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Report of the
Workshop on Scientific Opportunities for
Infrared Free-Electron Lasers
Volume I

Lawrence Berkeley Laboratory
Berkeley, California
October 31–November 1, 1988

February 1989

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LBL-26783
Vol. I

Report of the Workshop on Scientific Opportunities for Infrared Free-Electron Lasers

Materials and Chemical Sciences Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

February, 1989

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Report of the

Workshop on Scientific Opportunities for

Infrared Free-Electron Lasers

February, 1989

Sponsored by the Lawrence Berkeley Laboratory
and
the Brookhaven National Laboratory

Organizing Committee

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Foreword

The workshop on Scientific Opportunities for Infrared Free-electron Lasers was held on October 31-November 1, 1988 in Berkeley, California. The objective of the workshop was to bring together chemists, physicists, device physicists and engineers to review the current status of IRFEL technology and to discuss the scientific opportunities that will emerge because of the unique characteristics of these devices. The contents of this report serve as a fair testimony that the objective was accomplished in excellent form.

This report on the workshop consists of two volumes: the working group reports and the workshop summary form the major part of Volume I, and a copy of the viewgraphs used by all the speakers is in Volume II. In the process of preparing this report a decision was made to collect the parameters of existing IRFELs and of facilities that are under construction. This information is included as Appendix III of Vol. I.

On behalf of the workshop Organizing Committee and my co-chairs Claudio Pelligrini and Kwang-Je Kim, I would like to thank the speakers again for their stimulating presentations. The chairmen of the working groups, Rick Woodin (chemistry), Ron Shen (surface and condensed matter physics), and Charlie Brau (FEL technology), worked hard to draft their respective and excellent reports. Bill O'Connor and Ann Weightman did an outstanding job in co-ordinating the workshop. Darlene Gonzales' exceptionally skillful assistance simplified the job of preparing this report. Funding by the Department of Energy, Office of Energy Research through the Lawrence Berkeley Laboratory and the Brookhaven National Laboratory is gratefully acknowledged.

Berkeley, California
February, 1989

A.H. Kung
Co-chairman

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Introduction and Summary

With the characteristics of very broad wavelength coverage, high average and peak power, and variable time structure, the free-electron laser (FEL) shows great promise of having a major impact in many areas of science and technology—an impact similar to those of the ultrahigh vacuum system, the computer, and the conventional laser. As a technology, the FEL has reached an advanced development stage. There are several FELs in operation and several more in the design stage. However, as a tool for scientific research and applications it is still very much in its infancy. Now is an appropriate time to define the FELs that are needed to perform the science that should and can be done, particularly with the characteristics that are unique to FELs.

A workshop co-sponsored by Lawrence Berkeley Laboratory and Brookhaven National Laboratory was held on October 31-November 1, 1988 with this goal in mind. The workshop focused on the infrared region where there is a scarcity of intense sources and where the FEL technology is most mature. The purposes of the workshop were: (1) to review the performance of existing infrared FELs; (2) to identify the significant scientific experiments that could be done, as well as those that are being done, with these FELs; and (3) to define the FEL characteristics that are required to realize these possibilities and how they can be achieved.

More than 50 scientists from universities, national laboratories, and industry representing the fields of chemistry, surface science, condensed matter physics, and FEL device physicists from most of the major FEL facilities in this country gathered for two days of intense presentations and discussions. At the conclusion of the workshop it was clear that important science for much of the infrared region remains to be explored, and that suitable infrared FELs can be constructed to meet the needs of these explorations.

In chemistry, intense infrared beams can be used to manipulate molecular vibrations and chemical reactions in both the condensed and the gas phases. Multiphoton excitation and dissociation at wavelengths previously unattainable can be used to study intramolecular vibrational energy transfer and perform mode-selective chemistry. The infrared FEL can produce and probe radicals and reactive transients via single photon or multiphoton processes. Vibrational photochemistry becomes possible for a large variety of systems. Organic free radicals, inorganic

intermediates, organometallic intermediates, metal and other molecular clusters, Van der Waals molecules—all of which are related to material syntheses, combustion, or energy storage processes—can be studied. The IRFEL will afford access to a significantly wider range of species across the periodic table than is available now.

In the surface sciences, the broad tunability coupled with picosecond time resolution and high peak power of the infrared FEL (IRFEL) will open doors to quantitative understanding of many surface phenomena. The vibrational mode of a surface layer, or of an adsorbed molecule, can be selectively excited to saturation. The dynamics of the system after excitation can then be followed. Time dependent redistribution of surface molecules, diffusion on surfaces, desorption, and photon-induced surface reaction can all be studied using pump-probe techniques involving the IRFEL and a second light source, which can be another FEL, a conventional laser, or a synchrotron radiation source. Conventional surface spectroscopy will become routine with higher sensitivity and better signal-to-noise ratio. Improved understanding of surface phenomena could lead to more efficient energy conversion systems, more efficient catalytic processes, better preparation of material surfaces, and reduction of surface erosion.

The high brightness of the IRFEL will make new studies in semiconductor physics possible. Measurement of high T_c superconductor bandgaps requires the high intensity of the FEL. Two dimensional electron gas dynamics at metal insulator-semiconductor junctions can be probed. Carrier dynamics and spectroscopic of deep impurity states can be studied. Quantitative understanding of these problems has a very high priority in the electronics industry.

The IRFEL is the only laser that can provide intense, continuously tunable, infrared radiation. This facilitates energy relaxation studies in solids where important features of how solids take up energy are missing. Accurate and complete infrared absorption data for molecules even as simple as water are not available. The IRFEL will rectify the problem. Studies of quantum wells, superlattices, amorphous materials, and magnetic materials could all use the IRFEL.

The development of a new technology will very often stimulate the research and development of related, but previously unexplored, technologies. In this case, diagnostics and applications of infrared and far-infrared FEL pulses will require the

development of ultrafast detectors, fast pulse switching, infrared cavity dumping schemes, highly sensitive infrared photomultipliers, and accurate energy and wavelength calibration techniques.

Participants of the workshop developed a set of IRFEL parameters required to accomplish the science that was discussed. The IRFEL pulses should be transform-limited with a frequency stability at about 10% of the frequency bandwidth. The ideal tuning range is from 2 to 200 microns, but, for many experiments, a range of 3 to 50 microns will suffice. Intensity stability of better than 1%, or in some special cases 0.1% is desired. For the dynamics studies, sub-picosecond pulses are desirable while for the spectroscopic applications the pulses should be as long as possible. Desired micropulse energy is >100 microjoules. Average power should be at least several watts. The ability to select a single micropulse from a macropulse train is important. There are significant advantages for the IRFEL to operate synchronously with synchrotron sources and conventional lasers or to operate with dual wavelength outputs.

It was concluded that at least two types of IRFELs are required to provide the complete wavelength coverage: a linac based machine for 2 to 100 microns and a Van de Graff accelerator machine for the far-infrared. More than one machine of each type should be available to satisfy the variety of different users. Frequency stability of the IRFEL is directly related to the energy stability of the electron beam from the accelerator. Room temperature RF-linac based IRFELs are close to achieving a performance that will permit most of the science to proceed. They can meet most of the power and pulse duration requirements, but the frequency stability, a very important criterion, must be improved. Superconducting linacs offer a better potential of meeting this stringent requirement but at a sacrifice on single pulse power and will cost more than the room temperature linacs.

The consensus of the workshop is that an IRFEL that has all the required characteristics can be built, perhaps in a few years time, if funding is available. It is anticipated that it will create the same level of excitement that pulsed visible and near-IR lasers have generated and will offer great opportunities for many new and significant scientific accomplishments.

The following Sections consist of reports prepared by the participating working groups. A summary of the performance and design characteristics of

IRFELs based on information collected by the Technology group appears in Appendix III. The speakers' vugraphs are compiled as Appendix IV and distributed in a separate volume of the report.

Chemistry Working Group Report *

Ideally, chemists want a tunable laser with enough energy to drive to saturation molecules in the gas phase and in the condensed phase, in a time scale of several femtoseconds to continuous wave. It will then be possible to manipulate molecules in such a way that particular chemical reactions work well. To achieve these goals, it will be preferable to drive vibrational resonances as hard and as cleverly as possible, and in as many different conditions as possible: gases, liquids, solids and surfaces. Having the IRFEL (or several of them) will be a major step closer to meeting these goals.

The group concluded that the major benefits of IRFELs flow from their broad, continuous tunability throughout the infrared spectrum (ideally 1-50 μm). Wavelength availability will be important for all classes of experiments; some will be traditional experiments extended to currently unobtainable wavelength regions (e.g., transient flash spectroscopy on the microsecond timescale), others will be entirely new with the IRFELs (e.g., picosecond infrared multiple photon dissociation).

A second conclusion of the group is that it is unlikely that a single IRFEL will be able to satisfy the needs of all chemistry experiments. Depending upon the specific application, very short pulses may be desired (picoseconds) and the resulting broad bandwidth will be acceptable. Alternatively, narrow bandwidth may be necessary and the experiment will necessarily be arranged to deal with longer pulses (microseconds to cw). The applicable chemistry timescales vary from subpicosecond for events that happen in a few molecular vibrations to seconds for slow kinetics. In some cases, the experimenter can arrange the experiment for a desired timescale (e.g., bimolecular chemistry) whereas Nature sets the timescale for other processes (intramolecular energy flow).

Several experiments can be done on currently available single color devices. Pump-probe experiments are envisioned as a necessary future capability and may take the form of FEL/conventional laser, FEL/synchrotron, or FEL/FEL configurations. The following provides details of the discussions of this group.

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* Chemistry Group Members: R.L. Woodin (Chairman), D.J. Bamford, A. Kung, C.B. Moore, J.H. Mulvey, E. Weitz, and B.E. Wurfel.

A. Chemistry Studies that can be done with an IRFEL

(1) Probing Reactive Transients

Chemistry is often dominated, not by the easily observable stable molecules, but rather by transient, energetic and usually reactive intermediates. Lifetimes for these intermediates range from picoseconds for molecules with selected internal state distributions and for cage recombinations in the liquid phase, to nanoseconds or microseconds for species which may unimolecularly decompose, or to microseconds or milliseconds for species which undergo bimolecular reactions. Infrared spectroscopy is particularly suitable for extracting structural information about these intermediates. Currently available lasers in the infrared include primarily the CO_2 laser (900-1100 cm^{-1}), CO laser (2000 cm^{-1}), optical parametric oscillators (2500-4000 cm^{-1}), Raman shift lasers (1000-10000 cm^{-1}) and diode lasers. These suffer from lack of continuous tunability, commercial availability, stability, tuning range, or combinations of the above. An ideal IRFEL would not suffer from these problems. Tunability of the IRFEL is the key to success here.

Specific examples of important intermediates and their relevance are:

- Organic free radicals—combustion chemistry, soot formation, pyrolysis chemistry;
- Inorganic free radicals—materials processing, semiconductor and microelectronics processing;
- Organometallic intermediates—homogeneous catalysis, C-H activation,
- Van der Waals clusters;
- Metal clusters and adsorbates on clusters.

(2) Vibrational Photochemistry

Adding short duration to the tunability of pulses now affords opportunities to induce chemical reactions either by single photon infrared photochemistry or by multiple photon processes. Additionally, picosecond pulses will allow processes on the 1-1000 picosecond timescale to be studied.

Current devices with 10 μJ micropulse energies and diffraction limited focusing should produce fluences necessary for infrared multiple photon dissociation, typically 1 J cm^{-2}. These fluences are currently available from

conventional picosecond lasers, but at low repetition rate and limited wavelength coverage. Also, the necessary fluence is achieved in an extremely small volume. Few products are produced. Thus, it is unlikely that the products will be detectable in a low repetition rate experiment (e.g., 10 Hz). The high micropulse repetition rate available for an IRFEL will allow enough products to be made so that they can be detected, either by conventional analytical techniques (gas chromatography) or by a real-time probe such as multiphoton ionization. In this case, experiments can be performed which are not possible with conventional lasers. With the ultra short pulses infrared excitation experiments at high pressures (where excitation competes with high collisional deactivation rates) will be possible. Excitation experiments analogous to Rabinovitch's chemical activation/collisional clock experiment will also be possible. This will allow probing for the possibility of effecting selective chemistry on the time scale of fast reactions and intramolecular vibrational relaxation.

(3) Selective Excitation and Vibrational Energy Redistribution

The IRFEL will selectively populate a specific mode. The transfer of energy from this vibrational mode to another, either intramolecular or intermolecular, can be followed. This is one of the most important and fundamental processes in chemical reactions.

(4) Dissociation Spectroscopy

For systems in which there are sensitive particle detectors (Channeltrons, particle multipliers) infrared multiphoton dissociation can be used as a spectroscopic probe for long-lived species in densities low enough that absorption spectroscopy cannot be performed. The large number of micropulses in a macropulse of the FEL is a definite advantage. Examples in which this has been demonstrated using CO_2 laser radiation are dissociation of methanol from iron clusters in a molecular beam and ions in an ion cyclotron resonance trap. In these cases, this is virtually the only method for obtaining vibrational spectra and hence structural information about these species.

(5) Two-Color Experiments

A majority of the applications of the IRFEL will involve two-color experiments where the IRFEL is used as a pump to induce chemistry or prepare a particular molecular state while a second laser (well synchronized with the first) is added as a probe at a later time. In particular, the second pulses is used for infrared or visible absorption to induce fluorescence or for photoionization. Picosecond pulses with commensurate low temporal jitter will allow intramolecular kinetics (or bimolecular kinetics in liquids) to be followed on the picosecond time scale. Selecting individual pulses or tailoring the pulse separation will allow slower kinetics to be followed. An advantage of utilizing FELs with multiple wavelength outputs will be the high repetition rate of the devices. A very attractive possibility is to use the UV or VUV pulses from a synchrotron source as the probe radiation. Conversely, the IRFEL may be used as the probe pulse in situations where a conventional low repetition rate laser can be slaved to the IRFEL.

(6) Materials Processing

Laser driven syntheses of small, pure, equi-axed powders have been demonstrated particularly for silicon carbide, silicon nitride, titanium dioxide, and iron carbide catalysts. A severe limitation in these gas-phase syntheses is finding precursor molecules with absorption bands in the wavelength region of available high power CW lasers (generally CO_2 lasers). High average power IRFELs would ultimately allow materials to be synthesized from across a much wider range of the periodic table.

B. Best Candidate Experiments for Existing IRFELs

Three experiments are essentially "ready to go" on current devices.

1. Infrared multiple photon dissociation. Available peak intensities and fluences should be sufficient for initial experiments (a) to determine whether multiphoton dissociation is feasible and (b) to repeat the Rabinovitch collisional clock experiment with short infrared pulses.
2. Infrared fluorescence. Time averaged infrared fluorescence can be used to follow internal vibrational energy flow within a molecule by tuning the IRFEL to a specific vibrational mode and observing the spectrum of infrared emission. As different modes are populated the emission

spectrum will change. If the available IRFEL radiation can be used to trigger a fast optical shutter, then the time evolution of the emission spectrum can be obtained. Photon-counting IR detectors are essential here.

3. Materials synthesis. The current average powers of 10-30 watts are sufficient for initial experiments on new materials synthesis. Conventional experiments utilize 50-100 watt lasers.

C. Desired Characteristics of Future FEL Devices

1. Wavelength: Optimum tunability from 1-50 μm. Many experiments can be carried out with 2-15 μm tunability, but many important metal-ligand frequencies are excluded by not having wavelengths available beyond 15 μm.
2. Bandwidth: Transform limited at whatever pulse width is appropriate for the experiment. This will vary depending upon the specifics of the experiment. A particular concern is frequency stability in high resolution experiments.
3. Frequency stability: Considered very important for high resolution experiments. For short pulse/low resolution experiments, 0.1% is adequate. However, for high resolution experiments, it should be <10% of the bandwidth.
4. Intensity stability: Not considered as critical as frequency stability. Operation typical of conventional pulsed lasers required 1%, and 0.1% desired.
5. Peak energy: Current 10 μJ micropulse energies are marginal, but a factor of ten or more is preferable .
6. Average power: Current 10-30 W is usable, but for peak energy, an additional factor of ten is desirable (particularly for materials processing).
7. Time structure: While macropulses and trains of micropulses are acceptable for long-time and short-time applications, for intermediate (nanosecond-microsecond) time regimes it will be desirable to select out one pulse at longer time intervals. If combined with cavity dumping, this may increase peak pulse energy.
8. Shorter pulse length: Sub-picosecond pulse lengths are desired for liquid phase dynamic studies, for intramolecular energy transfer, and for generation of continuum radiation for broad-band time-resolved spectroscopy.

D. Support Equipment for User Facility

1. Support lasers for laser-induced fluorescence and multiphoton ionization detection.
2. Infrared spectrometer to determine initial tuning requirements.
3. User control of laser frequency.
4. Adequate experimental space: (1) for setup, (2) for running experiments, and (3) for several experiments to be on-line simultaneously to make maximum utilization of available radiation.
5. Synchrotron radiation capability with the FEL.
6. Sensitive, infrared optical multichannel analyzer (particularly for IR fluorescence measurements).
7. Standard infrared detectors.
8. Standard signal processing electronics (transient averagers, gated integrators, synchronous amplifiers, standard amplifiers, computer data processing, hardcopy data output).

Condensed Matter and Surface Applications **
Working Group Report

As in the case of ordinary lasers, two types of IRFELs generally suit two different kinds of experiments. CW or quasi-CW IRFELs, with very narrow linewidth, are useful for high-resolution spectroscopic work. Pulsed IRFELs with high peak power and short pulsewidth are useful for nonlinear spectroscopy and transient or dynamic studies. In condensed matter, the width of an absorption band is often fairly broad. High-resolution spectroscopy is seldom needed, although in special cases with impurities and defects in solids, such as the work of Sievers, it is applicable and has yielded many interesting and exciting results. The group focused its discussion on the applications of FELs with short pulses.

Two areas in condensed matter physics are identified that will benefit significantly from an FEL: surface science and semiconductor physics. Each area is considered separately, focusing on experiments that are difficult to carry out without the FEL.

1). Surface Science: A tunable infrared laser with high peak power and ultrashort pulsewidth allows selective excitation of a surface mode or of an adsorbed molecule to saturation in an extremely short time duration. Other methods can then be used to extract a wealth of information about the surface. For example, surface vibrational spectroscopy using the recently developed sum-frequency up-conversion generation technique can be used to track a particular adsorbed molecular species in time. It should then be possible to see the time variation of the distribution of different molecular species on a surface, follow the diffusion of a certain specie on a surface, monitor a surface reaction with the possibility of identifying the intermediate species, and study other surface dynamics involving mixed species. In pump-probe experiments, using the IRFEL to pump and another short infrared or visible/UV pulse to probe, many important and exciting experiments on surfaces can be imagined: namely, the routes of energy transfer after vibration excitation of an adsorbed molecule (energy transfer between molecules and between molecule and surface), redistribution of molecules on a surface after selective desorption of a

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** Participating Group Members: Y.R. Shen (Chairman), P. Alivasatos, G. Williams, Y.J. Chabal, S. Etemad, D. Lambert, A Sievers, V. Jaccarino, G. Edwards, S. George, S. Perkowitz, S. Conradson, G Doncas.

part of the molecules, and photo-induced kinetic and dynamic effects. Even in the case of simply using an IRFEL as a source in conventional surface spectroscopy a higher sensitivity and a better signal-to-noise ratio can be anticipated, especially in the far infrared because of the high brightness and directionality of the FEL. This should help greatly in the study of surface states and molecule-surface interactions.

2). Semiconductor Physics: It is anticipated that substantial information will be obtained from pump-probe experiments. The most important areas are the studies of carrier dynamics; coherent coupling and energy transfer between phonons and carriers; excitation and relaxation of impurities; and, nonlinear optical excitations in semiconductors, quantum wells, and superlattices. It should be possible to utilize the high brightness of the FEL beam to carry out spectroscopic studies of deep impurity states in semiconductors. This is currently a problem because of insufficient intensity in conventional IR spectroscopy.

3). Other Applications: There are many other important applications. For example, IR spectroscopy with the FEL can allow more accurate measurements of the energy gap of a high-T_c superconductor film, the metal-insulator transition of a film under high pressure, the local and collective absorption modes of amorphous materials, water absorption, etc. Energy relaxation in solids can be studied by saturation spectroscopy or persistent hole-burning techniques.

4). Requirements: For most of the experiments discussed above, an FEL with the following characteristics will be required:

Tuning range:	2-200 μm (4-50 will suffice for many experiments)
Peak energy of micropulses:	$\gtrsim$ 100 μJ
Average power:	$\gtrsim$ 1 W
Pulsewidth:	~ 1 psec (micropulse) for dynamics studies
Bandwidth:	transform-limited
Intensity stability:	1% or better for a probe laser, <5% for pump laser (0.1% is desirable for special cases)
Frequency stability:	10% of bandwidth
Timing stability:	10% of pulsewidth
Directional stability:	10% of beam divergence
Mode quality:	single TEM_{00} mode
Rep rate:	100 Hz

The best operation mode of an IRFEL would be to have it next to a picosecond synchrotron source so that ultrafast pump-probe experiments can be carried out easily. It would be very helpful if the FEL could give two beams with synchronous pulses but at different wavelengths. Other types of lasers (excimer lasers, dye lasers, mode-locked lasers, etc.) would also greatly help the design and execution of various experiments.

The group feels that existing infrared FEL facilities do not presently satisfy the needs of the ordinary users. First, they are mostly machines for research on FELs; therefore, it is hard to obtain machine time for applications. Second, the lasers still need careful characterization and diagnostics. Third, the stabilities of the systems are clearly a problem, and tuning could be difficult. Dedicated facilities are required to achieve the science discussed.

To facilitate experiments, an FEL facility should have as much support equipment as possible.

In conclusion, in the past two decades tunable lasers in the visible region have created tremendous opportunities and excitement in almost all disciplines of science. Many of the most beautiful and stimulating experiments were carried out using the same general experimental approach outlined in the discussion earlier. The group is, therefore, confident that similar opportunities and excitements can be expected if dedicated IRFELs become available to the scientific community.

IRFEL Technology Working Group Report***

I. Introduction

At the present time, the number of free-electron laser facilities in the world is about to expand rapidly. In the United States, facilities exist at Stanford, Santa Barbara, Los Alamos, Boeing, and Livermore, and new facilities are under construction at Vanderbilt, Duke, Brookhaven, AT&T Bell Labs, and the National Institute of Science and Technology. In Europe, facilities exist at Orsay, and Novosibirsk and new facilities are under construction at Nieuwegein, Twente, Frascati, Darmstadt, Dortmund, and Israel. Applications programs are actively under way at Santa Barbara in the far infrared and at Stanford using the Mk III laser facility in the near infrared and the SCA/FEL laser facility in the visible and near infrared. The experience accumulated in these early experiments is proving valuable to both users and free-electron-laser developers alike. Limited experimental time is also available at some of the other installations, but several new facilities under construction will be largely dedicated to biomedical and material applications.

It is important now to consider the applications for which these new facilities can be used. It is important in the first place to be ready with applications when the facilities become available. But it is important also to consider the parameters and features which will make the new devices most useful for applications while the lasers are still being developed and upgrades are being planned. It is therefore the purpose of this report to acquaint potential users with the possibilities and limitations of free-electron lasers so that they might plan their applications and understand and influence the directions in which the technology might be extended.

Because of the broad wavelength range accessible to free-electron lasers, a correspondingly broad range of applications is possible. Free electron lasers will undoubtedly have the greatest impact in the infrared and ultraviolet, where powerful, tunable lasers are not available. In this report we limit our attention to

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*** Group members: C.A. Brau (Chairman), S. Benson, W.B. Colson, J. Galayda, J. Gallardo, K.-J. Kim, C. Pellegrini, R. Rohatgi, T.I. Smith, M. Xie, L.-H. Yu, M. Zisman.

infrared free-electron lasers. For a broader overview, the interested reader is referred to the recent review by Brau [*Science* **V 239**, 1115 (1988)].

II. Status

Appendix III is a list of existing FEL facilities and FEL facilities under construction. The parameters are supplied by developers of the respective facility.

III. Problems

Initially, free-electron lasers were troubled by three problems, reliability, wavelength, and energy fluctuations.

As more experience has been accumulated, reliability has improved significantly. Operations at Santa Barbara have improved to the point where user periods lasting several months are routinely planned, with few serious interruptions expected and availability generally better than 90%. A similar level of performance is achieved at Stanford with the Mk III FEL. Fundamentally, rf linacs are complex devices and require some time to "shake down." However, unlike the fast, high-current pulse technology of excimer lasers, for example, the pulse technology used in particle accelerators is high-impedance, relatively low current, and non-stressing so that reliable operation is generally achieved. This reliability is expected from free-electron lasers as well. Electrostatic devices involve more mechanical components, but experience with ion accelerators, such as the 10-MeV device at the University of Oxford, shows that similar reliability can be expected of electrostatic machines.

Large linewidth and wavelength jitter in free-electron lasers occur because there is no natural wavelength for free-electron lasers. This, of course, makes possible their tunability. The linewidth of rf devices is fundamentally limited by the micropulse structure of the electron and optical beams. The relative width of the Fourier transform of a 3-ps pulse in the near infrared is about 10^{-3}, and this width can now be achieved in free-electron lasers. The short pulses are, of course, useful for a variety of time-dependent experiments. On the other hand, very narrow linewidth, of the order of 10^{-7} for individual pulses, is believed to be achieved in the electrostatic free-electron laser at Santa Barbara, although the evidence is indirect.

Wavelength jitter needs to be held to a value comparable to—or even less than—the linewidth. The wavelength jitter in the electrostatic machine at Santa Barbara is comparable to that of rf machines, of the order of 10^{-3}. Various methods are being investigated for removing the jitter. These include intra-cavity gratings, injection locking, and Fox-Smith resonators.

Intensity and pulse-energy fluctuations are also observed in free-electron lasers at the present time. Although improvements in the lasers have brought about reductions in the energy fluctuations, the fluctuations remain at the level of a few percent, or more, from shot to shot. These fluctuations are difficult to explain since the electron-beam fluctuations are generally smaller. Thus, it is not entirely clear how far the fluctuations can be reduced. Normalization of data to pulse energy can be used for short-term improvement. In the long term, improved understanding of the factors affecting the laser fluctuations is needed. It is also important to establish the level of stability required for applications.

IV. Upgrades and Extensions

Numerous upgrades and extensions of the present level of free-electron laser technology have been suggested which will make widespread utilization possible. Besides extending operation to wavelengths not yet available, these improvements include shorter pulses, larger pulse energy, narrower lines, more varied pulse format, the ability to scan the wavelength conveniently, and simultaneous operation at more than one wavelength.

Wavelength Coverage

At the present time, free-electron lasers cover the entire infrared spectrum from 1μm to 1mm, with the exception of the region from about 45μm to 125 μm. It may be possible to extend operation of the Los Alamos device into the short-wavelength end of this region, and the group at Nieuwegein may extend operation of their rf device throughout this region as an upgrade of the device they are now constructing. In addition, a group at Oxford proposed to construct an electrostatic free-electron laser which would span this region.

Tunability

In addition to tuning to an arbitrarily selected wavelength, it is often useful to scan the laser over a prescribed interval. There are primarily two ways to change the wavelength of a free-electron laser. For large changes in wavelength, it is necessary to change the electron energy, but for small changes in wavelength, perhaps as much as ±25 percent, it is possible to change the magnetic field of the wiggler by mechanically adjusting the gap between the upper and lower magnets. Since this corresponds to a single adjustment, it is possible to scan the wavelength over this wavelength range if the wiggler is designed to do so. In the past, most wigglers have not been so designed. For large changes in the electron energy, corresponding to wavelength changes larger than a few percent, it is necessary to realign the electron beam through the beamline. Done by hand, this can require from a few minutes to several hours to accomplish. In the future, computer control of the laser will improve this situation. For tuning over a wavelength range of a few percent it is presently possible to scan the electron energy and laser wavelength conveniently.

Linewidth and Wavelength Stability

Narrow linewidth is a desirable feature for many applications. For long single pulses, as from electrostatic free-electron lasers, the linewidth can be exceedingly small. Indirect evidence suggests that a relative width of 10^{-7} has been achieved at Santa Barbara, but wavelength jitter from shot to shot increases the usable linewidth to about 10^{-3}. It is necessary to reduce the jitter by one of several means. Injection locking with a conventional, fixed-wavelength laser has been demonstrated at Santa Barbara, but has the disadvantage of the laser operating only at the wavelength available from conventional lasers. A promising approach which will be developed at Santa Barbara is the use of a Fox-Smith resonator. This technique increases the spacing between resonator modes. With a reduced number of lines within the gain bandwidth of the laser, oscillation should start on the same longitudinal mode each shot. Gratings and filters inside the resonator may also help.

With rf linacs, the laser linewidth is limited by the transform of the optical micropulse length to about 10^{-3}. Shot-to-shot jitter is therefore much less of a problem. Because of the high peak power developed in rf-linac free-electron lasers, synchrotron instabilities are observed. These instabilities can increase the total

pulse energy, but they also modulate the intensity in the micropulse and broaden the linewidth to as much as a few percent. Various techniques have been used to suppress the instabilities and narrow the linewidth to the Fourier-transform limit of the micropulse. These include shortening the length of the optical resonator so that the round-trip time is not quite synchronous with the accelerator frequency, and introducing gratings into the optical resonator. With a grating in the resonator, the cavity length can be varied to tune the laser wavelength over a fraction of the gain bandwidth. To try to produce linewidth narrower than the transform limit of the micropulse, the group at Rijnhuisen proposes to phase-lock several closely-spaced optical micropulses and thereby suppress most of the cavity modes which could otherwise comprise the mode-locked pulses. With the increased effective mode spacing, of the order of 10^{-4}, it should be possible to use a monochromator to select a single longitudinal mode, with exceedingly narrow linewidth.

All the techniques described above can, in principle, be used on a single machine, provided that user demands are supported by adequate funding. Of course, many of the techniques interfere with one another, and mechanical complexity will be required to resolve the interferences.

Multiwavelength Operation

An interesting proposal for the Stanford superconducting free-electron laser is to operate the laser at two independent wavelengths simultaneously. The electron beam would be split into two, with every other micropulse accelerated to a higher energy to operate a shorter-wavelength laser. This would provide micropulses at two wavelengths synchronized in time to better than a picosecond for pump-probe experiments. Alternatively, the rf drive used for an rf linac can be derived from the rf driver of a synchrotron radiation source or other master oscillator for a mode-locked conventional laser with picosecond accuracy for pump-probe experiments.

Polarization

It may be possible to exploit the polarization properties of free-electron lasers. Generally, these lasers use plane-polarized wigglers to generate linearly polarized light, but helical or otherwise polarized wigglers can, in principle, be used to generate circularly or elliptically polarized light.

Pulse Duration

Because of their broad gain bandwidth, free-electron lasers can amplify optical pulses as short as N_W optical cycles, where N_W is the number of periods in the wiggler. Typically, N_W is of the order of 40 to 150 periods. Moreover, simulations indicate that the nonlinear behavior of free-electron lasers at high intensity can be used to produce pulses a factor of five, or more, shorter than N_W cycles. Various techniques can be used to form these pulses, and, in principle, long-wavelength analogs of "conventional" techniques can be used to compress the pulses from a free-electron laser.

For wavelengths shorter than about 20 or 30μm, bandwidth-limited pulses are longer than a few picoseconds, and electron pulses of this length are easily formed by rf linacs. Thus, optical pulses of this length can be formed in this spectral region. At wavelengths longer than 50 or 100μm, the electron pulses from rf linacs are too short to fill the entire optical pulse, and laser operation becomes difficult. For these and larger wavelengths electrostatic accelerators with pulse lengths several microseconds long are more suitable. Shorter pulses can be obtained from electrostatic free-electron lasers by optical gating techniques as have been demonstrated at Santa Barbara. In addition, it is possible, in principle, to pulse the electron gun of an electrostatic accelerator to produce picosecond pulses from the free-electron laser, after the manner of rf linacs. Photoelectric guns with cathodes driven by mode-locked lasers are being developed at Los Alamos and elsewhere to produce electron pulses in the range from 50 to 100ps long, and it should be possible to adapt this technology to electrostatic accelerators if short (mode-locked) pulses are desirable.

For wavelengths shorter than 20 or 30μm, the optical pulse length is limited by the electron pulse produced by rf linacs to the order of a picosecond, regardless of the wavelength. It may be possible to produce shorter optical pulses by adapting "conventional" techniques such as using optical fibers with a grating pair. Alternatively, it may be possible to impress an energy chirp on the electron micropulse and produce, in this way, an optical micropulse from the free-electron laser which has a wavelength chirp. This chirped pulse could then be compressed with a pair of gratings.

Pulse Energy and Pulse Format

Because the electron micropulses from rf linacs are small in intensity, the optical energy from a single micropulse is limited to a few hundred microjoules. Cavity dumping might increase this by as much as an order of magnitude. This approach is under development at the Mk III free-electron laser facility. It should also be possible to vary the spacing between micropulses in an rf linac free-electron laser by using a mode-locked laser to pulse the electron gun at a subharmonic of the accelerator frequency. It is, of course, necessary to make the laser cavity round-trip time an integer multiple of the electron-pulse spacing. Most existing FELs are not designed to change the pulse format, apart from the macropulse repetition frequency and, in most cases, the macropulse duration. In the future, as facilities are developed to serve a broad variety of users, it will be desirable to include flexibility in the pulse format.

V. Recommendations

In summary, a broad range of wavelength, pulse length, and other parameters are available from free-electron lasers to address an even broader range of applications. It is not, however, possible to get a complete range of all these parameters from a single machine. In particular, it is not possible to tune a single machine over the entire wavelength range from 1μm to 1mm. For wavelengths less than 30μm, electrostatic accelerators cannot reach sufficient electron energy to operate with useful gain. Thus, the near- to mid-infrared belongs exclusively to rf linacs. On the other hand, for wavelengths longer than 100μm, the micropulses from rf linacs are shorter than the slip distance of the optical pulse relative to the slower-moving electron pulse, and laser operation becomes difficult. Thus, the far infrared is the province of electrostatic machines. In the wavelength range from 30μm to 100μm, it may be possible to obtain the advantages of both types of machine.

Relative to rf linacs and electrostatic accelerators, storage rings are much more expensive to build and operate in the infrared. Their real importance is in the ultraviolet part of the spectrum. Likewise, induction linacs are very expensive and, since they operate as amplifiers, they enjoy less flexibility in wavelength. Their greatest importance is for high-power applications.

peak power is much less than that of room-temperature linacs, but the average power is comparable because the duty factor is higher. In addition, long-pulse or CW operation generally is more stable than short-pulse operation. Thus, the selection of which type of linac to use depends on the applications for which the facility is intended.

It is expected that it should be possible to operate the device over a wavelength range exceeding an order of magnitude. Indeed, by operating on both the first and third harmonics it has already proved possible to operate the Los Alamos free-electron laser from 4 to 45 μm. Thus, with careful design it might be possible to construct a single facility to operate over the entire range from a few to perhaps 100μm. As discussed above, many variations in pulse format are also possible.

Long Wavelengths (> 30μm)

For this wavelength regime electrostatic accelerators are suitable. As with rf linacs, it should be possible to operate a single device over a wavelength range exceeding an order of magnitude. Indeed, the device at Santa Barbara has been operated over the range from 125 to 800μm.

In principle, as discussed earlier, electrostatic accelerators are capable of great flexibility in terms of pulse format and linewidth. However, with only one electrostatic free-electron laser in existence and one under development, these devices are not as well developed as rf linac free-electron lasers. Increased effort will be required to realize the potential advantages of these electrostatic free-electron lasers. Techniques for reducing wavelength jitter, such as Fox-Smith resinators, should get more attention, and means for generating short pulses, cavity dumping and short-pulse electron guns, must be developed. The resulting precision and flexibility will be of enormous benefit to spectroscopic applications in the far infrared.

Acknowledgement

The Committee express their appreciation to the many free-electron laser groups cited in this report for the information and comments they have provided.

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LBL/BNL WORKSHOP ON SCIENTIFIC OPPORTUNITIES OF THE IRFEL
Berkeley Conference Center

Program

MONDAY, OCTOBER 31, 1988

8:00 - 8:30 am	Registration
8:30 - 8:45 am	Welcome and Opening Remarks *Dr. Gerd Rosenblatt, LBL* *Dr. Martin Blume, BNL*

Source Technology Review:
Dr. K. J. Kim, Chairman

8:45 - 9:45 am	Overview of IRFEL Performances *Dr. Claudio Pelligrini, BNL and Dr. K.J. Kim, LBL*
9:45 - 10:15 am	Infrared Detectors for FEL Experiments *Prof. Paul Richards, UCB/LBL*
10:15 - 10:45 am	Coffee Break
10:45 - 11:15 am	Cryogenic Photon Counting IR Detectors *Dr. Michael Petroff, Rockwell International*
11:15 - 11:45 am	Scientific Applications of the BNL IR Beamline *Dr. Gwyn Williams, BNL*
11:45 - 12:00 noon	The LBL ALS IR Beamline *Dr. Brian Kincaid, LBL*
12:00 - 1:00 pm	Lunch

Condensed Matter and Surface Applications:
Prof. Y. R. Shen, Chairman

1:00 - 1:30 pm	Condensed Matter Science with the UCSB FEL *Prof. Vincent Jaccarino, UC Santa Barbara*
1:30 - 2:00 pm	On Persistent Spectral Holeburning with IR Laser Radiation *Prof. Albert Sievers, Cornell University*
2:00 - 2:30 pm	Nonlinear Optical Properties of Conjugated Polymers: An Application of the Stanford IRFEL *Dr. Shahab Etemad, Bellcore*
2:30 - 3:00 pm	Surface Spectroscopy by IR-VIS Sum Frequency Generation *Prof. Y. R. Shen, UCB/LBL*
3:00 - 3:30 pm	Coffee Break
3:30 - 4:00 pm	Surface Dynamics with the IRFEL *Prof. Steve George, Stanford University*
4:00 - 4:30 pm	Kinetics at Surfaces *Dr. Yves Chabal, AT&T Bell Labs*
4:30 - 5:00 pm	High Sensitivity Diode Laser Spectroscopy of Adsorbed Gas *Dr. David Lambert, General Motors Res. Lab.*
5:00 - 5:30 pm	Discussion

TUESDAY, NOVEMBER 1, 1988

8:30 - 9:00 am	Breakfast
Chemistry Applications:	*Prof. Steve George, Chairman*
9:00 - 9:30 am	IR Flash Kinetic Spectroscopy with the FEL *Prof. C. Bradley Moore, UCB/LBL*
9:30 - 10:00 am	Cluster Chemistry and Physics *Dr. Richard Woodin, Exxon*
10:00 - 10:30 am	Transient IR Spectroscopy of Radicals and Co-ordinatively Unsaturated Metal Carbonyls *Prof. Eric Weitz, Northwestern Univ.*
10:30 - 11:00 am	Coffee Break
11:00 - 12:30 pm	Working Group Sessions
12:30 - 2:00 pm	Working Lunch
2:00 - 3:00 pm	Workshop Summary
3:00 pm	Adjourn

Appendix II

Workshop on Scientific Opportunities of the Infrared Free Electron Laser

31 October – 1 November 1988

Lawrence Berkeley Laboratory

Workshop on Scientific Opportunities of the Infrared Free Electron Laser

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Appendix III

List of IRFEL Facilities

The following is a list of existing FEL facilities and facilities funded and under construction in the U.S. and Western Europe. The description and FEL parameters have been supplied by the developers of the corresponding facility through publications and/or private communications. The parameters for existing facilities represent demonstrated performance and those for other facilities are design goals. For further information please contact the individual facility management. The authors of this report are not responsible for problems due to errors or omissions in the transcription of the information.

Existing Facilities

Lawrence Livermore National Laboratory

This is an induction-linac free-electron laser whose pulse format consists simply of repeated intense pulses. Since it is an amplifier, rather than an oscillator, the wavelength is fixed by the CO_2 laser input. The facility is dedicated to FEL development and no time is currently available for applications.

Wavelength:	$\lambda = 10\mu m$
Linewidth:	$\Delta\lambda/\lambda < 2X10^{-6}$
Wavelength jitter:	$\Delta\lambda/\lambda < 4x10^{-7}$
Pulse energy:	$E = 1J$
Pulse duration:	$\tau = 10\text{-}15ns$
Pulse repetition frequency:	$f = 1Hz$

Contact: E.T. Scharlemann, Lawrence Livermore National Laboratory, Livermore, CA 94550 (415) 422-5797

Los Alamos National Laboratory

This is a repetitively pulsed rf-linac free-electron laser whose pulse format consists of micropulses within a longer macropulse. The machine has the broadest tuning range of any laser of any type, and has intense micropulses. Since the facility is dedicated primarily to FEL development, time for applications is limited.

Wavelength:	λ = 4-45 μm
Linewidth:	$\Delta\lambda/\lambda$ = 0.3%
Wavelength jitter:	$\Delta\lambda/\lambda$ = 0.2%
Micropulse energy:	E_μ = 500μJ
Micropulse duration:	$\tau\mu$ = 8ps
Micropulse repetition frequency:	$f\mu$ = 22MHz
Macropulse power:	E_M = 1J
Macropulse duration:	τ_M =100μs
Macropulse repetition frequency:	f_M =1Hz

Contact: Lawrence B. Warner, Mail Stop J579, Los Alamos National Laboratory, Los Alamos, NM 87545, (505) 667-1992

Duke University MK III

This is a repetively pulsed rf-linac free-electron laser whose pulse format consists of a train of closely-spaced micropulses within a macropulse. The machine is used for both applications and FEL development. This machine was originally operated at Stanford, and is now being moved to Duke. Initial operation at Duke is expected in 1989.

Wavelength:	λ = 1.4-9.1μm
Linewidth:	$\Delta\lambda/\lambda$ ~0.5-1%
Wavelength jitter:	$\Delta\lambda/\lambda$ <0.1%
Micropulse energy:	E_μ = 5-7μJ @ 3.5μm
Micropulse duration:	$\tau\mu$ = 1-2ps
Micropulse repetition frequency:	$f\mu$ = 2.8GHz
Macropulse power:	E_M = 200μJ
Macropulse duration:	τ_M = 0.5-6μs
Macropulse repetition frequency:	f_M = 15Hz

Contact: John M.J. Madey, Department of Physics, Duke University, Durham, NC 27706

Stanford University Superconducting Accelerator

This is a repetitively pulsed rf-accelerator free-electron laser, whose pulse format consists of a train of micropulses within a long macropulse. Because of the long macropulse and large macropulse repetition frequency the average power is

high. Four laboratories are now outfitted, and an optical beamline delivers the laser beam to each laboratory. The laser is being tested for both FEL development and applications.

Wavelength:	$\lambda = 0.5\text{-}3\mu m$
Linewidth:	$\Delta\lambda/\lambda = 0.1\text{-}0.2\%$
Wavelength jitter:	$\Delta\lambda/\lambda = 0.2\%$
Micropulse energy:	$E_\mu = 1\text{-}5\mu J$
Micropulse duration:	$\tau\mu = 2\text{-}4ps$
Micropulse repetition frequency:	$f\mu = 12MHz$
Macropulse power:	$P_M = 10\text{-}50W$
Macropulse duration:	$\tau_M = 1\text{-}100ms$
Macropulse repetition frequency:	$f_M = 10\text{-}20Hz$

Contact: Todd I. Smith, Hanson Laboratory, Stanford University, Stanford, CA 94305, (415) 723-1906

University of California at Santa Barbara

This is a repetitively pulsed electrostatic accelerator whose pulse format consists simply of repeated pulses. The facility is dedicated to both applications and FEL development and user laboratories are available with an optical beamline to distribute the laser beam to the various experiments. Several experiments have been performed and a number of others are in progress.

Wavelength:	$\lambda = 130\text{-}400\mu m$
Linewidth:	$\Delta\lambda/\lambda = (10^{-7})$
Wavelength jitter:	$\Delta\lambda/\lambda = 10^{-3}$
Pulse power:	$P = 1.5k \quad W$
Pulse duration:	$\tau = 3\mu s$

Contact: Vincent Jaccarino, Physics Department, University of California, Santa Barbara, CA 93106, (805) 961-2121

Facilities Under Construction

Vanderbilt University

This facility will use a laser similar to the Duke University Mk III FEL. The installation is dedicated to biomedical and materials applications. User laboratories have been completed; initial operation is expected in 1990.

Contact: Charles A. Brau, Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, (615) 322-2559

AT&T Bell Laboratories

This facility will use a conventional, pulsed microtron with a pulse format consisting of a train of micropulses within a macropulse. The facility is dedicated to solid-state physics applications.

Wavelength:	λ = 100-400μm
Micropulse energy:	$E_\mu = \mu J$
Micropulse duration:	$\tau\mu$ = 17ps
Micropulse repetition frequency:	$f\mu$ = 3 GHz
Macropulse energy:	E_M = 60mJ
Macropulse duration:	$\tau_M < 20\mu s$
Macropulse repetition frequency:	f_M = 30 Hz

Contact: Earl Shaw, 300 Mountain Avenue, Murray Hill, NJ 07974, (201) 582-5403

Brookhaven National Laboratory

This facility will use a repetitively pulsed rf-linac, and the pulse will consist of a train of micropulses within longer macropulses. The facility is intended for FEL development with time for applications. Initial operation is expected in 1991.

Wavelength:	λ = 0.4-20 μm
Micropulse energy:	E_μ = 0.5mJ
Micropulse duration:	$\tau\mu$ = 5ps
Micropulse repetition frequency:	$f\mu$ = 80MHz
Macropulse energy:	E_M = 80mJ
Macropulse duration:	$\tau_M = 2\mu s$

Macropulse repetition frequency: $f_M = 3Hz$

Contact: Claudio Pelligrini, Brookhaven National Laboratory, Upton, NY 11973, (516) 282-4635

Darmstadt

This facility will use a superconducting rf linac with a pulse format consisting of a continuous series of micropulses. The facility is to be shared between nuclear physics research, FEL development, and applications. Initial operation is expected in 1991.

Wavelength:	$\lambda = 2.6\text{-}5.2\mu m$
Micropulse energy:	$E_\mu = 0.6\text{-}0.9\mu J$
Micropulse duration:	$\tau\mu = 1.85ps$
Micropulse repetition frequency:	$f\mu = 10MHz$

Contact: A. Richter, Institute für Kernphysik Technische Hochschule Darmstadt Schlossgartenstrasse 9, D6100 Darmstadt, Germany, 06151-162116

ENEA, Frascati

Two devices are under development for operation in the infrared. Both will use pulsed microtrons with a pulse format consisting of a train of micropulses within a macropulse.

Conventional microtron. Initial operation is expected in 1989.

Wavelength:	$\lambda = 20\text{-}40\mu m$
Micropulse energy:	$E_\mu = 20\mu J$
Micropulse duration:	$\tau\mu = 20ps$
Micropulse repetition frequency:	$f\mu = 3$ GHz
Macropulse energy:	$E_M = 700$ mJ
Macropulse duration:	$\tau_M = 12\mu s$
Macropulse repetition frequency:	$f_M = 150$ Hz

Contact: E. Sabia, Dip. TIB, U.S. Fiscia Applicata, P.O. Box 65, 00044 Frascati (RM), Italy

Recetrack microtron:

Wavelength:	$\lambda = 5\text{-}100\mu m$

Micropulse energy:	E_μ = no information
Micropulse duration:	$\tau\mu = 20ps$
Micropulse repetition frequency:	$f\mu = 250MHz$
Macropulse energy:	E_M = no information
Macropulse duration:	$\tau_M = 5\mu s$
Macropulse repetition frequency:	$f_M = 50Hz$

Contact: E. Sabia, Dip. TIB, U.S. Fiscia Applicata, P.O. Box 65, 00044 Frascati (RM), Italy, (6) 94005-747

FOM Institute (Nieuwegein)

This facility will use a repetitively pulsed rf linac with a pulse format consisting of a train of micropulses within a macropulse. The facility is intended for FEL development (in particular line narrowing and applications). Initial operation is expected in 1990.

Wavelength:	$\lambda = 8\text{-}80\mu m$
Micropulse energy:	$E_\mu = 50\text{-}150\mu J$
Micropulse duration:	$\tau\mu = 3ps$
Micropulse repetition frequency:	$f\mu = 1$ GHz
Macropulse energy:	$E_M = 1\text{-}3J$
Macropulse duration:	$\tau_M = 2\mu s$
Macropulse repetition frequency:	$f_M = 10$ Hz

Contact: P.W. van Amersfoort, FOM-Institute for Plasma Physics, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands, (31) 3402-31224

INFN Frascati (LISA)

This facility will use a repetitively-pulsed superconducting rf linac with a pulse format consisting of a train of micropulses within a macropulse.

Wavelength:	$\lambda = 12\text{-}22\ \mu m$
Micropulse energy:	$E_\mu = 0.3$ mJ
Micropulse duration:	$\tau\mu = 7ps$
Micropulse repetition frequency:	$f\mu = 50$ MHz
Macropulse energy:	$E_M < 0.15J$
Macropulse duration:	$\tau_M < 10\mu s$

Macropulse repetition frequency:	$f_M = 1$ kHz

Contact: M. Castellano, IBFN-Laboratori Nazionali di Frascati, C.P. 13, 00044 Frascati (RM), Italy

National Institute for Science and Technology

This facility will use a 185-MeV CW microtron, making it possible to extend the wavelength to the near ultraviolet. The pulse format consists of a continuous train of micropulses. The installation is dedicated to biomedical and materials applications. Initial operation is expected in 1990.

Wavelength:	$\lambda = 0.2\text{-}10\mu m$
Micropulse energy:	$E_\mu = 1.4\text{-}4\ \mu J$
Micropulse duration:	$\tau\mu = 3ps$
Micropulse repetition frequency:	$f\mu = 61$ MHz

Contact: Phillip Debenham, National Institute for Science and Technology, Gaithersburg, MD 20899, (310) 975-5602

Orsay (CLIO)

This facility will use a pulsed rf linac with a pulse format consisting of a train of micropulses within a macropulse. Initial operation is expected in 1990.

Wavelength:	$\lambda = 1\text{-}20\mu m$
Micropulse energy:	$E_\mu = 0.1\text{-}1mJ$
Micropulse duration:	$\tau\mu = 10ps$
Micropulse repetition frequency:	$f\mu = 30\text{-}250$ MHz
Macropulse energy:	$E_M < 0.15\text{-}1.5J$
Macropulse duration:	$\tau_M < 12\mu s$
Macropulse repetition frequency:	f_M = up to 50 Hz

Contact: J.-M. Ortega, LURE, Bat. 209 d, Universite Paris-Sud, 91405 Orsay, France, (1) 6446-8017

Twente University

This facility will use a repetitively pulsed microtron, and the pulse format will consist of a train of micropulses within a macropulse. The facility is intended for FEL development and applications.

Wavelength:	λ = no information
Micropulse energy:	E_μ = no information
Micropulse duration:	$\tau\mu = 9$ps
Micropulse repetition frequency:	$f\mu = 50$ MHz
Macropulse power:	E_M = no information
Macropulse duration:	$\tau_M = 50\mu$s
Macropulse repetition frequency:	f_M = no information

Contact: W.J. Wittleman, University of Twente, Department of Applied Physics, 7500 AE Enschede, The Netherlands

Weizmann Institute (Israel)

This facility will use a pulsed electrostatic accelerator with a pulse format consisting simply of repeated pulses. The facility is intended for FEL development and applications.

Wavelength:	λ = no information
Pulse energy:	E = no information
Pulse duration:	τ = no information
Pulse repetition frequency:	f = no information

Contact: J. Ben-Zvi, Department of Nuclear Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

Japan and China

Several facilities are under development in each country, but details are not available.

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