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Into the Future at the Speed of Light
The Advanced Photon Science Intitiative

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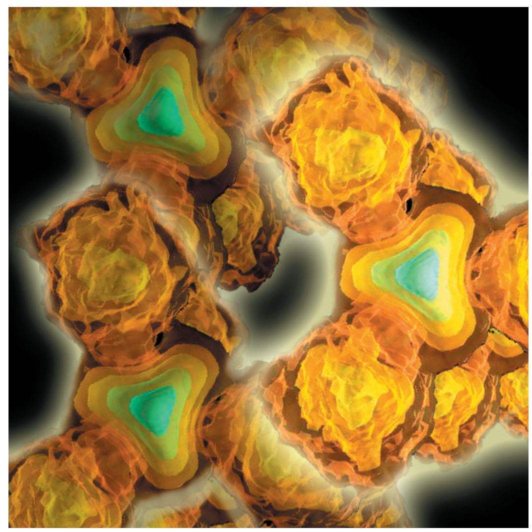
Imagine watching a novel nanostructure assemble at the atomic level, electrons joining forces, atoms snapping together within millionths of a billionth of a second, the real time of chemical reactions.

Imagine using this ability to analyze and ultimately control the magnetic, electronic, photonic, or spin properties of materials—perhaps even to discover the well-hidden secret of high-temperature superconductivity.

It's the kind of prospect the Department of Energy calls a Grand Challenge. But before that challenge can be met, scientists will need a new generation of light sources, superbright and superfast. Because today's most advanced synchrotron light sources are fast approaching their ultimate capabilities, achieving higher flux and brightness while slicing time ever more finely will depend on new devices based on superconducting linear accelerators (linacs) and free-electron lasers, or FELs.



Electron interactions that control chemical reactions and the assembly of nanostructures take place within millionths of a billionth of second, a time scale only now coming within reach of powerful new light sources.

To explore the most promising ideas for new light sources, Berkeley Lab scientists and engineers from the Accelerator and Fusion Research Division (AFRD), the Advanced Light Source (ALS), and the Chemistry, Materials Sciences, and Engineering Divisions have joined together in an Advanced Photon Science Initiative (APSI). APSI is supported by the Lab's Directorate as a strategic initiative and will help guide three research projects funded in this year's Laboratory Directed Research and Development program (LDRD). All are aligned with the potential for a linac-based FEL light source at Berkeley Lab.

Steve Gourlay, Director of AFRD, says, "Through support by work-for-others projects at the cutting edge of accelerator technology and laboratory R&D funds over the past several years, scientists and engineers from the Accelerator and Fusion Research and Engineering Divisions have been honing their skills and developing light source concepts that will give researchers capabilities that exist nowhere else in the world. The next step is an R&D program to turn these ideas into reality. And we are ready to take that step."

Says Roger Falcone, Director of the ALS Division, "The potential of x-ray FELs, for examining ultrafast processes and fine energy structures in chemistry, physics, materials, and biology, is being recognized internationally. At LBNL, we have a world-class group of scientists and engineers who are working to understand the requirements set by grand scientific challenges in these fields—and leading the R&D necessary to build these machines."

AFRD's John Corlett is coordinating the APSI research effort. "Our goal is to develop and clearly articulate the unique scientific applications for these new kinds of light sources, and to define what's needed to achieve them," he says. "To that end, although the results will be widely applicable, we want to get specific about what would be needed for an actual facility, with a vision of a future FEL facility here at Berkeley Lab."

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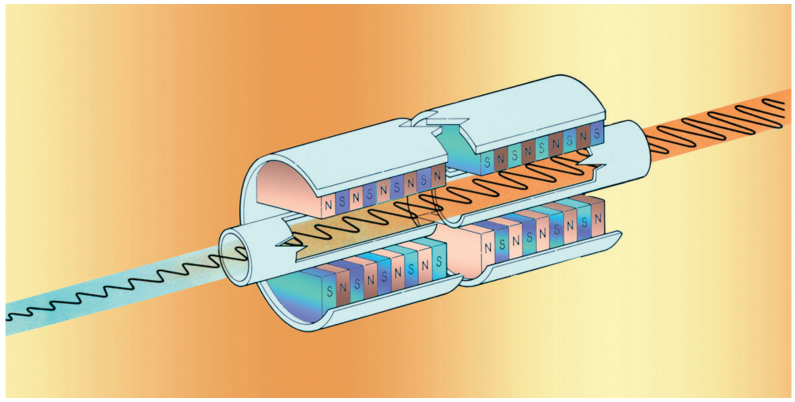
Free electron lasers work by accelerating bunches of electrons to relativistic speeds, then sending the bunches through arrays of magnets called undulators or wigglers; as the electrons slalom back and forth, they emit photons in the direction of the beam. The electron motion is in phase with the emitted light, and the resulting light is coherent, all the same phase—thus, a “free electron laser”—and quickly builds to high intensity. The wavelength of the light is determined by the energy of the accelerated electrons and the arrangement and strength of the magnetic fields used to wiggle them.



In a free electron laser, a relativistic beam of electrons is sent through an undulator, an array of dipole magnets with alternating north and south poles. The magnetic field of the undulator forces each bunch of electrons to oscillate back and forth, causing them to emit a laser-like beam of light.

(Illustration by Flavio Robles, Creative Services Office)

“One great advantage of free electron lasers is their tunability,” Corlett says. “Another important factor is the pulse repetition rate, which is determined partly by the electron source that feeds the accelerator. We are working on designs for sources with megahertz repetition rates”—a megahertz is a million cycles per second—“with excellent electron beam properties.” Important aspects of FEL systems designs include not only advanced photocathodes for electron sources but low-emittance beam control and transport as well.

Corlett notes that since the FEL operation is sensitive to the electron beam distribution, “we are learning how to produce and maintain exquisite beams that will make FELs more affordable. To get the most from an FEL, we also plan to accurately control the lasing process by ‘seeding’ the electron beam with a conventional laser.”

Seeding the beam, feeding the FELs

To “seed” electron accelerator, a conventional laser fires a beam through an undulator as the electron bunch moves through it; the laser beam copropagates with the electron beam.

“As they travel together through the undulator, the electric field of the laser pulse manipulates the electrons locally,” Corlett explains. “The field can force the electrons together into tight, high-energy, rapidly repeating microbunches. This enhances the FEL process, and introduces coherence over the timescale of the laser pulse. Thus we can control the FEL’s x-ray output by manipulating the optical-laser input signal.”

The wavelengths most critical to studies in materials science and chemistry are soft x-rays, in which the Lab’s synchrotron-based Advanced Light Source has core expertise. Optical manipulation through seeding also makes it possible for an FEL to achieve wavelengths in the VUV (vacuum ultraviolet, or “far” ultraviolet) and soft x-ray region. One way is to pass the microbunched electron beam through a second undulator, forcing it to emit light at frequencies that are harmonics (multiples) of the original wavelength. A “cascade” of paired undulators allows even higher harmonics to be reached.

Optical manipulations also allow precise control of the FEL output signal, and particularly the timing and duration of the x-ray pulses. Techniques are being developed to achieve near transform-limited pulses—the shortest possible pulses given the pulses’ optical spectra—of 10 to 1,000 femtoseconds. Even pulses of 100 attoseconds look achievable. (A femtosecond is 10^{-15} second; there are as many femtoseconds in one second as there are seconds in 32 billion years. An attosecond, 10^{-18} second, is a thousand times shorter still.)

“At these incredibly short intervals, synchronization with pump lasers is key to many experiments,” says Corlett, “and Berkeley Lab already has world-class expertise in timing and synchronization systems.”

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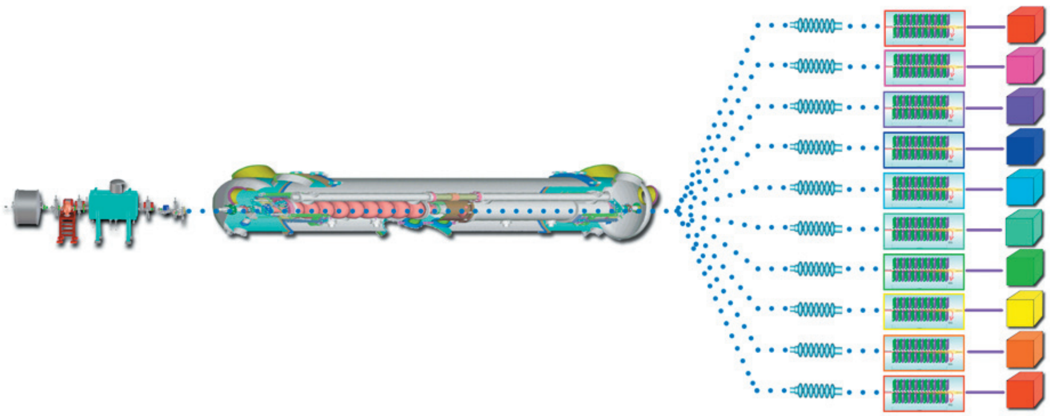
The highest electron beam repetition rates and brightnesses are produced by linacs that use cold, superconducting accelerator cavities. As experimental facilities, however, ring-shaped synchrotron light sources have an advantage over linacs: they can emit radiation virtually anywhere around the ring, so there is room for numerous beam lines and experimental stations. The simplest linac FELs emit only a single, straight-ahead beam.



The next-generation light source facility envisioned for Berkeley Lab would use a superconducting linac to feed 10 or more free electron lasers, each tuned to the user's needs.

One solution, Corlett says, is to distribute the electron beam after it leaves the linac, transporting bunches to several FELs, each of which can be separately tuned and manipulated with a seed laser or other FEL configuration. The facility envisaged for Berkeley Lab would have 10 or more separate FELs feeding off of one main superconducting linac.

This vision for a future light source would turn Berkeley Lab's hilly setting into an asset, by housing the linac in a tunnel that would pass beneath the ridge on the southern edge of the Lab's site and re-emerge at the former location of the Bevatron, where an experimental hall for the array of FELs, x ray beamlines, and experimental end stations would be stationed.

The key elements of such a facility would be a high-brightness, high-repetition-rate, low-emittance electron gun (low emittance means, roughly, a tight beam); systems for conditioning and transporting the high-brightness electron bunches produced by the gun; a superconducting linac that would boost the beam to an energy of 2 billion electron volts (2 GeV), followed by distribution in a beam switchyard to 10 or more FELs.

Each FEL would be individually configured to meet experimental needs of the particular beamline, and tuned to a precise wavelength between extreme ultraviolet and soft x-rays, with a specific pulse duration —from femtoseconds to as short as 100 attoseconds—and the particular polarization desired by the experimenter.

Challenging research to meet a Grand Challenge

Corlett names some of the crucial physics and materials sciences questions that must be answered to realize the potential of such a facility:

- The electron gun. The electron source will use a photoemission cathode at megahertz pulse rates, "producing electrons with high efficiency by knocking them off the cathode material with a laser beam." After selecting the best photocathode designs, researchers plan to test them in APEX, the Advanced Photoinjector Experiment proposed for the ALS's Beam Test Facility, a novel electron injector featuring high repetition rate and high brightness for a range of future light sources.

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- The electron beam. High-resolution computer modeling and accelerator design will be used to understand and control the many perturbative effects that can deteriorate the electron beam's brightness. The multiplex FEL facility's linac will require continuing research into the design of superconducting accelerating cavities and cryomodules, work that would be based at collaborating institutions having expertise in these fields.
- The switching yard. To distribute the accelerated electron bunches to the individual free electron lasers requires fast "kicker" magnets and other advanced means to send selected bunches of electrons from the single high-repetition-rate linac to each of the FELs.
- A range of free electron lasers. Finally, the researchers will study the design of the free electron laser systems to insure a range of controlled, coherent, x-ray pulses that can meet a wide variety of user requirements. "We want to examine different techniques for FEL configurations matched to scientific needs," Corlett says, "including harmonic cascades, seeding with very high frequency lasers using high harmonic generation in gases, self-amplified spontaneous emission, careful shaping of the x-ray pulse, and other methods."

Corlett is sanguine about the prospects of important advances in the whole field of free electron lasers that has emanated from work done at Berkeley Lab and will continue in future.

"We have done critical work in all these areas, from the physics of accelerators to high-powered optical lasers to free-electron lasers, and from advanced accelerator modeling to materials and surface science," he says. "Through the Advanced Photon Science Initiative, Berkeley Lab is ideally suited to perform this research. The Lab has the expertise needed to help advance the field."

Additional information

More about Berkeley Lab's contribution to FERMI@Elettra, the free electron lasers now under construction at the Italian light source near Trieste is at http://www.lbl.gov/today/2006/Aug/04-Fri/Elettra_pdf_FINAL.pdf

More about seeded harmonic cascades is at http://www.lbl.gov/Science-Articles/Archive/sabl/2007/Jan/free-electrons.html

More about synchronizing accelerator components on femtosecond and attosecond time-scales is at http://www.lbl.gov/Science-Articles/Archive/sabl/2007/Jun/nSync.html