator and the experimental apparatus. But beginning in the 1950s, scientists began to realize that this nuisance had desirable qualities—that x-rays of unparalleled intensity could be obtained. The pioneers of synchrotron-radiation work obtained this radiation "parasitically" from electron accelerators meant for high-energy physics.

In the 1970s, there appeared a second generation of synchrotron-radiation sources: a generation of electron storage rings* whose reason for existence was the production of synchrotron light. AFRD advanced this new field by developing practical versions of magnetic devices called "wigglers" and "undulators" that could further manipulate an electron beam, producing radiation with selectable bandwidth, better coherence, and higher brightness.

During the early and mid-1980s, AFRD began designing a third-generation synchrotron-radiation facility. The hallmarks of the third generation are high-quality electron beams (small source diameter and low transverse energy), along with a ring design that lends itself, both mechanically and in terms of maintaining beam quality, to the insertion of numerous wigglers and undulators. In 1986, detailed design began for the **Advanced Light Source**, which was commissioned and opened to users in 1993. (As a Department of Energy user facility, the ALS provides all qualified investigators with free beam time. Beam time for proprietary research is also available on a cost-recovery basis.) Work continues on design and fabrication of additional insertion devices and beamlines. Development of the user program also continues, with LBL and outside researchers designing experiments and equipment to take advantage of this bright new source as they enter the second century of the x-ray.

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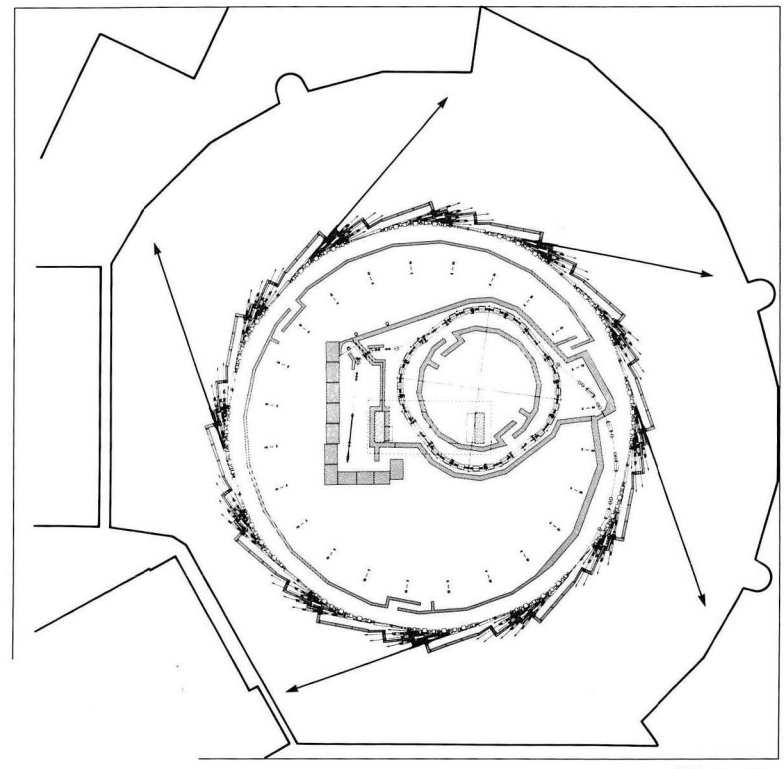
* In a storage ring, a variation on the general theme of the synchrotron, a large number of accelerated particle bunches go around millions of times for repeated reuse, as opposed to being delivered once to a fixed target.



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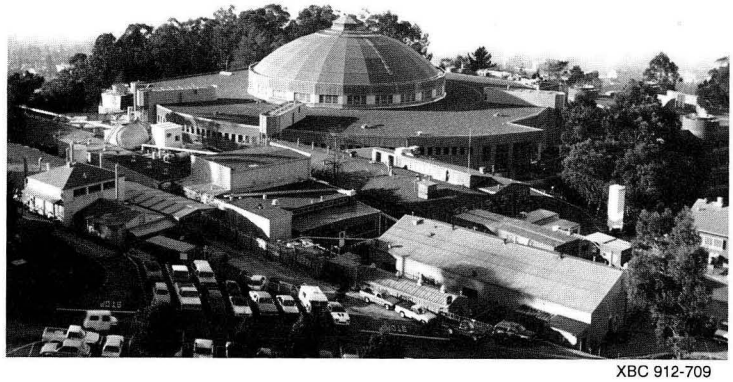

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The multiple straight sections in the ALS can each accommodate a magnetic insertion device to enhance synchrotron-light production. The bending magnets in the arc sections produce useful synchrotron radiation as well. The high-brightness beams of ultraviolet and soft-x-ray light from the ALS are of interest to a wide variety of researchers in fields ranging from structural biology to the fabrication of next-generation computer chips. The design and construction of the ALS has itself benefitted U.S. industry—for example, by advancing the state of the art in optical fabrication.

Magnets for the Accelerators of the Future

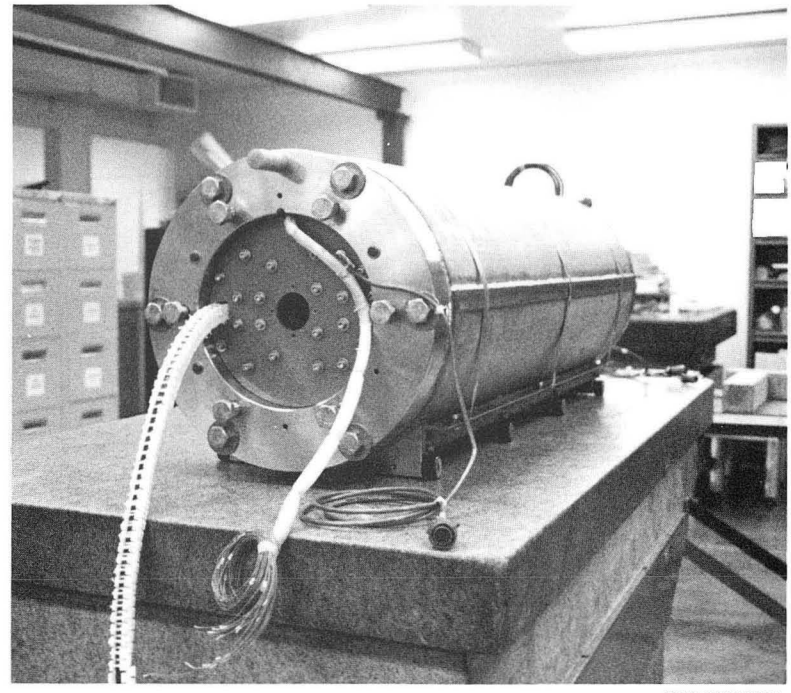
The multi-TeV energies of next-generation hadron colliders will open the hunting grounds for particles that have been postulated but never observed and measured, such as the top quark and the Higgs boson. Perhaps users of these colliders will even find particles, phenomena, or parameters that do not fit today's theories—an exciting prospect that has been a hallmark of accelerator-based physics.

The design and construction of these large facilities inevitably occupy researchers from many laboratories. AFRD's Superconducting Magnet Program has played a key role in such efforts for several years, concentrating on the design and manufacture of the superconducting wire and the cable made from it, and on design and testing of the magnets themselves. These magnets have to meet exacting performance specifications, especially in terms of magnetic-field uniformity. They must also be extremely reliable in order to give users the high experimental statistics needed at the frontiers of high-energy physics. Much effort has gone into optimizing seemingly minute design details that would affect performance under those conditions. Finally, they must lend themselves to mass production by industry.

Accordingly, interaction with private industry plays a vital role in all of the program's comprehensive, "from melt-to-magnet" investigations. Especially in research and development focused on basic materials, our work goes beyond technology transfer and into the realm of genuine two-way collaboration. In 1993, the program continued its long-term shift toward generic R&D that will benefit future accelerators for high-energy and nuclear physics. While working to enhance the performance of the usual superconductor (niobium-titanium in a copper matrix), the program is also exploring other materials that are not currently as well-proven and economical but hold the promise of higher fields and possibly lower costs.

Innovative approaches are also being taken in ancillary fields and in nonaccelerator uses of high-field magnets, such as nuclear magnetic resonance equipment. The program is rooted in the technology of advanced accelerators, a community that it continues to serve, but its work also has the potential for direct and indirect payoff in several other fields that could benefit from cheaper and better superconducting materials.

The Superconducting Magnet Program takes a vertically integrated, "melt-to-magnet" approach encompassing everything from basic development of better superconducting materials to evaluation of finished magnets. We are testing innovative mechanical designs and superconducting materials in the ongoing attempt to make magnets stronger, more efficient, cheaper, and more reliable. The D19B accelerator-type magnet and the "artificial pinning center" wire (produced by one of our industrial collaborators) are examples of recent achievements.



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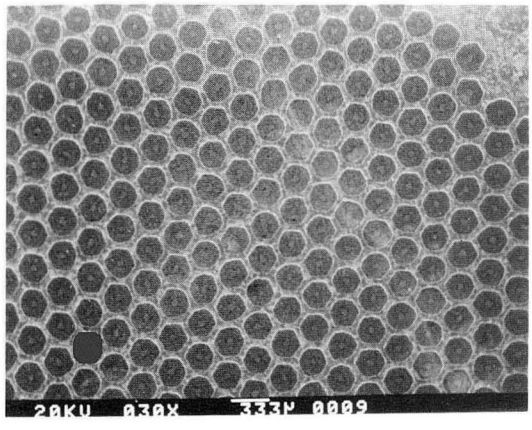

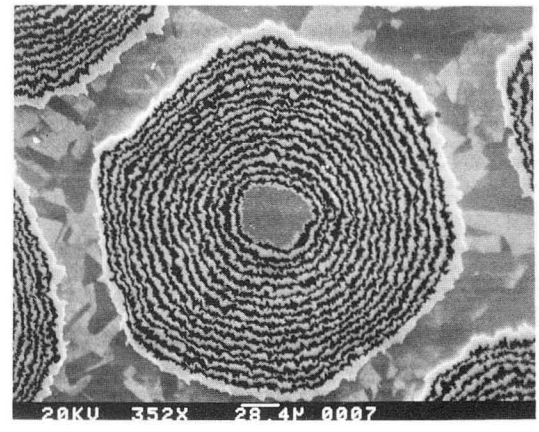

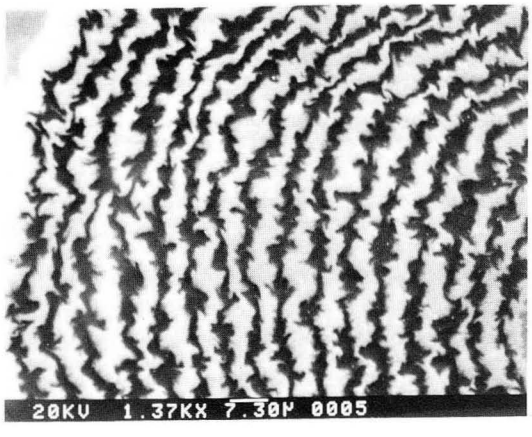

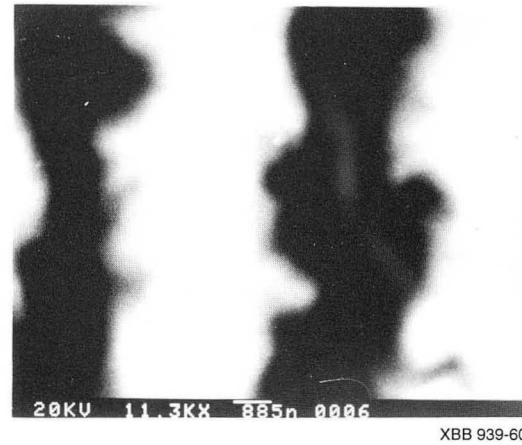

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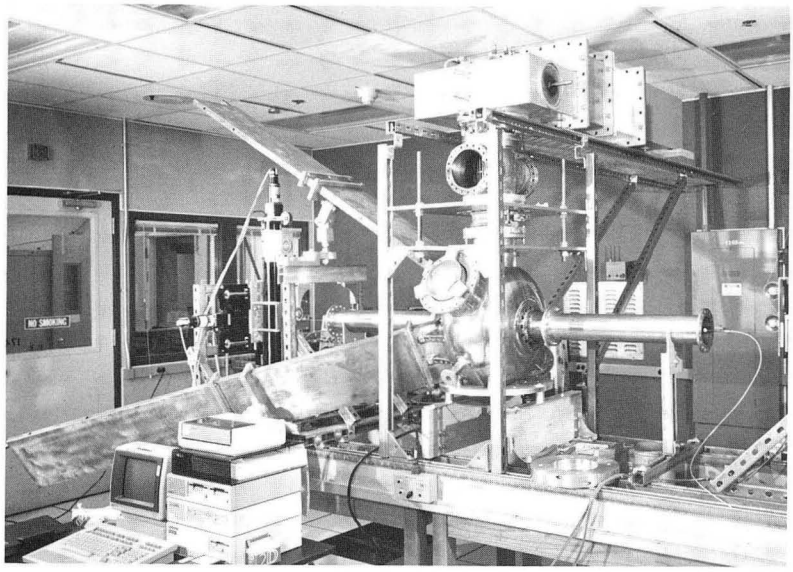
Center for Beam Physics: "Nothing Happens Unless First a Dream"

The **Center for Beam Physics** is a key element in several of the division's diverse activities, assisting with immediate programmatic needs and—as indicated by the Carl Sandburg quotation in the title—also laying foundations for future research. The highlight of the Center's year was undoubtedly the Department of Energy's approval for the construction of PEP-II. This five-year effort is centered at the Stanford Linear Accelerator Center with the collaboration of LBL and Lawrence Livermore National Laboratory. The ultimate result, circa 1998, will be an energy-asymmetric B-meson "factory" based on the existing Positron-Electron Project storage ring at the Stanford Linear Accelerator Center. Creating B mesons and their antiparticles in electron-positron collisions that have a moving center of mass, an idea originated by LBL Deputy Director Pier Oddone, will spatially separate the decay products, making detection simpler than it would be if the center of mass were fixed. The B factory will enable high-energy physicists to study charge-parity violation and rare B-meson decays. The year's achievements in the LBL portion of the program centered on design refinement of the rf system, multibunch feedback system, and magnetic lattice, as well as a better understanding of beam-beam interaction.

To meet the technical challenges of this and other initiatives and to generally enhance LBL's capabilities in particle- and photon-beam research, the Center continued adding to its experimental capability in 1993. The highlight of these achievements was the construction of the Beam Test Facility, which is now being commissioned. This facility will leverage the investment in the Advanced Light Source injector linac by using it for beam physics experiments during the several hours of otherwise idle time between ALS injection cycles. Many experiments are possible; immediate plans include generation and detection of x-ray pulses as short as tens of femtoseconds (a long-standing interest) and focusing of a beam by using plasma lenses.

Among the Center's other diverse activities, research continues in accelerator theory, nonlinear dynamics, and fundamental FEL physics. The High-Energy Collider Physics group continued its long-range Two-Beam Accelerator research. The Beam Electrodynamics Group contributed to and supervised the ALS and PEP-II rf and feedback design efforts. It also began exploring beam-cooling techniques for a challenging new application: the Relativistic Heavy Ion Collider (RHIC) that is being built at Brookhaven National Laboratory.



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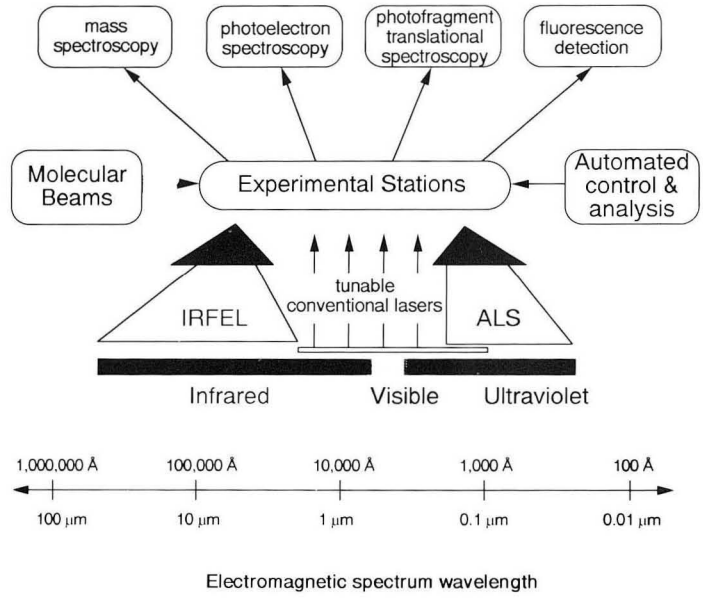
The Center for Beam Physics contributes to a wide range of programs in the physics of accelerators and beams. Much of the Center's effort is presently devoted to PEP-II, the B-meson factory being built at the Stanford Linear Accelerator Center. This prototype rf cavity has precisely located ports, which lead to ferrite loads, to remove potentially disruptive higher-order modes. Among the Center's many other investigations is the study of free-electron lasers, which fill important gaps in the spectral coverage of other radiation sources.



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Ion Beams for Science and Commerce

The design and operation of proton and ion accelerators was the central legacies of AFRD's origins. Even though the Division is no longer operating a nuclear-physics accelerator, its pool of expertise has not been lost to the research community—nor to industry. The new Ion Beam Technologies Program unites scientists and engineers from the Bevalac, the former Magnetic Fusion Energy Program, and other operations, concentrating their talents on nuclear science and spinoff applications.

One of the main efforts is a proposed investigation of accelerator technology for nuclear physics. There are two main thrusts, each leading to the development of integrated, application-oriented systems. One, which will be performed in close collaboration with the Center for Beam Physics, is the stochastic cooling of bunched, relativistic heavy-ion beams. This effort will culminate in the development of a practical beam-cooling system that can be operational in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory by the time of its commissioning as a user facility. Preliminary studies indicate that beam cooling, which makes the beam bunches more orderly and thus more intense for longer periods, will be important for maximizing the scientific productivity of RHIC.

The other main thrust is the generation and acceleration of low-mass, low-charge-state heavy ions. This takes advantage of the accelerator expertise developed by AFRD as part of the Bevalac program, as well as ion-source knowledge that comes from fusion-energy research. No other U.S. accelerator R&D is presently addressing this very-low-velocity, high-mass regime. The investigations will provide enabling technologies for one of the frontiers in the understanding of the nucleus: the study of nuclear isospin.

Biomedical applications of accelerators, another legacy of the Bevalac and programs in which AFRD participated, are also being studied as part of the Ion Beam Technologies Program. An energy-deposition phenomenon known as the Bragg peak allows doctors to use beams of protons and heavy ions as a "magic scalpel," killing certain kinds of tumors while sparing healthy tissues nearby. As proton therapy continues taking its first steps out of the laboratory and into routine, hospital-based medical practice, continued development and transfer of the technologies will be needed for acceleration, precise beam control, dose measurement, and so forth.

The efforts of the Ion Beam Technologies Program will also benefit industry and serve as a showcase for DOE technology transfer. The performance, durability, and economic attractiveness of today's high-technology products are often predicated upon specialized materials and effective, affordable techniques for manufacturing them. The program's researchers, in close interdisciplinary collaboration with colleagues from LBL and elsewhere, investigate plasma and ion-beam techniques for modifying and synthesizing materials. Surface hardening of metal machinery parts, ion-beam lithography, and the synthesis of biocompatible coatings are a few of the current and potential spinoff applications for the beam and plasma techniques that originated in nuclear physics, fusion, and AFRD's other scientific pursuits.

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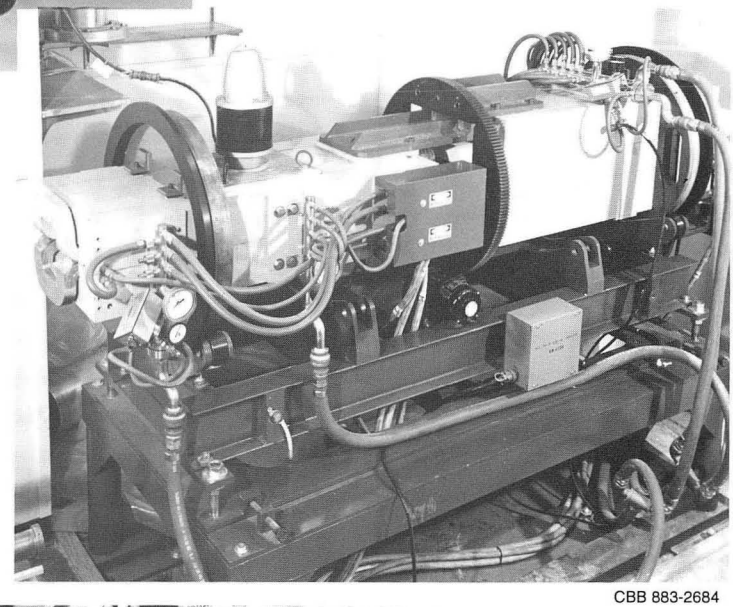
The DC Broad-Beam High-Current Metal Ion Source, one of many spinoffs from AFRD scientific investigations, could make some types of industrial ion implantation several orders of magnitude faster, accomplishing in minutes what now takes a day. Above, the 50-cm-diameter electrodes are shown with previous generations of the technology, including a subminiature version. This ion source was recognized with an R&D 100 award in 1992, as was the Raster Scanner (right), a beam delivery system for treating tumors with ion beams. Another recent achievement is this compact cyclotron (below), which opens new frontiers in portability and operating convenience by using permanent magnets rather than electromagnets. Creating spinoffs like these and enhancing industrial access to them are major goals of the Ion Beam Technologies Program.



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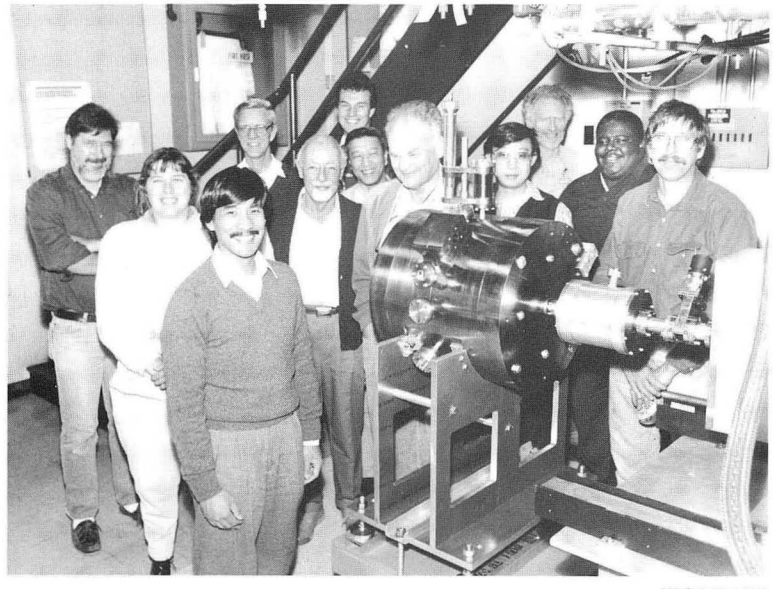

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THE FUSION ENERGY RESEARCH PROGRAM IN AFRD is involved in both of the principal approaches to fusion: inertial and magnetic. The inertial fusion energy effort has the long-range goal of developing heavy-ion accelerators for fusion-energy production. Heavy-ion fusion, like laser fusion, uses intense beams to implode and ignite, or "drive," small targets containing thermonuclear fuel. This creates a burst of energy that can be contained, absorbed, and converted into heat in a target chamber. The HIFAR Group investigates the generation of high-power, high-brightness beams of heavy ions; the understanding of the scaling laws that apply in this hitherto little-explored physics regime; and the validation of new, potentially more economical accelerator strategies. In 1993, the group concentrated on designing a series of experiments that would, over several years, address most of the remaining beam-control and beam-manipulation issues at partial driver scale.

In the other main approach to fusion, magnetic fusion energy (MFE), the fuel is confined by magnetic fields and burns in long pulses or continuously. The proposed International Thermonuclear Experimental Reactor, or ITER, is the next major step in the worldwide MFE program. Its goals include ignition of the plasma and are likely to include self-sustaining burn for as long as two weeks at a time. In 1993, the MFE Group continued contributing to ITER in its longtime specialty—design and development of neutral-beam injectors—with a study of injection options for the latest ITER design. The group also continued development of ion sources and accelerators, conducting a successful joint experiment with the Japan Atomic Energy Research Institute (JAERI).

At the end of 1993 the Magnetic Fusion Energy and HIFAR Programs were integrated, yielding the Fusion Energy Research Program. Much of the former MFE effort has been merged into the new Ion Beam Technology Program (see Chapter 5 of the AFRD Summary of Activities). There the group's expertise in ion sources and accelerators is being leveraged for nuclear physics research and for industrial uses such as semiconductor processing and metal surface hardening.

Heavy-Ion Inertial Fusion Accelerator Research: Developing a Promising Approach to Inertial Fusion Energy

*The Heavy-Ion Fusion Accelerator Research program in AFRD has the long-range goal of developing accelerators for inertial fusion energy (IFE). Heavy-ion IFE, like laser IFE, uses intense beams to implode and ignite, or "drive," small targets containing thermonuclear fuel (*sidebar*). This creates a burst of energy that can be contained, captured, and converted into heat in a target chamber or reactor. The beams from the driver (a particle accelerator or laser) are focused onto the target, located at the center of the chamber, by lenses outside the chamber. The targets typically would have a radius of a few millimeters, and the target chamber would have a radius of a few meters. In any of these schemes, the fuel "burns" in pulses that take place so rapidly the reactants are confined by their own inertia. This may be contrasted with the other main approach to fusion, MFE, in which the fuel is confined by magnetic fields and burns in long pulses or continuously.*

During the last decade, nearly all high-level DOE and Congressionally mandated committees that studied IFE have identified heavy-ion accelerators as the most promising drivers for power plants. For engineering and economic feasibility, drivers must be both reliable and efficient. They must also have a high pulse repetition rate (several pulses per second) and long life (about 30 years). Existing drivers—lasers and light-ion accelerators—are excellent for near-term research, but they have been

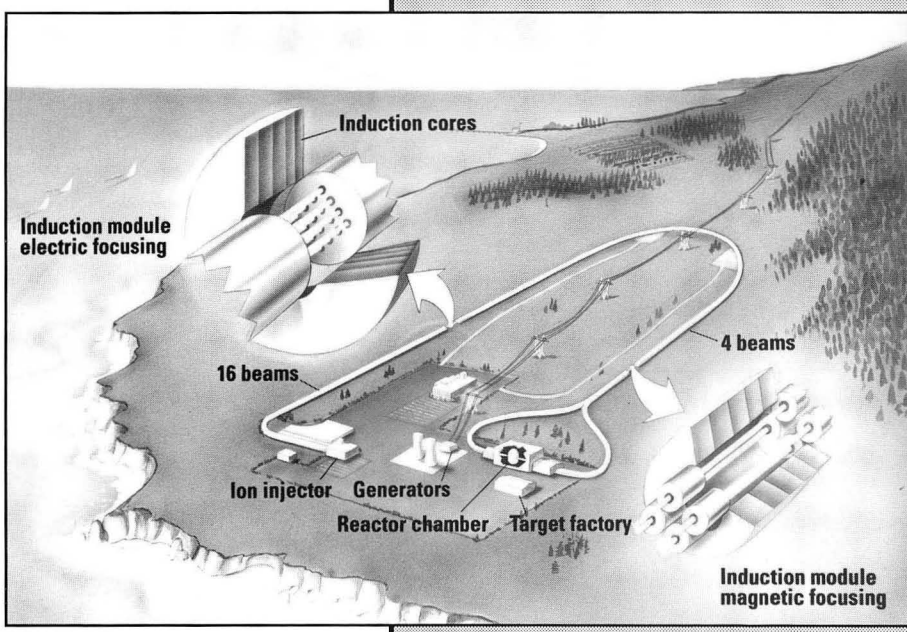
Driver Candidates

The accompanying artist's conception shows the major systems of an IFE power plant and gives an impression of the size. There are several ways to "drive" a deuterium-tritium target—that is, to impart sufficient energy to it (about 10^{15} W) to cause fusion. LBL is investigating one of these approaches, the heavy-ion induction linac. Other laboratories are studying and experimenting with lasers and beams of lighter ions (to date, ranging from protons through lithium) and pursuing rf-accelerator options for heavy ions. The requirements for a driver are quite stringent; they include:

- Low cost.
- Power sufficient to drive the target.
- Repetition rate (a few pulses per second; the lower limit is set by the maximum size of explosion the reaction chamber can handle in each shot, and the upper limit is set by the chamber's ability to prepare for the next shot).
- Shot-to-shot reliability combined with long lifetime.
- Efficiency.

Lasers, such as Nova at LLNL, have been investigated for some time in the context of inertial-confinement fusion. Glass lasers like Nova can be made quite powerful, but at this time, pending further R&D on cooling techniques, they have low repetition rates because of the time needed for the glass to cool between "shots."

Also, today's lasers are only a few percent efficient, whereas heavy-ion drivers are projected to achieve operating efficiencies of 30% or more. For an economical power plant, the product of driver efficiency and target gain will have to be greater than about 10. Because target gain (the energy produced in the fusion reactions, divided by the energy put in by the driver) is expected to be on the order of 100, driver efficiency is a stringent criterion. Lasers definitely have a place in inertial-confinement fusion and in defense research as the most-advanced drivers for target experiments, but their candidacy as power-plant drivers will remain uncertain until the efficiency and repetition-rate issues are resolved.



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Light-ion diode accelerators are also being studied for this purpose, notably at Sandia National Laboratories. The disadvantage of light ions is that much greater beam current is needed to achieve sufficient power at the proper energy. The proper energy, in turn, is a function of the necessary range of target penetration. For heavy ions, the energy is higher (a few GeV versus tens of MeV) but attainable. The beam current, a more troublesome parameter, is lower for heavy ions (kA versus MA), suggesting that collective effects might be much less severe. Both the Fusion Policy Advisory Committee and a National Academy of Sciences panel have stated that the heavy-ion accelerator is the approach of choice for commercial IFE.

designed for a low repetition rate, typically a few shots per day. Heavy-ion accelerators, building as they do on decades of development and operation of sophisticated accelerators for high energy and nuclear physics research, promise a highly reliable, efficient solution. As a result, recent reviews by the Fusion Policy Advisory Committee, the National Academy of Sciences, and the Fusion Energy Advisory Committee have recommended an expanded program.

The HIFAR Program in AFRD

The HIFAR program addresses the generation of high-power, high-brightness beams of heavy ions; the understanding of the scaling laws that apply in this hitherto little-explored physics regime; and the validation of new, potentially more economical accelerator strategies. (Cost minimization is especially important because an inertial-fusion power plant will have to be a success not only in physics and engineering, but also in commerce.) Figure 1-1 shows a schematic outline of the ultimate goal of this research: a heavy-ion driver for an IFE power plant.

Throughout this driver, intense beams moving in parallel are focused by strong electrostatic or magnetic quadrupoles (one set per beam) and accelerated by induction modules that radially encircle the array (thus affecting all the parallel beams). At an energy of about 50 to 100 MeV, beams exiting the electrostatically focused section are transversely combined. The combined beams go into larger-aperture magnetic quadrupoles (at this energy they become more economical than electrostatic ones). At the end of the accelerator, the beams are longitudinally compressed by a factor of 10, then individually focused from a radius of about 10 cm to a spot a few millimeters in radius.

Previous HIFAR experiments—the Single Beam Transport Experiment (SBTE) and the Multiple Beam Experiment (MBE-4)—have verified at a small scale that beams of sufficient brightness can be transported, accelerated, and compressed in the electrostatically focused accelerator. The task of the HIFAR program is to extend these results to an experiment of the same transverse beam size as a driver so that engineering issues can be addressed at the proper scale, and to verify that the remaining beam manipulations of the driver—magnetic transport, beam bending, combining, final focus, chamber transport, and possibly recirculation and beam splitting—can be accomplished while maintaining good beam quality.

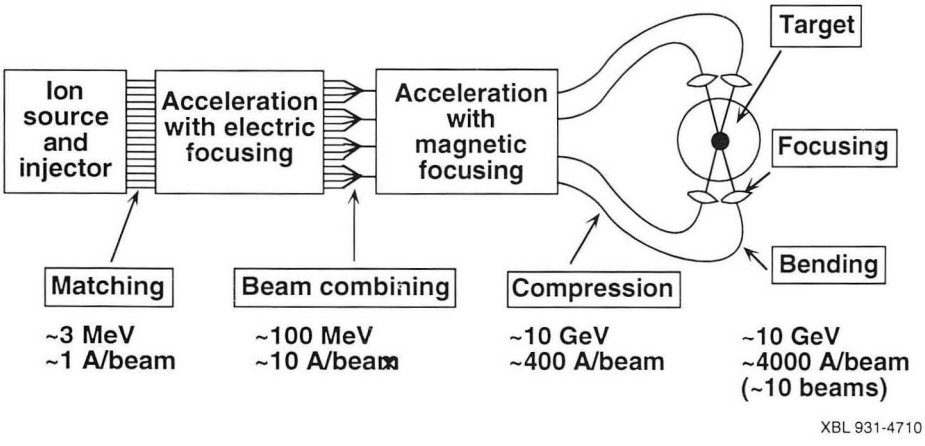

Figure 1-1. The accelerator systems and beam manipulations found in typical heavy-ion driver designs are represented by boxes. A highly accurate alignment system, not shown, will be used throughout. The shaded boxes represent systems that have been tested in past experiments. The remaining issues, except target physics, could be tested in ILSE and its experimental program. Typical driver values of energy, current, and pulse length are shown at various stages.

In recent years, the HIFAR Program has been concerned principally with the next step toward a driver: ILSE, the Induction Linac Systems Experiments. ILSE would address most of the remaining beam-control and beam-manipulation issues at partial driver scale. A few parameters—most importantly, the line charge density and consequently the size of the ILSE beams—would be at full driver scale. In the ILSE conceptual design (Figure 1-2), four beams are accelerated and electrostatically focused, then combined into one. The beams are further accelerated in a subsequent section, this time with magnetic focusing. In both the electrostatic-focus and the magnetic-focus sections, the beam is compressed, as in a driver. Then the beam is used for experiments in drift compression and final focus. In Table 1-1 some parameters of the ILSE design are shown and compared to those of previous experiments, as well as to driver parameters that were derived by our researchers, drawing upon the Laboratory Microfusion concept.

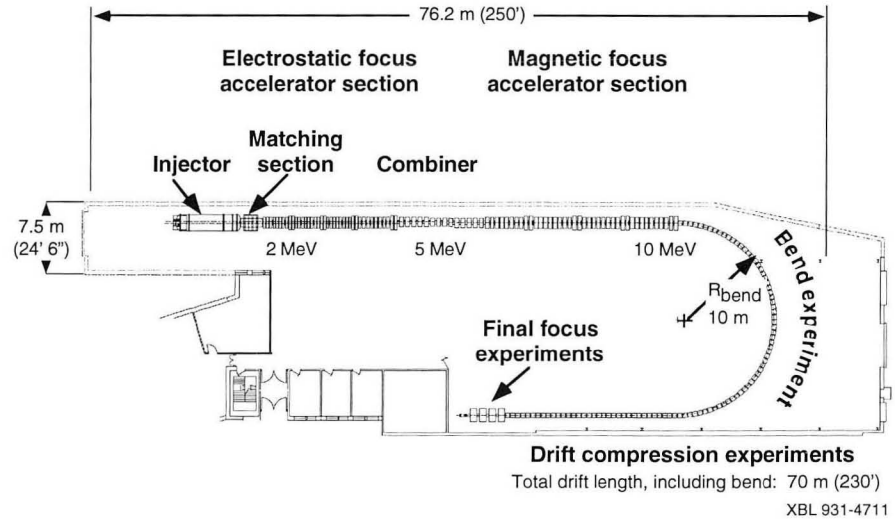

Figure 1-2. This diagram shows the physics design of the ILSE accelerator and a possible arrangement of some of the experiments. The 2-MeV injector provides four beams of K+ in 1-μs pulses at driver line-charge densities. A matching section transforms the round beams to an alternating gradient profile and "squeezes" them together for insertion into the electrostatically focused linac. To amplify the current, the electrostatic-focus induction linac imparts a velocity shear or "tilt" to the beams as it accelerates them to 4.5 MeV. A subsequent magnetic-focus induction linac, which also amplifies current, takes one of the beams to 10 MeV. A later phase of ILSE would combine the four beams into one for injection into the magnetic-focus linac.

Table 1-1. Key parameters of HIFAR experiments and an example driver.

	SBTE	MBE-4	ILSE	LMF-based example
Ion species	Cs^+	Cs^+	K^+	Kr^+
Number of beams	1	4	4→1	20→4†
Final energy (MeV)	0.15	1	10	2500
Total final energy (J)	0.07	0.08	32	5×10^6
Final ion velocity/c	0.0016	0.004	0.024	0.25
Bunch length (m)	8.0	1.1→0.25	3.1→2.8*	70→10*†
Pulse width (μs)	20	2→0.4	3→0.4†	24→0.1†

* These pulse lengths are given at the end of the accelerator section. In a driver, drift compression would further shorten the pulse. Note also that smaller, less-intense beams can be compressed further.

† The bunch lengths and pulse widths specified here, with their beam-compression implications, are hypothetical driver values, not calculated LMF values.

Unfortunately, despite multiple review-committee findings that pressed for the construction of ILSE, and despite a cost reduction from $72.2 to $53.3 million that resulted from technical improvements and the re-use of existing infrastructure after the decommissioning of the Bevalac, start of construction has not been approved.

HIFAR Physics and Technology R&D: Progress Toward Driver-Scale Systems

A high-energy, high-current, one-beam injector at driver scale was successfully completed in 1993. The effort was helped by extremely detailed three-dimensional computer modeling of the electric field configuration and beam dynamics of the injector. In addition, considerable progress was made in magnet design and component development. Future projects include small-scale experiments, theoretical support of both the ongoing experimental program and long-range driver design, and the next steps in driver-scale experiments.

Injector-Related R&D

The 1993 injector program centered on the construction of a 2-MV, 800-mA injector for singly charged potassium ions (Figure 1-3). As a result of a six-month LBL-Livermore joint study in 1992, the electrostatic quadrupole (ESQ) configuration had been chosen as the optimal injector for heavy-ion fusion applications. The ESQ injector had been studied for a number of years at LBL and in Russia for neutral-beam applications in magnetic fusion energy.* However, IFE applications require substantially different machine parameters; the associated issues had to be addressed before the ESQ design could be finalized. Therefore, the 1993 injector program involved substantial supporting activities in simulation, experimentation, and engineering R&D.

Injectors for heavy-ion IFE must produce ion beams that have very low normalized emittance (less than 1 millimeter-milliradian) so that they can be focused to the required spot size at the target. A potentially deleterious phase-space distortion is known to affect low-energy ion beams traversing strong electrostatic quadrupoles, and may lead to unacceptable degradation of beam quality if not properly controlled. This "energy effect," a result of using the quadrupoles to accelerate as well as to focus, can be reduced by increasing the diode energy and/or varying the focusing strength of the quadrupoles. Extensive theoretical studies were performed in conjunction with 3-D simulations to quantify these effects.

The problem of ion transport through an ESQ is intrinsically three-dimensional, and space charge plays a dominant role, so the particle-in-cell code WARP3D was an indispensable design tool for specifying machine parameters that gave sufficiently low output emittance. To gain confidence in the code's predictions, a scaled experiment was performed with a 100-keV, 10-mA K^+ beam in SBTE. The phase space distortion experienced by the beam as it traversed four quadrupoles (which in the scaled experiment are one-fourth the size of those in the ILSE injector design) was in excellent agreement with the code results.

High-voltage breakdown was another critical issue in the design of the injector. The insulator columns are protected by thick metal shields. The geometries of these shields, as well as the electrodes and associated structures inside the column, were simulated in detail to minimize surface fields. Around the column, pressurized sulfur hexafluoride provides electrical

* These pulse lengths are given at the end of the accelerator section. In a driver, drift compression would further shorten the pulse. Note also that smaller, less-intense beams can be compressed further.

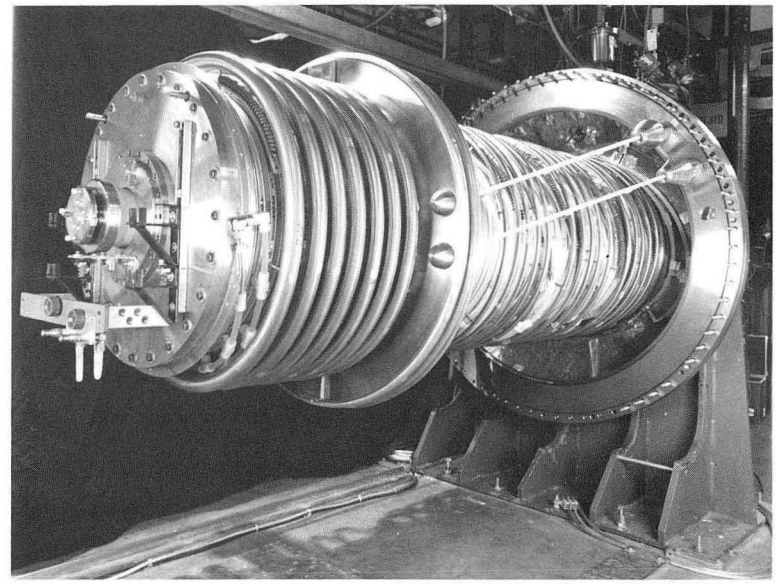

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Figure 1-3. In contrast to conventional Pierce columns with axisymmetric apertures, the ESQ injector for ILSE consists of several electrostatic quadrupoles arranged to provide strong focusing and acceleration simultaneously. The front end of the injector is a conventional diode. This configuration has inherent advantages, including lower accelerating gradients as well as and large transverse fields that sweep out secondary electrons that may cause electrical breakdown or generate excessive x-rays. The major structures are (left to right) the ion source, the diode, and a stack of ESQ accelerator modules that consist of alternate matching-and-pumping and accelerating stages.

insulation. Design and construction of the protection system with metal oxide varistors, and of the water resistor circuitry that determines the quadrupole voltages, were performed by Pulsed Sciences, Inc., our industrial partner on this project.

An essential element in the design of the ESQ accelerator was the choice of beam energy at the transition between the front-end diode and the quadrupole section. This energy should be as high as possible to avoid or minimize the "energy effect," but as energy is increased, voltage-holding (breakdown) problems are eventually encountered. To specify this key parameter, we performed a diode experiment in which 800 mA of beam was accelerated to 960 keV. On the basis of the results, we selected 750 kV for the injector diode.

To validate our thinking about the mechanical and electrical design of the electrostatic quadrupoles for the injector, we performed an experiment early on, building a full quadrupole section at driver scale and performing a breakdown test (without beam). After some conditioning, the full-sized quadrupole was shown to hold more than 700 kV. These data gave us confidence that our ESQ design, with quadrupole voltages of less than 400 kV, was workable.

In addition to these key physics issues, unique mechanical engineering problems were associated with the ~ 225-kg column structure. The fully assembled column is supported and put under compression by four insulator rods. Some experimentation was required to find the optimal brazing cycle for the ceramic column. Similarly, we found that the large aluminosilicate ion source (Figure 1-4) was sensitive to the brazing cycle; it took several empirical attempts to arrive at a smooth, even surface.

The 2-MV injector is powered by a newly constructed 36-module Marx generator. The pulse-forming-network is composed of multiple stages, each with a simple combination of an resistive-capacitive and an inductive-capacitive circuit, arranged to provide a 4-μs flattop ($\leq$ 1% energy variation). The new generator was completed in August and reached 2.2 MV on the first day of operation. The measured voltage flattop was in excellent agreement with design values. The pulser for current extraction was designed to switch from –80 kV before turn-on to +80 kV at the peak of turn-on.

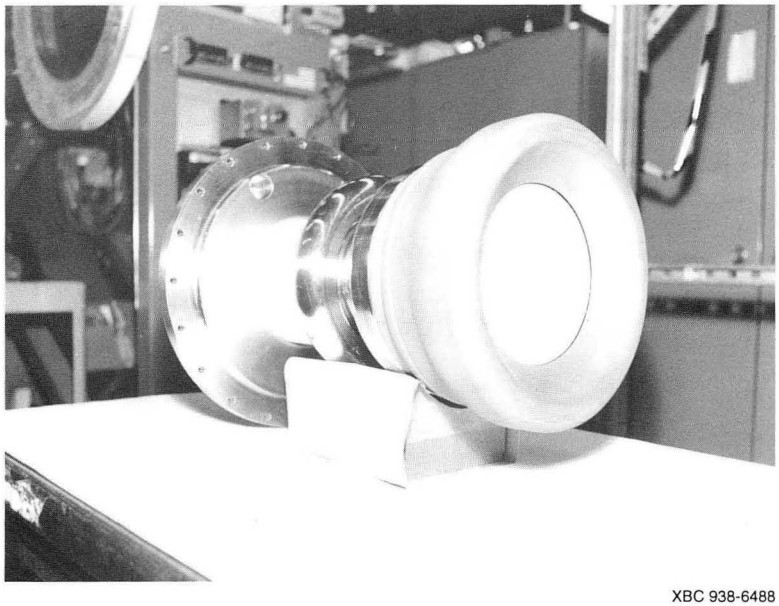

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Figure 1-4. This 10-cm-diameter ion source incorporates two LBL-developed improvements to an existing technology: artificial aluminosilicates, or zeolites, incorporating the desired ion species, which in this case is potassium. The two innovations are applying the zeolite to a porous tungsten plate and heat-treating it between 1400° and 1700° C. In this range, the zeolite neither sinters nor vitrifies, so crystals a fraction of a millimeter in length, similar to the mineral cristobalite, are formed. The use of porous tungsten helps keep the zeolite coating from puddling into nonuniformities on the curved surface, a defect that would show up in the extraction optics, and also contributes to mechanical strength. The result is a source that meets our severe requirements for low beam "temperature" and also durability. Shown at the right side of the photo are the curved zeolite surface, surrounded by a graphite Pierce electrode. A driver injector might require a source with a diameter of about 22 cm and a current density of about 2 mA/cm^2.

On October 27, 1993, the assembly of the injector was completed, three days ahead of schedule. The next day, we turned on the entire machine and measured over 800 mA of K^+ at 2.15 MeV, a level of performance that exceeded the requirements for the beginning of the experimental program.

ILSE-Scale and Driver-Scale Technology Development

Another important achievement was redesign of the electrostatic quadrupole for the low-energy section of ILSE. Compared to earlier designs, this quadrupole features better resistance to high-voltage breakdown; use of a metal-forming process (as opposed to machining, which would be more expensive) to fabricate the electrodes; and lower weigh. During the initial electrical breakdown test, the revised model was able to operate with good stability at the ILSE design voltages.

Work on induction modules continued in 1993. A two-week test was carried out on one of the three cells that make up the ILSE-scale, 100-kV induction module. The test was performed at 1 pulse per second, accumulating approximately one million pulses. This test was extremely valuable in uncovering some of the weak points of our preliminary design of the core insulation and the reset pulser.

Significant progress was made in the development of the sensors and control software that will eventually be necessary for accurate real-time quadrupole positioning in the ILSE experiments. Accurate, stable, and repeatable actuators were built and tested. Software was developed that makes the sensor output linear with respect to the actual positioning-wire motion in the alignment system. Two diagnostic systems were developed this year: an optically coupled voltage monitor used for relaying signals generated at the 2-MV potential of the injector source, and also a current-measuring Rogowski loop. Devices similar to this Rogowski loop could be used for measuring the current in an ILSE-like 5-MeV accelerator.

Looking even further ahead—to the electrostatic quadrupoles used for transport in an ILSE-scale experiment or in a driver—we made one of our most important discoveries of the year: an experimental determination that, for the

quadrupole sizes of interest, the breakdown voltage has a nearly square-root dependence on the quadrupole radius. This information, combined with various assumptions on the required clearance between the beam and the electrodes, leads to the result that the optimum aperture radius for a driver is about 2.3 cm. This is somewhat smaller than previously assumed, which will reduce the cost of future experiments. The quadrupole dimension will be an important component in setting the transverse scale for the driver, and because its dimension determines the amount of current carried in each beam at the beginning of the accelerator, it will also provide important input for determining driver design parameters such as the number of beams to be merged.

HIFAR Research in Beam Transport: Theoretical Studies and Technology Development

An important issue in the design of heavy-ion fusion drivers is the dynamic aperture of short magnetic quadrupoles, which in some designs are used immediately after the transition from electrostatic to magnetic focusing. They might also be used immediately following the injector and in the region between the end of the accelerator and the reactor. The interest in short quadrupoles evolved from the scaling rule that governs the maximum transportable current for a space-charge-dominated beam (sidebar). In 1993, the group completed a theoretical study of the usable aperture ratio for short magnetic quadrupoles, considering two cases: ILSE and a driver.

Aperture Ratios and Beam Quality

The maximum transportable current for a space-charge dominated beam scales as the square of the usable aperture ratio, a_b/L:

$$I_{\max} \approx \left(\frac{a_b}{2L}\right)^2 I_0 \frac{A\gamma^3\beta^3}{2Q}\sigma_0^2.$$

Here a_b is the maximum beam radius, L is the focusing lattice half-period, I_0 is the proton "Alfvén current" of 31.07 million amperes, A and Q are the atomic mass and charge state, respectively, of the ion, g and b have the normal Lorentz definitions, and s_0 is the betatron phase advance per full lattice period in the absence of space charge.

Since a large maximum current permits more-efficient use of the accelerating core's cross section, thus lowering the cost of the accelerator, there is great advantage to making the beam aperture ratio as large as possible. However as the aperture ratio increases, fringe fields from the ends of the magnet become more significant compared to the main quadrupole field of the magnet. Degradation of beam quality—in terms of emittance growth or actual particle loss—due to the nonlinearity of these unwanted fields can limit the usable aperture. In 1993 we completed a theoretical study of the usable aperture ratios of short magnetic quadrupoles, considering both ILSE-sized magnets and those of a postulated driver.

From both analytical decomposition of the magnetic field in a periodic lattice and particle-code simulations of beam transport, we found that fringe-field nonlinearities and associated emittance growth become quite large when the beam radius ab exceeds approximately one-quarter of the half-lattice period. For the parameters of ILSE-sized experiments, the ratio a_b/L is of order 0.1 or less, and a number of magnet designs could transport the specified line charge without significant difficulties. For larger beams, as in the low-energy part of some driver designs, matching problems would begin as a_b/L exceeded 0.2.

Aperture Ratio Studies

For the parameters of the ILSE conceptual design, a number of magnet designs could transport the specified line charge without any significant difficulties. For larger beams at low energy, as in some driver designs, there would be problems with matching the beam to the transport lattice. For even larger aperture ratios, particle loss could occur. Figures 1-5 and 1-6 show the effect of increasing aperture ratio. We found that fringe-field nonlinearities and associated emittance growth become quite large when the beam radius exceeds approximately one-quarter of the half-lattice period.

We used analytical theory to make a preliminary design of the field coils for an ILSE-scale magnetic quadrupole. The beam dynamics were then checked using particle simulation. A mechanical model was made to test cooling, electrical reliability, and fabrication techniques. Measured coil losses were quite low; the water cooling design worked well, restricting the temperature increase to a mild 22° C while allowing no electrical contact with the coil.

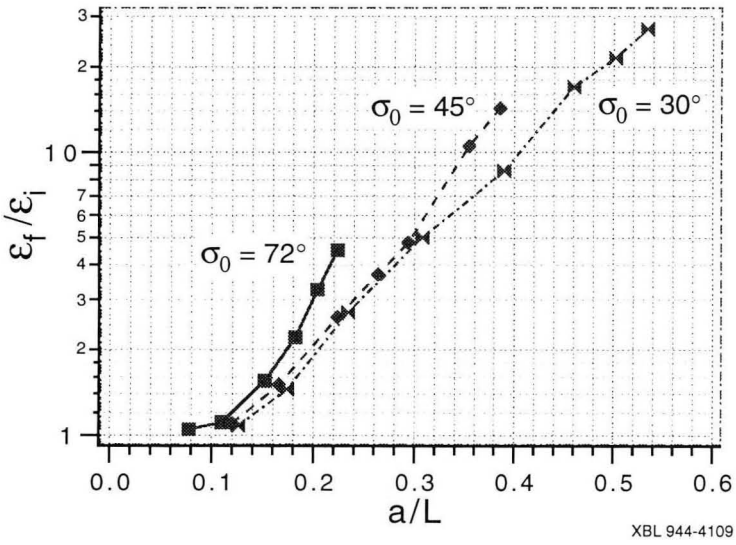


Figure 1-5. Emittance growth as a function of magnetic quadrupole aspect ratio over 100 m of transport for an ILSE-like beam, for three values of σ_0. (Sigma-nought is the betatron phase advance per full lattice period in the absence of space charge.) In the computer simulation that produced this graph, each curve was terminated when particle losses exceeded a few percent. For identical values of a_b/L, the transported λ is much larger at σ_0=72° than at σ_0=30°.

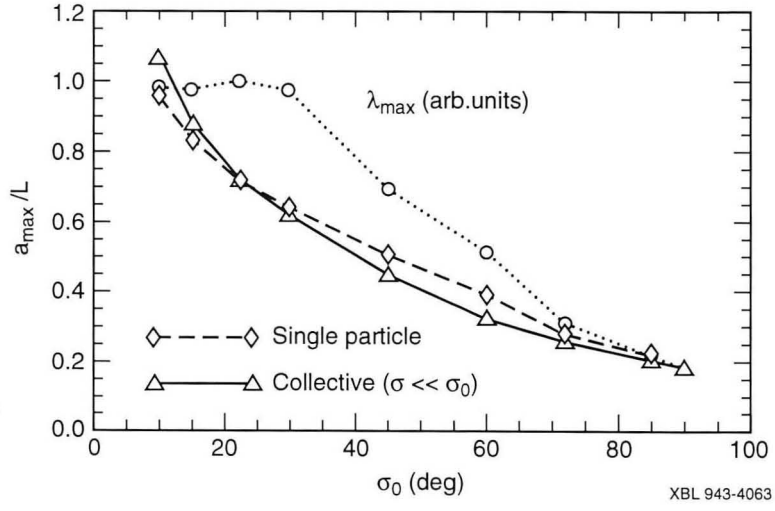


Figure 1-6. The maximum usable aperture (i.e., the aperture beyond which particle loss becomes significant), normalized to the half-period length L, as a function of σ_0 for a space-charge-dominated beam. Also shown is the maximum transportable line charge λ_{max} (in arbitrary units) . The dashed curve gives the equivalent maximum aperture when the beam is fully emittance-dominated.

HIFAR Plans for 1994 and Beyond: Continuing Driver-Oriented R&D

The 1994 HIFAR program will encompass investigation of accelerator issues at small scale and further driver-scale research. Experiments to characterize the beam from the 2-MV injector will be carried out. They will include studies of ion current dependence on Marx-generator and pulser voltages; beam size and emittance measurements; studies of transients; and some beam-energy measurements. In a program that will run through mid-1995, we will begin design and fabrication of a matching section to give the beam from the injector the size and convergence required for transport in an electrostatic or magnetic channel or final-focus experiment.

Experimental Plans

The first-ever experiments in transversely combining space-charge-dominated beams are scheduled for this year. Four beams will be bent toward each other and then combined, with diagnostics measuring the change in beam quality. The effect of beam merging has been examined by passing a single beam through a multi-aperture "mask," thus forming several beams which then merge, but this will be the first experiment to bend the beam trajectories together and merge beams of particles with the proper spatial and velocity properties. Since the resultant beam quality depends on how closely the beams can be packed, mechanical precision will be important. The experiment will use the transport system from the old MBE-4 experiment.

Continuing our longstanding collaboration with LLNL, we are participating in a small recirculator experiment there. Initial studies indicate that recirculating the driver beams through the same induction cores a number of times could lead to cost savings. However, physics issues such as resonant particle effects, charge exchange effects, and injection and extraction from high-current rings must be studied experimentally. Technological challenges are also involved, especially in waveform fabrication and induction-core switching.

The initial design for the recirculator experiment contains 20 periods, each 64 cm long, forming a ring approximately 4 m in diameter. Transverse focusing is provided by permanent magnet quadrupoles, and bending by electrostatic dipoles. Two milliamperes of K^+ will be accelerated from 80 keV to 320 keV to give a final current of 4 mA. During 1994, the injector for the recirculator will be fabricated and tested. Potassium beams from the injector will be matched to a magnetic quadrupole transport line using six electrostatic quadrupoles from SBTE.

Besides supporting these experiments, the HIFAR theory group will continue its longer-range theoretical work. Their efforts will include combiner studies for future driver-scale experiments, exploration of driver final-focus options, and planning for the National Ignition Facility, a non-LBL experiment presently in the proposal stage that would use laser drivers to study the design and dynamics of inertial fusion targets.

MFE R&D Progress: Neutral-Beam Injection Options for ITER

Heating a plasma to thermonuclear temperatures is one of the many significant challenges in fusion-energy research, especially for the extended periods that will be needed as the missions of next-generation tokamaks incorporate engineering tests and materials research as well as demonstration of ignition and burn. The primary focus of the MFE Group at LBL has been the development of neutral-beam injector systems for this purpose. The group's 20 years of work in this field began with the invention of novel multiampere positive-ion sources and of improved, computer-optimized acceleration systems. The most prominent achievement thus far has been the design, development, and transfer to industry of the Common Long-Pulse Source (CLPS). It is used in the Tokamak Fusion Test Reactor (TFTR) at Princeton and the DIII-D tokamak at General Atomics, two of the principal MFE experiments now operating in the U.S., and strongly influenced the neutral beam systems at the Joint European Torus.

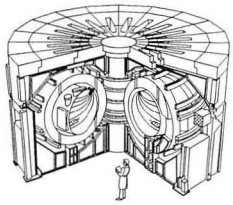
The positive-ion-beam technology of the CLPS, though, is limited to a few hundred keV for efficient beam neutralization. In the coming generation of tokamaks, such as ITER, larger plasmas will require higher injection energies—around 1 MeV, as compared to the 120-keV CLPS—for adequate penetration. Accordingly, we use negative ions, accelerating them to the necessary energies and subsequently neutralizing them by the simple process of detaching the extra electron. In contrast to systems based on positive ions, the neutral-particle yield of negative-ion systems does not decrease with increasing energy. However, it is difficult to produce large quantities of negative ions.

Efforts to develop suitable sources of negative hydrogen ions at the ampere or multiampere levels are now under way here and at several other laboratories. Design, construction, and testing of prototype accelerator systems must go hand in hand with development of a negative-ion source, so substantial effort has been devoted to accelerators. Highlights of 1993 research and development include a study of several options for beamlines on the latest ITER design; a successful joint experiment with JAERI that merged multiple H^- beamlets from a JAERI ion source and accelerated them with an LBL-built accelerator; and tests of rf-driven ion sources at high power levels and in long pulses.

An important remaining step would be the development and test of a high-current (tens of amperes), continuous-duty H^-/D^- accelerator in the MeV energy range—a combination of parameters that seems within reach but has never been proven experimentally. In earlier years we had proposed a Proof-of-Principle Experiment (POPX) that would accelerate 1.4 A of H^- to 1.3 MeV for two seconds. The POPX is based on negative-ion sources and our constant-current, variable-voltage ESQ accelerator concept. The project has an estimated cost of less than $15 million and would take approximately 30 months. DOE funding was on hold, pending the ITER Council's decision on whether to use neutral beams in the first phase of ITER operations. In the wake of DOE's 1994 termination of the US-based neutral beam development program, it appears likely that any further work would be carried out under the aegis of JAERI.

ITER Beamline Studies: Options for the Detailed Design

One of the options for ITER is the injection of neutral deuterium beams with a total power in the 60–135 MW range. The beams would supplement other options for plasma heating and would drive the toroidal current in the center of the plasma for confinement during steady-state operation, as shown in Figure 1-7 and explained in the sidebar. The energy needed to ensure the required plasma penetration, 1.3 MeV, is an order of magnitude greater than that of the CLPS. Building upon previous work that was



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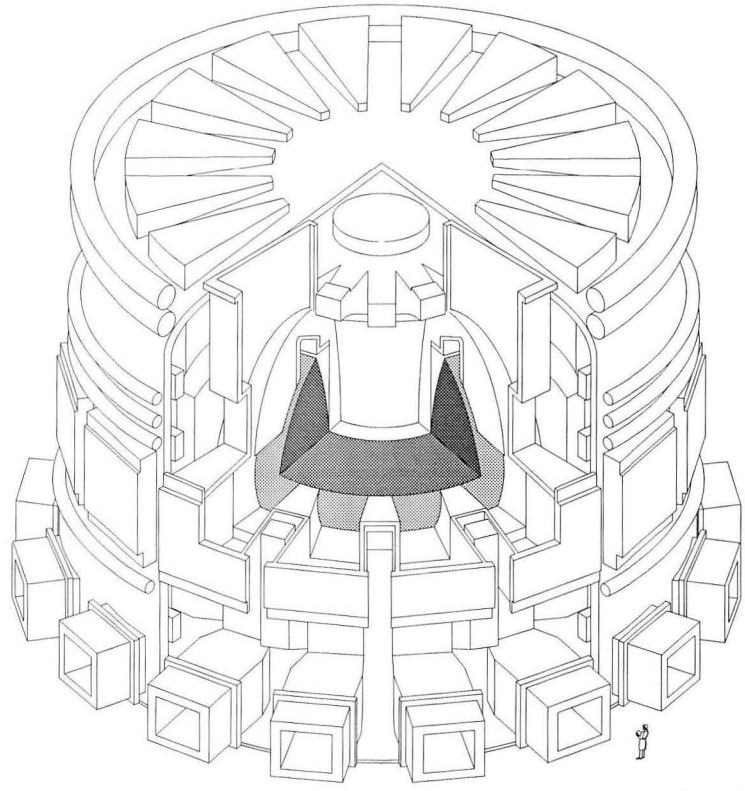

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Figure 1-7. The proposed International Thermonuclear Experimental Reactor is an ambitious scientific and technological step toward a demonstration power reactor. LBL's role within the U.S. effort involves the design and development of neutral-beam systems to heat the plasma and drive the toroidal current. The artists' renderings show approximately how ITER's "core" (*right*) compares in size to that of the Tokamak Fusion Test Reactor now running at the Princeton Plasma Physics Laboratory (*above*). (After PPPL and LLNL artwork.)

Neutral Beams and Current Drive

In addition to their primary role of heating the plasma, injected neutral beams help confine and control it. In a tokamak, the plasma is confined by the combination of two principal magnetic fields: a toroidal field in the plane of the torus and a poloidal field wrapped around it, as shown here.

A fusion plasma is very hot—that is, the charged particles move at high speeds. In the absence of a magnetic field, they would move randomly; the toroidal field guides them circumferentially through the torus, spiraling along the lines of force. This field is generated by external coils. Under the influence of the toroidal field alone, the plasma would move toward the outer wall, so a poloidal field is added. The poloidal field is the result of a very large electrical current—about twenty million amperes in ITER—coursing through the highly conductive plasma.

This current in the plasma is initiated inductively by a transformer coil—the plasma is the secondary of the transformer. The resultant "ohmic heating" is not sufficient to reach thermonuclear temperatures and must be supplemented by rf or neutral-beam heating. For confinement purposes, inductive current drive may be sufficient during the initial physics phase of ITER operation, with its short pulses.

However, as the ITER Council defines the reactor's mission, they may retain the plans for a subsequent technology phase that will involve sustained burns of up to two weeks. This is far beyond a transformer system's ability to store and deliver power at the monotonically increasing voltages that are needed, so supplemental noninductive drive will be required.

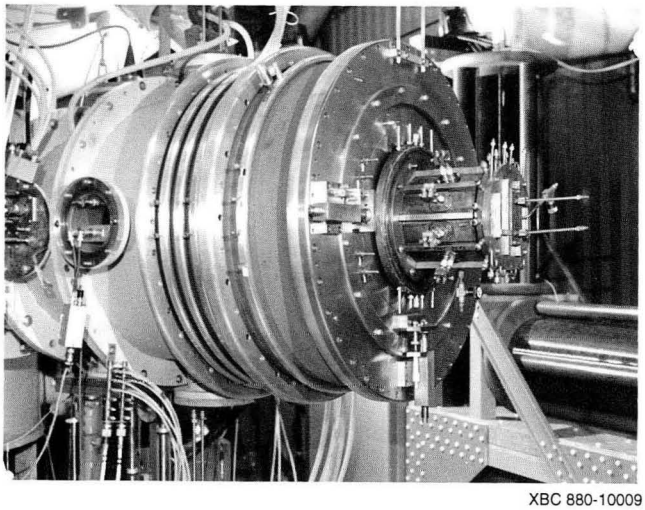
In these longer experiments, the bulk of the current could be driven by the neutral beams, which primarily affect the center of the plasma. (The beams are neutralized so that they can pass through the magnetic fields; after entering the tokamak, they are re-ionized by collision and transfer their energy to the cooler plasma by Coulomb interaction.)

oriented toward earlier revisions of the ITER design, we studied several options for delivering the required power through a single port. In an additional exercise, we considered designs with a minimized port height, which would reduce the mechanical stresses caused by eddy currents during a plasma disruption.

The studies assumed the use of a multiple-channel version of our constant-current, variable-voltage (CCVV) electrostatic accelerator design, as shown in Figure 1-8. In each channel, after pre-acceleration of the 2-A beam to 200 kV, a short matching stage focuses the beam and feeds it into the first acceleration stage. Each acceleration stage increases the beam energy by as much as 125 keV and uses electrostatic quadrupoles for focusing.

For ITER neutral-beam-injection applications, the energy range of the CCVV accelerator has to be widely variable. The output beam energy may be varied by tuning the acceleration voltages and the ESQ focusing voltages; this may be performed rapidly without altering the accelerator's mechanical configuration. Because the electrostatic quadrupoles provide strong focusing (as contrasted with designs that depend on the accelerating electrodes for weak focusing), the energy can be varied without requiring a change in the current. The average accelerating gradient can be kept as low as 3–5 kV/cm to enhance insulator lifetime. Another advantage is that the transverse electric fields sweep away electrons at a mean energy of several tens of keV, minimizing x-ray generation. Secondary positive ions are similarly swept away.

We studied two high-power beamline options (Figure 1-9). The first provides 63 MW (which could be raised to about 84 MW by using a plasma neutralizer rather than the simpler, cheaper gas neutralizer). The second, by using simple bend magnets between the accelerator and neutralizer, incorporates more channels and can provide 101 MW (135 MW with plasma neutralization). We also prepared two designs that assumed severe restrictions on the size of the beam port: an 18-MW system for a height-minimized, 30-cm-tall by 80-cm-wide beam port, and a 19-MW system for a 60 × 60 cm port.



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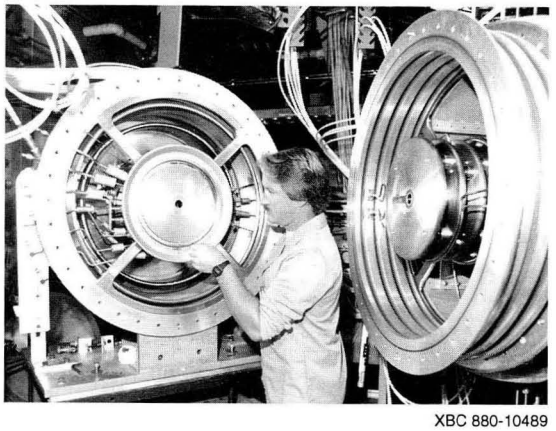

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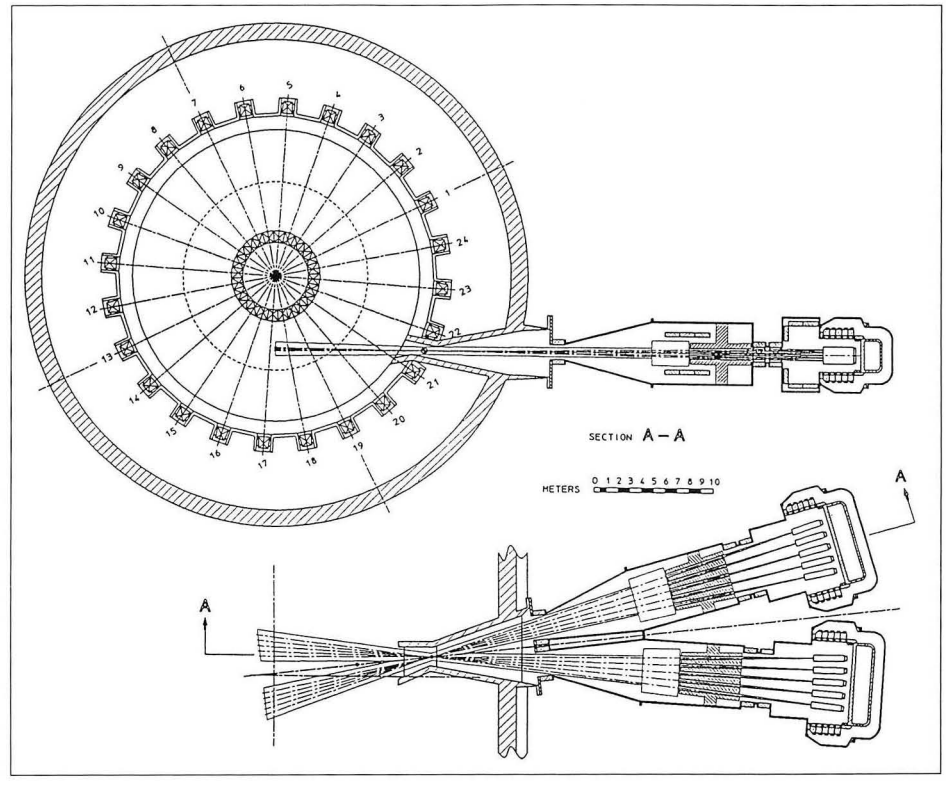
Figure 1-8. The ITER beamline studies assumed the use of a CCVV accelerator with ESQ focusing. The accelerator was a scaled-up and modified version of this one, which we have been working with since 1987. Typically each channel of the paper design for the ITER study took 2 A of D^- from an injection energy of 300 keV to a final energy of 1.3 MeV.



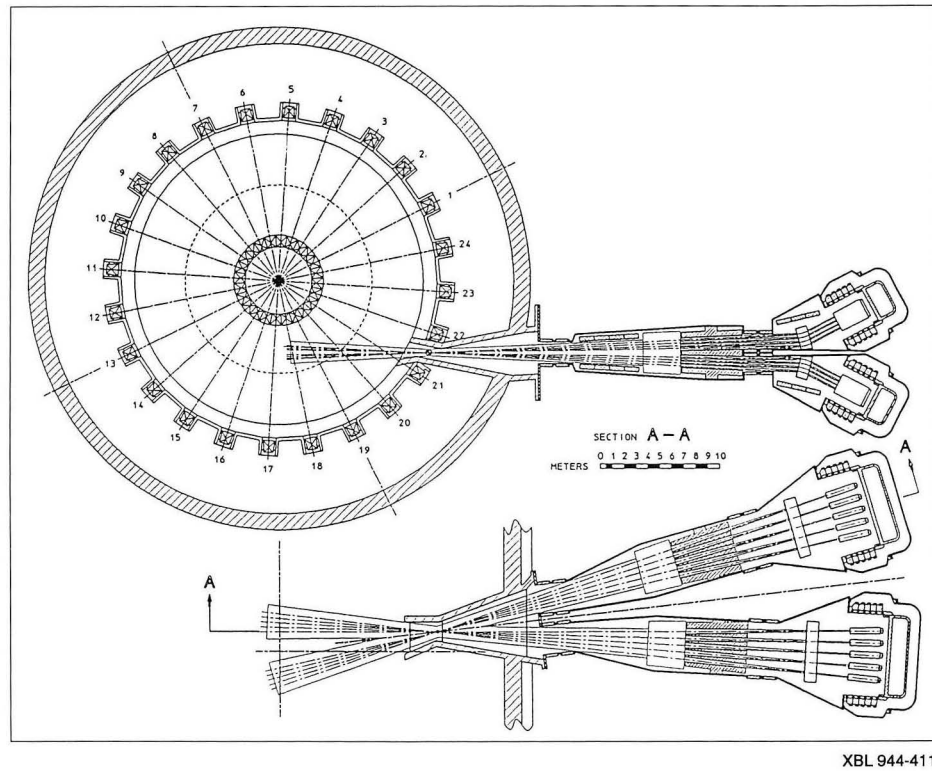


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Figure 1-9. The key differences between the beamline concepts are the grouping of beam channels into different arrays; the energy and/or current per channel; and whether the beams follow a straight or a magnetically bent path. These designs could deliver 63 (above) or 101 MW of D^0, respectively (which could be upgraded to 84 and 135 MW by substituting a plasma neutralizer for the gas neutralizer). Compared to the Conceptual Design Activity scheme, these new designs provide more power through a single port by using more beams per channel and higher beam current; the tradeoffs are reductions in redundancy and in vertical beam-steering ability. We also examined two lower-power (<20 MW) beamline designs for scenarios in which the beam port size was greatly restricted.

Compared to our earlier designs, which were based on a nine-port ITER configuration, these injection options have less redundancy and a greater number of shared components, implying a need for more-reliable and thus more-expensive components. Furthermore, they provide less ability for vertical beam steering for control of the toroidal-current profile. They could, however, provide 60–135 MW of 1.3-MeV D^0 through a single port, and, if the detailed mechanical design of the torus reveals a potential problem with eddy-current stresses, height-minimized options are available, albeit at lower power. The results of the study have been documented and will be available to the community should ITER choose neutral-beam injection.

Merging Beams: A Joint Experiment with JAERI

Neutral-beam injection systems have generally required a great deal of space around the tokamak (Figure 1-10), and as we look toward ITER-sized tokamaks with their high power requirements, the port sizes also become a matter of concern. To solve these problems, LBL researchers proposed merging numerous beamlets to produce a beam that combines high current with small diameter. This single beam is then accelerated with an ESQ accelerator, or, in an actual injection system, one channel of a multichannel ESQ accelerator. In collaboration with the Neutral Beam Injection Heating Laboratory of JAERI, we began analysis and experimentation in 1992 at LBL.

JAERI provided a multicusp source and a multiaperture preaccelerator that also acted as a combiner; this system fed our ESQ accelerator. The 19-aperture beam combiner yielded a 100-mA H^- beam with an envelope diameter of 23 mm. The focusing angle of the beam optics could be reduced to the range of +30 to –30 milliradians (where a positive value indicates convergence and a negative value, divergence), and the emittance was in the

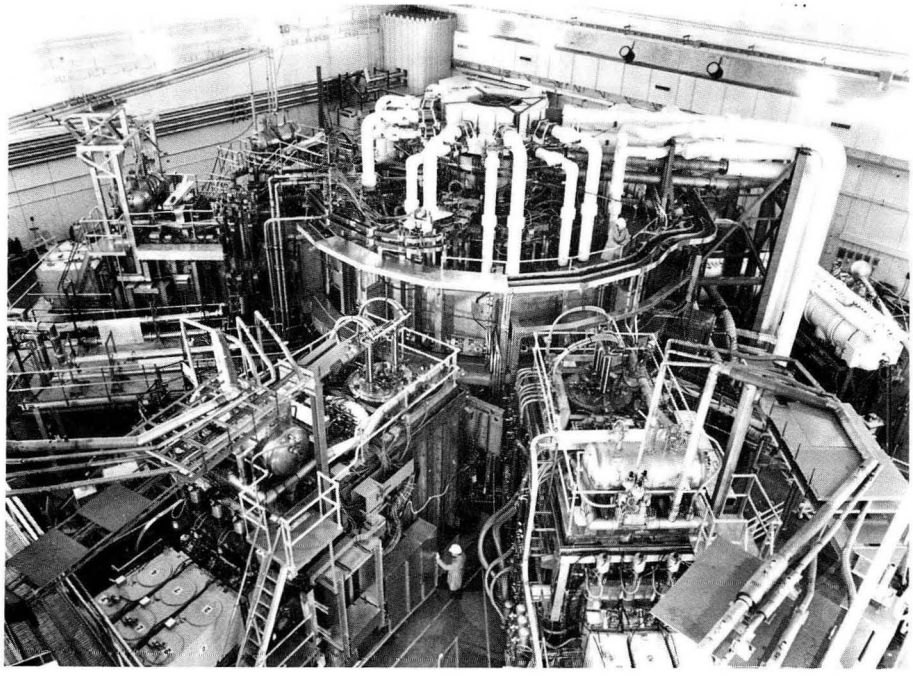

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Figure 1-10. As shown by this photo of the Thermonuclear Fusion Test Reactor at the Princeton Plasma Physics Laboratory, neutral-beam systems of conventional design seem to occupy more space than the tokamak itself. An LBL idea—merging the beamlets from a multi-aperture preaccelerator into one intense beam—can help greatly reduce the size of neutral-beam injection systems for future tokamaks. In 1993 LBL tested this idea in a highly encouraging joint experiment with the Japan Atomic Energy Research Institute. (Photo courtesy PPPL)

range of 1.0 π cm-mrad; these values proved acceptable for matching into the ESQ accelerator. We successfully transported and accelerated a 100-mA H^- beam with an input energy of 100 keV and a final energy of 200 keV with no measurable beam loss or emittance growth.

Ion Sources for MFE: Technology, Tools, and Spinoffs

It is not yet clear which of several negative-ion-source technologies will be best suited for high-current, long-pulse neutral-beam injection systems. Much of our work has focused on surface-conversion sources (sidebar), but in recent years, "volume-production" sources that produce ions throughout a volume of gas rather than on the surface of an electrode have emerged as promising candidates. (We are also involved in a collaboration with the Japan Atomic Energy Research Institute that may lead to better ion sources for ITER and other applications.) The main goal is to increase the steady-state current capability of these sources.

In the meantime, we have continued to obtain promising results with an rf-driven surface-conversion scheme. Already being used in spinoff applications such as high-energy-physics accelerators, they could eventually supplant conventional schemes for very-long-pulse operation.

We are also investigating photocathodes—bright electron sources that offer a singular feature: electron pulses of the same length as the ultraviolet laser pulses that excited the cathode material. We are studying various low-work-function materials, such as monocrystalline lanthanum hexaboride and thin films of barium, and measuring the sensitivity of quantum yield to various parameters such as laser polarization and angle of incidence. The long-range goal is to make them both efficient and rugged enough for practical applications. Work also continues in the laser and spectroscopic diagnostic of plasmas in our group's various ion sources, concentrating primarily on clarifying the H^- production processes in rf-driven plasmas.

Production of Negative Ions

Volume production and surface conversion are two fundamentally different ways of producing negative ions. Both types begin with a gas of the desired species (hydrogen or deuterium in our work) that is partially ionized by any of several means, but thereafter the two methods diverge at the level of chemical physics.

In surface conversion, a negatively biased element (either a coated converter/cathode or a separate, coated converter element) draws positively charged ions from the plasma. Some of them are backscattered, a process in which they sometimes become transformed into negative ions by capturing two electrons from the metal surface.

Meanwhile, the surface has been adsorbing the species that makes up the plasma. Of the incoming positive ions that are captured rather than backscattered, some sputter the adsorbed atoms out of the surface; the atoms that are sputtered out can also emerge as negative ions.

The sheath of positive ions that surrounds the converter—a sheath a few tenths of a millimeter thick in an intense discharge—accelerates the negative ions. Those that leave the source by this means are said to have been "self-extracted."

In volume-production sources, gas-phase reactions are dominant (though surface conversion can take place at the chamber walls) and vibrational excitation of diatomic hydrogen atoms is thought to play a key role. The model involves a two-step reaction:*

$$(1) \qquad H_2\,(v'' = 0) + e^- (\geq 25\ \text{eV}) \rightarrow H_2\,(v'' \geq 6) + e^-$$

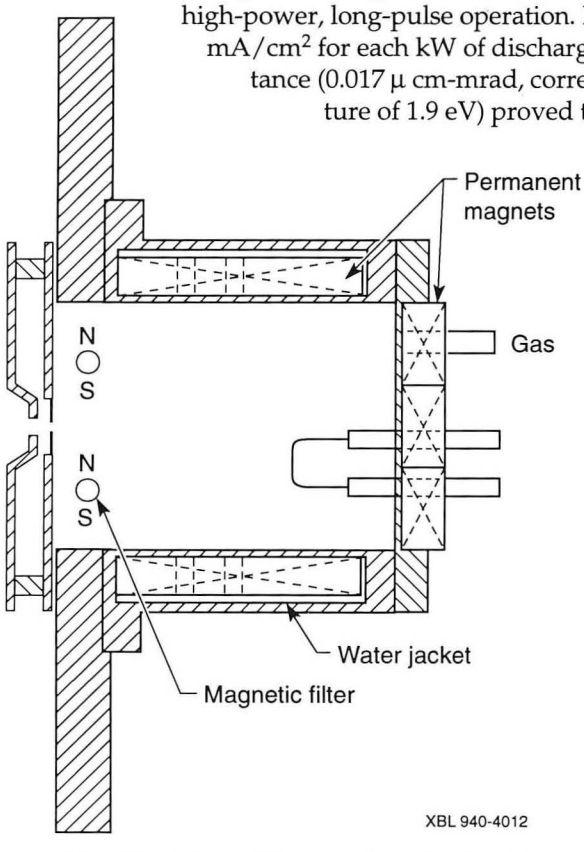
$$(2) \qquad H_2\,(v'' \geq 6) + e^- (\approx 1\ \text{eV}) \rightarrow H^0\,(v'' \geq 6) + H^-$$

Reaction (2) can also work in reverse, and is thought to be an important mechanism for H^- loss in the discharge. Using selective absorption of tunable laser radiation in the vacuum-ultraviolet region of the spectrum, we measure the densities of various ground-state and excited neutral components of the plasma. These measurements indicate that this simplified model, although incomplete, is essentially correct.

An RF-Driven H^- Source for High Power and Long Pulses

High-frequency rf (around 1.7 MHz in our present work) offers a different and potentially more robust approach to generating the plasma in both volume-production and surface-conversion sources. For several years now, we have been refining and customizing a family of rf-driven sources. The rf-driven source is based on the same "bucket" with a multicusp magnetic field as the thermionic-cathode ion sources, but it uses a porcelain-coated antenna instead of a filament cathode. The rf energy sets up an oscillating magnetic field, which, in turn, induces an electric field that provides energy to the electrons, producing a plasma. The antenna's long-term survivability in the plasma has been demonstrated; the porcelain-coated antenna can maintain a clean plasma in continuous operation for a week or more. This is an attractive feature in high-power, steady-state applications. Other features include fast start-up, ease of high-power operation, and absence of contamination from filament material.

In short-pulse applications, such as injection at the Superconducting Super Collider, this approach had proven highly successful. In 1993 we began experimenting with a larger rf-driven source (Figure 1-11) meant for high-power, long-pulse operation. H^- production efficiency (2.8 mA/cm^2 for each kW of discharge power) and beam emittance (0.017 μ cm-mrad, corresponding to an ion temperature of 1.9 eV) proved to be similar to the figures obtained from filament-type sources of otherwise similar design. Thus far we have used rf power levels of 10 kW for 50-ms pulses with a porcelain-coated antenna and have



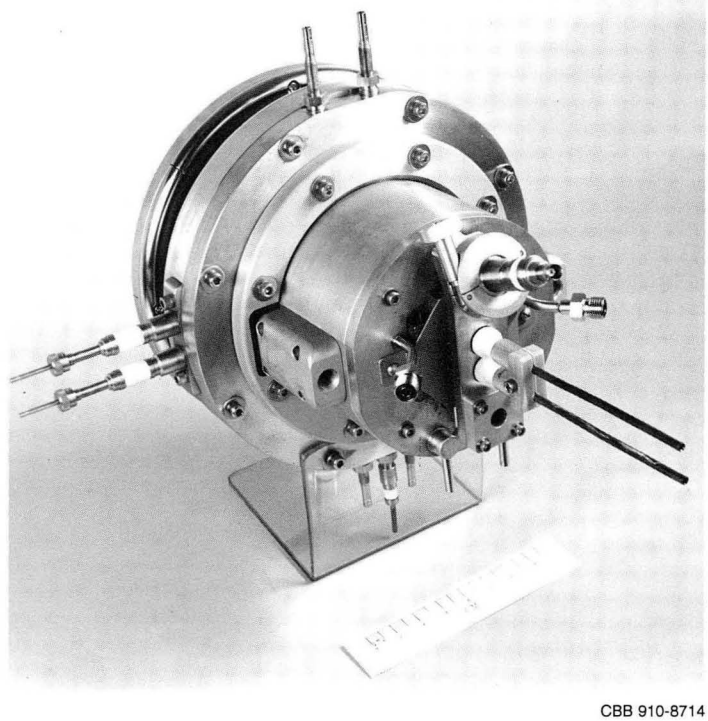


Figure 1-11. The rf-driven H^- source shown in the photo was installed for beamline test at the Superconducting Super Collider, and the design has been adapted with great success to other low-power and short-pulse applications. Long-pulse and high-power tests with a larger version indicated that improvements are needed in the coating of the antenna, which is immersed in the plasma, to make it suitable for neutral beam injection for fusion energy. The H^- yield and production efficiency (2.76 mA/cm^2/kW with abundant cesium) are quite comparable to the performance of filament sources.

gone as high as 15 kW for a second at a time with an additional quartz sleeve. However, the sleeve had an adverse affect on negative-ion production. Although the source remains highly promising for use at high power levels in long-pulse or continuous operation, a better antenna coating will have to be developed.

We have also designed an electrostatic injector to match the beam into the next stage of the SSC injection system, a radio-frequency quadrupole (RFQ) accelerator. The injector consists of four electrodes operating in an acceleration-deceleration-acceleration scheme. The first two employ an acceleration voltage of 50 kV to extract both the H– ions and the electrons from the source. The electrons are swept away by a filter consisting of a pair of permanent magnets. The extracted beam is decelerated by the third electrode, expanding as it slows, and is reaccelerated and compressed by the fourth electrode. This simple, compact accelerator and transport system can deliver 30 mA, matched into the RFQ.

Plasma Theory and Nonlinear Dynamics

The MFE Program at LBL maintains a plasma-theory group operating in the borderland where physics blends into mathematics. The group's pure and applied studies help other researchers understand the phenomena observed in hot plasmas and the possibilities for future development. We have sought new ways of analyzing gyroresonant absorption; the goal is to understand the physics of the phenomenon and thereby describe it in simpler mathematical terms. Our work in this area has yielded not only simplified mathematical approaches, but also insights into the geometry of wave propagation in a plasma.

Wave Dynamics and Gyroresonant Energy Absorption

The immediate purpose of this work is to understand heating and wave transport in plasmas—in particular, gyroresonant absorption of energy. Ion cyclotron range of frequency (ICRF) heating, one of the important heating schemes for tokamaks, involves irradiation of the plasma by a coherent magnetosonic wave excited by an antenna. This radiation is partially absorbed at a resonance layer, where the wave frequency w matches either twice the local gyrofrequency of a dominant ion species or the fundamental gyrofrequency of a minority species. In studying gyroresonant absorption, it is important to understand mode conversion (how and where the waves couple into one another) inside a tokamak.

In 1993 we continued extending our analytic treatment of ion-gyroresonant heating in tokamaks from the perpendicular-fluid model, which is appropriate to passing particles, to a kinetic model that accounts for trapped particles, and from one-dimensonal models to realistic geometries. The long-term goal, here and generally, is to advance from simple, analytically tractable problems to more-comprehensive, more-detailed treatments of realistic geometries and phenomena.

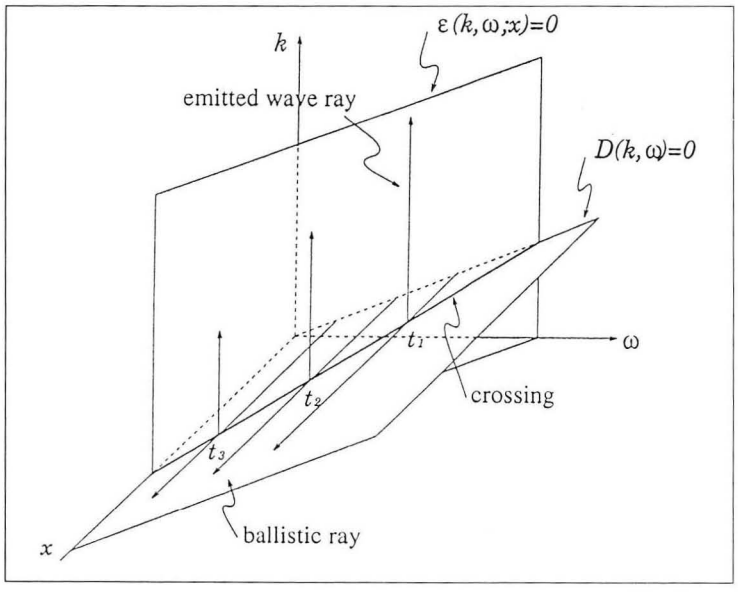
Recent accomplishments include a derivation, using phase-space methods, of the local radiated wave field from a moving test particle and the corresponding Wigner function. Figure 1-12 shows a simple process of wave emission in phase space from a test particle that is moving with constant velocity in a nonuniform medium.

For many years, the theory of wave propagation in nondissipative media has been based on two implicit assumptions. First, the governing wavefunction is assumed to be Hermitian (non-Hermiticity being associated with dissipation).

Second, the fundamental conservation law for local wave action is assumed to be based on eikonality (that is, the variation in amplitude is slow compared to the variation in phase). We had earlier shown that both of these assumptions are false, introducing the concept of "pseudo-Hermiticity" (with respect to a Hilbert space of indefinite metric) and illustrating this with numerous practical examples. Continued investigations along these lines have examined, among other topics, wave-action conservation for pseudo-Hermitian fields. This concept leads to a variational principle for which the wave field's local phase variation yields an action-conservation law without invoking eikonality.

We have applied this law to several problems of mode conversion and have realized that the results may have useful implications in understanding other fields. Mode conversion is a wide-ranging scientific motif that, to take a few examples, occurs in seismology, stellar dynamics (where acoustic waves are coupled into gravity waves), and the reactive scattering observed in atomic and molecular physics. However, the practitioners of these various fields use different terminology for their different applications of mode conversion. An effort to cross-cut these fields, looking at the similarities in theme rather than the differences in context, could reduce duplication of effort and provide analytical tools from which all could benefit. Examples of such multidisciplinary applications in 1993 included a study of autoresonant laser-stimulated Brillouin scattering and a study of gauge fields in the n+1-body problem.

Our nonlinear-dynamics effort encompasses several themes. We are especially interested in wave phenomena of all types, with an emphasis on geometrical methods such as symplectic geometry, Berry's phase and associated gauge structures, group theory, and catastrophe and bifurcation theory. There are applications for the results of our nonlinear-dynamics work in a variety of fields, including plasma physics, astrophysics, optics, and atomic, molecular, and nuclear physics. For example, we are applying our studies of chaotic adiabatic energy diffusion to statistical fluctuations in one-body dissipation in nuclear dynamics and to the Fermi mechanism for cosmic ray acceleration.



XBL 944-4111

Figure 1-12. The geometric interpretation of the wave emission process in phase space. Here $\varepsilon(k,\omega;x) = 0$ is the dispersion surface for the wave rays and $D(k,w) = 0$ described the corresponding dispersion surface for the ballistic rays of the test particle. When a ballistic ray crosses the intersection of the two dispersion surfaces, a wave ray is emitted.

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Advanced Light Source 2

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SEVEN YEARS OF WORK CAME TO FRUITION IN 1993 as the Advanced Light Source, bellwether of the third generation of synchrotron-radiation sources, was commissioned as a user facility—on time, within budget, and performing as specified.

The October 22 dedication ceremony for the ALS concluded an exciting year of successive achievements. Between milestones there were extensive efforts to commission and gain operational experience with the storage ring and to perform accelerator physics studies, building upon the work performed in previous years with the injection linac and booster synchrotron. The goal of these exhaustive commissioning activities is "pushbutton" operation, if not literally then at least metaphorically, meaning a comprehensive understanding of the machine's performance that will optimize service to users.

The scientific programs of those users continued taking shape as well. The high brightness of the ultraviolet and x-ray beams from the ALS will enable forefront research in a variety of scientific disciplines. Anticipating high demand, we are placing major emphasis on creating a user-friendly atmosphere and on being ready to launch an exciting research program.

As Figure 2-1 shows, the ALS consists of an electron source, a linear accelerator, a booster synchrotron, and a low-emittance storage ring. The storage ring has 12 long straight sections, 10 of which can accommodate insertion devices. Additionally, there are provisions for 48 radiation ports at the bend magnets; 24 will be available for initial development.

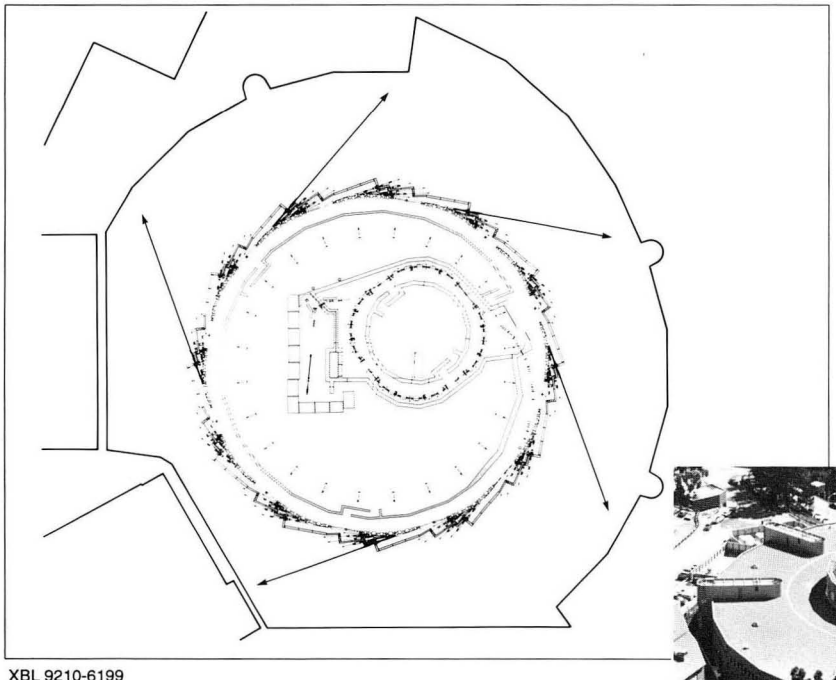

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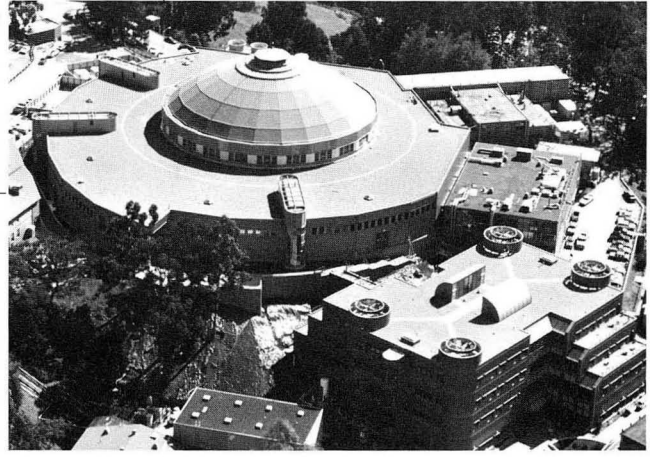
Figure 2-1. In the ALS, a linac and a booster synchrotron inject electron bunches into a storage ring. The multiple straight sections in the storage ring can each accommodate an insertion device to enhance production of synchrotron light from the very-low-emittance electron beam; the bend magnets also produce useful synchrotron light.



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Commissioning Progress

The completion of the storage ring in December 1992 marked the home stretch in the race to finish the ALS by the agreed-upon deadline. Progress thereafter was a feat not only of technical work, but also of scheduling and coordination of dovetailing tasks.

For all the people at LBL, elsewhere in the research community, and in government who have worked for so many years to make the ALS a success, one of the year's highlights was the dedication ceremony on October 22. Government officials and scientific leaders joined hundreds of LBL staff members to mark the official opening of the facility (Figure 2-2).

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Figure 2-2. David Shirley, senior vice president for research and dean of the graduate school at Penn State, who was the director of LBL during much of the ALS project, cuts the ribbon at the ALS dedication. Other speakers at the October 22 dedication ceremony included (*left to right*): Jay Marx, who was the ALS project director until he moved on to head the STAR detector collaboration for the Relativistic Heavy Ion Collider; Donald Pearman, Jr., of the Department of Energy, who managed DOE's San Francisco Operations Office during most of the ALS construction project; Martha Krebs, former associate director of LBL and now director of the Office of Energy Research at the DOE; and, on Professor Shirley's right, Gayle Wilson, representing California Governor Pete Wilson, who helped procure funding for ALS construction during his U.S. Senate term; Brian M. Kincaid, ALS director; Charles V. Shank, director of LBL; and Hermann Grunder, now director of the Continuous Electron Beam Accelerator Facility and, formerly, AFRD director while the project that would become the ALS took shape.

Storage Ring Commissioning

On January 13, when the personnel safety system checkout was completed, commissioning began. That same night, the injection system (linac and booster synchrotron) was turned on for the first time in four weeks—an exercise that took only about 45 minutes, thanks to the intensive effort in previous years to gain operating experience with the injection system—and the extracted beam was successfully threaded down the transport line to the storage ring. The following night, the beam was successfully transported through the fast injection magnets and into the storage ring itself. On February 4, after two weeks of hardware shakedown, the beam was circulated for 60 turns without any ancillary steering—a tribute to the design and construction of the ring.

The many accelerator physics investigations made with this "coasting"* beam gave us confidence in the model of the storage ring that is embodied in the control system. The next step was to add acceleration. On March 16, rf power was applied and, with only minimal tuning of the storage-ring parameters, the beam began to accumulate in the ring. On that occasion, the beam current was a mere 6 mA, with a lifetime of only 5 minutes, but clearly all systems were functioning. Eight days later, the technical baseline require-

* More accurately, a beam that was not accelerated in the storage ring.

ment of 50 mA was met and exceeded, and on April 9, the project goal of 400 mA was reached. By the end of April we could routinely achieve 1.5-hour beam lifetimes at 100 mA. Although a great deal of work remained in order to achieve a long-lasting, low-emittance beam so that good service to users could be provided, the basic performance requirement had been met.

In May the accelerator was shut down to permit installation of two undulators and the front ends for the first five beamlines. The entire storage ring was baked (heated so that any remaining contaminants and adsorbed gases would be given off and pumped out) and was then completely surveyed and aligned. During part of this four-month period, we operated the injection system to test beam loading compensation (which reduces the energy spread of the linac beam at high intensities), to optimize buncher operation, and to test improvements to booster injection and to the extraction kicker magnet power supplies.

When operations resumed at the end of August, bringing the accelerators back on-line took less than two hours (a testimonial to, among other things, the accuracy and long-term stability of the power supplies). The accelerator physicists had taken advantage of the shutdown to expand and improve their arsenal of diagnostics. Parameters that had been measured before, such as betatron tune, chromaticity, the most appropriate rf frequency, momentum dispersion, and closed-orbit correction factors, were measured again in preparation for the use of undulators, which perturb the beam. After some beam conditioning of the vacuum system (photoelectric effects from synchrotron radiation cause the surface of the metal vacuum chamber to emit some gas) and commissioning of the ancillary titanium sublimation pumps, high-current running was reestablished. We measured a beam lifetime of 12 hours at a current of 100 mA.

The fruits of this intensive work were just beginning to be seen at the end of 1993. A synchrotron radiation beam was delivered to one of the first experiments—the x-ray microprobe on beamline 10.3—and soon thereafter, using a minute 0.5 mA of electron beam, the undulator radiation was characterized on beamline 7.0. A diagnostic beamline that images the source electrons by using bend-magnet radiation was in operation by the end of October.

Table 2-1. ALS "beamline scoreboard" as of March 1994.

Beamline	Source	Research	Energy Range	Avail.
3.1	Bend magnet	Diagnostic beamline	200 eV	Now
6.1	Bend magnet	High-resolution zone-plate microscopy	250–600 eV	1994
6.3	Bend magnet	Metrology and standards	50–4000 eV	1994
7.0	U5 undulator	Surfaces and materials, spectromicroscopy	70–1200 eV	Now
8.0	U5 undulator	Surfaces and materials	70–1200 eV	Now
9.0.1	U8 undulator	Atomic physics and chemistry	20–300 eV	1994
9.0.2	U8 undulator	Chemical dynamics	5–30 eV	1994/95
9.3.1	Bend magnet	Atomic and materials science (double crystal)	700 eV–6 keV	1994
9.3.2	Bend magnet	Chemical and materials science	30–1500 eV	1994
10.3	Bend magnet	Materials science and advanced microprobe instrumentation	3–12 keV	1994
11.0	EW20 elliptical wiggler	Materials science and biology, magnetic materials	50 eV–10 keV	1995
12.0	U8 undulator	X-ray projection lithography, optics development	60-320 eV	1995

Although the facility is now open for business and the research program has begun, accelerator physics challenges remain. Initial measurements indicate that the beam in the storage ring is very stable when measured at a 1-s time scale. As expected, evidence of very small transverse oscillations at frequencies of several hundred Hz has been obtained, and longitudinal oscillations are expected at extreme conditions. Plans are being made for rf feedback systems that could deal with these oscillations should they be found to degrade the photon beams. Another issue is the "dance of the undulators": as the gaps in undulators are opened or closed to tune the photon energies of their beamlines, the residual dipole fields perturb the electron orbit. Correction of these kinds of behaviors will form the foundation of the next level of investigations as we push toward the ultimate performance of the ALS.

Experimental Systems

In the final drive toward commissioning as a user facility, the experimental systems—insertion devices for enhanced production of synchrotron light and beamlines for delivering the light to users' experiments—became perhaps the greatest focal point of fabrication and testing activity. (See also the later section on "Service to the User Community.") Two insertion devices—the key to producing small, spectrally bright, tunable beams of synchrotron light—were completed and installed in 1993; a third awaits installation and a fourth is being fabricated.

Also essential to scientific success are high-performance beamlines that do not compromise the brightness of the beams. By the end of 1993, experimental beamlines for two undulators and two bend magnets were complete or nearly so, and a diagnostic beamline that uses bend-magnet radiation to image the electron beam was ready. Figure 2-3 and Table 2-1 show the locations and purposes of the beamlines that are operational, under construction, or planned.

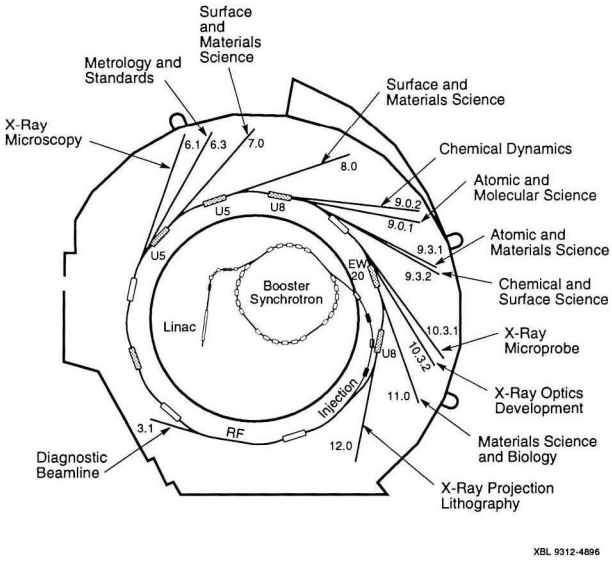
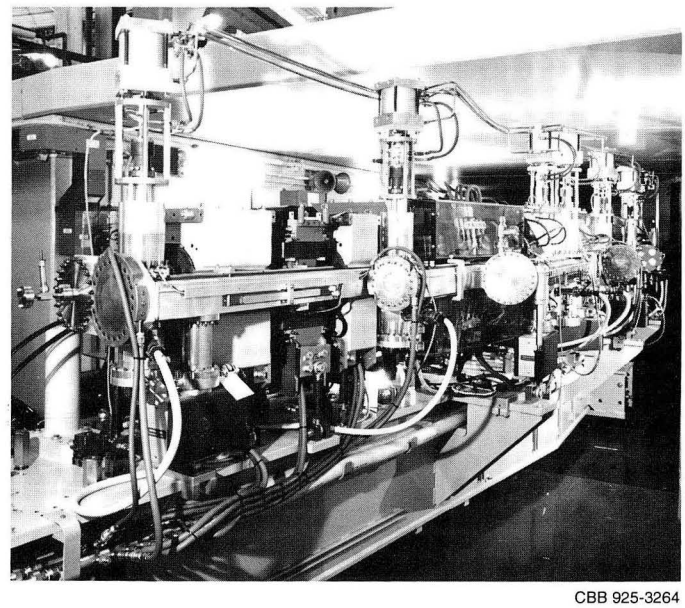


Figure 2-3. A diagram of the ALS floor shows the beamlines that are planned for construction through 1995. The numbering scheme for beamlines is related to the storage-ring sector where they begin. The photo gives a glimpse inside the storage-ring shielding, revealing the ports (covered, circular openings directly underneath tall structures) for connection of beamline "front ends." The first four from the left are bend-magnet ports; the rightmost one is for an undulator and comes off the straight section immediately behind the arc sector shown in this photo. The tall structures are photon stops and their actuators; associated with each photon stop but hidden below the vacuum chamber is a titanium sublimation pump for immediate, local removal of photon-desorbed gases.



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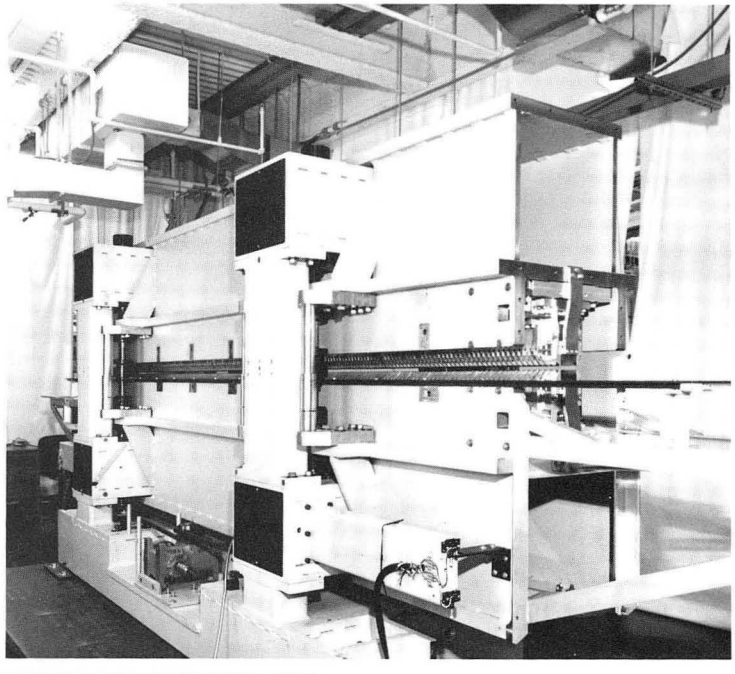
Beamlines 7.0 and 8.0: The First Undulator Beamlines

The first two undulators, designated U5.0 for their 5-cm magnetic periods, were completed and installed in 1993 (Figure 2-4). They are installed in the seventh and eighth of the 12 straight sections to serve Beamlines 7.0 and 8.0, respectively.

Beamline 7.0, designed and built at the ALS, uses a spherical grating monochromator—a type pioneered at LBL and used in a prototype monochromator at Beamline 6 at the Stanford Synchrotron Radiation Laboratory. This monochromator, designed for three diffraction gratings that may be interchanged easily to choose the desired spectral response, is now assembled and ready to test with undulator light. After undulator characterization with a transmission grating spectrometer, the monochromator will be connected to the first mirror system and the beamline will be commissioned for soft x-ray absorption and spectromicroscopy.

Present plans call for a photoelectron spectrometer at one end station, equipped with two microscopes—a scanning photoelectron microscope (SPEM) and a scanning transmission x-ray microscope (STXM)—both with better than 500-Å resolution. The beamline will be operated by a team, whose



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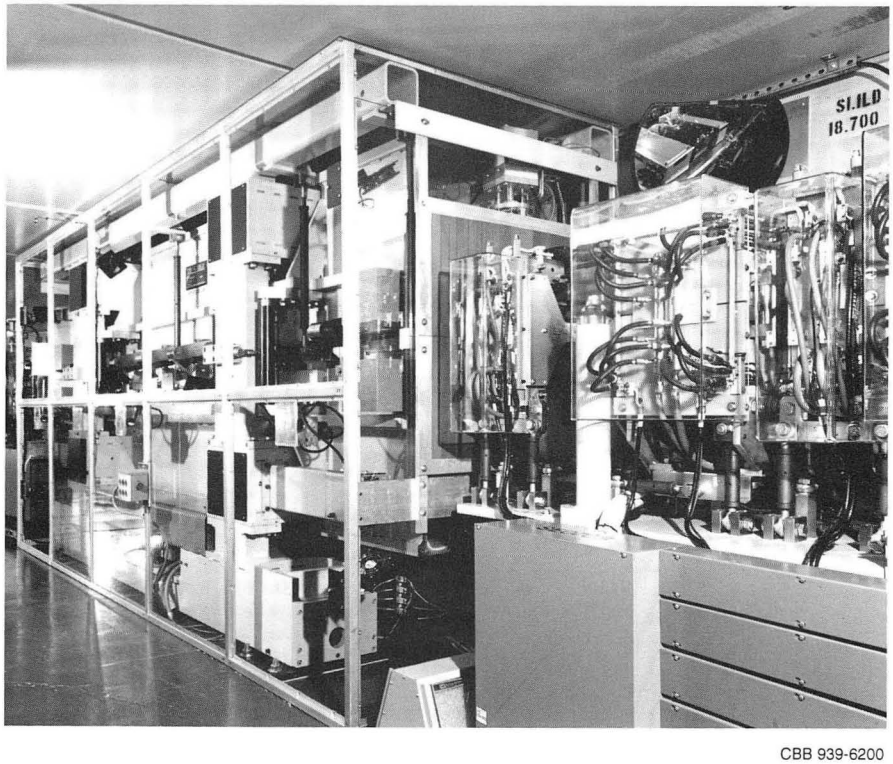

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Figure 2-4. Two U5.0 undulators like this one (shown during assembly and after installation) have been installed and commissioned. A U8.0 undulator with an 8-cm magnetic period is following them through the assembly process, which involves painstaking alignment and magnetic characterization. The undulator gap is adjustable in order to change the magnetic field and hence the wavelength of the synchrotron light. During this process, the position control must be accurate and reproducible to ±1 μm despite magnetic attraction of nearly 40 metric tons; hence the massive construction. The specification called for field errors to be low enough so that we would obtain greater than 70% of the performance to be expected for a perfect device. Computation of the spectral characteristics derived from measurements of the magnetic fields of the device indicate that we will obtain a brightness of 76% of the theoretical maximum with zero errors when the undulator is set at its minimum gap and thus its strongest magnetic field.

spokesperson is Brian Tonner of the University of Wisconsin at Milwaukee, that is primarily interested in materials science and the physics and chemistry of surfaces and interfaces. This instrument will match the world's record in resolving power over a range of 100–1000 eV and at the same time exceed the photon flux of any of today's x-ray sources. Figure 2-5 shows Beamline 7.0, which typifies ALS insertion-device beamlines in its major functions and systems.

Beamline 8.0 teams a commercial monochromator with optics from IBM's Almaden Research Center and front-end systems designed and built by the ALS. This beamline, supported by a consortium of IBM, Tulane University, and the University of Tennessee, is now being used. Its team of users is led by Joachim Stöhr and Franz Himpsel (both of IBM), Thomas Callcott (University of Tennessee), David Ederer (Tulane University), and Rupert Perera (LBL). The initial research program will investigate the electronic and crystallographic structure of surfaces using established techniques such as core-level photoelectron spectroscopy, near-edge x-ray absorption spectroscopy, and x-ray emission spectroscopy.

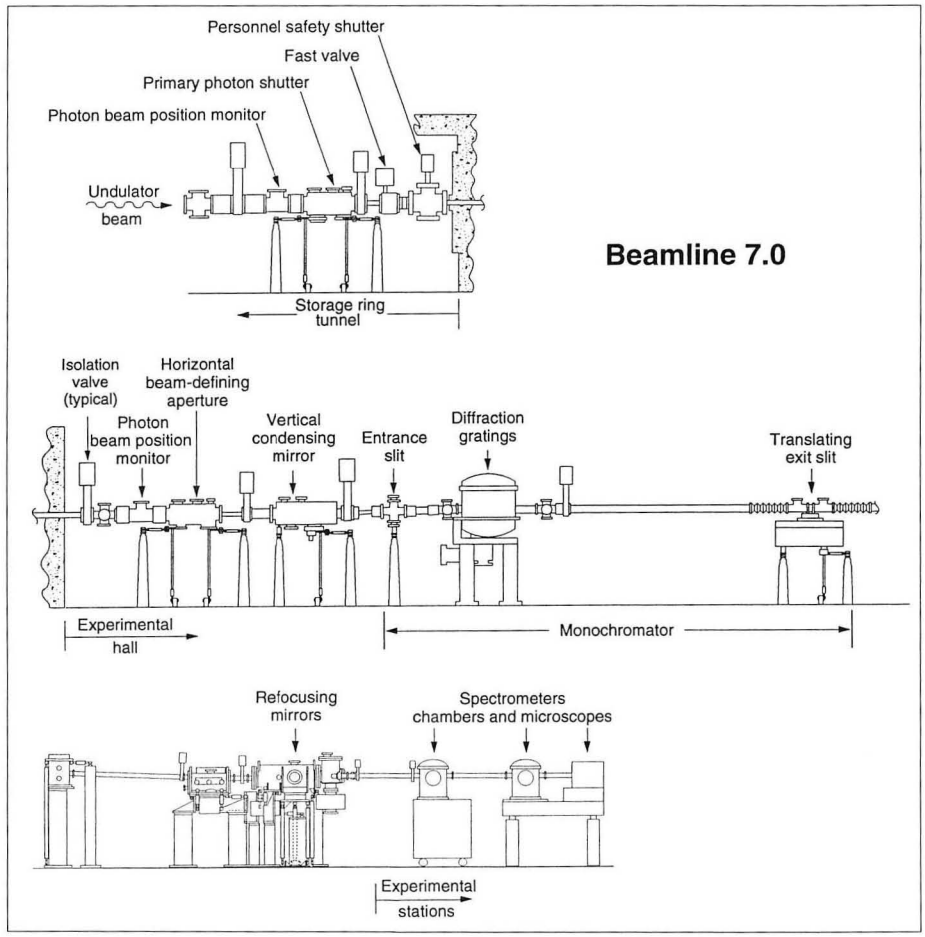


Figure 2-5. Beamline 7.0 (fed by one of the U5.0 undulators) typifies an ALS undulator beamline, with its LBL-designed spherical grating monochromator. This beamline will be devoted to spectromicroscopy with UV and soft-x-ray light. Besides the requirements for extreme precision in overall figure and in surface finish of optical components, the power and intensity of ALS photon beams has led to a great many engineering challenges for the beamlines and front ends.

XBL 938-4558A

Beamline 9.0: The Next Step

The first branch of Beamline 9.0 is well into the construction phase and will be available for use after its undulator, U8.0, is installed and commissioned late in spring 1994. This beamline, incorporating an ALS-designed spherical grating monochromator, will be used for high-resolution gas-phase spectroscopy in the vacuum ultraviolet and the low-energy end of the soft x-ray region to investigate photoprocesses in atoms, molecules, and ions. The team's spokesperson is C. Denise Caldwell of the University of Central Florida.

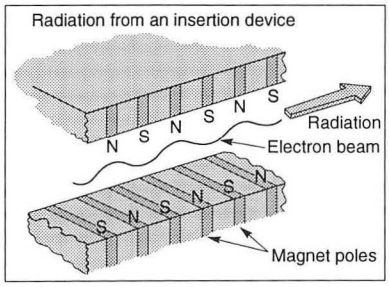
A second branchline with two experimental stations will multiply the user service provided by Beamline 9.0. One station, scheduled for fall 1994 completion, will provide "white light" (i.e., raw undulator light that has not been spectrally selected with a monochromator) to an end station for high-flux experiments. The other station, to be completed in early 1995, will use an off-plane "eagle" monochromator to achieve a spectral resolution of greater than 2×10^5 in the low-energy VUV region (5–25 eV). This station, which will serve the Chemical Dynamics Research Laboratory, will also be fed by molecular-beam sources, enabling the study of a wide range of problems in chemical reaction dynamics, including combustion.

Bend-Magnet Beamlines: 10.3, 9.3.2, and 9.3.1

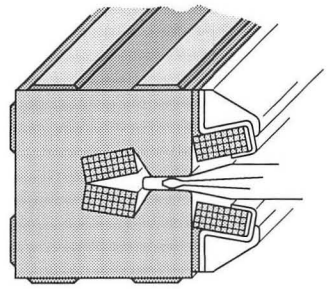
Bend-magnet beamlines, which provide different spectral characteristics (Figure 2-6), will also be important in the research program at the ALS.

The first ALS beamline to receive light was Beamline 10.3, built by LBL's Center for X-Ray Optics (CXRO). Essentially a tube connecting a photon port to an experimental end station, this beamline serves two white-light microprobes—one already on hand (a past winner of the R&D 100 award) and one of a novel design—to detect and determine trace quantities of elements as small as 10^{-15} g. Both branches employ mirrors to select light around 10 keV and focus it to extremely small spot sizes. The existing microprobe uses spherical mirrors in a Kirkpatrick-Baez configuration to achieve a spot size of 3–4 μm^2. The system has already produced microfocused light during initial commissioning. The new microprobe will use "tiny bendable mirrors"—flat metal pieces bent into an elliptical shape—to achieve a spot size of less than 1 μm^2. In both microprobes, the tiny spot illuminates a sample, which gives off fluorescence x-rays; by measuring their wavelengths and scanning the sample, the system produces a trace-element map of the material's composition.

Beamline 9.3.2, formerly installed at the Stanford Synchrotron Radiation Laboratory, has been moved to the ALS and modified to make the best use of the brighter photon beams. The beamline has an SGM with three interchangeable gratings, thus covering a broad range of photon energies—from 30 eV to 1.5 keV. Beamline 9.3.2 features an experimental chamber outfitted with an angle-resolved photoemission spectrometer (ARPES) system for studying problems in materials and chemical sciences. Charles Fadley, of the University of California at Davis and LBL, is spokesperson for the PRT operating the beamline.

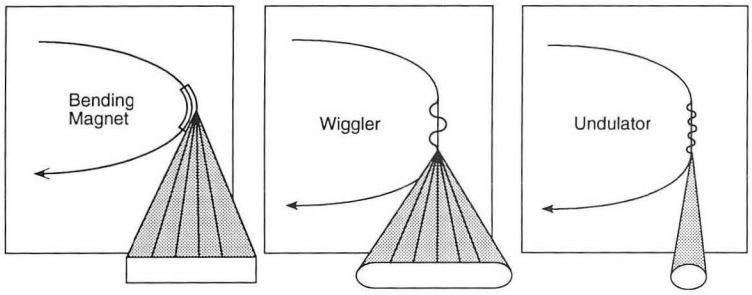


XBL 927-6125

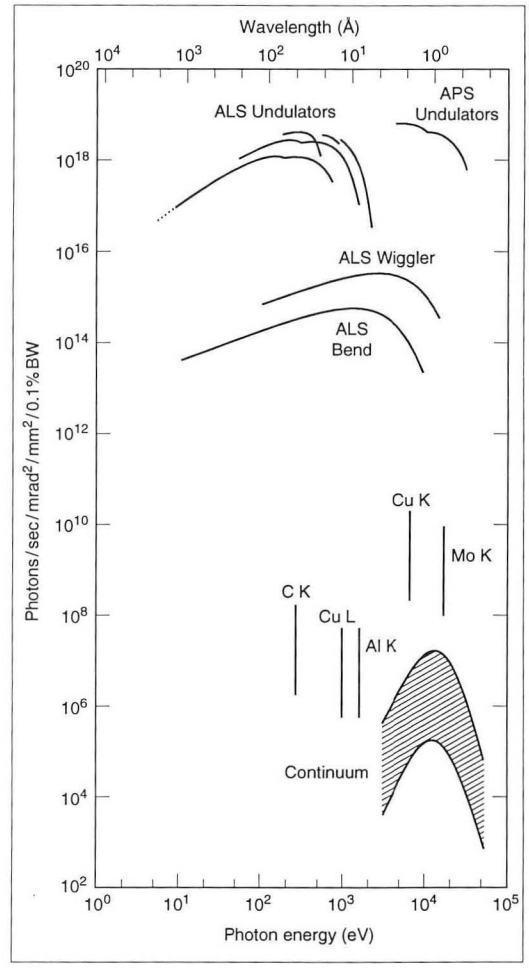


Bending magnet

XBL 927-6127



XBL 9010-6757A



XBL 923-5647A

Figure 2-6. The bend magnets that principally determine the electron beam's course around the storage ring also cause it to give off a fan-shaped beam of synchrotron radiation. The spectrum is broad and continuous; its characteristics are fixed by the strength of the bend magnet and the energy of the electron beam. The kind of magnetic insertion device known as a "wiggler" deflects the electron beam through an angle much larger than the natural emission angle of the synchrotron radiation. This produces a broad fan of radiation much like that of a bend magnet, but much more intense and with a continuous spectrum that can be tuned by varying the wiggler's gap. Another kind of insertion device, an undulator, deflects the electrons through a smaller angle so that light waves of certain wavelengths reinforce or cancel each other at certain angles. The result is a narrow cone of partially coherent (that is, somewhat laserlike) radiation. The output is sharply peaked at certain frequencies within the overall envelope shown here, and is tunable.

In summer 1994, bend-magnet beamline 9.3.1 will be completed. Its double-crystal monochromator will provide high-brightness beams in the 1–4 keV region.

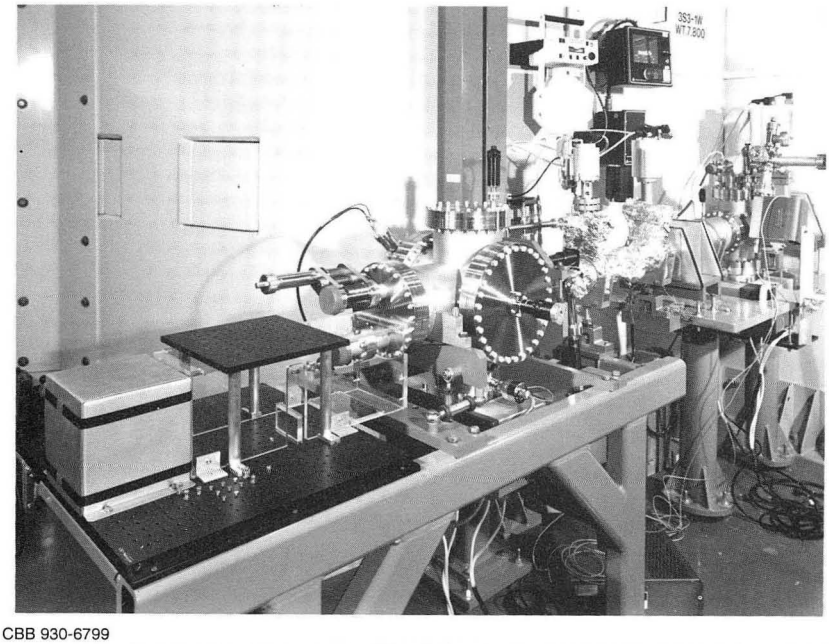
We are also working on front ends for bend-magnet beamlines 6.1 and 6.3; these beamlines, intended respectively for microscopy and x-ray-optics metrology, will be built by CXRO. A front end is also being built for a new undulator and undulator-beamline that CXRO will use for interferometric metrology at soft-x-ray wavelengths.

Diagnostics: Assuring Quality of Electron and Photon Beams

One of the key attributes of the ALS is the very small emittance, or vertical and horizontal beam size and divergence, of the electron beam; this enables similar qualities to be achieved in the photon beams, giving the brightness that is so desired by users (sidebar). Therefore one of the most important tasks in initial commissioning has been to quantify the size and divergence of the electron beam. We have also taken pains to quantify the electron beam's positional stability because the resulting photon beam is usually focused onto either an aperture or a slit; positional oscillation would be seen as an intensity variation and would also degrade the time-averaged brightness.

The ALS has a natural emittance of 3.4×10^{-9} meter-radians and, in the first bend magnet, has horizontal and vertical beam sizes σ_h and σ_v of 44 μm and 83 μm, respectively, assuming a 10:1 ratio of horizontal to vertical emittance. Simple diffractive optical calculations show that it is not feasible to get an undistorted image of this tiny beam with visible light; imaging must be performed using photon energies greater than 100 eV. Therefore, in a crowded part of the experimental floor that is not highly desirable for user experiments, we have set up Beamline 3.1, a diagnostic beamline that uses bend-magnet radiation for precision imaging and transverse measurement of the electron beam.

As Figure 2-7 shows, the beamline is based on a crossed pair of cylindrical mirrors in the Kirkpatrick-Baez arrangement. The focused x-rays impinge



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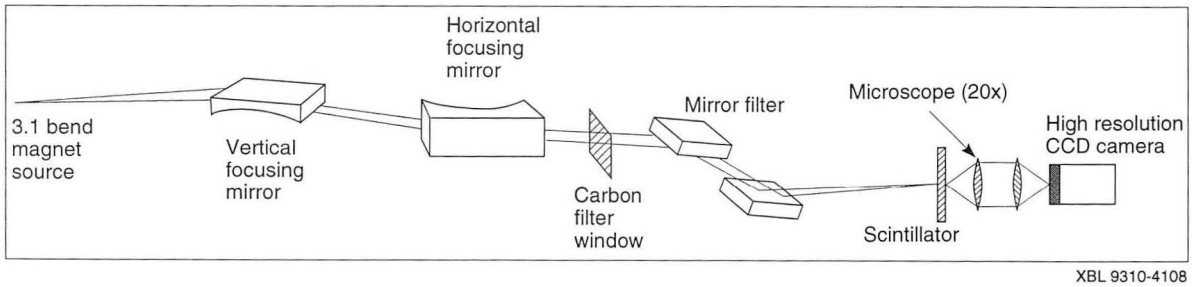

XBL 9310-4108

Figure 2-7. The diagnostic beamline uses bend-magnet radiation to image the electron beam. The light is filtered with a carbon window and a multiple mirror arrangement that provides a passband of about 220–287 eV. Use of 1:1 imaging eliminates coma, thereby producing an image of the source limited only by the residual aberrations of the optics.

Benefits and Challenges of Brightness

Spectral brightness is the most prized virtue of XUV light from the ALS. The rays of light occupy a small cross-sectional area and can be focused onto a small spot (in more-technical terms, brightness is defined as a high photon flux per unit source area and per unit solid angle into which the source radiates). The source radiates into a narrow cone with an opening angle of a few hundredths of a milliradian or less for undulators, or a few tenths of a milliradian for bend magnets. Spectral brightness is the brightness per unit spectral bandwidth. Brightness is conserved as light travels through an ideal optical system—in other words, it cannot be improved by focusing or other means; it is limited by the quality of the source.

Experiments with synchrotron light tend to fall into three categories. Spectroscopy provides information about quantum states; elastic scattering (such as x-ray diffraction) locates the position of atoms and molecules; and imaging provides a view of microstructures and nanostructures. Brightness brings distinct advantages to each of these experimental groupings.

The most direct beneficiaries are researchers in the physical and life sciences who hope to achieve enhanced spatial resolution down to distance scales of about 100 Å in x-ray microscopy, or who plan to pursue spatially resolved UV and x-ray spectroscopy. A typical benefit accrues to the study of solid surfaces, which are mostly heterogeneous, making it hard to interpret spectroscopic data obtained by illuminating the entire surface. With spatial resolution, spectral features could be directly associated with specific surface areas and structures.

For the spectroscopist, brightness allows high spectral resolution without the usual penalty of reduction in signal and increase in measuring time. Experiments whose measuring times were once impractically long, perhaps because of inherently weak signals, become reasonable to contemplate.

Finally, brightness and the pulsed nature of synchrotron radiation bring another opportunity: the ability to observe short-lived or transient systems by means of time-resolved spectroscopic, scattering, and imaging experiments. The ultimate time resolution, made possible because there are enough photons in a single pulse of bright synchrotron light to generate a useful signal, would be to follow events in real time on a sub-nanosecond time scale.

The small size of the ALS photon beams creates new challenges for beamline designers, as does the emphasis on insertion devices. First, the source size and divergence have become very small. For undulators at the high-photon-energy end of the spectral range, the rms photon-beam size is typically 330 μm horizontal by 65 μm vertical, and the rms divergence is typically 40 μrad horizontal by 30 μrad vertical. To avoid loss of light from this small source, tighter tolerances are needed for the overall shape and small-scale smoothness ("figure" and "finish") of relay optics and monochromator components. Further, it is now practical to achieve higher resolution by the use of narrower monochromator slits; therefore, monochromator components need tighter tolerances to avoid loss of resolution. Finally, the photon-beam power has increased to several kilowatts per square centimeter, implying that the optical components must hold their precision when a tiny area, and only that area, is continually illuminated with what is essentially a powerful x-ray laser.

The resulting requirements for control of thermal distortion and stress complicate the design (along with the requirement that everything in a beamline be compatible with ultrahigh vacuum, and, of course, the desirability of fabricating the apparatus on schedule and within budget). Extensive and innovative uses of computer-aided engineering, along with standardized use of common elements, helped ALS beamline designers ensure that thermal effects would not place a limit upon the ultimate performance of the optics. Their results, including a monochromator entrance-slit design that is being patented, will be of use throughout the synchrotron radiation community, especially as more high-brightness sources come on line in the 1990s.

upon a scintillator screen, are focused with a microscope objective, and are imaged in real time with a charge-coupled-device camera and saved digitally with a frame grabber. Initial measurements showed that the system has high sensitivity, and it is now being used in routine machine physics studies of the beam. Initial work is aimed at damping instabilities and understanding the causes of beam growth at high current. The design of the diagnostic-beamline imaging system for the ALS was implemented with an eye toward application in other third-generation synchrotron radiation sources, all of which will present challenges similar to these.

The diagnostic beamline provides some information on positional stability. Further data are inferred by monitoring the photon beams from the undulators. Each undulator beamline uses two beam monitors at separate distances from the source to measure beam position; from these measurements, we can extrapolate to infer the changes in beam position and angle at the center of the long insertion device. The goal is to make these measurements in real time and to feed the data back into a magnet correction system that will stabilize the beam at the center of the straight section where the insertion device is located. We have found that the "noise" in beam position is quite low in both the short and the long terms (less than 1.5 μm per hour), so an active feedback system should be simple to implement if it proves to be necessary at all. This level of stability—one to two orders of magnitude better than most storage rings have achieved—is attributable to the care and attention paid to the mechanical and electrical stability of the storage-ring components. This will be a key element in successful use of the ultrahigh-brightness photon beams from the insertion devices.

The photon beams from the undulators also have to be characterized. To measure the angular and spectral distribution of undulator light, we use a transmission grating spectrometer, shown in Figure 2-8. Initial results from the U5.0 undulator on Beamline 7.0 clearly indicate that the undulator is working well, although further work is required to fully quantify its performance.

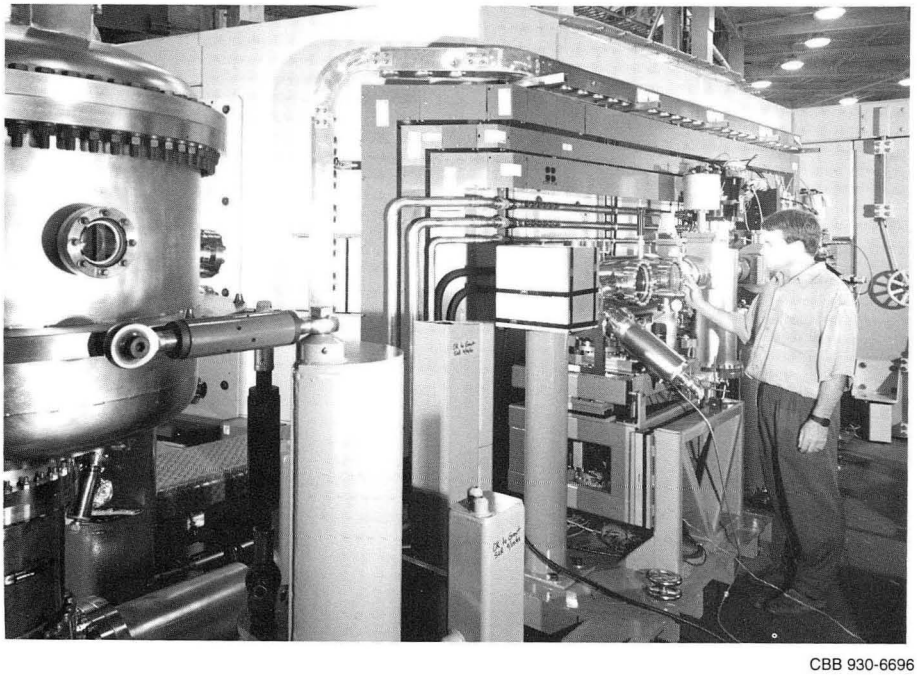

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Figure 2-8. To characterize photon beams, we use an instrument based on a transmission grating spectrometer. Light from the undulator is focused by a spherical mirror through a transmission grating, which provides dispersion onto a scanning detector. By rotating the detector, we can measure the spectral distribution; by fixing the detector arm and moving the whole system in a plane perpendicular to the beam, we can measure the spatial distribution. The components of the spectrometer, mirror, grating, and detector have been calibrated absolutely so that the spectrum can be compared directly to values calculated from magnetic measurements.

Charting a Course for Progress: The ALS Beamlines Initiative And Other Plans

We are well into the design of an elliptical wiggler for generating high intensity circularly polarized radiation. The magnetic structure of the device resembles that of a conventional multipole wiggler, but in addition has a horizontal field structure shifted by half the width of a block of magnetic material. This gives a vertical trajectory with the proper deflection so that light of the same helicity from adjacent poles is superimposed and is radiated along the optical axis of the device. Design work is also underway for the large-acceptance optical systems that are needed for successfully using the light from this source. The elliptical-wiggler beamline will be used in the study of a large range of problems in biology and materials science in which information can be gained on spin state or geometry by using either magnetic circular dichroism or natural dichroism.

Another large project now under way is the building of a multipole wiggler and beamline for protein crystallography. Department of Energy funding for construction of the wiggler is being sought, as is industrial participation in the beamline and the three experimental end stations. The goal is a crystallography facility that is semi-automatic in operation, with automatic beamline and sample alignment and automated switching of the beam into one of the three stations, using monochromators that can be inserted into the beamline easily. The effort will be complemented by a comprehensive biology support laboratory; the first stage of this three-year project has been funded and is now in progress. In addition to fully equipped sample-preparation laboratories and offices, the facility will be equipped with a comprehensive computing infrastructure that will allow data reduction on-site.

Now on the drawing board is the ALS Beamlines Initiative. This proposed enhancement would add five insertion devices and the associated beamlines at a total cost of approximately $64 million. We are examining various design options for advanced monochromators for use in these beamlines.

Characterizing Optical Components: Award-Winning Innovations

One of the most important areas of beamline engineering has been characterization of optical surfaces. The typical quality of optical components for use in this demanding field had been sub-optimal for many years. Our requirements are stringent (slope errors in the range of 1 microradian, for example), so optical metrology plays a key role. To this end, the ALS project funded the construction of two long-trace profilers based on a surface-profiling instrument developed at Brookhaven National Laboratory. One of them is operating in the new ALS Optical Metrology Laboratory, where it is housed in a class-10 000 cleanroom to avoid contamination of optical surfaces. The other is installed at Rocketdyne Corporation, a private company with which we have been cooperating to develop manufacturing techniques for water-cooled metal beamline optics. The design team included scientists and engineers from LBL, Brookhaven, Continental Optics Corporation, Baker Engineering, and Photon Sciences, Inc.

These and other developments (Figure 2-9) have opened a new era in the availability of high-quality grazing-incidence optical elements for synchrotron radiation. The significance of these multiyear, cooperative efforts, which benefit not only the ALS but our industrial partners and the synchrotron radiation community in general, was recognized with the Federal Laboratory Consortium's Technology Transfer Award in 1992. This year the Long Trace Surface Profiler was further honored with the R&D 100 award, given by the magazine *Research and Development* to recognize the 100 most significant technical innovations of the year.

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Figure 2-9. The optics challenges of the ALS have resulted in a series of technological innovations, many of them made in close collaboration with private industry. To date, the R&D 100-winning Long Trace Surface Profiler (left) has been able to measure the surface slope error of optical components to better than 1 microradian rms. With the help of these instruments, water-cooled metal optical components that are at least as good as the best glass components have been fabricated for the ALS. Surface microroughness figures of 2 Å rms—five times better than previously achievable—have been obtained on 15-inch-long copper alloy mirrors coated with electroless nickel. An improved manufacturing method for bendable mirrors (above) is one of the latest innovations.

Service to the User Community

Close and extensive interaction with prospective users has been a hallmark of ALS program planning. The research program may be thought of in four categories:

- *Materials, interface, and surface sciences.*
- *Atomic, molecular, and chemical sciences.*
- *Life sciences.*
- *Instrumentation and technology.*

The program emphasizes the high brightness of soft-x-ray and extreme-ultraviolet (XUV) light available from the ALS. The first experiments will be carried out by Participating Research Teams (PRTs)—groups of researchers with related interests from one or more institutions. The primary responsibility for experimental apparatus rests with the PRTs; the responsibility for the beamlines and insertion devices will be shared by the ALS and the PRTs. In return for its commitment, each PRT receives a guaranteed fraction of the ALS operating time at its beamline. Through a proposal process, a substantial fraction of running time at each beamline will also be made available to independent investigators not affiliated with a PRT.

In addition to the beamline fabrication and commissioning work described in the previous section, we continue putting forth extensive effort to create a physical and procedural infrastructure that will help researchers use the ALS safely, easily, and efficiently.

Availability to Researchers

In addition to PRTs, the ALS is open to qualified independent investigators who submit proposals for beamline access, provided that they intend to publish their results in the open literature. Although largely free from the responsibility of furnishing experimental facilities, independent investigators may choose to provide their own experimental chambers. As a Department of Energy user facility, the ALS provides all qualified investigators with free beamtime.

Four beamlines are expected to be available to independent investigators within the first year of operations: undulator beamlines 7.0 and 9.0.1 and the bend-magnet beamlines 9.3.1 and 9.3.2. Further details may be found in PUB-3104, *ALS Beamlines for Independent Investigators*, which is available on request from the ALS.

User Services

To make using the ALS as convenient as possible, a comprehensive program to cover all aspects of a visit is being developed after considerable study of other user facilities. The first stop is the new "one-stop shopping" LBL Reception Center in Building 65, near the shuttle-bus terminal. There, users complete visitor forms, take safety training, and receive a parking permit—all at the same location. The Reception Center can also provide information on hotels and housing.

To ensure safe and efficient operation, assistance with the logistics of research is provided by operations coordinators. At least one operations coordinator is always available on the experimental floor, serving as a first contact for answering questions or solving problems and for ensuring compliance with environment, health, and safety regulations. The operations coordinators inspect and turn on beamlines, verify that users have had the appropriate training for the beamline and experimental equipment, and make sure that hazardous materials are handled properly. In addition, they can help users gain access to LBL and ALS crafts and trades assistance, such as survey-and-alignment specialists, crane operators, and electronics and mechanical technicians.

Workshops and ALS Science

An ongoing series of workshops is held as part of the ALS's mission to identify and explore new scientific opportunities for synchrotron light. The workshops flesh out new ideas and encourage participation by all segments of the scientific community .

Approximately 40 scientists and engineers participated in an informal workshop in April 1993 to discuss the production and use of elliptically polarized radiation at the ALS. The objective was to exchange views on the scientific and technical cases for the elliptical wiggler presently being designed at the ALS. An additional purpose was to discuss an eventual second insertion device that will produce elliptically polarized radiation with a crossed undulator.

"Soft X-Ray Interferometry" was the topic of an ALS workshop held in June. The participants discussed the proposed technical design of a soft-x-ray Fourier-transform spectrometer being developed at the ALS to operate in the energy range of 60–80 eV. We would like to extend the performance of this spectrometer technology to 100 eV, allowing it to be used in soft-x-ray photoabsorption experiments in atomic physics that today are only feasible with the lower resolution of grating spectrometers.

ALS Advisory Panels

Two committees provide advice on ALS planning and operation to the LBL Director. The Science Policy Board (see Table 2-2) provides advice on high-level policy issues affecting the ALS. The Program Review Panel (Table 2-3) gives advice on the scientific program through the ALS Director. Until the research program by independent investigators begins in earnest, this panel's main task will continue to be evaluation of PRT proposals and reviews of progress by previously approved PRTs. Accordingly, the panel devoted its 1993 meetings to proposals from both insertion-device and bend-magnet teams and to discussions of guidelines for PRT progress. The panel also encouraged independent users to submit proposals once the ALS becomes operational.

Table 2-2 ALS Science Policy Board, 1993

Dean E. Eastman, IBM Thomas J. Watson Research Center (chair)
E. Morton Bradbury, School of Medicine, University of California at Davis
William F. Brinkman, AT&T Bell Laboratories
John C. Browne, Los Alamos National Laboratory
Bernd Crasemann, University of Oregon
J. McEwan Paterson, Stanford Linear Accelerator Center

Table 2-3 ALS Program Review Panel, 1993

Neville V. Smith, AT&T Bell Laboratories (chair)
Franco Cerrina, University of Wisconsin-Madison*
Charles S. Fadley, University of California at Davis and LBL
John W. Hepburn, University of Waterloo, Ontario, Canada
Franz J. Himpsel, IBM Thomas J. Watson Research Center
Christof Kunz, University of Hamburg, Germany
Gerald J. Lapeyre, Montana State University
William Orme-Johnson, Massachusetts Institute of Technology
François Wuilleumier, University of Paris-South, France

* New member.

ALS Users' Association

The opportunity to see the first experimental results from ALS beamlines attracted a record number of persons to the Users' Association Annual Meeting in October. For most of the 220 attendees, this was the first chance to see the ALS in operation and view the initial set of beamlines on the experimental floor. The meeting program focused on the scientific opportunities offered by the ALS's ability to produce the world's brightest beams of ultraviolet and soft x-ray synchrotron radiation. A special highlight was the chance to participate in the formal ALS Dedication Ceremony on October 22.

At the meeting, new members were nominated to the Users' Executive Committee (Table 2-4), which serves as the voice of the user community. The UEC is an elected body comprising 11 members with staggered terms of three years. During 1993, the UEC made important contributions to planning for ALS operations, defining space requirements for user offices and laboratories, and devising the user safety program.

Table 2-4 ALS Users' Executive Committee, 1993

Thomas A. Callcott, University of Tennessee
C. Denise Caldwell, University of Central Florida
George Castro, IBM Almaden Research Center
Stephen P. Cramer, University of California at Davis
Norman Edelstein, LBL
David L. Ederer, Tulane University (chair)
Piero A. Pianetta, Stanford Synchrotron Radiation Laboratory (past chair)
Linda S. Powers, Utah State University
James G. Tobin, Lawrence Livermore National Laboratory
Brian P. Tonner, University of Wisconsin at Milwaukee and Synchrotron Radiation Center, University of Wisconsin at Madison
Michael G. White, Brookhaven National Laboratory (vice-chair)

Publications and Presentations

F. Cerrina, A.K. Ray-Chaudhuri, W. Ng, S. Liang, S. Singh, J.T. Welnak, J.P. Wallace, C. Capasso, J.H. Underwood, J.B. Kortright, and R.C.C. Perera, "Microscopic-scale lateral inhomogeneities of photoemission response of cleaved GaAs," Appl. Phys. Lett. **63**, 63 (1993).

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IN 1993, AFTER NEARLY FIVE YEARS OF RESEARCH and planning, construction of PEP-II was approved by the U.S. Department of Energy. This B-meson "factory," based on the Positron-Electron Project storage ring at the Stanford Linear Accelerator Center, is scheduled for completion in 1998. The Center for Beam Physics has played a key role in it since the beginning, working closely with SLAC and Lawrence Livermore National Laboratory. The year's achievements in the LBL portion of the program centered on design refinement of the rf system, multibunch feedback system, and magnetic lattice, as well as a better understanding of beam-beam interaction.

To meet the technical challenges of this and other initiatives and to generally enhance LBL's capabilities in particle- and photon-beam research, the Center continued adding to its experimental capability in 1993. The highlight of these achievements was the construction of the Beam Test Facility, which is now being commissioned. This facility will increase the benefits of the investment in the Advanced Light Source injector linac by using it for beam physics experiments during the several hours of otherwise idle time between ALS injection cycles. Many experiments are possible; immediate plans include generation and detection of x-ray pulses as short as tens of femtoseconds and focusing of a beam by using plasma lenses.

Among the Center's other diverse activities, research continues in accelerator theory, nonlinear dynamics, and fundamental FEL physics. The High-Energy Collider Physics group continued its long-range Two-Beam Accelerator research. The Beam Electrodynamics Group contributed to and supervised the ALS and PEP-II rf and feedback design efforts. It also began exploring beam-cooling techniques for a challenging new application: the Relativistic Heavy Ion Collider (RHIC) that is being built at Brookhaven National Laboratory.

PEP-II: Refining The Design and Preparing for Construction

The worldwide high-energy physics community has become intensely interested in B factories, which are electron-positron colliders that produce copious $B\overline{B}$ pairs. They enable fundamental studies of charge-parity (CP) violation and other phenomena measurable through rare B-meson decays, the ultimate goal being an explanation of why the universe as we know it is dominated by matter rather than antimatter (*sidebar*). A collaboration of the Center, the Stanford Linear Accelerator Center (SLAC), Lawrence Livermore National Laboratory (LLNL), and Caltech has designed a B factory called PEP-II with one high-energy and one low-energy storage ring. This "energy-asymmetric" collider, an idea pioneered at LBL, will be built in the tunnel of the old Positron-Electron Project (PEP) collider at SLAC and will reuse many PEP components, resulting in a design that is both scientifically and economically attractive.*

An international review panel, set up jointly by the Department of Energy and the National Science Foundation, examined both the PEP-II proposal and the other U.S. B-factory initiative, CESR-B at Cornell University. The panel found that the PEP-II design was sound and conservative and that the schedule and budget were well-founded. In October 1993, President Clinton announced Secretary of Energy O'Leary's selection of SLAC as the preferred site, and Congress followed through with $34 million for a PEP-II construction start in fiscal year 1994.

* A B meson and its antimatter equivalent produced together. Pronounced "bee bee-bar."

B Decays and CPT Symmetry

The universe appears to be made almost entirely of matter. Why not almost entirely antimatter? Why not equal proportions of matter and antimatter, annihilating each other whenever they came in contact? For that matter, why not just energy? PEP-II may help provide the answer.

Judging particle interactions by the standards of the familiar macroscopic world, one would think that if the objects participating in some process were replaced either by their antimatter equivalents or by versions of themselves as seen in a mirror, the rate of the process would remain the same. It seems equally intuitive that reversing the process would yield the original participants, much as though one were running a movie in reverse and watching the actors run backward in their own footprints.

But on the scale of subatomic particles and the quarks that make them up—a scale where the weak interaction becomes the strongest of forces—the first two rules, called "conservation of parity" and "charge conjugation," are not necessarily obeyed. Not even CP symmetry, which combines both rules, necessarily holds true. The remaining variable is time; we are left with CPT symmetry—a scheme in which C, P, and CP symmetry violations can occur, but only if the arrow of time is allowed to take a different course when reversed, going back to a different beginning.

Thus far, CP violation has been observed through asymmetries in the decay modes of the neutral K meson and its antiparticle. The K^0 and $\overline{K}^0$ contain a "strange" quark that is not part of the group of quarks that make up ordinary matter. In a few of the K's wide variety of possible decay modes, the K^0 decays a few tenths of a percent differently than the $\overline{K}^0$, a sign of CP violation. But studies of the K system have left many questions unanswered about the mechanisms and magnitude of CP violation.

The B meson, which contains a different unusual quark ("bottom" as opposed to "strange"), is predicted by the Standard Model of Particles and Interactions to have asymmetries as great as 30% in some rare decay modes. This makes it a very promising candidate for CP-violation studies. However, the branching fraction—the proportion of $B\overline{B}$ pairs that will not only decay through the unusual modes but also violate CP symmetry in doing so—is only about 10^{-4} to 10^{-5}. Therefore, about 10^7 to 10^8 $B\overline{B}$ pairs will have to be produced to get good CP-violation statistics. This requirement, implying the need for many e^+e^- collisions, brings us to the luminosity frontier of accelerator physics, the source of most of the physics and engineering challenges in PEP-II.

The ultimate goal of this research is to test the validity of the Standard Model—today's partial theory of the building blocks of nature and how they interact—or replace it with a new, more satisfactory theory. In either case, CP violation will have to be better quantified, and its origins will have to be explained. The present Standard Model does not disallow CP violation but does not explain it either. These studies also have ramifications beyond particle physics.

In 1967, not long after the discovery of CP violation, Andrei Sakharov pointed out that it might explain one of the long-standing riddles of cosmology: why the universe did not originate with equal, evenly distributed quantities of matter and antimatter. For some reason, the laws of nature appear to prefer matter over antimatter—a phenomenon that makes possible the physical universe we see every day.

Conceptual Design Overview

During 1993, the PEP-II collaboration continued refining the design of a B factory in which a 9-GeV electron beam in PEP collides with a 3.1-GeV positron beam circulating in a new storage ring. The new low-energy ring will be of the same circumference as PEP and will be mounted above it in the existing tunnel, as shown in Figure 3-1. The chosen energy combination reaches the Upsilon (4S) resonance, at which $B\bar{B}$ pairs are produced in the abundance required for the study of CP violation (*sidebar*). The challenge in the design of a B factory is to reach an initial luminosity of 3×10^{33} cm^{-2} s^{-1}, which is more than an order of magnitude beyond the luminosities achieved to date in electron-positron colliders.

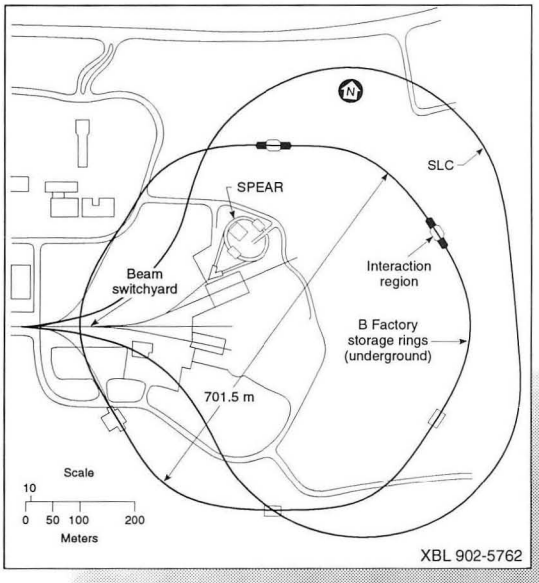
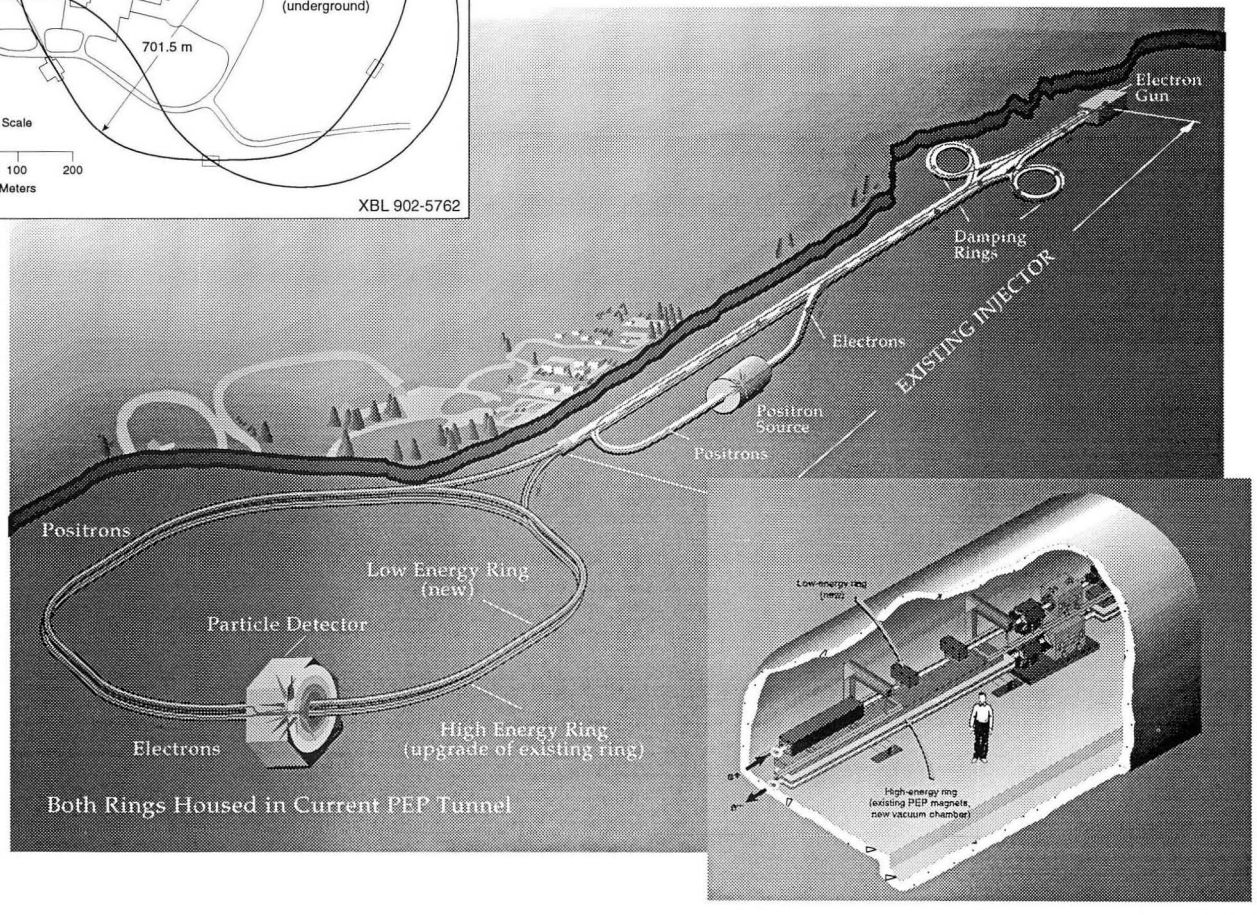


Figure 3-1. The asymmetric B factory PEP-II is being built in the Positron-Electron Project tunnel at the Stanford Linear Accelerator Center, using a substantial amount of the existing hardware for the PEP collider. The year's achievements in the LBL portion of the program centered on design refinement of the rf system, multibunch feedback system, and magnetic lattice, as well as a better understanding of beam-beam interaction. (Artist's impression courtesy SLAC)



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An Overview of PEP

In PEP-II, the electrons, at 9 GeV, are supplied by a modified version of the Positron-Electron Project ring built by SLAC and LBL in the mid-1970s. It uses all the original PEP magnets. The rf system is new, as are the beam pipe and the vacuum systems. The low-energy ring, a new accelerator in the same tunnel, supplies 3.1-GeV positrons.

PEP-II is designed to produce a luminosity of 3×10^{33} cm^{-2} s^{-1}, an increase by a factor of 15 over the current record, achieved at the Cornell Electron Storage Ring. Table 3-1 summarizes the main parameters.

Compared with present-day colliders, PEP-II has unextraordinary single-bunch parameters (bunch current, emittance, rms bunch length, and beam-beam tune shift), along with a vertical beta function of only a few cm at the interaction point. The extreme luminosity comes primarily from a far greater number of bunches. This means higher beam current, implying that the vacuum system and rf system must be considerably improved because of synchrotron radiation, and also that feedback systems to combat coupled-bunch instabilities are needed.

The key enabling circumstances of the PEP-II project include not only the existing PEP ring and tunnel, but also the availability of the "two-mile linac" that feeds the Stanford Linear Collider. The linac can produce 120 pulses per second at about 3×10^{10} electrons or positrons per pulse, giving at least a 300% safety factor above the injection requirements for PEP-II. This uniquely powerful linac should be able to fill both rings from zero current in about 6 minutes, then top them off within 3 minutes when necessary.

Table 3-1. Main PEP-II Collider Parameters.

	Low-Energy Ring	High-Energy Ring
Energy, E [GeV]	3.1	9
Circumference, C [m]	2199.32	2199.32
$\varepsilon_y/\varepsilon_x$ [nm·rad]	2.6/64	1.9/48
β_y^*/β_x^* [cm]	1.5/37.5	2.0/50.0
$\xi_{0x,0y}$	0.03	0.03
f_{RF} [MHz]	476	476
V_{RF} [MV]	5.9	18.5
Bunch length, σ_z [cm]	1	1
Number of bunches, k_B	1658†	1658†
Bunch separation, s_B	1.26	1.26
Damping time, τ_E/τ_x [ms]	19.8/40.3	18.4/37.2
Total current, I [A]	2.14	0.99
U_0 [MeV/turn]	1.14	3.58
Luminosity, $\mathcal{L}$ [cm^{-2} s^{-1}]	3×10^{33}	

†allows for gap of ≈5% for ion clearing

Lattice Design Progress

The basic lattice designs of both rings were completed in earlier years; the primary effort during 1993 was optimization of the lattices of the low-energy ring. Earlier, using single-particle-tracking simulation codes, we had identified a need to increase the dynamic aperture of the low-energy ring.* Enlarging the dynamic aperture increases injection efficiency and reduces the degradation of beam lifetime caused by beam-beam and quantum effects. Good dynamic behavior requires a stable aperture of at least 10 times the natural beam size. The simulation tools that we used accounted fully for nonlinearities, magnetic-field imperfections, and magnet-position errors. In 1993, we also began considering beam-beam interaction.

Increasing the dynamic aperture of the low-energy ring presents special difficulties. We knew that, to compensate for linear chromaticity, sextupole magnets would be needed in the ring arcs; this is a standard approach. However, PEP-II presents an additional challenge in the form of strong quadrupoles that focus the beams near the interaction point. Arc sextupoles strong enough to correct for the resulting linear chromaticity would introduce their own nonlinear chromaticity. We decided that the low-energy ring also needed "local" compensation in both planes near the interaction point, which is the source of the linear chromaticity.

Such a scheme requires sextupole magnets in the interaction-region straight section. Although straightforward in principle, it will be nontrivial to build, especially within the geometrical constraints imposed by the existing tunnel and by the relative position of the two rings. The detailed design of this system, in the larger context of interaction-region design, will be one of the ongoing challenges of building PEP-II.

We also discovered that the dynamic aperture of the low-energy ring is very sensitive to higher-order multipole magnetic fields in the first quadrupoles near the interaction point. Careful attention will have to be paid to their design in order to minimize higher-order fields.

Meanwhile we improved the lattice design of the high-energy ring by decreasing its vertical beta function from 3 cm to 2 cm. This reduced the beam current, formerly 1.5 A, to 1.0 A (proportionately reducing the synchrotron-radiation heat load, among other benefits); the change also relaxed the beam-emittance requirement. The expense was an increase in chromaticity and thus a decrease in dynamic aperture. However, because an electron beam can be made with lower intrinsic emittance and energy spread than a positron beam, the high-energy ring's dynamic aperture was already higher, and is now comparable to that of the improved low-energy ring.

Studying the high-energy ring's dynamic aperture showed that one of the limiting factors is coupling between synchrotron and betatron oscillations, arising from the energy dependence of the beta functions at the rf cavity. We are examining a chromaticity correction scheme, similar to the one devised for the low-energy ring, in the hope of alleviating this limitation. We also found that placing beam position monitors at additional quadrupoles would improve orbit correction.

We are continuing to optimize the design of both rings. However, designs that appear both dynamically and physically acceptable are in hand.

* The dynamic aperture is the area within which the particles exhibit stable betatron and synchrotron oscillations. The beam can be contained magnetically within this area. Particles that go beyond the dynamic aperture are lost to various nonlinear, dynamic processes.

Beam-Beam Interaction Studies

While working on the lattice design, we continued our studies of beam-beam effects. (These beam-beam studies are based on multiparticle tracking simulations, so they require much more computation than the single-particle dynamic-aperture studies. Progress toward combining the two approaches into one consistent whole was itself a significant achievement of 1993.) Closed-orbit effects resulting from parasitic collisions came under particular scrutiny. We also simulated various injection schemes, continued scanning for the most desirable operating point in parameter space, and began studying beam lifetime.

Because of their relatively close spacing, as the bunches enter and leave the interaction point where they are supposed to collide head-on, they experience "parasitic" glancing collisions in the horizontal plane. Although each beam experiences several of these collisions, the one closest to the interaction point is the most disruptive. The parasitic collisions distort the horizontal closed orbit, skewing the beam displacement and turning the intended head-on collisions into glancing or off-center collisions. With a first-order analytic calculation, we showed that these effects are small if the fractional horizontal tune is kept above a certain minimum value.

If the beams were injected in the horizontal plane, a special and severe case of parasitic collision could occur. At injection, the bunches are "bumped," or displaced transversely from their nominal orbits, by a distance of approximately eight times their diameter, so the parasitic collisions could be almost head-on rather than glancing. Vertical injection avoids this problem, since parasitic collision in PEP-II can occur only in the horizontal plane. However, vertical injection can also increase beam blowup. Nonetheless, simulations showed that the beam would still be easily accommodated within the dynamic aperture and that its emittance would still be acceptable, so the design continues to call for vertical injection.

Another of the ongoing detailed-design efforts has been the search for an adequate "working point" in the multivariate parameter space. A working point above the half-integer, with fractional tunes $(\nu_x, \nu_y) = (0.64, 0.57)$ for both beams, had been shown to give adequate luminosity in previous beam-beam simulations, but the dynamic-aperture studies, using single-particle tracking, showed a preference for (0.57, 0.64). So we carried out an extensive tune scan above the diagonal on the tune diagram, centering on (0.57, 0.64). The tentative conclusion is that it is harder (but possible) to find a good working point in this area than below the diagonal. However, with the horizontal tune closer to the half-integer, a dynamic beta-function effect shrinks the beam horizontally, so even if the beam is larger vertically than it would be at (0.64, 0.57), the net effect might be enhancement of luminosity.

In collaboration with SLAC (and also separately as a means of cross checking the results), we are beginning to simulate the effect that beam-beam interaction has on beam lifetime. This is much more difficult than studying most other beam-beam effects because the region of interest is primarily the tail of the particle distribution, where the particle density is much more sparse and the dynamic effects take longer to act. Although initial work has been promising, the nonlinearities and imperfections of a real accelerator are expected to be important, and they have been incorporated into the simulations only in a rudimentary way thus far.

In summary, most of the challenges of the PEP-II design have been addressed satisfactorily, and technical solutions are in hand. As the construction project gets under way, the collaboration is continuing to finish and then

optimize the detailed engineering design, and further suggestions for improvements continue to be put forth as the accelerator physics and other technical issues become better understood.

Beam Test Facility: Commissioning Progress and Experimental Plans

The ALS injection complex includes a valuable resource for other investigations: a traveling-wave linac that produces a 50-MeV electron beam. After the storage ring has been filled, the injection complex sits idle during the several hours of useful lifetime of the stored beam. A variety of interesting experiments can be conducted in the meantime with the linac beam, including plasma focusing of beams, tests of accelerator structures, and generation of short and "chirped" photon pulses. Accordingly the Center has built the Test Beam Facility (BTF), a DOE-funded initiative. The facility (Figure 3-2), which is now being commissioned, will use the linac between injection cycles to provide a highly productive and cost-effective program in beam physics with minimal disruption to ALS operations.

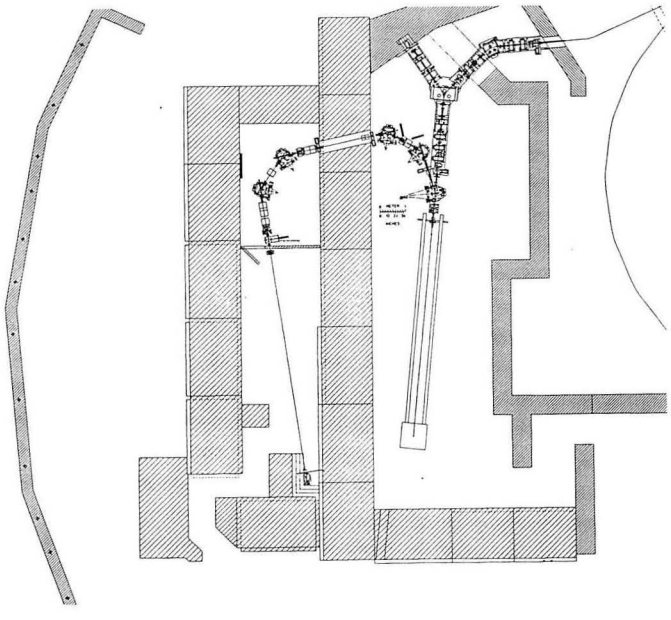

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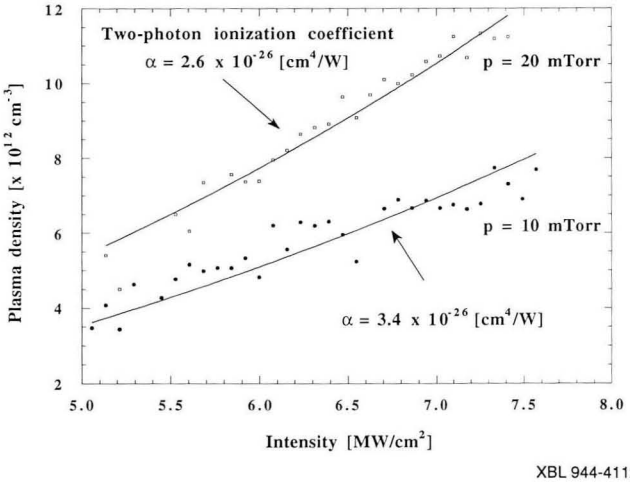
Figure 3-2. Because the ALS is based on a storage ring, the injector linac is idle much of the time. This affords a highly cost-effective opportunity to develop a facility for beam-physics research. This diagram shows the layout of the Beam Test Facility, which is now being commissioned. The facility will support a variety of experiments, such as plasma focusing of an electron beam. Tests of laser-produced plasmas suitable for the plasma focus experiment have been promising. Among other things, we have found that the density scales linearly with filling gas pressure and quadratically with laser intensity, as expected in a two-photon ionization process.



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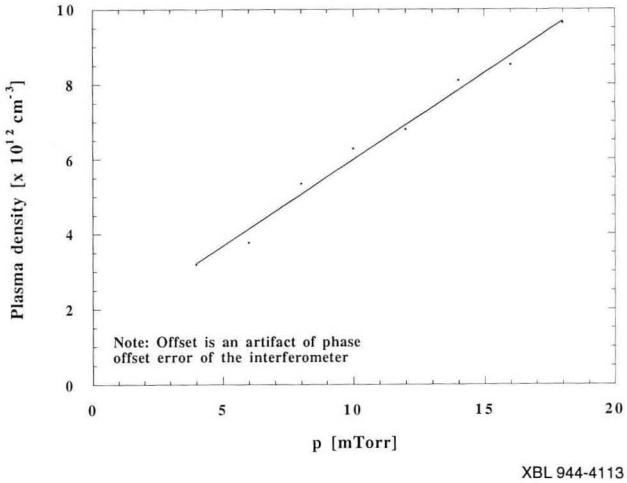

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Plasma-Focus Experiments

When a relativistic electron beam passes through a plasma, electromagnetic interactions focus the beam. To date, most work with the plasma-focus concept has involved thin "lenses." Continuous plasma focusing with thick lenses holds the promise of overcoming the so-called Oide limit—a fundamental limit of focusability arising from statistical emission of high-energy photons in a sharp focusing bend. Our plans include a proof-of-principle test and systematic exploration of plasma-focus ideas generated at our Center.

One of the ideas is a long, continuous plasma focus in which the plasma density is tapered by either diaphragms and differential pumping or a focused laser beam. The density will be tapered from about 1×10^{10} to 5×10^{12} cm^{-3} over a length of 0.5 m. We hypothesize that, at 50 MeV, such a device could focus a beam with a 3-mm cross section into a 400-μm spot. Our scaled proof-of-principle work will involve plasma lengths ranging from 10 to 50 cm, with density tapering from about 1×10^{11} to 5×10^{13} cm^{-3} over that distance.

Two requirements must be satisfied for an effective plasma focus: the plasma response time must be short compared to the pulse length, and the plasma return currents within the beam must be small. We have calculated parameters for a number of experiments that can be performed using the 50-MeV injector; they will allow careful study of these requirements in both underdense and overdense plasmas.* Furthermore, a study of how plasma return currents change the effectiveness of the focusing can provide insight into the usefulness of plasmas in reducing beam-beam interaction.

While BTF commissioning proceeds, we are using the Center for Beam Physics optics laboratory to generate and characterize plasmas whose densities and scale lengths are suitable for the BTF plasma focus. In these experiments, we use UV light from a class-IV excimer laser to ionize tripropylamine. By tailoring the cross section of the laser beam, we have produced plasmas as long as 50 cm with a 1-cm2 cross section. The plasmas were characterized with microwave interferometry equipment from Lawrence Livermore National Laboratory. Within the density range accessible to this equipment—from 1×10^{12} to 1.2×10^{13} cm^{-3}—we have found that the density scales linearly with filling gas pressure and quadratically with laser intensity, as expected in a two-photon ionization process.

The next step will be to generate plasmas with longitudinally varying density, which is necessary for studying adiabatic and tapered lenses. We are currently designing an optical interferometer with high spatial resolution to measure the radial density profile. To measure the temporal dynamics, we will use a visible-light streak camera to measure the light produced by an optical-transition radiation system and scanned along the path of the beam.

Sub-Picosecond X-ray Pulses

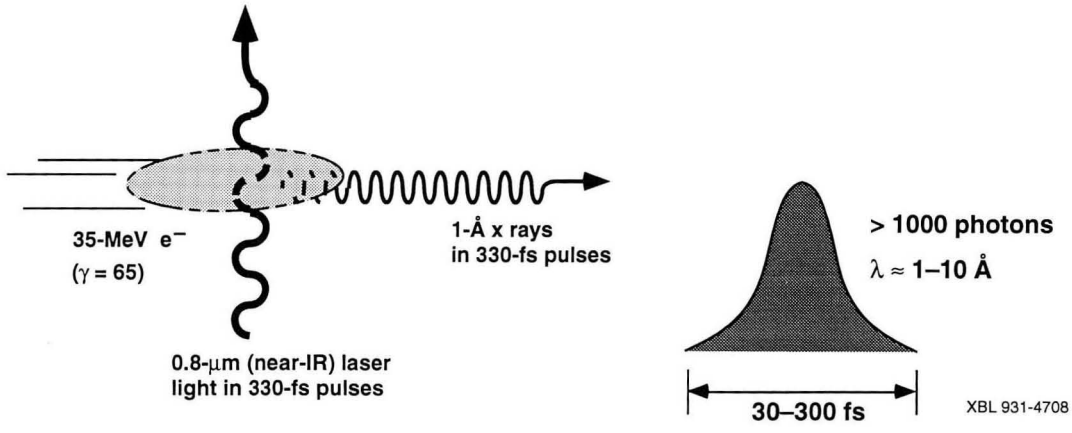
Another experiment at the BTF will produce ultrashort x-ray pulses. Today, the shortness of photon pulses that are produced by either interaction with a magnetic field (synchrotron radiation) or interaction with visible photons (Thomson scattering) is limited by, and comparable with, the length of the electron beam bunch. For the ALS linac beam, the shortest photon pulses

* The terms "overdense" and "underdense" indicate whether the plasma is denser than the particle beam or vice versa.

obtainable from a direct collinear interaction would be a few tens of picoseconds long. We have recently hypothesized that a third approach could break through this limit, producing sub-picosecond x-ray pulses.

The new approach, being supported with Laboratory-Directed Research and Development funds, is based upon 90° Thomson scattering with a visible laser (Figure 3-3). In this configuration, the shortness of the x-ray pulse is limited not by the length of the electron pulse, but rather by the length of the laser pulse or the transit time of the laser pulse across the waist of the focused electron pulse. Therefore it is crucial to focus the electron beam to a narrow waist matching the laser pulse length. The output pulse is much higher in energy than the laser pulse: the upshift is given by $4\gamma^2$, where γ is the Lorentz factor of the electron beam.

A short-pulse, solid-state laser (τ_L = 200 fs, E = 100–200 mJ) is nearing completion in the femtosecond laser laboratory of LBL's Materials Sciences Division. In cooperation with that division's Center for X-ray Optics, we are examining ways to direct the beam onto detectors and experimental apparatus. To detect the x-ray beam with femtosecond resolution, itself a



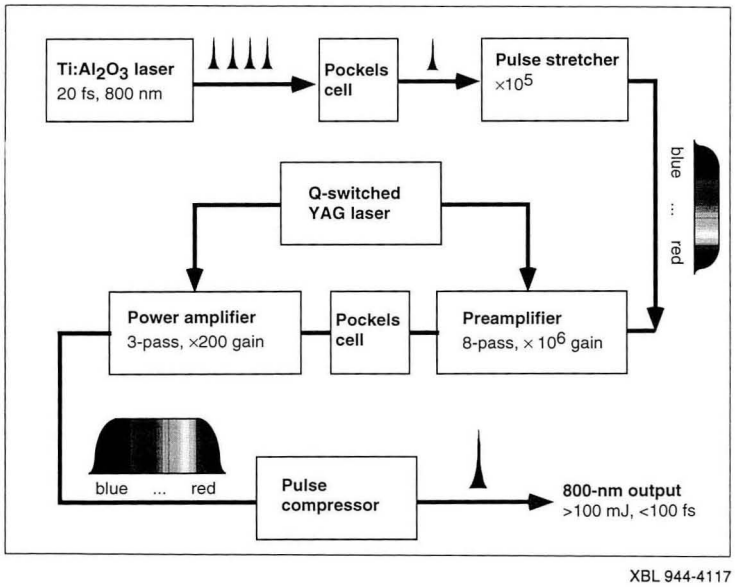


Figure 3-3. One of the most intriguing experiments for the Beam Test Facility is production of sub-picosecond x-ray pulses through 90° Thomson scattering of a visible laser beam against a relativistic (<50-MeV) electron beam. The femtosecond terawatt laser system that will be used in this experiment is being developed by LBL's Chemical Sciences Division.

challenging problem, this collaboration is developing an x-ray detector that uses part of the laser beam to melt a silicon wafer and then measures the change in diffraction pattern as a function of the known delay time before the arrival of the x-ray beam. (We are also exploring autocorrelation of the laser pulse with the visible pulse given off by a gas column that was photoionized by the x-ray pulse.) We are also designing the beamline components required to focus the electron beam to a 70–100 μm spot and then separate it from the x-rays after the interaction point. With the current design parameters, we should be able to produce a 100–300 fs x-ray pulse, containing about 10^5–10^6 photons, with a wavelength that can be varied in the range of 1–10 Å by changing the electron-beam energy.

A variety of other experiments will also be made possible by the facility, including beam-structure interaction studies, investigations of beam-conditioning cavities for free-electron lasers, and the "chirping"* of conveniently long (10-ps) electron-beam bunches to produce photon pulses much shorter than that.

Laser-Optics Laboratory

The Center for Beam Physics has a laser-optics laboratory that serves many efforts, including development of optical components and techniques for the Beam Test Facility. The highlight of the laboratory's 1993 work was continued development, together with Stanford University, of advanced optical diagnostics for infrared free-electron lasers (IRFELs).

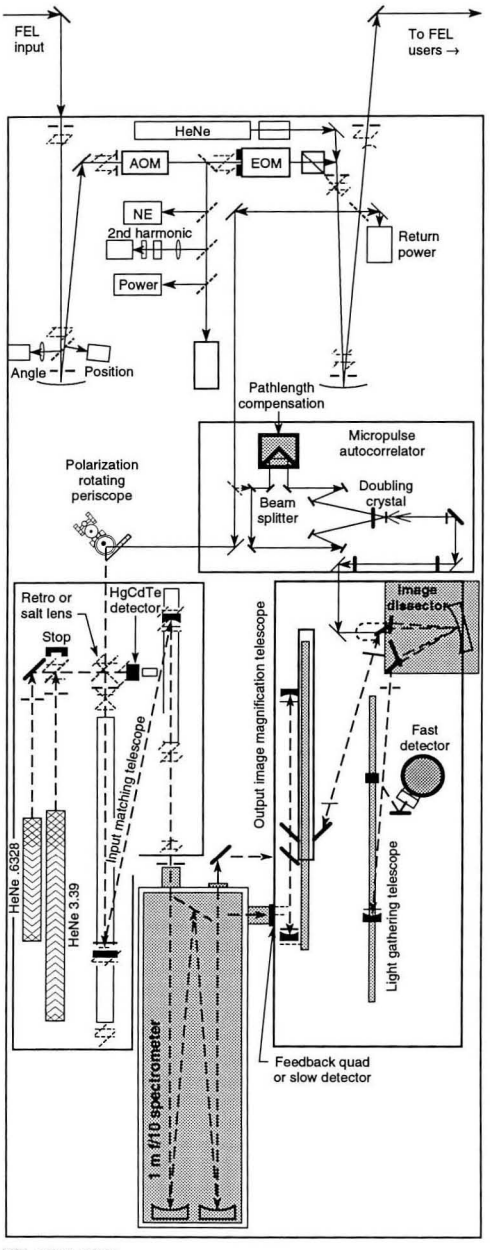
Advanced Optical Diagnostics for FELs

Working with colleagues from Stanford University, we had earlier designed a novel diagnostic system to measure the spectrum and pulse width of an IRFEL's output. By using an image dissector and a high-speed single-element detector with integrating sphere, the system provides spectral and temporal information for each micropulse within the pulse train. The system is shown schematically in Figure 3-4.

Key elements for the spectral diagnostics are the mode-matching telescope, high-resolution spectrometer, imaging telescope, and image dissector. The imaging telescope, located between the spectrograph and the image dissector, varies the magnification of the image that arrives at the dissector, thus allowing the desired spectral resolution to be selected. For pulse-width measurement, the system uses single-pulse autocorrelation through non-collinear optical mixing in a frequency-doubling crystal, along with the imaging telescope and the image dissector. The image is that of the region of the nonlinear crystal in which second-harmonic light was generated.

During the summer, after the spectrometer system was developed in our laboratory, we tested it using an FEL beam at Stanford that operates in the 3–12 μm region of the spectrum. In fall 1993, we used the system to measure the FEL's wavelength stability on a micropulse-to-micropulse basis and to study the sideband stability. These issues are important in the design of advanced FELs, such as the one that might be added to the Chemical Dynamics Research Laboratory proposed by LBL. Although data analysis is not yet complete, preliminary inspection indicates that, as expected, spectral sidebands develop when an IRFEL is operated close to saturation.

* A term for a small, rapid change in energy during a pulse, historically based in radio transmission of Morse code.



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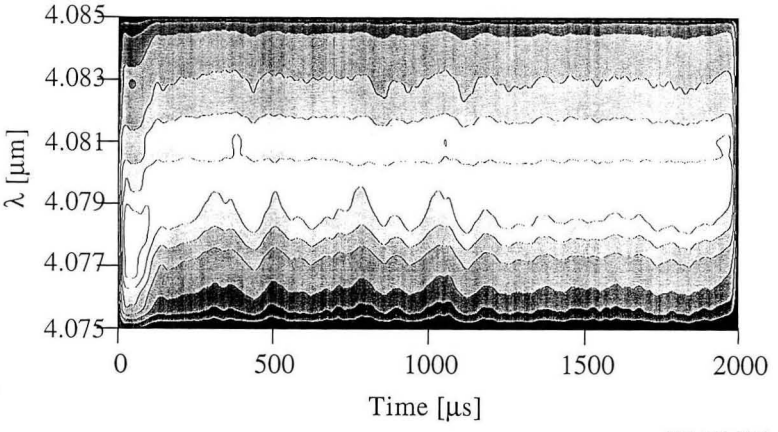

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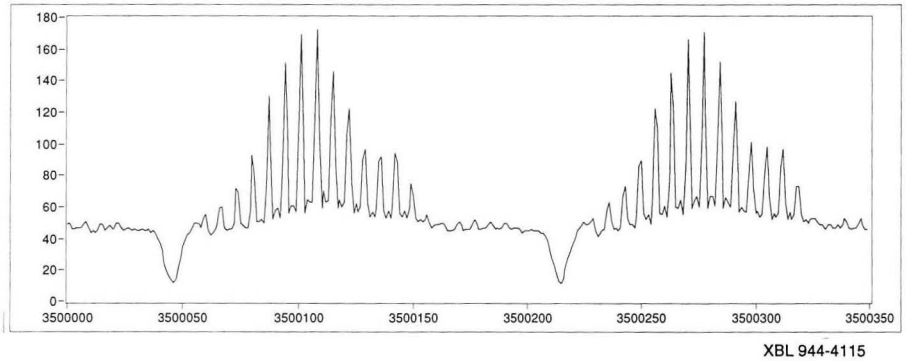
Figure 3-4. The LBL-Stanford collaboration in FEL diagnostics has resulted in a system that measures the optical spectrum of every individual micropulse during the complete macropulse. Experiments have been conducted on measuring the wavelength stability of the FEL with this system. *Above*, the wavelength of the FEL output is plotted as a function of time, with shading indicating intensity. The plot *below* details the spectra of two consecutive micropulses (separated by 85 ns). The spectral information is given by the envelope, the spiky structure being an artifact of the image dissection technique. In addition, the system has been used to study sideband development and evolution towards chaos as a function of desynchronization.



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Beam Electrodynamics

As greater demands are made on the performance of accelerators—such as PEP-II with its extreme integrated luminosity or the Relativistic Heavy Ion Collider (RHIC) with its intense heavy-ion beams at high energy—it becomes ever more important to understand potentially disruptive rf phenomena within the beam chamber and to perform various rf manipulations that monitor and control the beam. The Beam Electrodynamics Group within the Center approaches these problems through analysis, simulation, and experimentation.

An area of special interest is the understanding and control of the potentially disruptive electromagnetic interaction between the beam and the conductive walls of the vacuum chamber and various devices. Other specialties include the design and development of rf systems for stochastic beam cooling and other aspects of beam monitoring and control.

In 1993, the group continued its lead role in the design of rf and feedback systems for PEP-II, along with studies of beam impedances, feedback systems, and intensity-dependent effects at the ALS. Their history of contribution to the Tevatron continued with a study of a stochastic beam-cooling upgrade and improved beam diagnostics. And, in a new effort aimed at improving the beam's luminosity lifetime (and therefore user service) at RHIC, they began studying possibilities for stochastic cooling of intense, bunched heavy-ion beams.

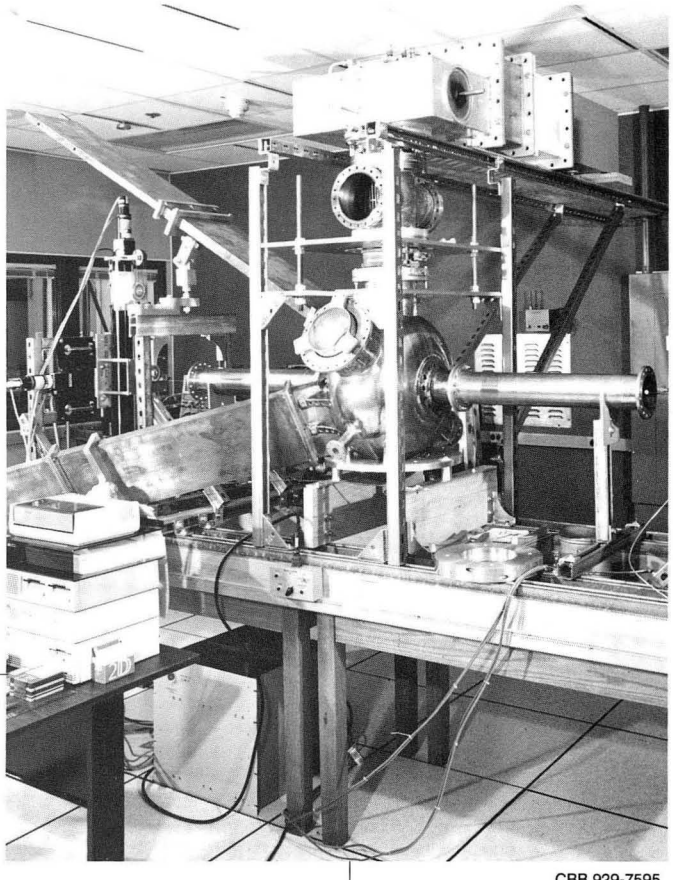
Progress in PEP-II RF Systems

The major rf-design challenge posed by PEP-II is control of coupled-bunch motions. The higher-order resonance modes of the rf cavities can drive a hundred or so unwanted beam motions at a growth rate thousands of times faster than the damping that naturally occurs in the accelerator. The first step toward stabilization is to reduce the shunt impedances of the higher-order modes by several orders of magnitude without corresponding degradation of the desired fundamental mode. Removal of the remaining instabilities will then be within the reach of a practical feedback system. To reduce the shunt impedance of the higher-order modes, we attach waveguides to the cavity to couple these modes to an external resistor.

Figure 3-5 shows a low-power prototype. Extensive measurements designed to examine which modes are damped and whether there is interference with the fundamental mode have shown good damping of the strongest longitudinal and transverse higher-order modes and also good agreement with calculations. The measurements were made with low-power prototype loads. The study of these loads continues; we are using an innovative broadband measurement technique that we developed to determine the complex permittivity and permeability of rf-absorbing materials. Recently we have begun the engineering design of full-power loads and a full-power test model of the cavity.

In addition to the problems caused by higher-order modes, the desirable fundamental mode of the rf cavity may itself drive beam instabilities, as some coupled-bunch modes fall within the width of the fundamental resonance. This problem, endemic to large-diameter rings, must be addressed with active rf feedback around the cavity and its driver. The design of both longitudinal and transverse feedback systems is underway in collaboration with SLAC. Computer simulations using measured data on the higher-order modes indicate that the problem of suppressing coupled-bunch modes, although difficult, can indeed be solved. The data are obtained from beam signals at the ALS, where we have been testing prototypes of the longitudinal feedback system and will soon test prototypes of the transverse system.

Figure 3-5. The PEP-II rf cavity accelerates the beam with the fundamental mode while diverting the disruptive higher-order modes into external ferrite loads that absorb the microwaves. (The cavity is the central sphere with the beampipe running through it; the "wings" contain the loads.) This low-power prototype was used for extensive tests to examine which modes are damped and whether there is interference with the fundamental mode. The tests yielded encouraging results and showed good agreement with calculations, so as the study of the prototype continues, we have pushed forward on the engineering design of full-power test models of the cavity and loads. Simulation is also useful. This finite-element model of part of a load design shows standing waves and absorption regions by the electric-field strength (the cores of the semicircles are maxima, the black parts minima). It reveals that essentially no power is dissipated in the last 30% of the load, which is therefore superfluous—an important finding for a device that must be installed in the limited space of the PEP tunnel. The standing waves are weak, and most of the incident power is indeed absorbed in the ferrite.



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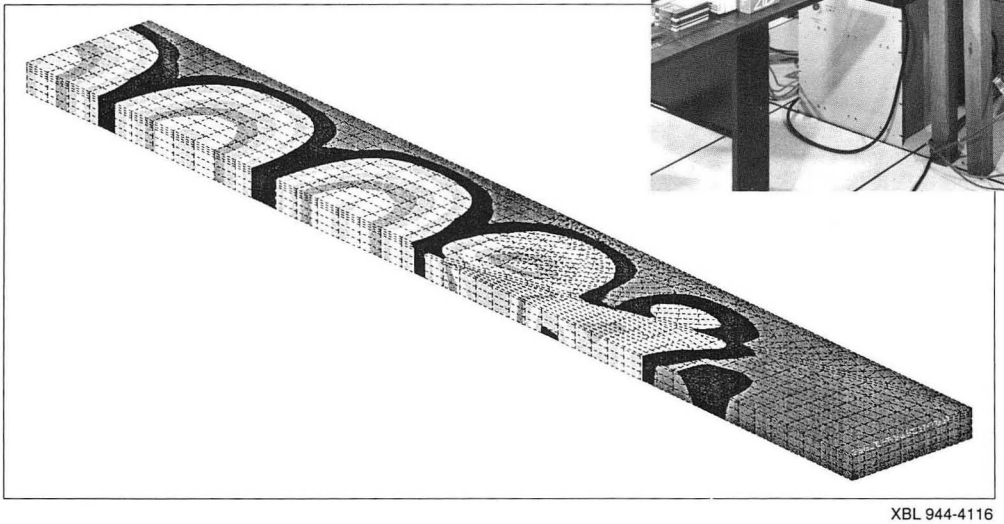

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Support for the Advanced Light Source

In addition to using ALS beam signals to test prototype PEP-II systems, we have continued our support of ALS commissioning and improvement. Using detailed knowledge, derived from our previous work, of the beam-impedance characteristics of the storage ring and the higher-order modes of the rf cavities, we have calculated and simulated the coupled-bunch beam dynamics of the machine. Building upon this achievement, we are designing a three-axis damping system to control coupled-bunch motion. The system measures errors in the position and phase of each bunch and applies the appropriate feedback. The transverse part of the system has been designed and components are being manufactured; work on the longitudinal part is under way.

Fermilab Antiproton Cooling System

The latest achievement in our ongoing collaboration with Fermilab is the design of a biplanar electrode system for more rapid cooling of the beam for the antiproton source.* LBL was involved in the initial design of pickup and kicker electrodes for this cooling system and has been continually engaged in analyzing the system's performance and seeking ways of improving it.

In earlier years, we had demonstrated that, for power-limited cooling systems, it is more efficient and cost-effective to double the number of cooling electrodes than to double the operating frequency, whereupon we developed biplanar electrodes that could effectively double the number of electrodes without using any more space. This scheme, with the existing 2–4 GHz electronics, appeared to yield better results than would a system with uniplanar electrodes and completely reworked 4–8 GHz electronics. Calculations indicate that the resulting performance would exceed the needs of any anticipated upgrade to the Tevatron complex, including the proposed new main injector. The validity of our beam-cooling calculations was affirmed by comparing the results with cooling data from Fermilab. In 1993, we began studying the performance of a prototype module. Full production awaits the results of the study and a go-ahead decision by Fermilab.

We have also designed a dual-cavity Schottky detector, based on a single-cavity design that we had tested successfully at Fermilab in the late 1980s, for measuring signals from the proton and antiproton beams independently. (In the Tevatron, the two beams rotate in opposite directions in a single beam pipe.) By using two of these detectors at different places in the storage ring and combining the phase information appropriately, the Schottky signals from the proton and antiproton beams may be separated and analyzed independently. Here, too, production awaits the results of performance studies and a subsequent decision by Fermilab.

Heavy Ion Beam Cooling for RHIC

In RHIC, currently under construction at the Brookhaven National Laboratory, stored beams ranging in mass from protons to Au^{79+} will be used for studies of nuclear phenomena in heavy ion collisions. Gold-on-gold collisions will be of particular importance for studies of the quark-gluon plasma, which are directed towards an understanding of the transition between nuclear matter and elementary particles. For highly charged ions like gold, intrabeam Coulomb scattering can cause beam growth and particle loss, which lead in turn to rapid luminosity deterioration. For much of the scientific program, long beam lifetime—as much as 10 hours—with well-maintained luminosity is essential or at least desirable. As part of the proposed program in Ion Beam Technologies for Nuclear Physics (see Chapter 5, "Ion Beam Technology," of the *1993 AFRD Summary of Activities*), we propose to study stochastic beam cooling to address this concern.

The RHIC design uses two rf systems. One provides acceleration at the harmonic number h = 342; the other operates at 196 MHz and serves to keep the bunches short and almost constant in length during storage. In one scenario, to achieve the full design luminosity while cutting cost, the maximum available rf voltage in storage mode is limited to 6 MV. Subsequently, based on experience acquired with the operation of the collider, more rf

* Beam cooling means measuring the "temperature" or internal motion of the particles in the beam and applying feedback to reduce this motion, thereby increasing intensity.

cavities, possibly superconducting, could be added up to a maximum total voltage of 16 MV. This voltage limit is required to minimize beam loss in the case of Au beams. Stochastic beam cooling might, however, prove more cost-effective.

During the last decade, stochastic cooling has been developed into a practical means for reducing beam emittance and controlling growth of momentum spread without loss of particles. In RHIC, it would keep the beam dimensions well within the magnet aperture and the bucket height and would lengthen the luminosity lifetime. One expects that a stationary and stable equilibrium density will develop when the emittance growth rate due to intrabeam scattering just matches the damping rate due to cooling. Estimates of the achievable damping rates for momentum cooling have been made, assuming a 4–8 GHz bandwidth. The use of momentum cooling, given 6 MV of storage rf, would reduce beam loss enough for a twofold luminosity gain at top energy. Further luminosity gains would require the addition of transverse cooling.

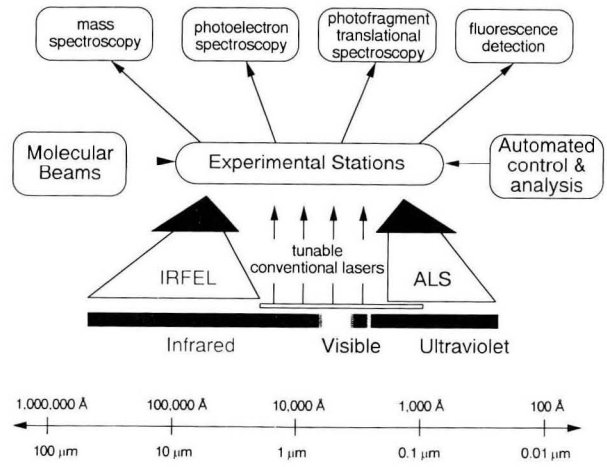
Our proposal establishes an R&D plan aimed at stochastic cooling of bunched beams in RHIC, especially for collider-mode running with Au beams. The initial effort (FY 1994 and 1995) emphasizes further study and conceptual design. The ultimate goal is to be operationally ready to implement such a system, should it prove necessary, after commissioning and operational start of the collider in late 1990s. Meanwhile, some crucial collider diagnostics will be designed and fabricated as part of a prototyping program, so beam and luminosity monitoring will be possible from the first day of commissioning.

Free-Electron Lasers and Other Radiation Sources

As mentioned in the earlier section on the Beam Test Facility, radiation sources beyond or complementary to the ALS are of great interest. They might be higher in some aspect of performance, smaller and cheaper, or useful in some hard-to-cover part of the spectrum (Figure 3-6). Investigating the possibilities for radiation sources has been a long-standing part of our work. Achievements in 1993 included further simulation and experimentation in various aspects of infrared free-electron lasers (IRFELs), studies of FELs that could operate at wavelengths as short as x-rays, and fundamental characterization of how coherent radiation propagates through optical elements.

Much of our current work was born of a design effort aimed at a high-stability tunable IRFEL for the Chemical Dynamics Research Laboratory (CDRL). That effort was mothballed in 1992, with a refined conceptual design published and archived for possible future use by the CDRL. Several resulting areas of inquiry proved to be of continuing interest and broader importance to the FEL community, including studies of superconducting rf cavities, laser-driven photocathodes, and optical resonators. We also reinvigorated our interests in high-gain FELs at higher frequencies (ultraviolet through x-rays) and in the fundamentals of optical radiation.

Figure 3-6. Many important phenomena could be probed if gaps in the spectral coverage of present-day radiation sources were filled by new sources that offered high power, consistent stability of power and wavelength, and narrow, precise bandwidth. Free-electron lasers are emerging as a promising approach to this problem. Our studies have emphasized FELs for the infrared region (especially important for chemical physics), and in recent years have increasingly focused on the technical challenges and scientific potential of FELs for the ultraviolet region and beyond.



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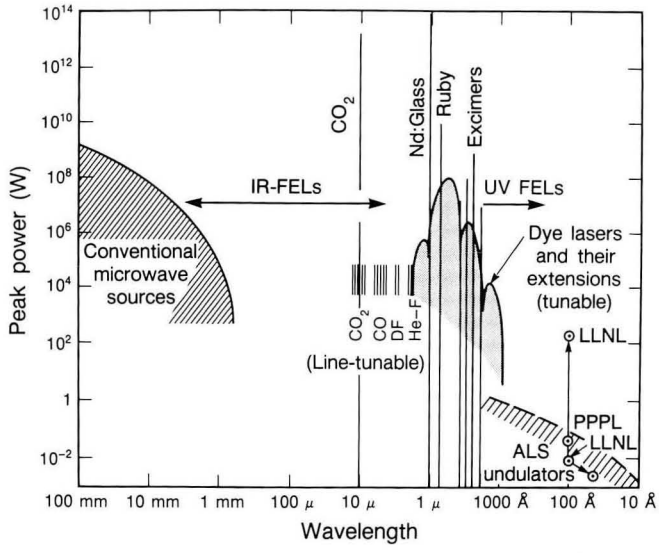

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Single-Pass Amplification: The Key to Short-Wavelength FELs

One of the biggest obstacles to using FELs much beyond the infrared part of the spectrum has been the need for highly reflective mirrors at the ends of the oscillator cavity. Mirrors that work at near-normal incidence at those wavelengths tend to be inefficient. Recent advances in laser-driven rf photocathode electron sources have made it possible to produce electron beams that are bright enough (referring to a combination of high power and low emittance) for extremely-high-gain FEL amplifiers. This might solve the problem because if enough gain could be obtained in a single pass, mirrors would not be needed. It seems possible, at least in principle, to generate coherent radiation at wavelengths shorter than 1000 Å with peak power levels ranging from hundreds of megawatts to several gigawatts—far greater coherent power than synchrotron radiation sources can provide.

We have carried out an extensive analytical and numerical study of such an amplifier in both the exponential-growth and the saturation regimes, and have extended our one-dimensional model of self-amplified spontaneous emission (the basic principle underlying the FEL) to a full three dimensions. This work has yielded the first exact 3-d solution for amplifier gain and FEL eigenmodes, taking into account the effects of beam emittance, beam energy spread, and betatron focusing. Through extensive simulations with the 3-d code TDA, we have also obtained a universal scaling law for FEL gain and an empirical formula for the saturation power.

These studies have laid the groundwork for a fundamental understanding of the start-up and amplification processes in FELs and have provided efficient tools for designing and optimizing high-gain FELs. The tools are currently being used in a feasibility study for an x-ray FEL, based on the existing linacs at the Stanford Linear Accelerator Center, that would operate in the "water window," a low-absorption slice of the spectrum that is of great interest to microscopists.

To develop one of the key enabling technologies for stand-alone high-gain FELs, we have been working with AFRD fusion energy researchers to characterize photocathode materials. With barium photocathodes we obtained electron quantum efficiencies as high as 10^{-3}, and we studied the dependence of the quantum efficiency on the polarization and angle of incidence of the nitrogen laser beam. Experiments with lanthanum hexaboride cathodes are now underway.

Optical Resonator R&D

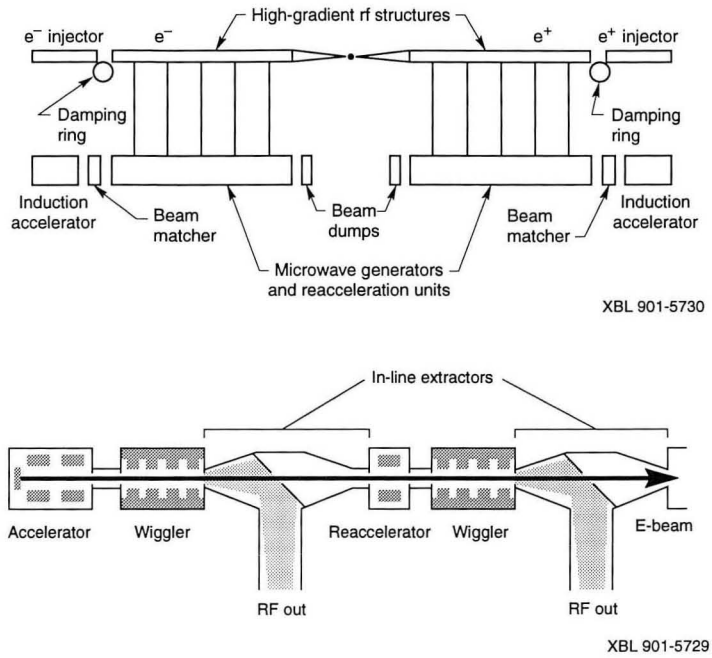
In our ongoing studies of optical resonators for FELs, we completed a versatile simulation code known as SWORD (Small Workshop for Optical Resonator Design). This code, developed in preliminary form as a design tool for the hole-coupled resonator in the CDRL IRFEL, has been broadened, enhanced, and bench-tested with a scaled experiment. It is now suitable for most kinds of optical resonator development. The CEBAF/LBL collaboration is using it to the design of a confocal ring resonator for their proposed IRFEL. We are using it to study a novel resonator configuration that we designed—a "double-confocal resonator," suitable for either chemical lasers or FELs, that is optimized for driving the Thomson backscattering source at the ALS Beam Test Facility.

High-Energy Collider Physics

Of the many ideas that have been proposed for the electron-positron colliders of the next century, the two-beam accelerator, or TBA, appears to be one of the more promising. Figure 3-7 illustrates the concept. The first of the two beams is a "drive" beam generated by an induction linac. It has high current but relatively low energy (perhaps 3 kA at 10 MeV in a full-scale TBA). This beam is passed through either an undulator-based free-electron laser (FEL) or a relativistic klystron (RK), generating microwave power on the order of 1 GW per meter of length. The power is applied to an adjacent high-gradient acceleration structure, which accelerates a second electron beam to high energy. Today, the TBA technology is in the early stages of development; designs are being developed and evaluated by researchers in the Center's High-Energy Collider Physics Group, in collaboration with colleagues from LLNL and from KEK, the high-energy physics laboratory in Japan.

In addition to the TBA, we have been studying a number of other ideas in and related to high-energy collider physics, such as the plasma focus described earlier, muon colliders, gamma colliders, spinoff concepts for FELs, and frontiers of electron-beam cooling. In several areas of our work, we are pursuing opportunities to collaborate with Former Soviet Union scientists, especially in various aspects of the TBA and FELs.

Figure 3-7. As shown in the TBA sketch (right), a high-current, low-energy drive beam is used for generating rf power that is applied to a high-gradient acceleration structure, where a low-current load beam is accelerated to high energy. The diagram below shows the progress of the drive beam through the rf-generating devices (FEL wigglers in this example) and the reacceleration units that replenish the drive beam in between.



Transversely Modulated RK

Initially the TBA/RK work involved longitudinal bunching of the drive beam, provided by the Advanced Test Accelerator (ATA) linac at LLNL. This longitudinal bunching is adequate for low energies, but at moderate energies (greater than 3 MeV or so) it becomes less effective. To extend our work to higher energies, we have been experimenting with a transverse chopper cavity or "choppertron," built according to our designs by Haimson Research. In 1991 trials, the choppertron produced impressive peak power—some 400 MW—but the pulses at such power levels were less than 10 ns in length; in 1992 we determined that the problem was beam breakup caused by a spurious higher-order mode generated in the output structure at 13.6 GHz. To solve the problem, we have added a damping structure; in 3-MeV experiments on ATA, we obtained 30-ns pulses at 120 MW. These pulses had a phase jitter of about 2°, which implies good spectral purity. This satisfying demonstration of high power output from an RK provides a good basis for our continuing R&D program. We continue investigating damping structures that could remove the higher-order mode without damping the desired mode, perhaps enabling us to simultaneously achieve the hundreds-of-megawatts power and the tens-of-nanoseconds pulse lengths.

In 1993, we began design and simulation of an important aspect of the TBA concept, namely, reacceleration of the "spent" drive beam, which is economically critical. Figure 3-8 shows the layout of the reaccelerator. The actual experiment will require increasing the drive-beam energy to 5 MeV.

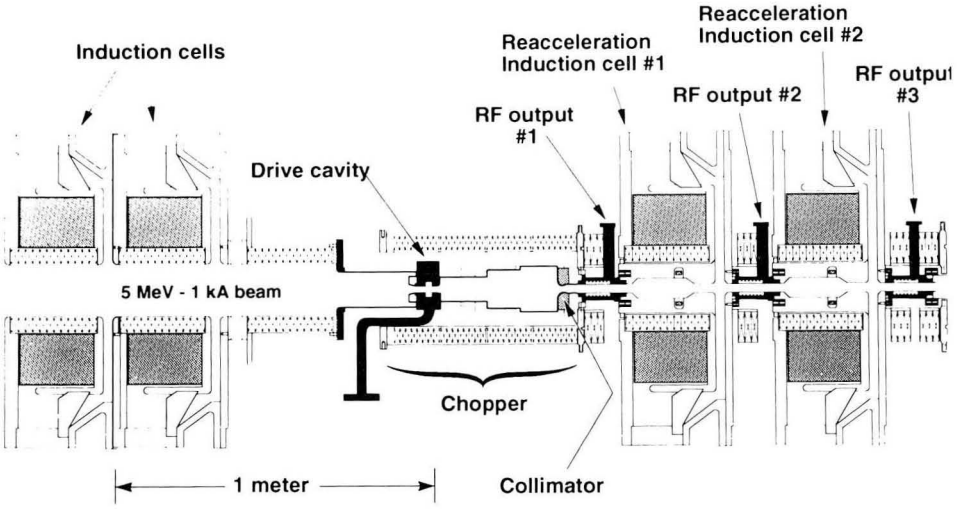


Figure 3-8. The "spent" drive beam in the TBA retains considerable energy and most of its original current, so reaccelerating it and tapping rf power from additional RKs would be very attractive economically. In 1993 we began design and simulation of a reaccelerator. In addition to construction of the reacceleration hardware, the actual experiment will require operating LLNL's Advanced Technology Accelerator at 5 MeV rather than the 3 MeV we have been using.

Standing-Wave and Multicavity FELs

The FEL, explored in our original TBA research, remains a proven candidate with great potential. We are developing an idea, called the "standing-wave FEL," in which the radiation is trapped in a standing-wave rf cavity (rather than the usual traveling-wave structure) and beat-coupled to a nearby high-gradient acceleration structure. Figure 3-9 illustrates the idea, which is undergoing analysis and theoretical study. The work focuses on such topics as beam breakup instabilities and sensitivity to changes in various parameters—especially the dependence of microwave amplitude and phase upon FEL parameters. No experimental program is anticipated in the near term.

We have recently begun analyzing a multicavity standing-wave FEL concept. In particular, we expect that it will be much better at generating

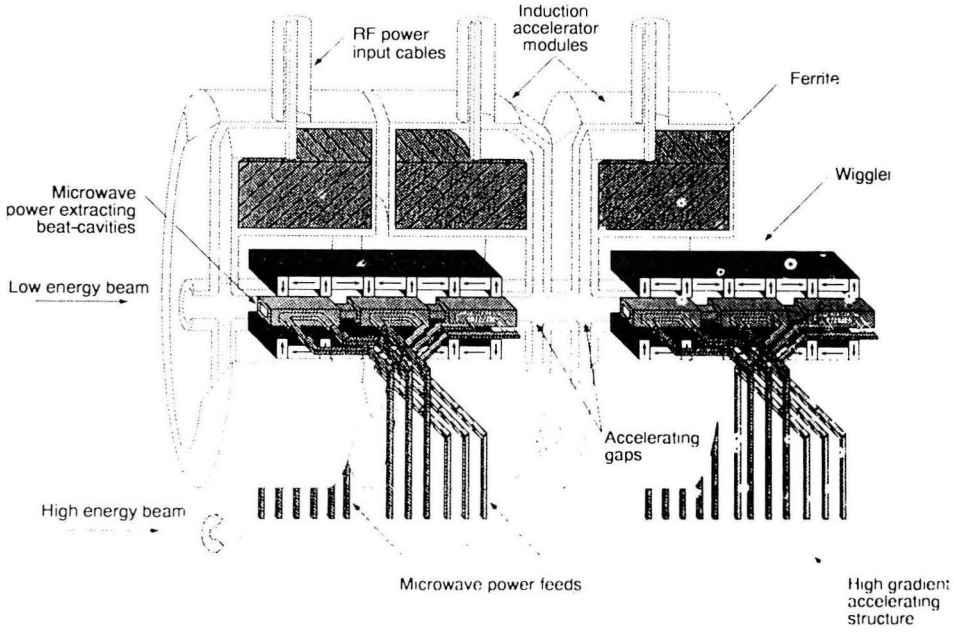


Figure 3-9. The FEL, which was the rf-power generator in our original TBA research, remains a proven candidate with great potential. We are developing an idea, called the "standing-wave FEL," in which the radiation is trapped in a standing-wave rf cavity (rather than the usual traveling-wave structure) and beat-coupled to a nearby high-gradient acceleration structure. This concept is undergoing analysis and theoretical study, focusing on such topics as beam breakup instabilities and sensitivity to changes in various parameters—especially the dependence of microwave amplitude and phase upon FEL parameters. No experimental program is anticipated in the near term.

harmonics than an FEL run in the traveling-wave or "amplifier" mode. A multicavity standing-wave FEL could be implemented by resonating the first few cavities at the fundamental, thus producing significant bunching, and resonating the next few cavities on a selected harmonic.

Beam Conditioning

The gain of an FEL or other resonant electron-beam device is limited by the spread in longitudinal velocity and, hence, the energy spread and emittance of a three-dimensional beam. The electron-beam emittance must be less than the wavelength of the radiation from the device divided by 4π. In practice, the energy spread of the beam often makes only a small contribution to the total spread in longitudinal velocity, so we realized that the beam could be "conditioned" with special rf cavities. These cavities would impart more acceleration to the particles traveling longer paths, reducing the spread in *longitudinal* velocity caused by beam emittance.

In previous years, we analyzed this idea with a simple numerical model for beam transport, assuming ideal rf cavities; analyzed an FEL to evaluate its performance with reduced axial-velocity spread; and computationally analyzed a cavity geometry that promises to greatly increase the beam-cavity coupling. We are now planning experiments to test the feasibility of a beam-conditioning cavity, perhaps at the Test Beam Facility described earlier in this chapter, perhaps at the Accelerator Test Facility at Brookhaven National Laboratory.

Seeking to obtain a crystalline beam (as described below), two groups—one in Aarhus, Denmark, and the other in Heidelberg, Germany—have begun using a laser to cool a stored beam longitudinally. Both have been able to achieve longitudinal "temperatures" (a measure of random motion within the beam bunch) in the millikelvin range. Transverse temperatures remain above 1000 K. Conditioner cavities could prove to be the ideal complement for this technique; because they couple transverse and longitudinal motion, they should allow laser cooling in all three dimensions, an idea that we are pursuing.

If a beam were made sufficiently cool, then the particles would in theory form a crystal lattice as the focusing forces imparted by the accelerator overwhelm the Coulomb forces within the beam. However, even though this subject has been discussed in workshops and in the literature for a decade or more, beam physicists have not paid great attention to it. We began investigating the phenomenon in 1993 because advances in laser cooling might bring it within the grasp of experimentalists before long. Our studies included computer modeling with molecular dynamics codes; an elucidation, for the first time, of the storage-ring and beam-cooling parameters needed; and the effects of storage-ring straight sections. We continuing our theoretical examinations of the subject while working closely with the experimental groups at Aarhus and Heidelberg that are attempting to crystallize beams.

Exotic Colliders

One of our most exciting areas of research has been the exploration of exotic colliders, including a muon collider and a gamma-gamma collider.

A muon collider may be thought of as a "Higgs factory"; muons have a stronger coupling to the Higgs sector than do electrons, which implies much greater data rates than could be obtained with an electron collider. Muon

collisions are also not expected to be radiation-limited, unlike the higher leptons. However, the challenges in accelerator technology are considerable. Muons are produced from beams of either protons or electrons striking a production target; the resulting beams occupy a large transverse phase space and therefore must be cooled considerably. However, since even at 100 GeV, muons only last about 2 ms before decaying, ionization cooling is likely to be the only practical method. Figure 3-10 illustrates a muon collider based on electroproduction that, according to our thinking, might result in cooled muon beams of sufficient energy and intensity to yield worthwhile physics.

Another scheme might open up new physics opportunities for the "traditional" electron-positron collider configuration: colliding gamma rays with each other or with electrons. (Gamma rays are energetic enough for their particle duality to be significant in this respect.) The greatest challenge is creating a sufficiently intense burst of gamma rays. This could be accomplished by Compton backscattering of a powerful burst of energetic (near-visible) light against a highly focused, hundreds-of-GeV electron beam. We will host a workshop on gamma-gamma colliders in March 1994 to explore this idea further, with particular emphasis on FELs and chemical lasers for generating the intense burst of light.

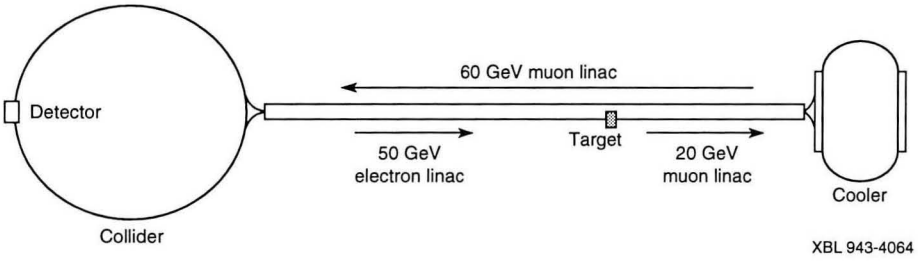


Figure 3-10. This concept for a muon-antimuon collider based on electroproduction may someday serve as a "Higgs factory" for high-energy physics. The need for beam cooling, combined with the 2-ms lifetime of muons, poses formidable (and interesting) challenges in accelerator physics and technology.

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Superconducting Magnets 4

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THOUGH PERHAPS MOST FAMILIAR IN ACCELERATORS, superconducting magnets have many other applications, ranging from magnetic-resonance imaging to magnetically levitated trains. The Superconducting Magnet Program in AFRD takes a vertically integrated approach by offering expertise "from melt to magnet"—that is, at all phases from basic development of better superconducting materials to evaluation of finished magnets.

Interaction with private industry is a vital part of our activities. Even when the goal is a magnet design for a particle accelerator, industrial partnership is important because the sheer size of today's large colliders mandates industrial production. But in many areas, especially in basic materials research and development, our work goes beyond "technology transfer" and into the realm of genuine two-way collaboration.

In 1993 our program continued its long-term shift toward generic R&D that will benefit future accelerators for high-energy and nuclear physics. Earlier we had set a field-strength record for accelerator-type magnets: just over 10 T in the magnet D19, made with niobium-titanium superconductor. That performance level, however, appears to be near the practical limit for niobium-titanium. While working to enhance the performance of NbTi through the use of artificial flux-pinning centers, we are exploring other materials that are not currently as well-proven and economical as niobium-titanium but hold the promise of higher fields (and possibly lower costs as well). They include brittle materials such as niobium-tin with and without artificial pinning centers.

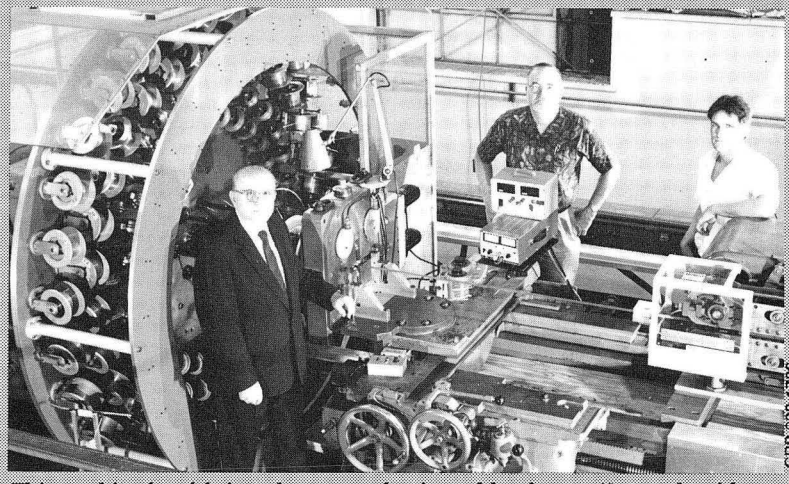
Innovative approaches are also being taken in ancillary fields. For example, a new type of strain gauge, using fiber optics to measure strain through optical interferometry, has passed fundamental proof-of-principle tests, and we are now working on ways to incorporate it in magnets and to implement it as part of an integrated circuit chip. And, after three years, our research into "high-temperature" bismuth oxide superconductor is approaching its first macroscopic demonstration: a small test solenoid. Although far from being ready for use as an engineering material in high-field accelerator magnets, this high-T_c material holds great promise for further exploration and industrial spinoffs.

Capabilities and Facilities

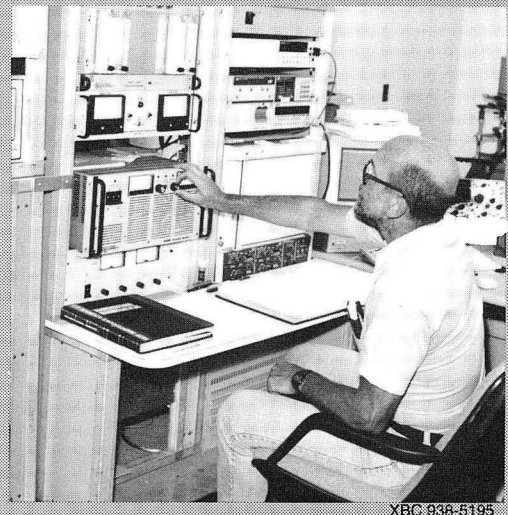
The Superconducting Magnet Program has expertise in all aspects of design and evaluation "from melt to magnet." In many years of collaboration with users, academic researchers, and industrial partners, we have amassed a track record of success that includes:

- Improved superconducting materials.
- Manufacturing of cable from superconducting wire and design of improved machines for cabling.
- Design of superconducting and normal-conducting magnets to meet a variety of needs.
- Computerized analysis of magnetic and mechanical properties expected from complex magnet designs.
- Testing and magnetic measurement, along with related instrumentation.
- Transfer of designs and fabrication skills to industry.

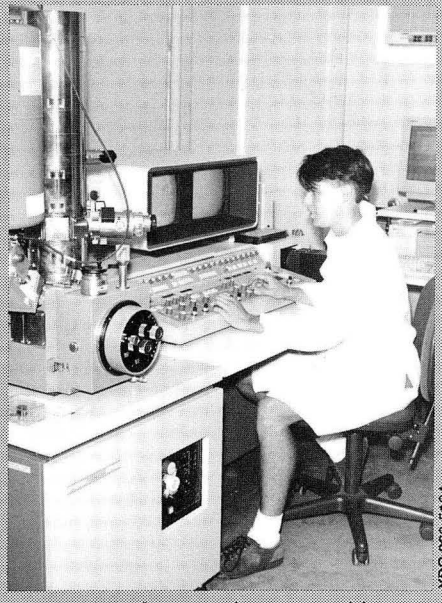
The program is also supported extensively by other LBL organizations, especially the Engineering Division.



This machine has fabricated superconducting cable of up to 60 strands with keystoned, rectangular, or other profiles.



Metrology capabilities include short-sample conductor testing in a 17-T field, from 1.8 to 20 K, and a device for accurately mapping magnetic fields in a bore up to 5 m long.



A scanning electron microscope with 3-nm resolution and analytical capabilities is the latest addition to a dedicated materials-testing laboratory.

Development of manufacturable magnets and transfer of technology to industry are among the proven strengths of the program.

Advanced Lattice Magnets: Higher Fields, Lower Cost

Applied development work for the Superconducting Super Collider dominated our activities for several years, but we continued to investigate other aspects of superconducting-magnet science and technology. The findings will be increasingly relevant to new and upgraded accelerators (especially colliders for high energy and nuclear physics) as their designers attempt to minimize costs, build advanced accelerators in existing tunnels, and face challenges such as final focus of energetic beams in the constrained spaces in and around detectors.

Our quest for higher fields in accelerator-style magnets has taken us in two directions. Niobium-titanium (NbTi) material has been used in most practical superconducting magnets to date because it is ductile and therefore workable in its superconducting form. In close collaboration with an industrial partner, Supercon, Inc., we are industrializing Artificial Flux Pinning Center (APC) technology. This approach to making NbTi superconductor with artificial flux pinning centers promises considerable improvements in critical current density at high magnetic fields, a key measure of performance, and, at the same time, cost reductions of 40% or more. (For higher fields, we are also experimenting with a ductile ternary alloy, niobium-titanium-tantalum or NbTiTa.) This combination of higher performance and lower cost will give NbTi superconductor many years of continuing usefulness.

In the long run, though, NbTi will reach a practical limit in the neighborhood of 10 T. To push accelerator magnets to much higher fields, we are revisiting various brittle materials, such as niobium-tin (Nb_3Sn), that were investigated in the 1970s but neglected in favor of the easier-to-fabricate NbTi. These materials present great challenges in cable-making and in magnet fabrication that are quite different from those of ductile superconductors. Our present thrust is toward 13 T with Nb_3Sn. On the drawing board is a magnet intended to reach 16 T—possibly by using the APC approach in brittle material such as Nb_3Sn or other A15 superconductors, assuming that we and our academic and industrial collaborators can make such materials.

D19B and -C: The Next Steps for a Record-Setting Magnet

To advance magnet performance and to support our development of superconducting cables and the machines to make them, we build experimental magnets comparable in size and shape to those used in accelerators. The aforementioned field-strength record for such magnets of 10.06 T central field (approximately 10.4 T near the conductor)* was set using D19, a high-field dipole.

D19 uses the same NbTi cables as the SSC collider dipole magnets: 30 strands for the inner layer of windings, 36 in the outer. The field record was set at 1.8 K, with a current of about 9.4 kA. With its more efficient coil and yoke design, D19 reached the SSC-specified dipole field of 6.6 T at 5.8 kA and 4.3 K, a considerable improvement over the 6.6 kA of the SSC dipole. The cross section in Figure 4-1 reveals the noncircular inner profile of the iron yoke. The use of this profile, an existing idea not previously applied to accelerator-type magnets, maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to reasonable levels. Since then, we have been evaluating improved superconducting materials for accelerator service by building and testing new variations on the D19 design.

* The record was recently edged by a group at CERN, the European high-energy physics laboratory.

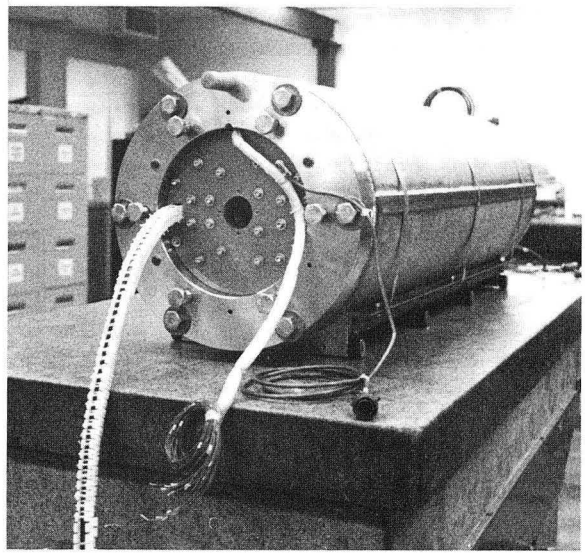


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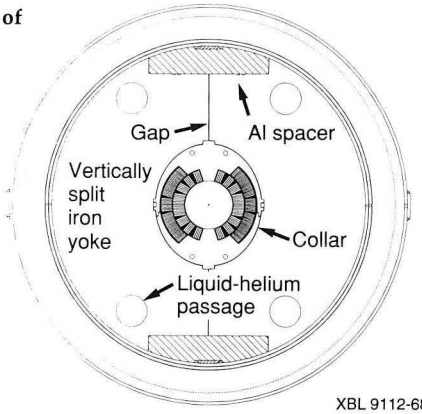
Figure 4-1. Dipole D19, the 10-T magnet now being used for APC testing, has an iron yoke with a noncircular profile for efficiency. This shape maximizes the magnetic-field contribution of the iron while keeping high-field saturation effects down to manageable levels. Another interesting feature is the vertically split iron yoke with aluminum-alloy spacers between the halves. The spacers maintain a predetermined gap between the halves at room temperature but allow them to shrink together tightly at cryogenic temperatures. This maintains the high compressive load on the coils and prevents the windings from shrinking faster than the iron yoke during cooldown. Such differential contraction would relieve the compression of the windings and thus undo the "training" process that allows the ultimate magnetic field to be reached.



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In 1993 we completed and began testing D19B, a follow-on project using the same design but incorporating superconductor that has artificial flux-pinning centers for higher critical current. This APC superconductor (whose principles and fabrication are explained in the later section on materials R&D) was produced by one of our frequent industrial collaborators, Supercon, Inc., with a novel "jelly-roll" process. Figure 4-2 shows training curves for D19 and its successor.

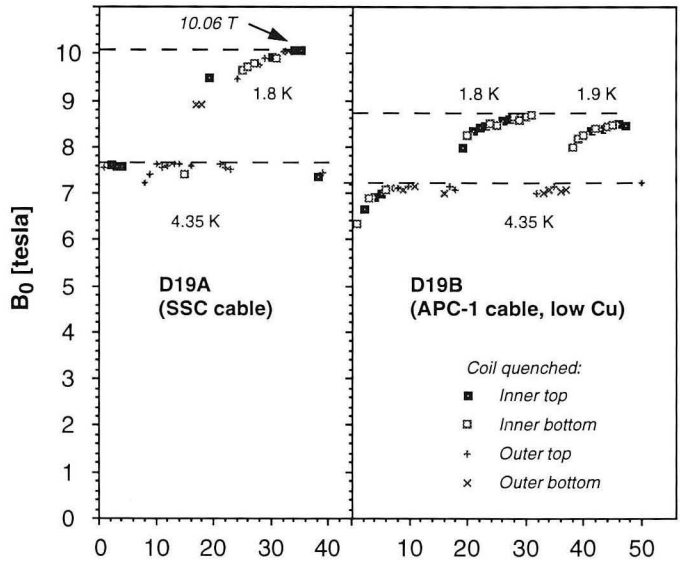

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Figure 4-2. This graph shows the training behavior of dipole D19B, along with its record-setting predecessor D19. After six training quenches, D19B, made with APC conductor from Supercon, Inc., plateaued at a magnetic field of 7.0 T at a temperature of 4.3 K (lower set of curves). Subsequently it reached 8.7 T at 1.8 K (upper set of curves). The dotted line in each half of the drawing indicates the maximum possible magnetic field predicted from critical current density measurements of the conductor and short samples of the cable. The various shapes of points indicate which of the four coils experienced the quench that ended each test. The plateau field observed was 97% of the field predicted—an excellent achievement for the first sample of a new type of cable.

Although D19B's performance reached a plateau at a considerably lower field than D19, it was a success. The main goals were not to set a new field record, but rather to demonstrate that a new material from a new process was qualitatively similar in behavior to the familiar NbTi materials (measurements thus far indicate that this is indeed the case) and to gain knowledge that will be useful as the materials process moves further from laboratory work to full manufacturing scale. Materials produced in the full-scale process will be evaluated in D19C, the next step in this part of the program.

After that, D19D will give us our first look at one of the higher-field ternary (three-part) alloys, NbTiTa, with artificial pinning centers. This project has been delayed somewhat because of difficulties in getting the constituent materials in the form needed for the jelly-roll process, but work is expected to get under way in 1994.

D20: The Push Beyond 10 T

Another advanced magnet, D20, is now being fabricated (Figure 4-3). D20 will press through the 10-T level, and hopefully well beyond, by using Nb_3Sn superconductor. The goal is a "short-sample" field of about 13 T at 1.8 K. (The short-sample field represents the maximum performance of the superconducting cable and is determined by measuring the conductivity of a short sample in an external magnetic field. An actual magnet incorporating the cable might, if designed and constructed well, approach the short-sample limit near the edge of the aperture, where the field is strongest.)

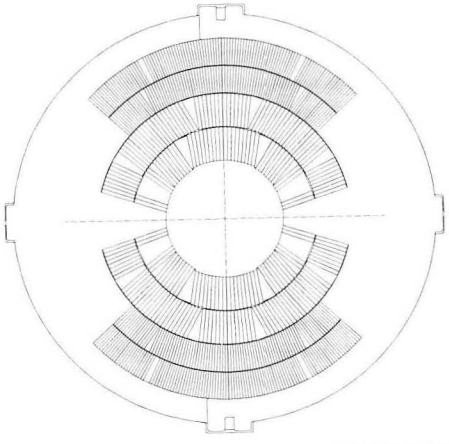

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Figure 4-3. With dipole D20, we will use Nb_3Sn superconductor in the push toward field strengths previously unachievable in accelerator-type magnets. Two layers of superconducting cable—47 strands in the outer layers, 37 in the inner layers—are being wound in a double-pancake configuration. The mechanical design is similar to that of D19. However, because Nb_3Sn is embrittled by the heat treatment that makes it superconducting, we will have to wind the cable first and then react it. After the reacting stage, which takes about two weeks at 650° C, epoxy is vacuum-drawn through the fiberglass insulation, resulting in a robust assembly ready to be encased in a pack of metal collars. The goal of D20 is 13 T, representing a short-sample limit for the Nb3Sn material of about 13.3 T.

The effort to reach beyond 10 T in accelerator-type magnets presents a number of challenges above and beyond magnetic design. Mechanical stresses become far greater than those in existing accelerator magnets: at 13 T, the windings in D20 would experience an axial force of about 820 000 newtons (185 000 lb), a horizontal force of 3900 kN/m (23 000 lb-in.), and a compressive stress of 100 MPa (15 000 psi). Such large forces exerted on a precision assembly of modest size can have a variety of adverse effects. In its most severe form, the strain can distort the magnet and damage the brittle superconductor. Short of that level, it can cause the small movements of the cable that lead to quenches, and can reduce the critical current of the superconductor, an effect that we are continuing to investigate.

Even more important, Nb_3Sn in its finished, superconducting form is brittle, as are all the other likely candidates for future high-field magnets. Cable containing the ingredients—still ductile at this point—is wound onto magnet forms and then baked at 650° C for about two weeks. The heating causes a chemical reaction that turns it into superconductor and also embrittles it. This magnet-making procedure is essentially a new technology. It is important because, although ductile ternary compounds like NbTiTa might offer small improvements over NbTi, the high-field frontier clearly belongs to brittle superconductors. They hold the potential for current densities much greater than that of NbTi, which is considered to have a theoretical limit in the neighborhood of 5000 A/mm^2 at 5 T and a practical limit of rather less than that.

Cabling, another important part of our vertically integrated capabilities, also plays an important role in the D20 project. Previous accelerator magnets from recent years had generally used "Rutherford-style" cable with a keystoned cross section, which allows robust Roman-arch construction of the magnet. However, to build a magnet that can withstand the extreme Lorentz forces of high-field operation, considerable pressure has to be applied mechanically during fabrication. This causes compaction of the superconductor, which in turn results in some degradation of critical current density (J_c).

Typically in the past, with NbTi, the degradation had only been about 5%, but as we studied cabling of Nb_3Sn—a subject that, as it turned out, had never been examined closely—we realized that the J_c penalty in D20 could approach 40%. Thus we went back to a rectangular profile for the D20 cable, changing the cross section of the magnet accordingly.

Although D20 is intended solely for testing Nb_3Sn, it has many features that are generically applicable to future hadron colliders. The high field permits an accelerator to achieve higher energies in a given radius, as when upgrading a collider or building a new one in an existing tunnel.

Beyond D20: Speculations on the 16-T Regime

Thus far, the familiar cosine-theta coil configuration, held in compression when idle and fortified against stresses during operation solely by an external yoke, has sufficed for our advanced magnets. Eventually, as we push the magnetic field strength into the high teens and accordingly increase the stresses and resulting strains inside the windings, we may need to use alternative designs for coils and cables. The problems are more severe in brittle superconductors than in NbTi because J_c is more rapidly degraded by strain: a strain of 0.7% is considered to be the limit, which must be obeyed everywhere in the magnet. Accordingly, we are considering some speculative designs, such as the "block" and "window-frame" configurations of Figure 5-4. At the appropriate time, such a design will be chosen, modeled in detail, and implemented in a future magnet. Building upon the D20 cable development work, we are also examining possibilities for cable made with other strand cross sections that may reduce strain degradations.

Other Advanced Magnets for Accelerators

One of the challenges of the high-energy, high-luminosity colliders of the future, such as the PEP-II B-meson "factory" recently approved for construction at the Stanford Linear Accelerator Center, is final focus of the beams just before the interaction point. (Various other beam manipulations may also be needed in these areas.) These and other magnets in and around the detectors

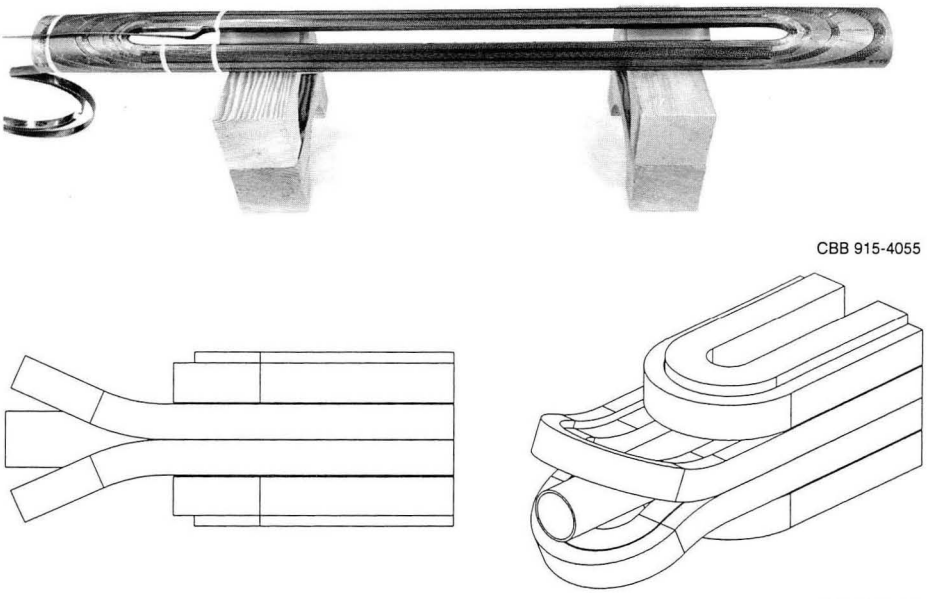


Figure 4-4. Most superconducting accelerator magnets thus far have used "cosine-theta" windings, as revealed in this photograph of D19 at an intermediate stage of assembly. In speculative designs for accelerator-style magnets that will reach beyond 13 T or so, we are considering a variety of alternate configurations, like the one shown, that may give the desired type and uniformity of magnetic field while minimizing the strain that results from the high stresses in these strong magnets. Building upon such concepts, the design process will involve detailed, computerized magnetic and mechanical modeling.

are usually quite challenging in shape and size as well as in field strength. We are working with the PEP-II collaboration to design and develop final-focus magnets and other advanced superconducting and normal-conducting magnets that might be needed. See Chapter 3, "Center for Beam Physics," of the 1993 *AFRD Summary of Activities* for further information on PEP-II.

Spinoff Applications

Although our program grew up alongside high-energy physics and is strongly oriented toward service to the accelerator community, there are many other applications for high-field superconducting magnets. One of them is the field of nuclear magnetic resonance (NMR) and magnetic-resonance imaging (MRI).* In a collaborative project with Wang NMR of Livermore, California and the Bitter National Magnet Laboratory at the Massachusetts Institute of Technology, we developed the conductor for a gigahertz NMR spectrometer at Pacific Northwest Laboratory.

This proton spectrometer would be part of the Molecular Science Research Center, an initiative proposed by Pacific Northwest Laboratory, and would be especially well suited to studying the large molecules and systems of molecules that are of interest to biologists. The spectrometer design requires a large 23.5-T magnet.† Large magnets for NMR spectrometers are also of interest to the National High Magnetic Field Laboratory at Florida State University.

* Generally speaking, NMR refers to the nonimaging scientific tool and to the underlying physical principle, whereas MRI refers to the imaging technique used for applications such as medical diagnosis.

† Note that the 10-T record mentioned earlier was for an accelerator-type magnet. The magnets for high-energy accelerators must exert their field over a considerable length in order to bend or focus the extremely "rigid" particle beam, and the field must be extremely homogeneous. Their design is also constrained by many mechanical and economic factors. NMR magnets, although challenging in their own way, are much different physically, so the apparent tremendous leap from 10 T in accelerator magnets to 23.5 T in this project is misleading.

Advanced Materials and R&D Techniques

In addition to designing and building magnets, we conduct a diverse program of investigations in superconducting materials. Current projects explore the use of artificial flux pinning center (APC) technology in ductile and brittle materials and investigate still-embryonic but promising low-temperature applications of high-T_c superconductors. Other projects include a novel interferometric method of measuring strain in magnets; it uses optical fiber not only in its conventional role as a "light pipe" for imaging or information, but also as the main element of a physical sensor.

APC Materials Development

Materials-science research plays a key role in achieving higher, more uniform, and more predictable magnetic fields—for example, a promising recent line of inquiry that involves the APC concept. In APC superconductors, the random distribution of pinning centers, which ordinarily arise from alpha-titanium precipitation when the superconductor is formed, is replaced with a more-precise distribution. Ideally the distribution matches the magnetic fluxoid lattice for a given field strength: 25 nm for 5 T, for example. The optimum diameter is roughly twice the electron coherence length, or about 11 nm.

A fluxoid is the site of one quantum of magnetic effect and may be thought of as the place where a line of magnetic flux penetrates the superconducting wire. Ordinarily, fluxoids can move through the superconductor in response to an applied magnetic field; this dissipates energy. In one approach to APC wire, niobium is introduced as a normal-conducting phase during wire manufacturing. The flux lines are localized to the regions where this material remains after the "jelly roll" of wire has been drawn down to the final size. Artificial flux pinning allows some measure of control over the final microstructure of the superconducting material, which is important because microstructure is an intrinsic characteristic that cannot be altered by the way the material is formed into wires. (The significant intrinsic factors are filament microstructure and composition. Extrinsic factors, such as the cross-sectional area, integrity, and uniformity of the superconductor, are also important.) Figure 4-5 illustrates this principle.

The ultimate application of this research is to enable the fabrication of multifilamentary superconducting wire that has higher J_c and is also more economical to produce. We have also worked with Supercon, Inc., on a method (Figure 4-6) of producing APC superconductor from sheets of Nb and Ti metal. This method improves the high-field performance of the APC superconductor and also promises to reduce the cost of the material.

After successful demonstrations, Supercon, Inc. scaled up to the wire sizes appropriate for SSC-type dipole magnets, and we obtained enough of the wire to fabricate cable and build the D19B magnet described in the previous section. Testing this 1-m-long dipole magnet gave us further information on the performance, reliability, and cost-effectiveness of APC material.

Superconducting magnets retain the desired electrical properties only up to a certain critical current; above that level, they regress to ordinary conduction. Current density, temperature, and magnetic field interact in this regard; the superconducting regime is often graphed along three axes and referred to as the "J_c, T_c, B_c surface." B_c and J_c can be limited by fundamental properties of the superconductor; however, J_c can be increased by optimizing the microstructure. Increases in J_c allow the use of smaller, cheaper cable or, alternately, the achievement of higher fields.

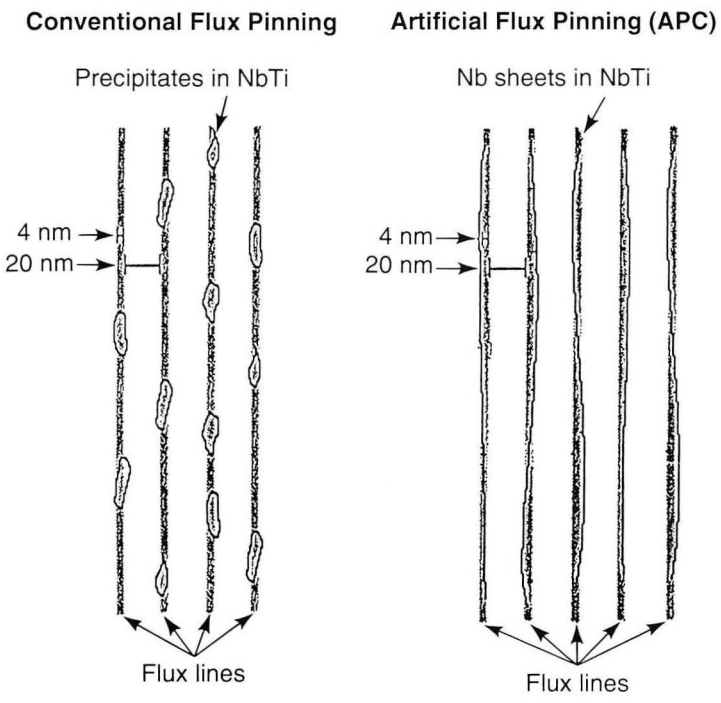


Figure 4-5. In conventional flux pinning *(left)*, the fluxoids, or places where field lines penetrate the conductor, are localized at the randomly distributed points where precipitates were formed by heat treatment. (These sites are elongated, as shown here, when the material is drawn into wire.) In artificial flux pinning, normal-conducting metal sheets are interleaved with the superconductor in the manufacturing process and drawn down to nanometer scale. This process provides better matching between the pinning sites and the flux lines. It also obviates the formation of pinning centers as a reason for heat treatment.

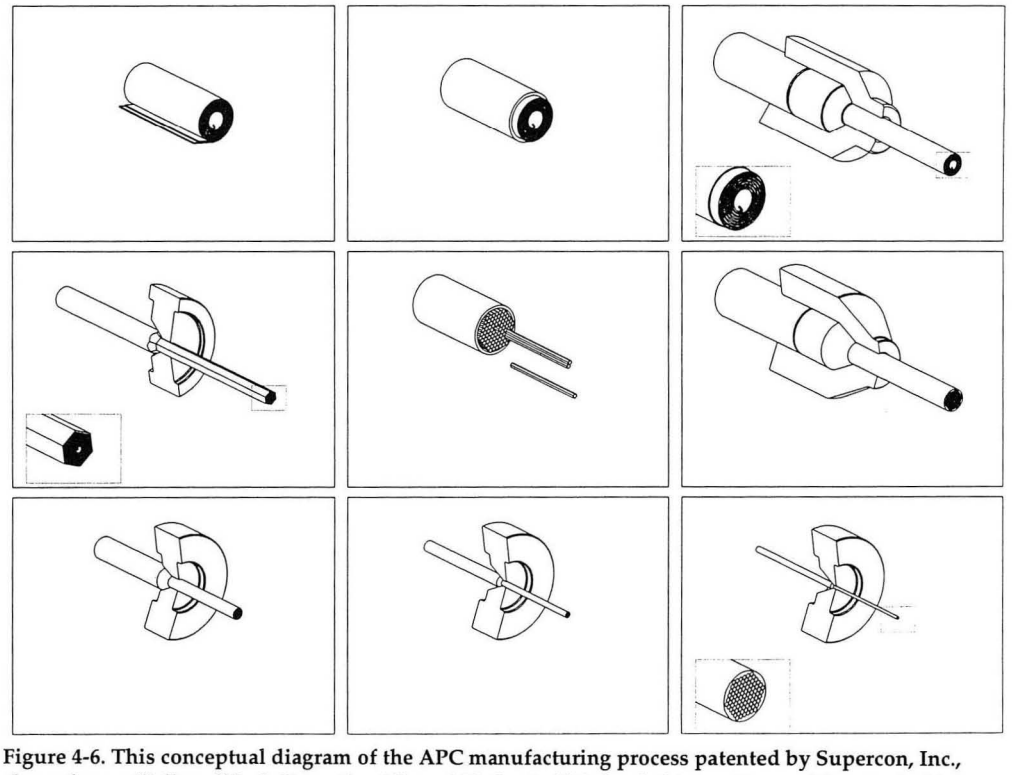
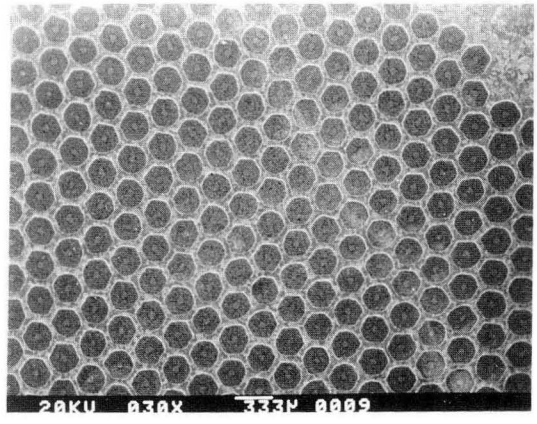


Figure 4-6. This conceptual diagram of the APC manufacturing process patented by Supercon, Inc., shows how a "jelly roll" of alternating Nb and Ti sheets (*1*) is loaded into a Cu can (*2*), extruded into a monofilament (*3*), and drawn through a hex die and cut into stackable lengths (*4*), which are then loaded into a can (*5*), which is extruded into a multifilamentary billet (*6*) and successively drawn into wire of the final diameter (*7–9*). Because no heat is applied during the process, the copper matrix remains unannealed (avoiding the introduction of large differences in mechanical properties between matrix and filament), and interdiffusion at the filament boundary is obviated.

The D19B wire—essentially the first example of a recently scaled-up production process—exhibited some filament "sausaging": about 12.5%, as opposed to the 6% typical of the final SSC production runs. (Sausaging is quantified by dividing the average diameter into the standard deviation after digital measurement of filament sizes in cross section.) The sausaging is attributed to a slightly higher ratio of inter-filament spacing to filament diameter (0.21 rather than the specified 0.17). This caused the average J_c (2200 A/mm^2) to be slightly lower than our goal, the SSC specification of 2440 A/mm^2 at 6.6 T and 4.2 K.

When the D19B wire was examined with scanning electron microscopy, some upset of the billet and distortions of the filaments were noted, probably because of excess void space in the billet at the time of extrusion. Surprisingly, despite the distortion, no difficulties were encountered in drawing a single, unbroken piece of wire 3300 m long. After it was formed into cable and used to fabricate D19B, we found that its performance was quite close to expectations, with nearly the predicted magnetic field and little J_c degradation. The distortion, upset, and sausaging problems all appear to be solvable through better process control, and Supercon, Inc., is proceeding with scale-up to full-sized production billets and optimization of J_c in SSC-type wire, which we will test in D19C. Figure 4-7 shows a cross section of this wire.



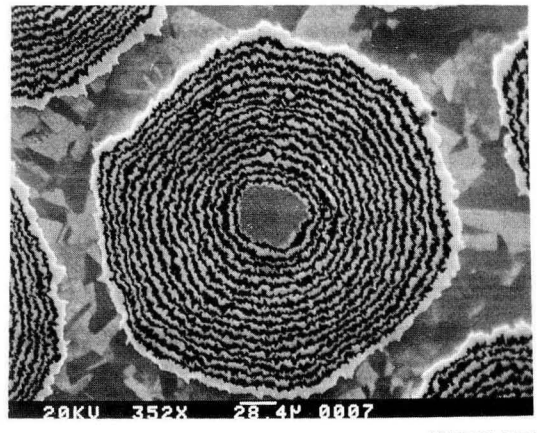


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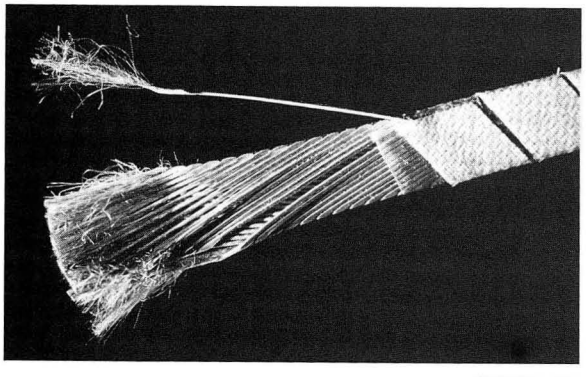
Figure 4-7. APC wire produced by Supercon, Inc., with a patented process in 1992 showed a uniform structure despite a local area ratio (copper matrix to superconductor filaments) of about 0.6. It is desirable to make this ratio as low as possible to increase the critical current density. The whole wire is shown at *top* and an electron photomicrograph of an individual filament at *bottom*. Further scale-up to full-production-size billets is proceeding.

Until results are available from the scale-up to full-production-sized multifilamentary bullets, it will not be possible to make detailed projections of the cost savings expected from the use of APC materials. However, the raw materials are significantly cheaper, and the manufacturing process costs less because (among other factors) a variety of direct and indirect costs associated with heat treatment are obviated. Combining these savings, we estimate that the APC superconductor will be about half the cost of conventional NbTi of comparable specifications.

Cable and Cabling-Machine Development

A longtime goal of our superconductor R&D program has been to develop improved techniques and tooling for the fabrication of Rutherford-style cable. The R&D cabling machine we developed to meet the needs of the SSC, and which is now available in a commercial version, continues to serve our R&D needs. In 1993 we upgraded the machine (Figure 4-8) with a new spool and a powered Turk's-head so that it could fabricate cables with as



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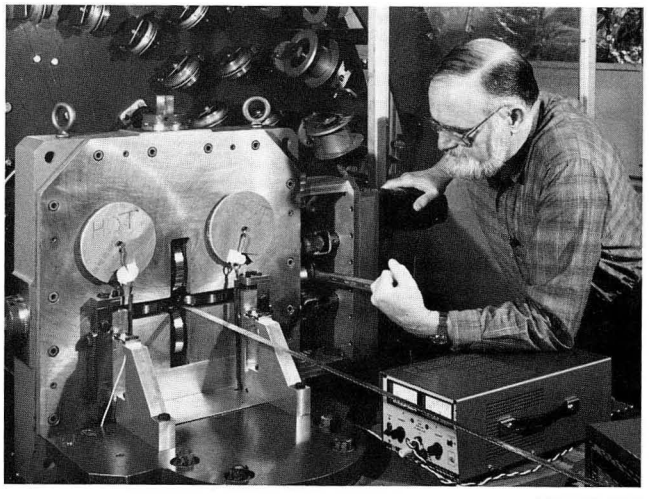

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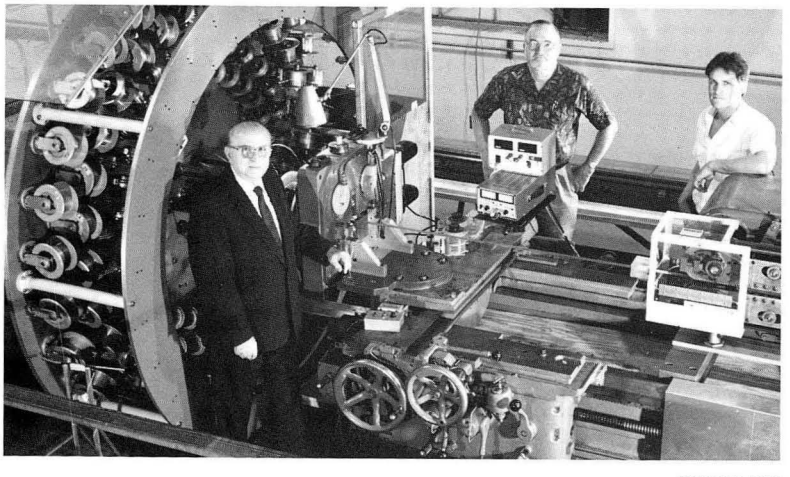

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Figure 4-8. This cabling machine (whose designer was recognized in 1992 with the DOE Technology Transfer Excellence Award) adds greatly to our experimental program. It can produce cable with as many as 60 strands—about a third again as many as other cabling machines. Cable can be produced in a variety of cross sections, including keystoned and rectangular. A close-up of a representative cable shows how thousands of filaments a few tens of μm in diameter, made of superconductor in a copper matrix, are braided into strands of wire, which are then formed into a cable.

many as 60 strands of superconducting wire. With this new equipment, we have been able to fabricate cables that are 30% wider and contain 25% more strands than the cable we developed in the late 1980s for the SSC dipole magnets. This 60-strand capability—nearly a third again as much as other machines—not only furthers cable manufacturing *per se*, but also, combined with the expert assistance of its operators, provides our magnet designers with additional flexibility in their choice of superconducting materials and cable designs. For example, we used it to make the rectangular 48-strand Nb_3Sn cable for D20, and, while D20 is assembled, we are continuing to use the machine to determine how best to cable this material.

High-T_c Superconductor at Low Temperature

Although most of the emphasis in the program has been placed on the traditional Bardeen-Cooper-Shockley (BCS) superconductors, we also have a promising investigation into so-called high-T_c superconductors. These materials, which are often used at liquid-helium temperatures in order to achieve high magnetic fields and maximum current density, might someday be useful for accelerator and other magnets. However, many challenges have to be overcome in order to turn them into useful engineering materials for devices such as accelerator magnets that must withstand great stress or must be built up into complicated shapes.

In an effort currently funded through the Laboratory-Directed Research and Development program (and interesting to at least one potential industrial partner), we are examining phase equilibria and microstructural texture in thick films of the bismuth oxide (BiSrCaCuO) family of compounds. In particular, we are studying ways of creating and preserving an aligned microstructure in the $Bi_2Sr_2Ca_1Cu_2O_2$ or "2212" phase throughout the phase transformations that occur during processing, both within the bismuth oxide compound and between it and its silver substrate. Earlier work indicated a J_c of greater than 1000 A/mm^2 for 2212 bismuth-oxide material. This figure seems to be on the same order as the J_c of NbTi conductor (albeit at a low magnetic field), although the sample was too short to be used in a magnet coil. Whether formed into tapes for windings or deposited onto surfaces as a coating (e.g., for superconducting rf cavities in accelerators), high-T_c compounds represent a promising area of development.

Following up on earlier short-sample tests, we have completed a vertical furnace to process tapes of significant length. In 1994 we expect to fabricate a solenoid using tapes of 2212 on a silver substrate.

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D. Dietderich and M. Walker, "Progress in the development of BSCCO-2212 superconducting," in *Proceedings* of the 5th U.S./Japan Workshop on High Tc Superconductor (Tsukuba, Japan, 1992); LBL-34662 (1992).

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Ion Beam Technology 5

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THE DESIGN, CONSTRUCTION, AND OPERATION OF PROTON and ion accelerators are the central legacies of AFRD's origins. Even though the Division is no longer operating a high-energy or nuclear-physics accelerator, its pool of expertise has not been lost to the research community—nor to industry. In addition to its responsibility for the "stand-down and secure" of the Bevalac, the new Ion Beam Technology Program unites scientists and engineers from the Bevalac, the MFE Program, and other operations so that they can work together on technology for nuclear science and for spinoff applications.

One of the highlights of the program is a planned investigation of accelerator technology for nuclear physics. There are two main thrusts, each leading to the development of integrated, application-oriented systems. One, which will be performed in collaboration with AFRD's Center for Beam Physics, is stochastic cooling of bunched, relativistic heavy-ion beams. This effort will culminate in the development of a practical beam-cooling system that can be operational in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory by the time of RHIC's commissioning as a user facility. Preliminary studies indicate that beam cooling, which makes the beam bunches more orderly and thus more intense for longer periods, will be important for maximizing the scientific productivity of RHIC.

The other main thrust of the nuclear physics program is the generation and acceleration of high-mass, low-charge-state heavy ion beams. This takes advantage of the expertise developed by AFRD as part of the Bevalac program, as well as ion-source knowledge that comes from fusion-energy research. No other U.S. accelerator R&D program is presently addressing this very-low-velocity, high-mass regime. The investigations will provide enabling technologies for one of the frontiers in the understanding of the nucleus.

Biomedical applications of accelerators, another legacy of the Bevalac and programs in which AFRD participated, are also being studied as part of the Ion Beam Technology Program. The energy-deposition phenomenon known as the Bragg peak allows doctors to use beams of protons and heavy ions as a "magic scalpel," killing certain kinds of tumors while sparing healthy tissues nearby. As proton therapy, in particular, continues taking its first steps out of the laboratory and into routine, hospital-based medical practice, continued development and transfer of the technologies will be needed.

In these and other areas, the Ion Beam Technology Program will benefit industry and serve as a showcase for DOE technology transfer. The performance, durability, and economic attractiveness of today's high-technology products are often predicated upon specialized materials and upon effective, affordable techniques for manufacturing them. The program's researchers, in close interdisciplinary collaboration with colleagues from LBL and elsewhere, investigate plasma and ion-beam techniques for modifying and synthesizing materials. Surface hardening of metal machinery parts, ion-beam lithography, and the synthesis of biocompatible coatings are a few of the current and potential spinoff applications for the beam and plasma techniques that originated in nuclear physics, fusion, and AFRD's other scientific pursuits.

Accelerator Technology for Nuclear Physics: Leveraging the Benefits of AFRD Expertise

Over a period spanning several decades, AFRD has built, enhanced, and operated several proton and heavy-ion accelerators, and has also contributed to other DOE programs, such as high energy physics and fusion energy, in which technologies relevant to nuclear physics were developed. The resulting body of knowledge and cadre of experienced scientists and engineers represent a sizable investment by DOE—an investment that can now be leveraged for the benefit of present and future programs in the DOE Division of Nuclear Physics and elsewhere. This program will provide diverse benefits to these projects and operations and to the user communities they support.

In this proposed initiative, the early work (fiscal years 1994-95) will emphasize modeling, simulation, and theoretical studies. Follow-on work (FY96 and beyond) will progress into hardware prototyping and testing. Future prospects include the study and development of ion sources to advance the technology of high-charge-state heavy-ion beams, and the integration of these sources with accelerating structures to best address the needs of the nuclear physics community.

Stochastic Heavy-Ion-Beam Cooling for RHIC

In the Relativistic Heavy Ion Collider, now under construction at Brookhaven National Laboratory (Figure 5-1), beams ranging in mass from protons to Au^{79+} will be injected, accelerated, and then stored for up to 10

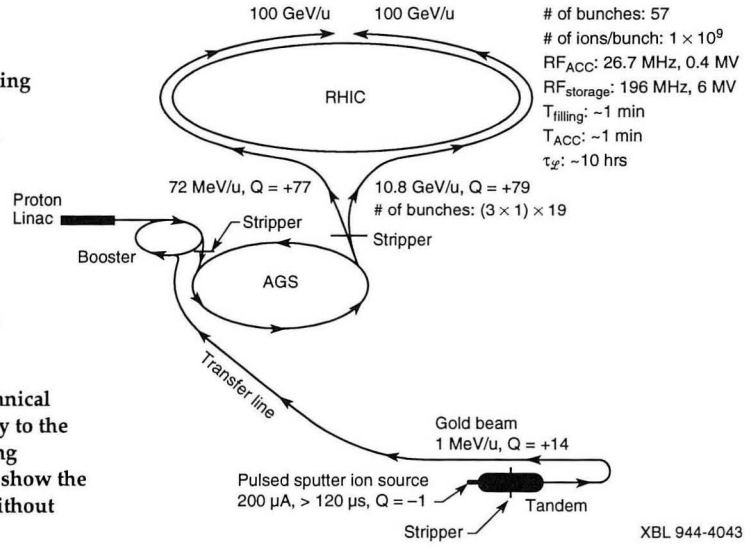
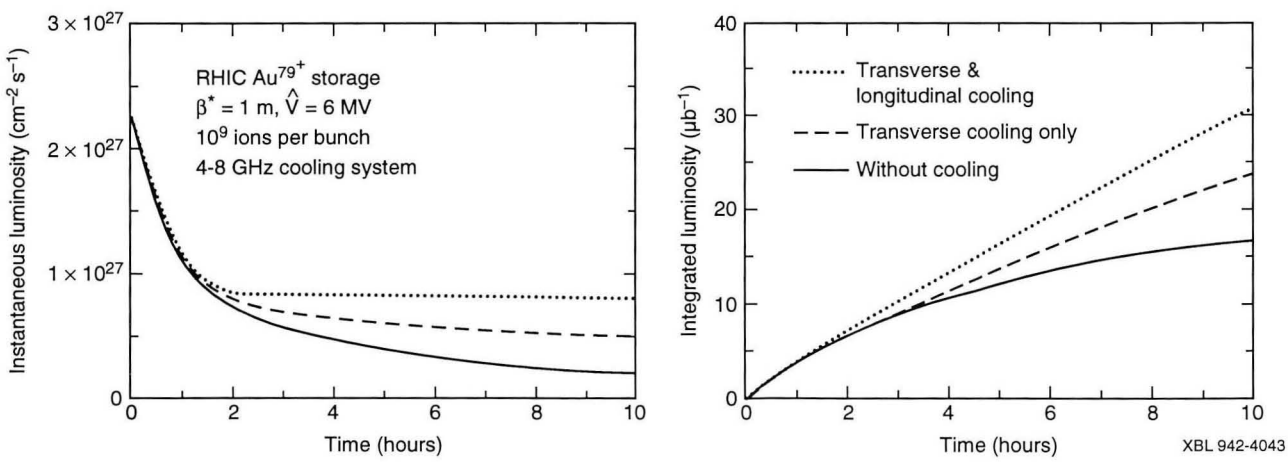


Figure 5-1. The Relativistic Heavy Ion Collider (RHIC), being built at Brookhaven National Laboratory, will be the forefront nuclear physics collider facility in the U.S. when it is commissioned in the late 1990s. Its mission is the study of nuclear phenomena in heavy ion collisions—in particular, the transition between nuclear matter and elementary particles via studies of the quark-gluon plasma in gold-on-gold collisions. Fully stripped gold beams will, however, be subject to various effects that degrade the luminosity and "luminosity lifetime" that are desired for physics experiments. AFRD is proposing a stochastic-cooling feedback system that acts on the beams simultaneously as they collide. The first step will be a technical feasibility study and conceptual design, leading eventually to the development of prototype bunched-beam stochastic cooling hardware. These plots, based on preliminary calculations, show the instantaneous and time-integrated luminosity with and without cooling.



hours for studies of nuclear phenomena in heavy-ion collisions. Gold-on-gold collisions will be of particular importance for studies of the quark-gluon plasma, which are directed towards an understanding of the transition between nuclear matter and elementary particles. For highly charged ions like gold, intrabeam Coulomb scattering can cause beam growth and particle loss, which lead in turn to rapid luminosity deterioration. We propose to study the application of stochastic beam cooling to address this concern.

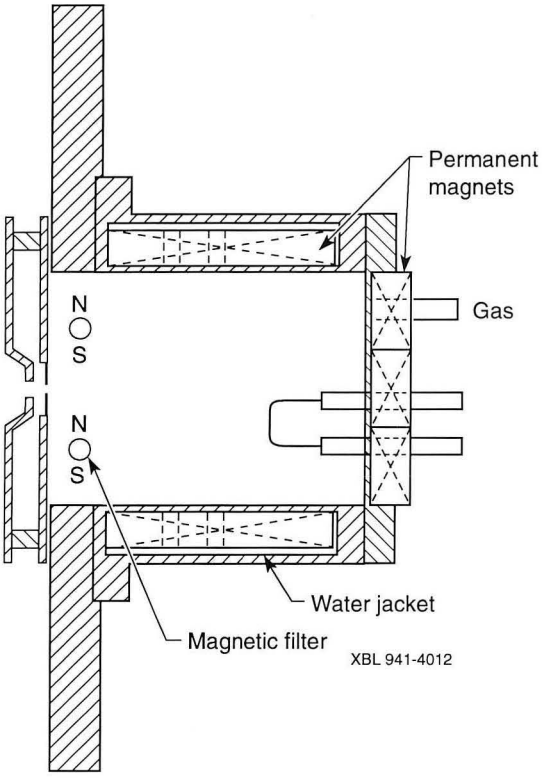
The RHIC design uses two rf systems. One provides acceleration; the other keeps the bunches short and almost constant in length during storage. In one scenario, to achieve the full design luminosity while cutting cost, the maximum available rf voltage in storage mode is limited to 6 MV. As experience is gained with the operation of the collider, more normal-conducting or possibly superconducting rf cavities could be added, up to a maximum total voltage of 16 MV. This voltage cap is required to minimize beam loss in the case of gold beams. Stochastic beam cooling might, however, prove more cost-effective.

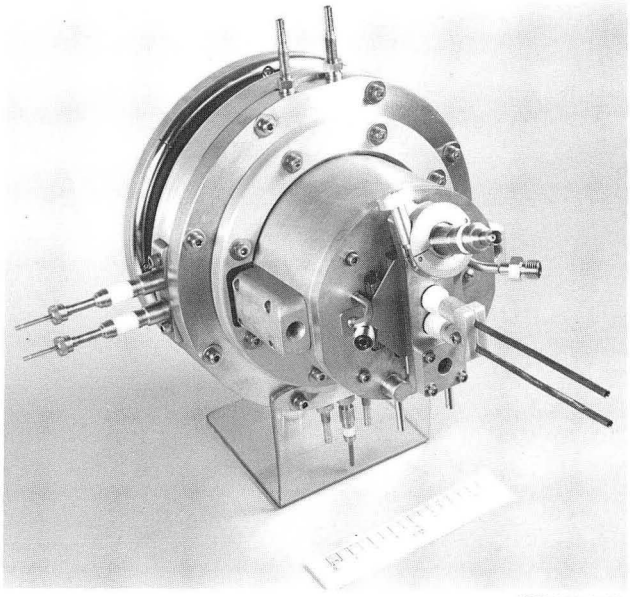
During the last decade, stochastic cooling has been developed into a practical means for reducing beam emittance and controlling the growth of momentum spread without loss of particles. In RHIC, it would keep the beam dimensions well within the magnet aperture and the rf-bucket height and would lengthen the luminosity lifetime. Estimates of the achievable damping rates for momentum cooling have been made, assuming a 4- to 8-GHz bandwidth. The use of momentum cooling, given 6 MV of storage rf, would reduce beam loss enough for a twofold luminosity gain at top energy. Further luminosity gains would require the addition of transverse cooling.

The LBL proposal establishes an R&D plan aimed at stochastic cooling of bunched beams in RHIC, especially for collider-mode running with gold beams. The initial effort (FY 1994 and 1995) emphasizes further study and conceptual design. The ultimate goal is to be operationally ready to implement such a system, should it prove necessary or desirable, after commissioning and operational start of the collider in late 1990s.

High-Efficiency, Low-q/A, Low-Beta Acceleration

The Accelerator Technology for Nuclear Physics initiative will also support the exploration of another nuclear science frontier: facilities that use secondary radioactive beams, such as an isospin beamline or dedicated isospin accelerator. We will use a variation of the volume-production ion source in which the plasma is confined by a multicusp magnetic field created by several permanent magnets (Figure 5-2). This is a well-proven technology that has been developed extensively for singly charged ions in LBL's fusion-energy research. The ion source will serve as the "front end" of a secondary-beams accelerator, that is, the part that ionizes the atoms produced by the primary accelerator's target. This kind of ion source is particularly well suited to providing low-charge-state heavy ions with very high efficiency. In this context, "efficiency" means that nearly 100% of the scarce radioactive products that diffuse from the production target area into the ion source are ionized and delivered to the secondary accelerator. The Tri-University Meson Facility (TRIUMF) in Canada has expressed a strong interest in testing the LBL ion source at their existing and proposed facilities.





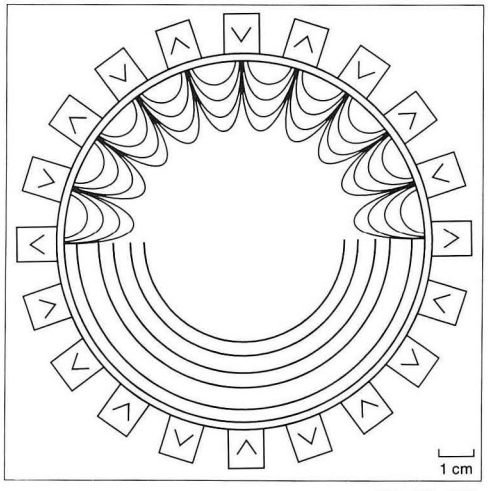
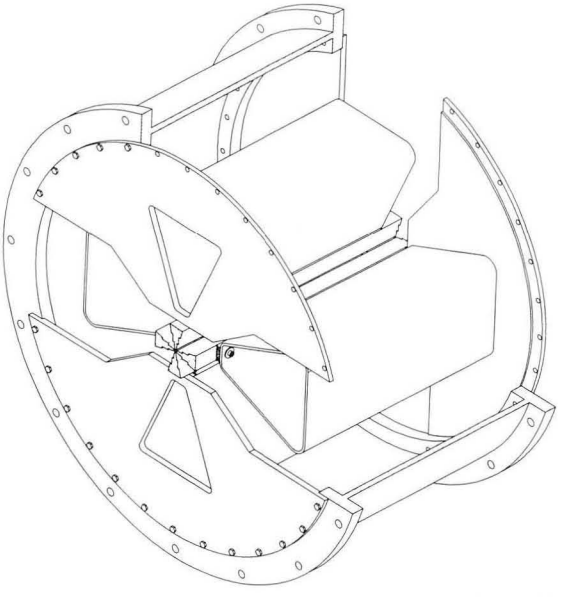


Figure 5-2. In the multicusp ion source, permanent magnets create a magnetic field to confine the plasma. In the computer plot of the symmetric magnetic field, the upper half shows the field contours corresponding to 10, 30, 100, and 300 G-cm, and the lower half shows the field intensity contours corresponding to 10, 30, 100, and 300 kG. In most of our recent designs, the plasma has been created and heated by a porcelain-coated rf antenna, which is extremely durable.

This part of the program also includes the development of a low-frequency rf quadrupole accelerator (RFQ) as an efficient first stage in post-acceleration. The secondary beams are extracted from the ion source with a very low velocity or beta ($b = v/c$) and charge-to-mass ratio (q/A). These parameter values present challenges in accelerator design, particularly if a 100% duty factor is required. To meet these challenges, we will investigate the use of either the split coaxial resonator or the four-rod RFQ concepts (Figure 5-3).

An early result of this ongoing program will be a "live" beam test (of the ion source only, not the RFQ) at TRIUMF's existing TISOL facility. It is planned that an ion source of this type will replace the on-line electron cyclotron resonance ion source currently being used there to produce radioactive beams. A second multicusp heavy-ion source may also be needed at TRIUMF to test prototype RFQ structures for their proposed ISAC facility.



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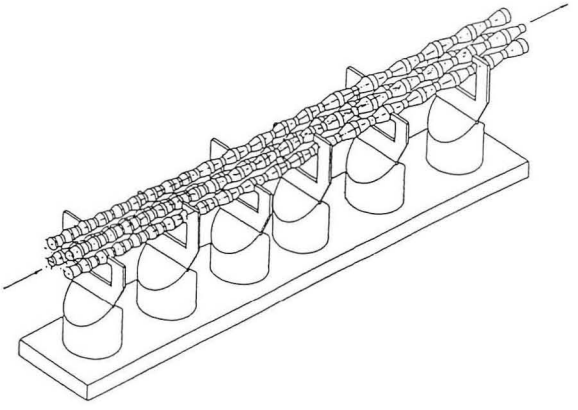

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Figure 5-3. In the Accelerator Technology for Nuclear Physics initiative, LBL's history of RFQ innovation will be applied to the ultraefficient acceleration of high-mass, low-charge-state ions moving at low speed. This presents a difficult set of challenges that will have to be overcome by future nuclear-isospin laboratories using the Isotope Separation On-Line (ISOL) target scheme. In this part of parameter space, accelerators must operate at low rf frequencies (10-25 MHz). At these frequencies, existing ambient-temperature RFQs would present severe mechanical engineering difficulties, as would superconducting RFQs. We will investigate capacitively loaded split coaxial resonator RFQs (left) and inductively loaded four-rod RFQs (right).

Future Directions

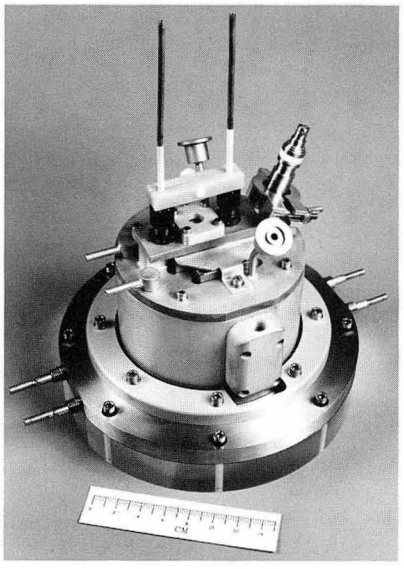
In FY 1994-95, our beam-cooling effort will concentrate on the initial feasibility study and conceptual design of the high-frequency stochastic cooling system for RHIC. Later years will focus on developing and fabricating electromagnetic devices that can monitor and correct intra-bunch phenomena at frequencies as high as 16 GHz. Attendant to the structure studies is the very important issue of developing algorithms (probably digital) for signal processing and pattern recognition. In addition to scientific and engineering studies and design, effort will be focused on fabrication of a single-channel, ~ 8 GHz monitor, finished in time for "day one" use in RHIC colliding beam operation.

Another important future topic is the extension of the ion source effort to technologies needed for *high*-charge-state heavy-ion production. This research might take any of several avenues, so initial efforts will be directed at preliminary evaluation of several promising ideas. Some of these involve electron cyclotron resonance (ECR) ion source technology, others use Electron Beam Ion Source (EBIS) technology, and still others are hybrids that combine these approaches with the multicusp source. We will continue our interactions with groups at the LBL 88-Inch Cyclotron and at Lawrence Livermore National Laboratory to explore ways of building on the past success of their efforts and incorporating recent advances in plasma physics developed by our own fusion program. We will integrate those ion-source efforts with the characteristics of an existing 200-MHz heavy-ion RFQ, which was used in the local injector of the now-decommissioned Bevalac, to test matching and acceleration. A primary goal of this effort is to develop advanced source technology suitable for upgrading facilities such as RHIC and the 88-Inch Cyclotron.

Meanwhile, an effort now under way will serve as an important precursor to the proposed activities: development of a negative-hydrogen-ion source and a properly matched low-energy beam transport system, designed and tested as part of an integrated system with an existing 400-MHz RFQ. This will address an outstanding problem in accelerator technology, namely, high-throughput extraction, matching, and pre-acceleration of negative hydrogen ions. Various beam-chopping schemes will also be studied. The results of this integrated project will be of immediate interest to various accelerator laboratories. The effort will also develop a beam-diagnostic test stand for use in the subsequent heavy-ion RFQ tests.

Besides these specific tasks, the program will serve as an ongoing resource for the DOE Division of Nuclear Physics, maintaining a support base of expertise that is relevant to other programs and projects such as the 88-Inch Cyclotron, various radioactive ion beam efforts, and other aspects of RHIC. A past example of such a contribution is the RFQ that LBL designed and fabricated for the Alternating Gradient Synchrotron injector upgrade at BNL. The program can also help improve the capabilities of foreign laboratories where scientists from the U.S. perform research. A past example of this is our contributions to the heavy ion injector for the CERN Super Proton Synchrotron, for which we designed and fabricated the RFQ. One especially promising opportunity is a possible expansion of our present collaborative efforts with TRIUMF using their TISOL facility.

Industrial interaction and technology transfer will also receive emphasis. The proposed nuclear physics program will operate administratively in a research environment that is actively involved with U.S. industry. There is considerable industrial interest in ion-beam technology for a variety of uses (Figure 5-4), such as surface modification, semiconductor fabrication, and the generation of small quantities of neutrons. In addition to the immediate benefit of establishing relationships with companies that can fabricate special industrial research equipment for Division of Nuclear Physics projects, the program will serve as a model for DOE-industry interaction aimed at innovative products and processes that help to bolster U.S. competitiveness.



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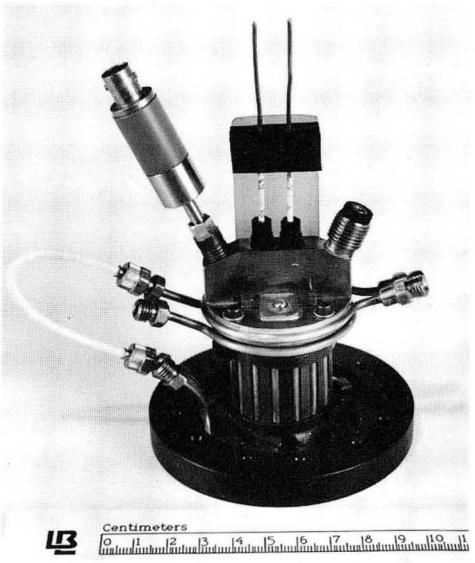

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Figure 5-4. Ion source development in the Ion Beam Technology Program benefits both science and industry. We are finalizing plans to test the 10-cm-diameter H^+ source (*left*) at a nuclear physics accelerator in the Paul Scheerer Institute in Villigen, Switzerland. We also developed a small (2.5 cm diameter) rf-driven multicusp source in 1993 on behalf of Sandia National Laboratory, as shown at *right*. Operated with a hydrogen discharge, the source yielded pulsed proton beams of greater than 80% purity at a current density of more than 650 mA/cm^2. It will be used in downhole neutron generation for oil-well logging and also has potential biomedical applications, such as boron neutron capture therapy. Other related R&D highlights of 1993 included a subcompact mass separator that greatly reduces the accompanying electron output, as well as low-energy beam transport optics that can match the beam properly into an RFQ accelerator afterwards.

Biomedical Accelerators: Proton Therapy for Cost-Effective Health Care

The use of accelerated ion beams to reach tumors precisely and in three dimensions has a long history at LBL. Over four and a half decades, radiotherapy with protons has become widely accepted for the treatment of an ever-increasing variety of tumors. LBL accelerator scientists and their life-sciences colleagues have made pioneering contributions to the design of special-purpose accelerators dedicated to medical use. Although the closure of the Bevalac ended LBL's ability to treat patients onsite, the work of these researchers may be just beginning.

Interest in particle therapy is burgeoning worldwide, and commercialization of basic technologies is beginning. However, to take full advantage of the potential of particle therapy, transfer of many advanced technologies, such as those developed by LBL (Figure 5-5), will be necessary, as will further technical advances. These LBL resources are necessary to ensure the immediate and ongoing competitiveness of U.S. industry in this area. The challenges ahead include:

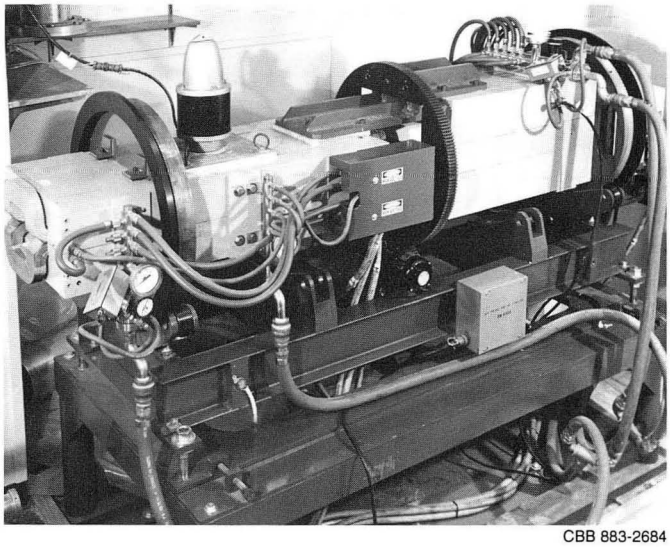

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Figure 5-5. An example of the technology advancements from the Bevalac biomedical program is the Raster Scanner Beam Delivery System. The Raster Scanner, commissioned for clinical use in 1991, was recognized with an R&D 100 award from Research and Development Magazine in 1992 as one of the year's 100 most significant innovations. It scans the rigid heavy-ion beam back and forth much like the electron beam in a television's picture tube. Biological measurements in the proximal peak of the field, using neon ions, showed results at least as good as those of the "wobbler" beam-delivery system, itself a previous R&D 100 winner. Another example of the precision apparatus needed is this patient positioner for the UC Davis eye treatment center, being demonstrated by its designer and builder, LBL mechanical technician Mario Cepeda. One of the challenges is to keep the critical R&D teams together in the wake of the Bevalac shutdown so that medical-accelerator programs can derive the greatest possible benefit from the expertise developed at the Bevalac.

- *Improvements in accelerator technologies applicable to existing and future medical accelerator facilities, such as ion sources, conditioning cavities, energy switching, beam tuning to achieve high intensity, uniform beam extraction, and controlled intensity modulation for beam scanning.*
- *Development of algorithms for modeling particle beams and optimizing dose distribution (three-dimensional conformal therapy delivery) to maximize biological and/or therapeutic gains.*
- *Development of on-line dosimetry and of reconstruction of three-dimensional dose distribution through the use of high-resolution detectors and electronics.*

Although the plans for building a dedicated proton therapy facility at the University of California, Davis, Medical Center have been shelved, the group has been interacting with colleagues at Loma Linda University Medical Center (home of the first hospital-based proton therapy facility) and the Crocker Cyclotron at UC Davis, and will play an important role in the Massachusetts General Hospital proton therapy project.

Progress in Facility Design and Construction

Early in 1994, we completed a proton therapy study funded by the National Cancer Institute. Encompassing technical and performance specifications but also functional and space needs and architectural concepts, the study performed much of the groundwork for a proton therapy facility. Unfortunately, the UC Davis project on which the study was focused did not receive construction funding, so the study will not be directly followed up with a new West Coast proton therapy facility.

Interest remains strong elsewhere. The National Cancer Institute has agreed to fund a proton therapy facility at the Massachusetts General Hospital in Boston. The hospital has awarded the construction contract to IBA, a Belgian cyclotron manufacturer, working in conjunction with General Atomics in San Diego. General Atomics is currently negotiating a cooperative research and development agreement with LBL to take advantage of the beam-delivery and instrumentation expertise developed by our biomedical operations group. Members of our group are continually receiving invitations to speak at meetings and to consult with interested groups outside the U.S. In Europe, Asia, and Africa, several new facilities are at various stages of planning, construction, or commissioning.

A great deal of LBL expertise and technology has also been transferred to a new therapy center at the Crocker Nuclear Laboratory on the UC Davis campus, the new home of the Bevalac eye-treatment program. The laboratory operates a direct descendant of one of E.O. Lawrence's original machines, the Crocker 60-Inch Cyclotron, which was moved to Davis from Lawrence's laboratory on the Berkeley campus. Its 68-MeV proton beams are ideal for the treatment of shallow tumors, such as ocular melanomas.

Our group, working closely with the Crocker staff, has designed a precisely controlled radiation field with a 3.5 cm range specifically for eye treatments. A new treatment room has been built and furnished with electronic equipment loaned from the Bevalac biomedical program, and is now ready for patients. A special patient positioner has been fabricated by the LBL group to ensure the necessary combination of accuracy and flexibility in holding the patient during treatment. The ocular melanoma program, to be administered by the Radiation Oncology Department of the University of California, San Francisco, is expected to treat up to 40 patients per year.

Plasma Applications: Using Accelerator Technology for Materials Modification and Synthesis

The performance, durability, and economic attractiveness of today's high-technology products are often predicated upon specialized materials and upon effective, affordable techniques for manufacturing them. A group within the Ion Beam Technology Program, in close interdisciplinary collaboration with colleagues from LBL (most notably the Materials Sciences Division and the Energy and Environment Division) and elsewhere, investigates plasma and ion-beam techniques for modifying and synthesizing materials.

The program has four parts: research on techniques for depositing metallic thin films and multilayers using metal-plasma guns; development and use of metal-vapor vacuum arc ion sources for ion implantation; modification of surfaces through metal-plasma immersion (MPI) techniques; and attempts to deposit industrially useful diamond coatings on surfaces. Most of our investigations are deeply collaborative. A broad-based community of researchers in materials science and allied fields comes from other LBL divisions, other laboratories and universities, and private industry to take advantage of our expertise and facilities.

An example of this collaboration is a planned project that will explore the vacuum spark ion source as a generator of highly stripped ions. The project could result in a novel kind of compact, inexpensive multi-MeV ion implanter, replacing implanters that are quite bulky and cost many millions of dollars.

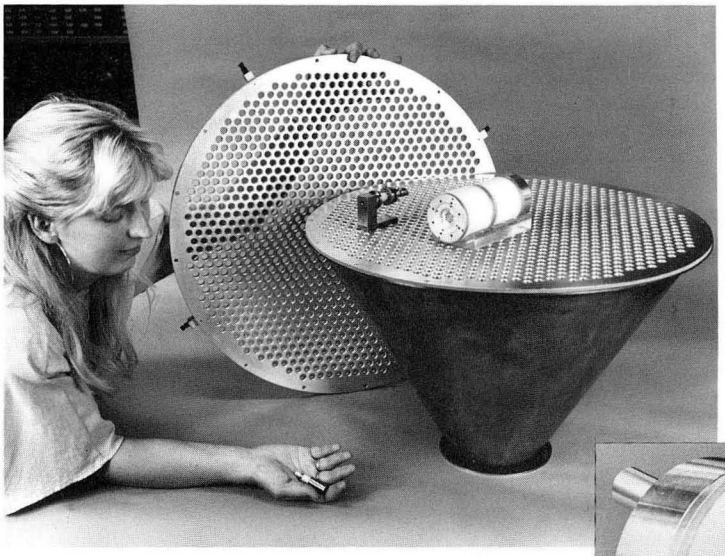
Metallic Thin Films and Multilayers

Since 1991, we have been exploring applications of a technique, which we developed, for synthesizing and modifying materials with metal plasma guns. The broadly collaborative three-year program, supported by the Office of Basic Energy Sciences, came to a successful conclusion in 1993. By adding gaseous species to the plasma, we can deposit not only metals, but also ceramics, oxides, and so forth. The result is a powerful and versatile technique for fabricating metallic thin films and multilayers. We investigated a number of possible applications, including catalytic surfaces, magneto-optical recording media, multilayer x-ray mirrors, and films of various metals and metal oxides. The technique is also useful as a tool for fundamental research in surface science.

Research highlights of 1993 included fabrication of high-T_c superconducting thin films (in collaboration with the University of California, San Diego) and the fabrication and examination of thin films of amorphous diamond. We also enhanced our test facility with highly efficient plasma ducts for "filtering" vacuum-arc metal plasmas, and added long-pulse, high-duty-cycle plasma guns to our array of equipment. Formal arrangements to commercialize these technologies are being negotiated.

Vacuum Arc Ion Source Development and Applications

In 1993, we continued the development of ion sources based on the metal-vapor vacuum arc principle, along with their use for high-dose metal-ion implantation. Our stable of implantation sources was enhanced by a "Leva" (low energy vacuum arc) metal ion source. The fist-sized device, shown in Figure 5-6, is based on the principles of our R&D 100-winning Metal Vapor Vacuum Arc (Mevva) ion source. It produces pulsed, high-current metal ion beams in the energy range of a few hundred to ten thousand eV. Applications include materials science research and injection into electron-beam ion sources for physics applications.



CBB 926-5122

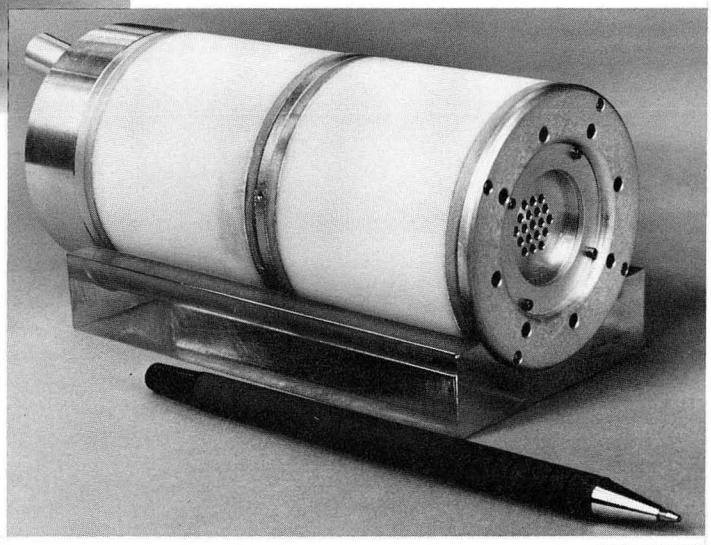


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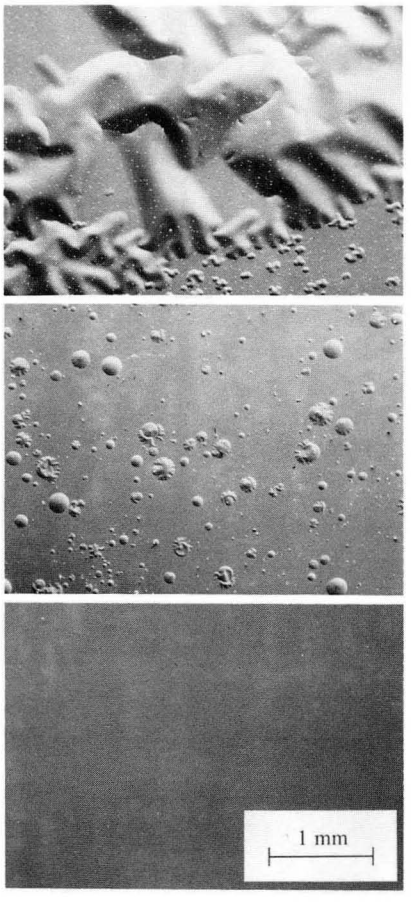
Figure 5-6. This Leva (right), or low-energy vacuum arc ion source, was added to our stable of implantation devices in 1993. It provides 10-100 mA beams of metal ions at energies of a few hundred to several thousand eV. The Leva joins the R&D 100 award-winning DC Broad-Beam High-Current Metal Ion Source, whose 50-cm-diameter electrodes are shown with previous generations of our metal-vapor vacuum arc ion source technology, including a subminiature embodiment. The objectives of our ion-source development program are the cost-effective treatment of large objects and of small objects with complicated geometries, such as the insides of pipes.

Metal Plasma Immersion (MPI) Surface Modification

In this technique, which also takes advantage of our plasma-gun technology, the kinetic energy of a plume of metal plasma is controlled by adjusting a negative bias pulse applied to the target. Thus, the incident plasma can be deposited on the target surface as a film or implanted energetically below the surface. Among the features of this technique are the abilitiy to create atomically mixed interfaces and to "stitch" a deposited layer into the substrate or into another layer for greater durability (Figure 5-7).

Earlier, in the first phase of a program sponsored by the Electric Power Research Institute, we studied the fundamental materials-science aspects of the technique and learned to control these effects by adjusting the parameters of the incoming plasma plumes, the voltage of the bias pulses, and the phase relationship between the two. In 1993, we began the second phase of the program. The goal of this ongoing effort is to scale up the technology and demonstrate its suitability to real-world industrial uses. We have processed surfaces that are 1000 cm^2 in size, representing a scale-up from the Phase I accomplishments by about three orders of magnitude. We hope to demonstrate MPI surface modification of several-square-meter surfaces at reasonable speed, as well as modification in difficult geometries, such as the insides of long, narrow pipes.



XBB 937-5035

Figure 5-7. The benefits of atomically "stitching" a thin film onto its substrate are graphically demonstrated by these photomicrographs. Thousand-angstrom films of Y-Ba-Cu/Ag high-T_c superconductor were deposited on a silver substrate, with a buffer layer of aluminum oxide in between. The image at *top* shows the kind of delamination that can occur when films are deposited without "stitching." The *center* image shows the results of deposition at an intermediate energy using our MPI technique, and the *bottom* image shows the problem completely eliminated with a well-chosen higher energy that atomically mixes the film interfaces.

Diamond Synthesis

Together with the Mechanical Engineering Department of the University of California, Berkeley, and with LBL's Materials Sciences Division, we continue to investigate the synthesis of polycrystalline diamond thin films on substrates that are of technological value. A suitable substrate is immersed in a microwave-produced hydrogen/methane plasma, and diamond films grow from the plasma state by chemical vapor deposition. The goal is to develop industrially applicable techniques for depositing diamond thin films onto large, three-dimensional substrates. We are now able to routinely synthesize high-quality films of polycrystalline diamond that are one to several μm thick and a few square centimeters in area.

The formation of very thin films requires a very high nucleation density. We are also studying ways to bond the film to the substrate more strongly—an important requirement for moving such diamond films out of the laboratory and into applications. One application we are pursuing is the use of ultrathin (~200-Å) diamond-film coatings for protecting the magnetic "platters" used in computer hard disks instead of the 1000-Å coatings in use today. This would permit greater information-storage density, which is proportional to the distance between the flying read/write head and the disk. The work has resulted in a number of important discoveries related to low-temperature pretreatment methods that enhance nucleation; a patent has been applied for.

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