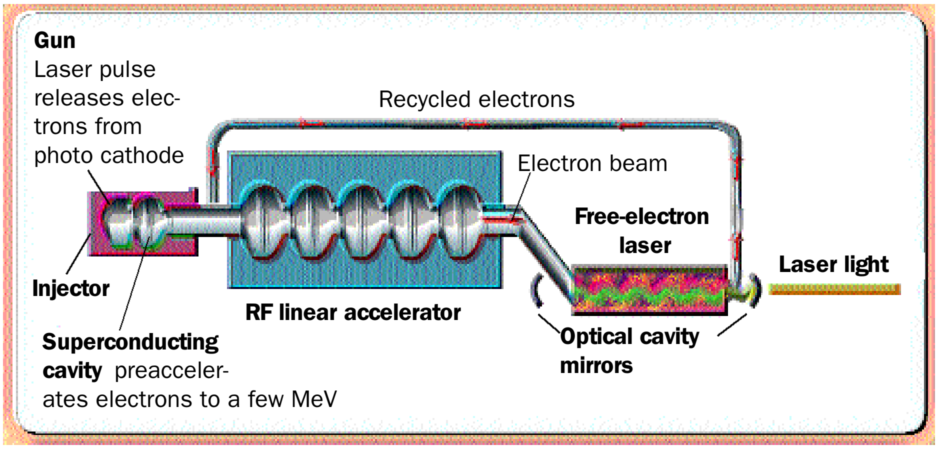
by Jennifer Ouellette

Free-Electron Lasers: A Radical Alternative

Free-electron lasers (FELs) are coming of age as a radical alternative to conventional lasers, not only for physics research, but also for commercial applications in areas such as metallurgy, aerospace, polymer processing, microprocessing, and micromachining. Some obstacles to widespread commercial use remain, but groups like the Laser Processing Consortium (LPC), formed in 1993 by the Thomas Jefferson National Accelerator Facility (the Jefferson Lab) in Newport News, Virginia, are hoping to make FELs the most powerful, versatile, and economical light source available.



The heart of the laser is the wiggler, in which a sinusoidal magnetic field converts electron energy into light. Varying the strength of the field can change the wavelength, giving tunability.

Photochemical processing dates to the 1920s, according to Michael Kelley of DuPont Central Research and Development (Wilmington, DE), but it never gained widespread acceptance in industry, apart from high-value-added processes such as lithography for microelectronics. The advent of lasers some 35 years ago and the subsequent development of thermal processing brought renewed interest in industrial applications for light. But for the most part the power levels, the cost per kilojoule of light, or the emission wavelengths of the available lasers prevented them from seeing widespread industrial use.

FELs use beams of unbound electrons rather than electrons bound to atoms or molecules to generate tunable, coherent, high-power radiation. Electrons boosted to relativistic speeds by an accelerator or other source are passed through the alternating magnetic field generated by a wiggler, which causes them to emit energy in the form of synchrotron radiation.

FELs currently span a wavelength range extending from millimeter waves to ultraviolet radiation and could potentially reach X-ray wavelengths. They share the optical properties of conventional lasers, such as monochromaticity and spatial coherence, but they also offer more flexibility in operating wavelengths because they can be tuned over a wide range by changing the kinetic energy of the electrons in the driver accelerator.

Existing FELs

There are about 12 FELs worldwide at institutions such as Stanford University; Duke University; Vanderbilt University; the University of California at Santa Barbara; the CLIO facility in Orsay, France; the FELIX facility in Rijnhuizen, Netherlands; and CIRFEL, a collaborative effort between Princeton University and Northrop Grumman (Los Angeles, CA). Most are used for research in solid-state, nuclear, or molecular physics, the biosciences, and medicine. FELs have also been proposed or are under development at Brookhaven National Laboratory, the University of California at Los Angeles (UCLA), and Germany's DESY facility.

Several groups, including ones at Lawrence Berkeley Laboratory, Brookhaven National Laboratory, and UCLA, are experimenting with FELs that can operate at UV or X-ray wavelengths. One of the primary obstacles to designing a laser that emits at these wavelengths is that short-wavelength mirrors have very low reflectances; this makes it difficult to achieve gain in an oscillator cavity defined by mirrors at its ends. One solution is the laser-driven radio frequency (rf) photocathode electron source, invented at Los Alamos National Laboratory. By shining a laser probe on a photocathode in the presence of an rf field, which accelerates the electrons away from the cathode, scientists have been able to produce electron beams bright enough for extremely high-gain wigglers. If enough gain could be obtained in a single pass, the mirrors would no longer be needed. A feasibility study for an X-ray FEL is now underway at the Stanford Linear Accelerator Center and DESY.

However, the biggest push for commercialization of FELs has come from the facility now being built by Jefferson Lab, supported by its industry-led consortium. The aim of the LPC—comprising the lab itself, twelve companies and eight universities—is to develop and build a commercially manufactured, rugged, economical, high-powered FEL that can be deployed at any plant site. So far, industry has pledged $15 million of experimental equipment support, with the Office of Naval Research providing $8.1 million in FY96 funding and the Commonwealth of Virginia committing $5 million.

The strategy is to develop a FEL based on rf acceleration by superconducting cavities, according to Frederick Dylla, who is heading the project. A superconducting cavity can sustain high field gradients efficiently, which in turn allows the system to be more compact, an important factor for commercial and military applications. The current FEL prototype at Jefferson Lab, which occupies a 15m by 60m footprint and costs roughly $30 million, is simply too big and too expensive for these applications.

In addition, standard room-temperature, copper-cavity accelerators dissipate much of the drive energy as heat, which is deposited in the walls of the accelerator cavity. To avoid overheating problems, they can be operated only about 1% of the time. Superconductors have no resistance to the flow of electricity. "It's essentially a tradeoff between the cost for the refrigerator, which you need for the superconductor, versus the energy that is wasted in a different accelerating system that doesn't require that kind of cooling," said Alan Todd of Northrop Grumman, an LPC member.

The Free Electron Laser Research Institute (FELI) in Osaka, Japan, is also interested in developing an industrial FEL, according to Research Director Takio Tomimasu. Its scientists have developed many associated technologies and devices, including a high-intensity electron accelerator and electron-beam transport system, and a high-accuracy wiggler for shaking the light out of the electron beam. In addition to achieving laser emission in the IR, visible, and UV regions, they are developing new optical technologies that make use of the FEL's tunability.

Applications ahead

One of the most promising applications for FELs is polymer surface processing, according to Kelley. Laser processing is more environmentally friendly than the wet chemical processes currently used. For example, by transforming amide groups to amine groups, short-wavelength UV light can be used to produce antimicrobial materials, such as mildew-resistant fabric for shower curtains, and packaging that prevents food spoilage.

"The problem has been to produce material in the kinds of quantities necessary to have a viable business in industry," said Kelley. According to the Fiber Economics Bureau, by the end of 1997 industries worldwide will have produced more than 40 billion pounds of artificial and synthetic fiber, excluding other polymer applications such as food packaging—an annual surface area equivalent to more than half the land area of the United States.

FELs could also enable more efficient production of microscopic machine components. Micromachining is broadly defined as the technology used to create features smaller than could be made with established mechanical methods, such as drilling, cutting, punching, or electrical discharge machining, and excluding technologies in which lithography is a critical step. Because of the wavelength flexibility of FELs, manufacturers would be able to drill smaller holes with less heat damage to the surrounding area.

Two high-volume micromachining applications are the orifice plates used in the fuel injectors of all automobiles and many light trucks, and the orifice arrays in ink-jet printer heads, which together total as many as a billion holes drilled annually. "Desired improvements over conventional technology for these applications include smaller size, greater aspect ratio, and greater materials versatility," said Kelley. "However, these must not come at the sacrifice of scale of production and unit cost."

FELs could also bring about revolutionary changes in the field of metallurgy, according to Daniel Henkel, president of Henkel Metallurgical Technologies (Palmer, MA), another LPC member. Metal surface processing with lasers is predominantly thermal processing, accomplished either by melting the metal's surface and rapidly cooling it, or by transforming the microstructure of the surface by methods such as annealing.

For example, melting can result in an increase in the chromium-to-iron ratio in stainless steel, improving corrosion resistance. Freezing a metal in a glassy state eliminates grain boundaries so that the material doesn't form cracks as easily, improving fatigue life by as much as two orders of magnitude. This process can completely prevent water-drop erosion of stainless steel. FELs could also be used to make what are called functional-gradient materials, coatings made of many nanometer-thick layers.

The U.S. Navy is interested in the potential of IR FELs for shipboard defense against guided missiles. Its researchers hope to use Jefferson Lab's facility to learn more about the propagation of IR lasers in air and the damage they do to materials. "Lasers might become fundamental weapons in modern-day warfare because they could provide a low-impact, surgical way to shoot down planes or missiles," said Bill Colson, who chairs the physics department at the Naval Post Graduate School in Monterey, California.

Medical applications FELI is proposing include polishing and surface hardening of the teeth, as well as the removal of hemorrhoids, using a wavelength of about 9.4 μm. FEL lasers with a wavelength of 6.4 μm could be used as laser scalpels, or to puncture the cell membrane of a lymphocyte without damaging the cell's cytoplasm. "It is entirely conceivable that a new medical equipment industry may be based on the FEL laser's medical uses," said Tomimasu.

Challenges

One of the largest drawbacks to FELs has been their low power levels. The current record for an FEL is 10 watts, achieved at Vanderbilt University. The initial goal of the Jefferson Lab FEL is to demonstrate a kilowatt in the infrared. Still, power requirements for most of the commercial applications envisioned by the consortium range between 10 and 100 kilowatts, with military applications requiring even greater power levels. "We still have a long way to go in terms of power," Todd concedes. "But we do believe we see a path for getting to those kinds of power levels."

However, there is a market for low-power FELs (1 to 100 watts) for medical applications and materials research. "We're hoping low-power FEL systems will become as common as electron microscopes in universities and labs around the world," said Colson. Northrop Grumman and Boeing (Seattle, WA) are interested in manufacturing and selling both large and small FEL systems and services to academia and industry.

On paper, at least, FELs such as that under development at Jefferson Lab have shown the capability to meet the stringent requirements for broad-based industrial applications. It remains to be seen whether this potential can be translated into real-world success. "It's not so much a technology push as a pull, in the sense that we know the economic targets that have to be met by the system," said Todd. "We know that if we can hit those targets, the commercial applications are there."