

PUTTING FREE-ELECTRON LASERS TO WORK

Imagine a laser that is continuously tunable over a wide range of wavelengths, including wavelength domains where conventional lasers cannot operate. This new kind of laser has already proven itself at microwave, far-infrared, visible, ultraviolet, and even x-ray wavelengths. Furthermore, it can run reliably and efficiently for days, or even weeks, with only minor maintenance, producing anything from continuous-wave laser light to subpicosecond pulses.

What we're describing is the free-electron laser. FELs contain only the essential ingredients for light amplification by stimulated emission: a beam of electrons, an external magnetic field to deflect them, and laser light. They dispense with nonessentials like the atomic nuclei and their bound electrons that impose limitations on conventional atomic lasers. The gain medium of the FEL is transparent to all wavelengths, and the physics of the gain mechanism is essentially the same for all wavelengths from a centimeter down to an angstrom.

The FEL uses a beam of relativistic electrons passing through a periodic, transverse magnetostatic field—the “wiggler” field—to amplify the laser light beam propagating along the axis of the electron beam.¹ Figure 1 shows a schematic of an FEL oscillator, including the wiggler field, the electron beam path, and the pair of resonator mirrors between which the laser beam bounces. Not shown is the accelerator or storage ring that provides the relativistic electron beam. (See the article by Phillip Sprangle and Timothy Coffey in *PHYSICS TODAY*, March 1984, page 44.)

A typical infrared FEL uses a beam of 50-MeV electrons, delivered as a train of picosecond pulses separated by many nanoseconds. The peak current within a pulse is usually of order 10^9 A and the diameter of the electron beam is typically about a millimeter. The electron beam energy is “pumped” through the FEL interaction volume at nearly the speed of light. The laser light is stored between the resonator mirrors as fresh electrons from the

By making a relativistic electron beam wiggle its way through an array of magnets, one can generate intense coherent light with wavelengths tunable from centimeters to angstroms.

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accelerator enter the wiggler. Traversing the wiggler, they contribute about 1% of their power to the copropagating light beam. The spent electron beam exits the wiggler without leaving behind any waste heat. That's another advantage FELs have over conventional lasers.

Most often, the wiggler is constructed from a series of permanent magnets with a period of a few centime-

ters over about 100 periods. The bottom panels of figure 1 show the phase-space evolution of the electron beam as it traverses the wiggler structure together with the optical beam that's being amplified. By the time the electrons reach the end of the wiggler, they have become bunched in such a way that they amplify the copropagating light by radiating coherently with it.

The light beam moves slightly faster than the relativistic electrons. FEL resonance is achieved when one wavelength of light passes over an electron in the time it takes the electron to traverse one period of the wiggler. This involves two Doppler shifts. The relativistic electrons see a Doppler foreshortened periodic wiggler structure approaching them. And the coherent radiation that the electrons emit in the forward direction as they wiggle appears blueshifted in the optical resonator, relative to its wavelength in the rest frame of the electron beam. This double Doppler shift generates a laser frequency that is many orders of magnitude higher than the frequency at which the electrons wiggle.

In the usual FEL oscillator configuration, the light begins as spontaneous emission. Just as in a conventional laser, mode competition between spontaneously emitted frequencies—as the light traverses the optical resonator many times in a few microseconds—determines the width of the narrow laser spectrum. It takes hundreds of passes between the mirrors in the presence of the wiggling electron beam to render the light coherent.

But there are other FEL configurations in which the light passes through the structure just once. Because they have to accomplish in nanoseconds what a conventional FEL oscillator takes microseconds to do, such configurations require much longer magnet arrays—typically several thousand wiggler periods—and much higher electron-beam currents. The high-gain FEL amplifier, for example, begins with an input seed laser beam that is to be amplified in a single pass. An even more demanding mode of single-pass FEL operation is called SASE (self-

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amplified spontaneous emission). SASE involves no external light input; the radiation and its coherence must grow, without mirrors, from spontaneous emission. SASE becomes particularly important at far-ultraviolet and x-ray frequencies, where there are no suitable seed lasers or mirrors.

Nearly every type of electron accelerator and storage ring is used as an FEL driver. FEL electron-beam energies range from MeV to GeV, and beam currents range from amperes to kiloamps. Many of the properties of the FEL radiation output are determined by the characteristics of the electron source. The radiation pulse structure in the FEL reflects that of the electron beam. Therefore it is easy to produce laser pulse lengths ranging from picoseconds, using a radio-frequency (RF) linac, to an almost continuous beam, using a recirculating electrostatic accelerator. FELs can also achieve high peak power, because of the high power density carried by relativistic electron beams.

The FEL has become an exciting conceptual and practical alternative to other radiation sources, such as microwave tubes and conventional atomic lasers. It can be extended well beyond the operational range of both. Because FELs require accelerators, they tend to be large and expensive. Nonetheless, they continue to attract widespread interest as unique and powerful light sources for optical science and for industrial and military applications.

Infrared facilities

The spectral region that provides an immediate target of opportunity for FELs is the infrared (IR), particularly at wavelengths longer than $18\text{ }\mu\text{m}$, where operation of conventional lasers becomes difficult. There are now a number of FEL facilities around the world operating in the IR, each of which provides several thousand hours per year of reliable beam time for optical science. These facilities are not all alike: There are important differences in wavelength coverage and beam parameters, and each facility exploits its own unique capabilities.

The FELs driven by superconducting linacs at Stanford University's W. W. Hansen Laboratory and the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, provide trains of optical pulses of exceptional quality and stability. Their pulse widths can be varied with ease from picoseconds down to a few hundred femtoseconds. In the mid-1990s, these capabilities were unique. They made possible the first comprehensive studies of vibrational dynamics in condensed matter systems.² The initial vibrational-echo experiments involved temperature-dependent measurements on glass-forming liquids. Subsequently, a Stanford–University of Illinois

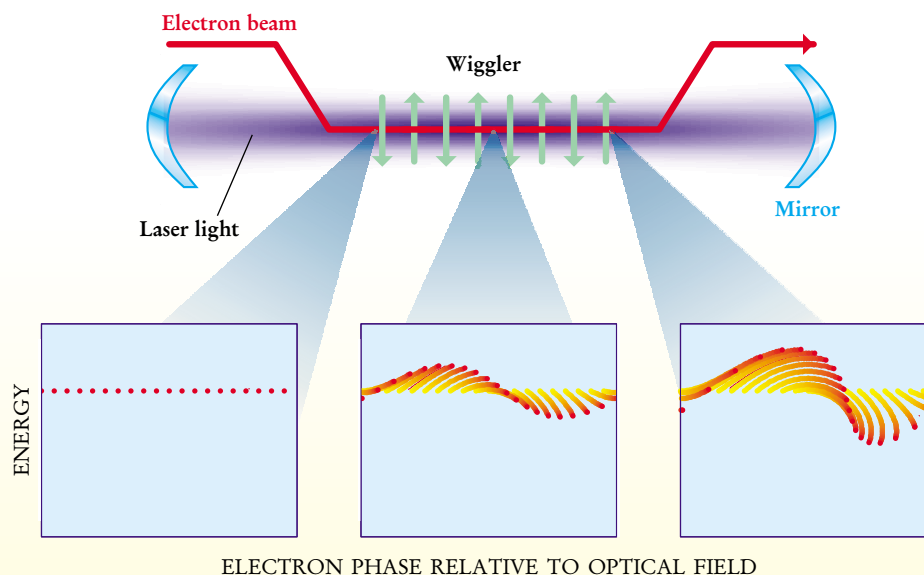


FIGURE 1. A FREE-ELECTRON LASER oscillator uses a beam of relativistic electrons passing through the periodic field (green arrows) of an array of wiggler magnets in the presence of a copropagating laser light beam stored between the mirrors of a resonator. The bottom panels, each having the width of one optical wavelength, show the phase-space evolution of bunching in the electron beam as it traverses the wiggler. The vertical axis designates the electron energy and the horizontal axis gives the phase of the copropagating light at the electron's position. A beam electron sees one optical wavelength passing over it as it traverses each wiggler period. The brown end of the evolving phase-space path gives the electron's status at that point. The beam bunches up, and thus begins radiating coherently with the laser light, as electrons continue to gain or lose energy, depending on the optical phase.

collaboration applied that method to myoglobin, a small protein that stores oxygen in muscle tissue.³ For his many studies of dynamical processes in condensed-phase systems, more than 20 of these being FEL-based experiments, Michael Fayer of Stanford was awarded the American Physical Society's Earl K. Plyler Prize for Molecular Spectroscopy in March 2000.

The recent commercial availability of optical parametric amplifiers that provide high-quality beams in the mid-IR wavelength regime from 3 to $18\text{ }\mu\text{m}$ has opened the study of vibrational dynamics to individual investigators with no access to FELs. Nonetheless, under special circumstances, there are still unique opportunities for FEL-based experiments at wavelengths shorter than $18\text{ }\mu\text{m}$. The recent measurements of the vibrational relaxation of hydrogen defects in silicon provide a good example.⁴ The small absorbance and good thermal conductivity of these samples made it possible to use the high repetition rate and high average power available at the Jefferson Lab's FEL. Given the low concentration and small absorbance of the hydrogen defects, these beam conditions were critical for achieving adequate signal-to-noise ratios.

The infrared FELs at Duke and Vanderbilt universities are driven by conventional RF linacs. Such FELs provide intense bursts of tunable optical pulses that can deposit energy into selected vibrational modes of a sample, producing a thermally localized vibrational excitation while leaving the system in its electronic ground state. This technique has been exploited in mass spectrometry of large biological molecules, in organic thin-film synthesis, and even in surgery.⁵ The FEL parameters are nearly ideal for mass spectrometry of large biological molecules, where one must ablate the molecule from the sample

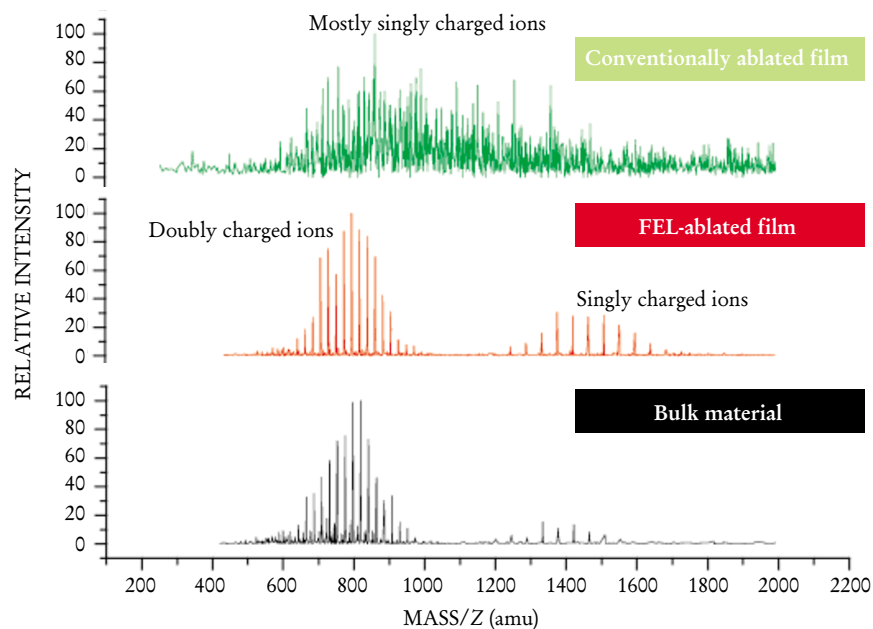


FIGURE 2. COMPARING MASS SPECTRA of polyethylene glycol films deposited by pulsed-laser deposition with conventional versus free-electron lasers. The top trace is from a film created by a conventional ultraviolet pulsed excimer laser at 193 nm. The middle trace is from a film ablated and deposited by the Vanderbilt FEL operating at the molecule's 2.9- μm infrared vibrational resonance. The FEL deposition produces a much more faithful representation of the bulk target material, whose spectrum is shown in the bottom trace.

without fragmenting it.

Recently, this localized-excitation principle has been exploited to produce high-quality polymer films by resonant vibrational ablation of bulk polymer. For polyethylene glycol, a Naval Research Laboratory–Vanderbilt collaboration found that the mass spectrum of the FEL-deposited film is virtually identical to that of the starting material. That is to say, there has been no significant molecular fragmentation. By contrast, the mass spectrum of a thin film ablated and deposited by means of an argon fluoride excimer laser operating at 193 nm in the ultraviolet indicates extensive photodecomposition. Figure 2 compares the mass spectra of the two films. Similar results had been found by one of us (MJK) in an earlier study of polyimide ablation on and off resonance at the Jefferson Lab.⁵

Depositing energy into selected vibrational modes under conditions of thermal localization has also proved beneficial in surgical applications. Efficient ablation of tissue with minimal collateral damage has been achieved by targeting the overlapping resonances of protein and water molecules near 6.45 μm . At Vanderbilt, FEL medical applications have progressed to human surgery. Michael Copeland has led a neurosurgical team investigating the advantages of FEL tumor resection.⁵ Since December 1999, the team has demonstrated the precision and safety of the FEL as a surgical tool in three successful resections of benign brain tumors. Additional surgical applications are under investigation at Vanderbilt and Duke.

Conventional RF linacs drive FELs in the Netherlands, France, Japan, and China. These facilities cover the mid-IR range, but they also extend to wavelengths longer than 18 μm . At the FELIX facility near Utrecht in the Netherlands, resonance-enhanced multiphoton ionization using the FEL has made possible extremely sensitive IR spectroscopy when combined with mass-selective detection of gas molecules.⁶ That scheme is rather generally applicable. It has, for instance, been used at FELIX to record the IR spectral properties of titanium carbide nanocrystals and thus solve the long-standing “21- μm mystery” in astrophysics. (See PHYSICS TODAY, June 2000, page 22.) The upper trace in figure 3 is the infrared spectrum of a typical postasymptotic giant-branch star with

its characteristic 21- μm peak. Comparison with the TiC nanocrystal spectrum recorded at FELIX (lower trace) makes it clear that the puzzling astrophysical peak is due to the presence of these nanocrystals in the outflows of these giant-branch stars.⁶

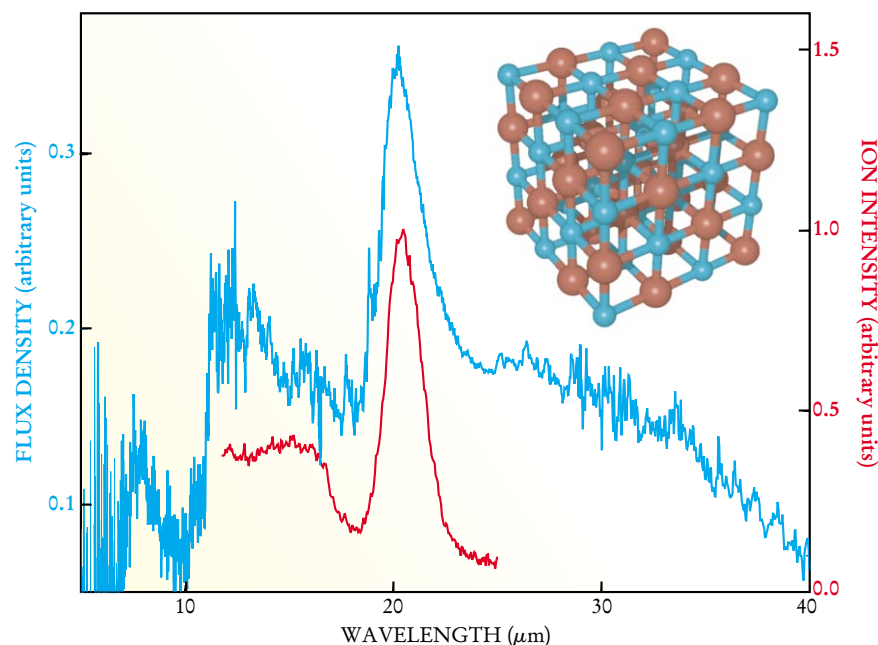
The scaling of many molecular-physics phenomena with optical pulse energy is highly nonlinear. To provide users with pulse energies that are orders of magnitude higher than what's available now, FELIX is proposing to set up an FEL for dedicated intracavity experiments. In this project, called FELICE, the experiments would be incorporated inside the FEL's optical resonator. In that configuration, 10 joules of infrared radiation, tunable from 3 to 100 μm , could be delivered to an experiment in a microsecond burst of picosecond pulses.

The FELICE optical cavity could reasonably accommodate two alternative experimental setups: a state-of-the-art ion trap or a pulsed molecular-beam apparatus. With the ion trap, one could undertake a wide variety of optical studies on mass-selected ionic species. Experimenters could study the IR optical properties, and hence the structure, of stored ions. One could also investigate processes induced by IR light: chemical reactions, photodissociation and the folding of biomolecules. Such studies on molecular ions, molecular complexes, and dust grains would be highly relevant for astrophysics. They would also offer important new capabilities in biochemistry.

With the pulsed molecular-beam apparatus, neutral species could be made to interact with a tightly focused beam of intense tunable IR light. Infrared multiphoton excitation, leading to dissociation and ionization, could then be used to unravel the geometric structures of nanocrystals and small clusters by recording their vibrational properties. The high peak intensities might also make it possible to select specific chemical reactions by inducing coherent multiphoton vibrational excitation of molecules in a single picosecond pulse.

The Van de Graaff-driven FEL at the University of California, Santa Barbara, provides a unique opportunity—namely, the study of semiconductor physics at far-infrared wavelengths from 60 μm to 2 mm. At present, only FELs can generate narrow-band, tunable radiation in this terahertz regime with peak power exceeding a kilo-

FIGURE 3. ASTROPHYSICAL MYSTERY of the prominent $21\text{ }\mu\text{m}$ peak in the emission spectra of certain giant stars was solved by comparing them with the spectrum of TiC nanocrystal clusters (red trace) produced by the free-electron laser at the FELIX facility in the Netherlands. The ultraviolet spectrum of the star SAO 96709 (blue trace) was recorded by the Infrared Space Observatory. The comparison makes the case that TiC nanocrystals are present in the outflows of such stars. The lattice is a pictorial representation of a typical 64-atom TiC nanocrystal. (Adapted from ref. 6.)



watt. That makes FELs indispensable for the investigation of THz science and the development of THz technology.

Over the past decade, important contributions of the Santa Barbara FEL to semiconductor physics have included the discovery of photon-assisted tunneling between semiconductor quantum wells, studies of relaxation mechanisms for excited electrons in quantum wells, and the use of THz radiation to modify interband optical properties of semiconductors.⁷

Recently, the Santa Barbara FEL has demonstrated that impurities in semiconductors can be used as model quantum bits. Quantum information processing is an exciting area of interdisciplinary research. A “qubit,” the fundamental unit of quantum information, is a two-state system that can exist in an arbitrary coherent superposition of the two states. One of the simplest nontrivial operations on a qubit is to rotate it through its Hilbert space from one well-defined state to another. That can be accomplished by irradiating the system at the transition frequency between the two states. The system will then oscillate between the states at the much lower “Rabi frequency,” which is proportional to the amplitude of the irradiation. By carefully timing the duration of the irradiation pulse, one can specify the system’s final state (see *PHYSICS TODAY*, March 1996, page 21). A recent experiment at the Santa Barbara FEL has demonstrated Rabi oscillations between orbital electronic states of hydrogenic impurities in gallium arsenide.⁸ (See figure 4.)

Throughout the infrared regime, FELs can be remarkably flexible and powerful instruments of research. In the mid-IR, where conventional laser sources are now available, the FEL remains unmatched in many respects. In the far infrared, the capabilities of the FEL are, as yet, uncontested.

Ultraviolet and x-ray

Wavelengths shorter than one can get with conventional laser technology present another window of opportunity for FELs. The scientific potential of the short-wavelength radiation has spawned a number of projects aimed at providing FEL sources in the ultraviolet and x-ray regimes. It’s not simply a matter of extending optical laser experiments to shorter wavelengths. Rather, FELs open up a new world of

physical processes that have never been explored.

Storage-ring-based FEL oscillators provided the first platforms for experiments at UV wavelengths. The FEL on the Super-ACO storage ring, at France’s LURE laboratory in Orsay, has supported an active research program in the UV, emphasizing time-resolved experiments on biological systems and semiconductors.⁹ Storage-ring FELs are also making an impact on nuclear physics. At the Duke FEL laboratory, an intense beam of 100% linearly polarized gamma rays, with photon energies from 2 to 58 MeV, has been produced by Compton backscattering of lower-energy FEL photons off the stored beam of relativistic electrons.¹⁰ This high-intensity gamma-ray source (HIGS) has been used recently in nuclear resonance fluorescence experiments to establish the parity of the various states of the barium-138 nucleus. This year, the gamma-ray energy at HIGS will be increased to 150 MeV. At the same time, the source’s intensity will be raised from 10^6 to 10^{10} gammas per second.

At wavelengths shorter than 150 nm in the ultraviolet, increasing mirror losses shift the FEL design emphasis away from the oscillator configuration to single-pass schemes like SASE. At shorter FEL wavelength, single-photon direct electronic excitation becomes possible. In the vacuum-ultraviolet regime, one can directly study the electronic structure of molecules such as CH_4 , H_2O , CO_2 , and the chlorofluorocarbons that are important in atmospheric photochemistry.

The direct single-photon excitation capability of FELs in the ultraviolet has important consequences for the choice of experimental technique and target. For instance, it greatly expands the reach of pump-probe experiments, widely used in the IR and visible. In such experiments, a pump laser pulse excites a system and a subsequent pulse, after a specified delay, probes the consequences. In the UV, the pump excitation may lead to the creation of an electronically excited state, a radical species, or a set of photofragments. The probe beam then identifies the species of interest by mass, fluorescence, or phosphorescence spectroscopy. The time relationship between pump and probe, coupled with the spatial distribution of reaction products, can provide the information needed to

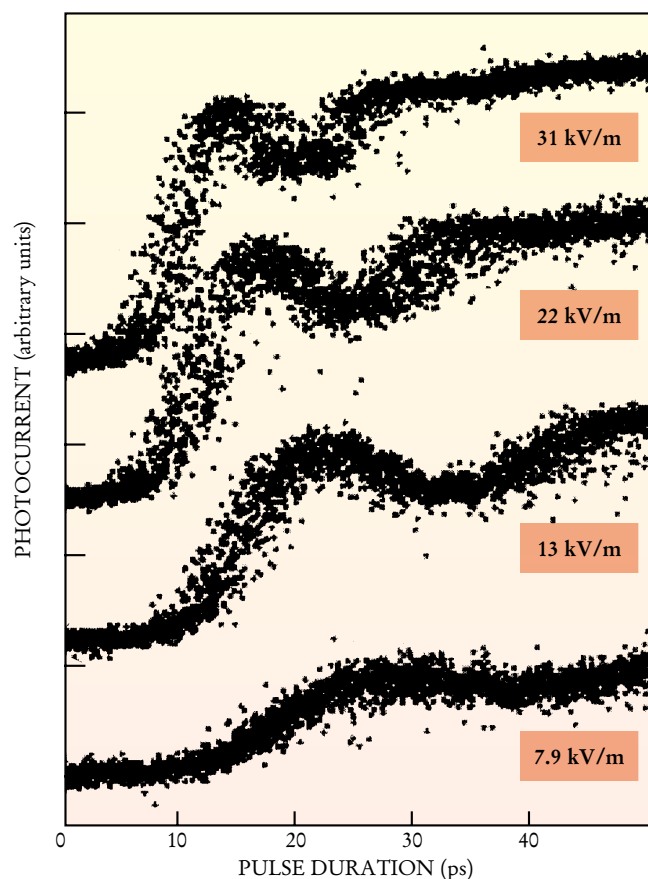


FIGURE 4. RABI OSCILLATION of electrons bound to shallow hydrogenic impurities in a GaAs crystal has been demonstrated with a free electron laser. Intense terahertz FEL irradiation promotes bound ground-state electrons to an excited state from which they can escape to the crystal's conduction band. The transition radiation induces Rabi oscillation between the two states. Where the electrons end up depends on the duration of the irradiation pulse and the Rabi oscillation frequency, which is proportional to the amplitude of the THz irradiation. Plotting the crystal's photoconductivity against pulse duration, for different irradiation intensities, exhibits damped Rabi oscillation. (Adapted from ref. 8.)

understand the reaction pathway.

In a single-pass ultraviolet FEL optimized for very high peak power ($10^9 - 10^{11}$ W), one can exceed the peak power available from synchrotron light sources by 12 orders of magnitude. That can be exceedingly important for the study of transient species, surface adsorbates, or dilute systems such as gases or molecular beams.

High peak power can also be important for studies of biological systems. The time-dependent decay of photoexcited sites is used in phosphorescence and fluorescence studies to derive structural information about biomolecules. The observed quenching rates are very sensitive to molecular conformation and the proximity of ions and amino-acid residues. To obtain adequate sensitivity with existing sources, experimenters often have to concentrate samples well beyond the level of their native environment. But then the increased intermolecular coupling can distort the results. The high peak power and tunability of FELs opens the possibility of studying such systems at their natural biological concentrations.

Some proposed ultraviolet FEL configurations, like Brookhaven National Laboratory's chirped-pulse amplifier scheme, would squeeze pulse durations below 10 fs, while maintaining fairly high (mJ) pulse energies. In principle, one could then obtain power densities on the order of 10^{21} W/cm². That would extend into the ultraviolet the superintense-radiation experiments in which atoms, at very high laser intensities and frequencies, become increasingly stable rather than being ionized.¹¹

The horizon for new physics expands further as the laser frequency is pushed into the x-ray range. X-ray sources can excite electrons deep inside atomic cores, and they provide probe radiation at a length scale that is interesting for important imaging and scattering tech-

niques. Synchrotron light sources, even without the coherent output for which one needs an FEL, are already useful tools for determining structure at atomic length scales. Proposals are afoot to incorporate x-ray lasers into high-energy electron accelerators like the SLAC linac at Stanford and the proposed TESLA collider at DESY in Hamburg.¹² The prototype FEL at the TESLA test facility has recently achieved the milestone of SASE operation in the ultraviolet.

Such instruments could explore dynamics at previously unavailable time and length scales. Inelastic scattering and direct time-resolved methods are complementary approaches to temporal information about structure, just as diffraction and imaging methods are complementary approaches to spatial information. The proposed x-ray FELs would significantly increase the overlap of these complementary approaches to the investigation of structure. The SLAC machine will use a 15-GeV electron beam to provide a 280-fs electron pulse with a peak current of 3.4 kA. When this beam transits a 100-m-long wiggler, the SASE gain mechanism should result in gigawatt pulses of coherent x-ray output at a wavelength of 1 Å.

X-ray time-correlation spectroscopy provides a way of investigating dynamics in condensed matter systems. X-ray FELs, by offering enormously increased peak brightness, will substantially expand the scope of that technique. The potential impact on the development of display and information-storage technologies could be great, because freestanding smectic liquid-crystal films, dipolar glasses, and thin-film magnetic materials could be examined by x-ray intensity-fluctuation "speckle" spectroscopy. One could acquire single-shot speckle patterns and thus, in principle, extend the study of condensed matter dynamics to the limit of the FEL repetition rate.

Using photon-induced coherent lattice motions to drive specific structural rearrangements, one might be able to create novel structures in condensed matter. Furthermore, the decay of these prepared states could serve as a new technique for characterizing materials. These coherent lattice motions might give us a new class of probes for studying the dynamics of structural and magnetic order at short length scales. That could be especially valuable for the study of fast switching in magnetic materials, which could lead us to future information-storage technologies. The extremely high fields that x-ray FELs produce can also be exploited in studies of the nonlinear optical properties of materials. They might even make it possible to create and probe plasmas as dense as solids.

Looking even farther ahead, we envision a particularly exciting prospect: the determination of detailed

structure from single biomolecules, even as the x-ray laser light blows the molecule apart. Figure 5 shows the simulation of such a microcataclysm. This approach would eliminate the need for crystallization required by conventional x-ray diffraction techniques. That would open a vast array of biomolecules that cannot be readily crystallized—membrane proteins, for example—to structural examination. But the FEL requirements are daunting: The x-ray source would have to provide enough intensity to obtain a diffraction pattern so quickly that radiation damage does not dominate the observed pattern. To examine a single lysozyme molecule, for example, one would need something like 10^{12} photons delivered to a 100-nm spot in 50 femtoseconds. That level of performance is beyond the initial goals of even the proposed SLAC x-ray FEL. But it is clearly a part of the frontier landscape we look forward to.¹²

Industry and defense

The unique ability of the FEL to produce copious light at desirable wavelengths opens the door to opportunities beyond science. Their ability to produce high average power suggests important industrial and defense applications. One gets high average power from an FEL by increasing the pulse repetition rate as well as the energy in each pulse. For industrial applications, costs are critical, but FELs could become economically attractive when the average power exceeds 10 or 20 kilowatts.¹³ For consumer goods, one needs to get operating costs below about half a cent per kilojoule and capital expense below \$200 per watt. For military applications, cost is less relevant, but the power requirements approach a megawatt.

The efficient generation of high average power has been the primary design objective of the Jefferson Lab's FEL. It has already exceeded 2kW at a wavelength of 3.1 μm . The spent electron beam is recirculated through the accelerator to recover its energy. That scheme not only increases efficiency but also decreases the need for radiation shielding. The laboratory is now extending operation of the FEL to the ultraviolet, increasing the average power capability to 10 kW, and exploring both industrial and defense applications.¹⁴

Among prospective industrial applications, micromachining has the greatest near-term potential. Work in that direction should also help resolve technical issues facing other applications such as large-area thermal processing and pulsed-laser deposition.¹⁵ The simplest micromachining applications are ink-jet printer heads and fuel-injector orifice plates. Both require drilling hundreds of millions of very small holes, precisely arrayed in a variety of patterns. More complex hole-boring applications concern boundary-layer control panels for aircraft and spinnerets for making synthetic fibers. Even more challenging is the use of FELs to cut printed wiring boards. Carving complex profiles for microelectromechanical systems takes us to yet another level of complexity.

At present, laser micromachining is based on nanosecond YAG lasers that deliver tens of watts to a single workstation, at a pulse repetition rate of perhaps 10 kHz. With FELs, one could look forward to picosecond (rather than nanosecond) pulses, higher repetition rates to cut more rapidly, and very high intensity for ultrafast

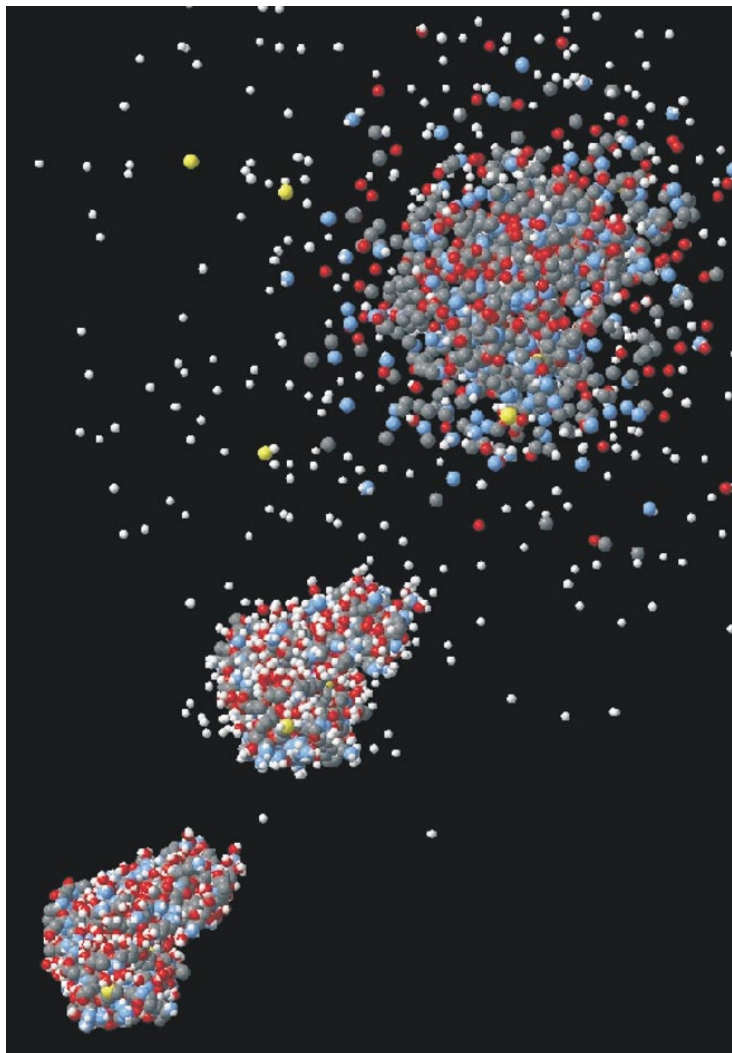


FIGURE 5. SIMULATED EXPLOSION of a single protein molecule (T4 lysozyme) by 12-keV x rays in a 50-femtosecond pulse of 3×10^{12} photons focused on a 100-nm spot. At lower left is the intact molecule before the pulse. In the middle, the pulse has ended but electrostatic repulsion has not had time to disperse the fragments, so that the diffraction pattern is not dominated by radiation damage. At upper right, we see the debris after another 50 fs. (Courtesy of J. Hajdu, Uppsala University, Sweden.)

cutting. Among the advantages of ultrafast cutting would be a substantial reduction of debris problems. This cutting mode will require pulse energies above 100 μJ , and it will tolerate repetition rates as high as 1 MHz. FELs can do both. Because ultrafast cutting has the virtue of being largely indifferent to wavelength, one could choose the FEL wavelength to optimize beam transport and optics.

At lower intensities, alternative cutting modes can take advantage of FEL tunability. One can, for example, drill holes precisely at a material's strongest absorption wavelength. (See MJK in ref. 5.) The industrial prospects are now focusing interest on the management of the FEL's array of downstream optical beam lines and workstations.

For high-average-power laser applications, FELs are under active consideration by the defense community. One important issue is the need to defend ships against attack by sea-skimming missiles that travel just a few meters above the surface at perhaps supersonic speed. They cannot be detected until they are a few miles from

the ship, and their ability to make rapid course changes in flight complicates defense. Megawatt lasers have demonstrated their ability to follow and destroy such missiles, but absorption in the atmosphere can cause unacceptable degradation of intensity. The unique advantage of the FEL is its ability to find and operate at the best wavelength for propagation through the atmosphere under prevailing conditions. A feasibility analysis of a shipboard megawatt FEL shows that it is compatible with the space, weight, and power constraints of naval vessels.¹⁶

Not all military applications require high power. At the University of Hawaii,¹⁷ an FEL is being designed for remote sensing of highly dilute levels of atoms, ions, and molecules in the atmosphere. The wavelength agility, spectral brightness, and high peak power of pulsed, phase-locked FELs make them attractive for applications requiring the characterization of diverse chemical species over large volumes of the atmosphere. An important direction for this remote-sensing capability will be study of the environment.

In the first half of the last century, researchers first generated coherent microwave radiation by means of oscillating beams of free electrons. In ensuing decades, bound electrons did the radiating in conventional infrared, visible, and ultraviolet lasers. Now, the FEL brings the free electron beam back to center stage, producing coherent radiation over an even broader range of wavelengths, which can be generated in subpicosecond pulses at very high repetition rates. We look ahead to the exploitation of radiation sources that can make use of both bound and free electrons.

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