extremely erratic at the boundaries and led to severe anoxia of the oceans and reduced temperature gradients. The biological effects of these extreme changes in terms of extinction profile might depend, says Kauffman, on how stressed the biota is from other environmental conditions, such as sea-level shifts. The same might be said for the effects of asteroid impact.

Comparison of all the mass extinctions is clearly a good way to look for patterns of causality, if such exist. Jablonski has done this and concludes that "marine regression is the most impressive common denominator." There are, of course, extinction events that coincide with transgression, not regression; and some regressions appear to leave the biota unscathed. Some of these differences might be accounted for by differences in the starting point of the regression, he suggests. Nevertheless, the pattern is clearly not simple.

One very consistent pattern of mass extinctions, however, is that although each event typically affects different suites of organisms, tropical biotas are nearly always hardest hit, for which there might be several explanations. For one thing, there is always a species diversity gradient from high in the tropics to low in temperate regions, and so there could be a statistical element in the bias toward tropical extinctions. But there are real biological properties that might bear on this too.

For instance, some clades, that is evolutionarily related groups of species, contain many species while others are species-poor. It often happens that species-rich clades have a high rate of extinction, which is matched by a high rate of speciation. In species-poor clades low extinction rates are paired with low speciation rates. Jablonski has shown that during "normal" times of background extinction there is no extinction bias towards either type of clade. During mass extinctions, however, species-rich clades are differentially affected: they suffer more, as might be predicted. Survivors tend to be generalist organisms that are not geographically provincial. (Provinciality turns out to be a very important determinant of vulnerability to extinction.)

As the tropics have a disproportionately high number of species-rich, geographically provincial clades, it is not surprising that this area of the world suffers disproportionately during mass extinctions. These, and other data, lead Jablonski to conclude that "macroevolutionary processes may be qualitatively different during times of background extinction and times of mass extinction."

The study of mass extinction has traditionally focused on the victims of the events. There was at the Flagstaff meeting, however, a strong undercurrent of feeling that more attention to the nature of survivors would provide keen insights into the larger patterns of extinctions and the overall history of life. Geerat Vermeij, of the University of Maryland, is beginning to probe this topic by looking at refuges to which certain species become restricted during mass extinctions. And in the ecological realm it would be extremely valuable to know how resilient various species are to extinction when faced with environmental perturbations of various magnitudes.

Vermeij was not being especially humble when he said, "I feel profoundly ignorant about the nature of extinction." He had articulated what many had felt. The Flagstaff meeting illuminated this large and supremely important subject by showing how very little is known in the face of how very much there is to be known.—ROGER LEWIN

A Visible Free Electron Laser in France

A string of firsts for an Orsay-Stanford collaboration: the first free electron laser in the visible, in a storage ring, and in Europe

A French-American collaboration working at the Laboratory for the Utilization of Electromagnetic Radiation (LURE) of the University of Paris–South in Orsay has reported the successful operation of a free electron laser that emits light in the red-orange region of the visible electromagnetic spectrum. The demonstration is the first of a number that are expected to roll in over the next several months as several second-generation free electron laser projects begin to bear fruit. "These are very exciting times for free electron lasers," enthuses George Neil of TRW, Inc., who heads one of these efforts.

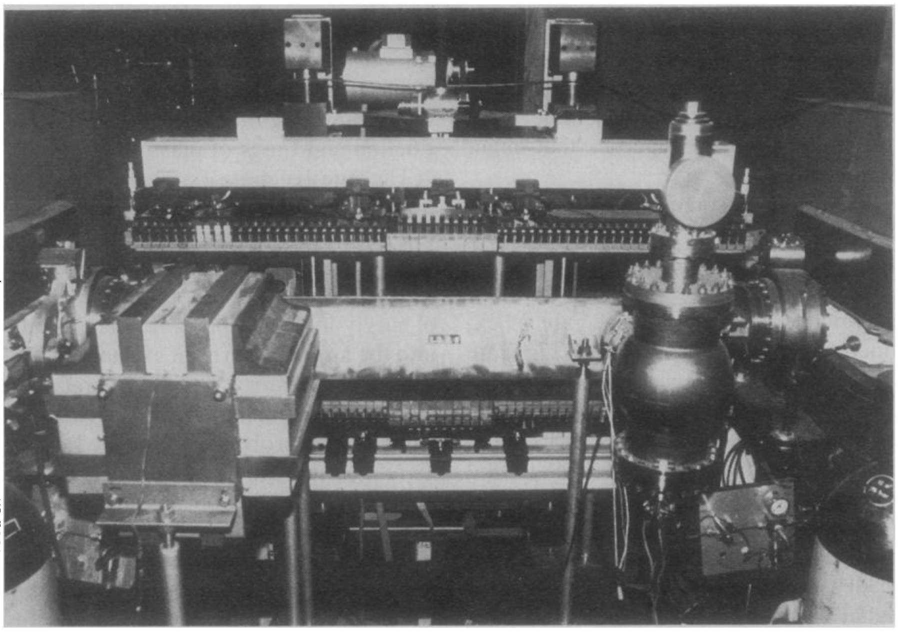
Free electron lasers combine the tunability associated with synchrotron radiation with the high brightness and coherence of conventional lasers and thus constitute an unparalleled tool for spectroscopic and structural investigations of all manner of samples. At the same time, free electron lasers offer the potential for exceptionally high efficiencies for the conversion of electrical to optical energy. This makes them candidates for the huge monsters that would be needed for commercial and defense applications.

In the commercial sphere only infrared carbon dioxide lasers are efficient enough to make them cost-effective for industrial materials processing, such as welding and cutting of metals. And, except for specialized processes like enrichment of uranium-235, no laser is currently a sufficiently inexpensive light source for laser-induced photochemistry.

On the defense side, applications are by nature more speculative, but high-power, short-wavelength lasers are much discussed for missile defense. Free electron lasers have also been mentioned as possible drivers for laser fusion, which can be used for both civilian energy production and nuclear weapons simulation. Most of the free electron laser research in the United States is sponsored by the Department of Defense, which has cautioned some of its contractors not to discuss research results without prior clearance.

Free electron lasers are so named because the electrons that generate the laser light are not bound to atoms in molecules or solids, as is customary. Instead, they are "free" particles in a high-energy, accelerated beam. When the beam passes through an array of magnets (an undulator) that forces it into a sinusoidal trajectory, it emits light. The principle is the same as that which causes synchrotron radiation in circular electron accelerators.

The wavelength of the light emitted is determined by the energy of the electron beam, the spacing between the magnets in the undulator array, and the strength of the magnetic field, rather than by the quantized energy levels of atoms, molecules, and solids. Hence, free electron



Deacon Research

Optical klystron

The array of dipole magnets comprising the optical klystron is shown here in the open position. During free electron laser operation, the jaws of the array fit closely around the electron beam pipe. The strength of the field can be adjusted by varying the vertical gap between the magnets.

lasers can, at least in theory, emit at any wavelength from microwaves to x-rays, although a single device would not cover the entire range.

Given the promises of free electron lasers, the LURE experiment is highly interesting. It marks the first time a free electron laser has emitted visible light; previous devices had given off radiation at infrared or longer wavelengths. It also signals the first use of an electron storage ring with a recirculating beam through the laser; in the first generation, a linear accelerator passed the beam through the laser only once. An extra wrinkle at LURE was the first use of a magnetic structure called an optical klystron in place of the more common undulator.

The idea of a free electron laser traces back to Hans Motz of the University of Oxford, who discussed the concept when he was at Stanford University in 1951. The modern "father" of one branch of the free electron laser family is John Madey of Stanford, who became intrigued with the devices as a student at the California Institute of Technology. At Stanford, Madey got Air Force money to pursue his dream.

Madey's experiment made use of the superconducting electron linear accelerator at Stanford and a 5.2-meter-long undulator. The undulator consisted of superconducting windings in a helical pattern so that the transverse magnetic field direction rotated around the axis of the undulator with a period of 3.2 centimeters. The first result (by Luis Elias, William Fairbank, Madey, Alan Schwettman, and Todd Smith) was the demonstration of "gain" in 1975. A 24-million-electron-volt (MeV) beam of electrons and a carbon dioxide laser beam of wavelength 10.6 micrometers passed together through the undulator. Energy passed from the electron beam to the laser beam, increasing its intensity, which constituted the gain.

The demonstration of lasing (by David Deacon, Elias, Madey, Gerald Ramian, Schwettman, and Smith) came in 1976. Mirrors placed 12.7 meters apart at either end of the undulator formed an optical cavity. The electron beam energy was raised to 43 MeV, but no laser was used. Light emitted by the electrons (spontaneous emission) as they passed through the undulator reflected back and forth in the cavity, increasing its intensity with each pass by withdrawing energy from the electron beam. The result was laser light at a wavelength of 3.4 micrometers. The shorter wavelength as compared to the gain experiment follows from the higher electron beam energy.

The spontaneous emission of light by the wiggling electrons is a kind of synchrotron radiation, and the amplification of that light in the laser optical cavity is described similarly. If the laser light and the oscillatory electron motion have the correct phase, the electric field of the laser light wave will slow the electrons down. The lost kinetic energy transfers to the light wave, increasing its intensity.

To describe this process in detail, theorists use two quite different approaches, which delineate the two main branches of the free electron laser family tree. If the density of electrons in the beam is low, they can be treated as independent particles. If the electron density is high, theorists must treat the particles collectively as a kind of plasma. The Stanford free electron laser was of the first type. In 1978, researchers at the Naval Research Laboratory and at Columbia University jointly demonstrated a free electron laser of the collective type. Because present technology limits high beam currents to electrostatic accelerators and hence to low beam energies, and because the electron density needed to enter the collective regime increases with the beam energy, free electron lasers of this kind are necessarily very long wavelength sources. The NRL/Columbia device used a 1.2-MeV electron beam and emitted radiation in the far infrared at about 400 micrometers.

In the years since these first demonstrations, free electron laser research has taken a number of directions. One, of interest for future commercial and military applications, is to increase the efficiency of energy extraction from the electron beam from a fraction of 1 percent to a much higher value. A group at NRL reached an efficiency of 2.5 percent in a more recent laser experiment, and researchers at the Los Alamos National Laboratory have attained 4 percent in a gain experiment.

Another direction is to make free electron lasers that operate at shorter wavelengths, from the visible to the x-ray region, for example. This is where the LURE-Stanford collaboration comes in. Among the radio-frequency accelerators that are needed to reach high electron beam energies (and hence short wavelengths), storage rings can handle higher electron current densities than linear accelerators can, at least up to now. To achieve a constant gain as the laser wavelength decreases, the current density must increase, which makes storage rings the best candidates for ultraviolet and x-ray free electron lasers.

The French-American collaboration began in 1979. LURE is headed by Yves Petroff, who succeeded Yves Farge, the originator of the project. French members of the collaboration are Michel Billardon, Pascal Ellaume, Jean-Michel Ortega, Claude Bazin, Michel Bergher, and Michel Velghe. Stanford contributed Madey, Deacon, and Kem Robinson. The LURE storage ring, named ACO, is mainly used as a source of ultraviolet synchrotron radiation and has a maximum beam energy of 536 MeV. At the start, the group had access to a superconducting undulator, the first device of its kind to produce useful amounts of light from a storage ring.

In what turned out to be a blessing in disguise, the undulator "burned up" after about 6 months of use and was scrapped. To replace it, the investigators called on Klaus Halbach of the Lawrence Berkeley Laboratory, who was designing wigglers and undulators that used rare earth–cobalt permanent magnets (*Science*, 18 March, p. 1309). Rather than helical windings, the permanent magnet undulator consists of an array of dipole magnets so that the orientation of the field alternated between pointing upward and downward, thus wiggling the electrons approximately sinusoidally in the horizontal direction. Not only was the new magnet less cumbersome to use but the optical quality of the undulator light was considerably improved.

A particular limitation of ACO is that it is quite small, 22 meters in diameter, and the space for the undulator is limited. This is unfortunate because the gain of a free electron laser increases with the cube of the length of the undulator. In order to get lasing, the gain has to exceed a certain value set by all the ways light can be lost in the optical cavity. The original Stanford free electron laser had a gain of about 15 percent with its 5.2-meter-long undulator. The 1.3-meter undulator at LURE would thus give a gain reduced by a factor of 100. To get lasing at all, everything would have to work perfectly.

As it happened, the mirrors forming the laser optical cavity posed a problem. Although magnificently reflecting by ordinary standards (loss of less than one part in 10^4), they deteriorated when placed in the free electron laser. One effect, apparently due to the high vacuum of the storage ring, increased the losses to 3.5×10^{-4} for each of the two mirrors. A second effect, traced to radiation damage by the spontaneous ultraviolet emission of the undulator, gradually lowered the reflectivity further until, after a few hours, the mirrors were useless. In one experiment with an argon ion laser of wavelength 4880 angstroms and a beam energy of 243 MeV, the group measured a gain of 1.5×10^{-4}, too small for lasing with mirror losses alone totaling 7×10^{-4}.

One remedy was to replace the undulator with an optical klystron, a concept invented by A. N. Skrinsky and N. A. Vinokurov of the Institute for Nuclear Physics in Novosibirsk. What this actually meant was that the center section of the 17-period undulator was replaced with a second set of rare earth–cobalt permanent magnet dipoles, thereby converting the three central periods into one long period of about 50 percent higher field strength. The reason for such a configuration is that it enhances the tendency for electrons, which travel in discrete bunches of particles with a distribution of speeds, to clump together in even tighter bunches with a smaller variation in particle speed. Bunching is a critical aspect of free electron lasers because, if it does not occur, some electrons will draw energy out of the laser beam rather than add to it. Bunching occurs naturally if the undulator is long enough. The optical klystron artificially speeds up the bunching by forcing electrons into a large oscillation in their trajectory during which slow electrons can catch up with those slightly faster.

The optical klystron worked right away, when tried early last summer. In one experiment at 5145 angstroms, the gain increased by a factor of 5.

Solving the mirror problem has yet to be accomplished. To achieve lasing, the LURE group in effect sidestepped it by lowering the electron beam energy. At 150 MeV, the undulator produced hardly any ultraviolet light, thus sparing the mirrors from damage. Unfortunately, storage rings have minimum as well as maximum operating energies, and 150 MeV is ACO's minimum. As a result, the current density that could be stored was too low to allow much gain. But by raising the beam energy slightly to 160 MeV, the gain was raised to 9×10^{-4}, just enough to cross the threshold for lasing, which was achieved on 20 June.

In 13 tries over the last month, lasing occurred every time.

The result is no fluke. According to Petroff, in 13 tries over the last month, lasing occurred every time. Moreover, the lifetime of the laser increased from 10 minutes in the first test to a typical value of 1 hour now. The time limitation is due to ACO, which stores beams for long times only at beam energies well above its minimum. Finally, in a finding that was unexpected, the free electron laser itself enhances the bunching process and thereby makes the storage ring more stable. Previous experiments at low beam currents and higher energies had shown that the spontaneous emission of the undulator lengthened rather than compacted the bunches.

As for the future, the space limitation of ACO means that there is no possibility of a very bright free electron laser there because of the low gain. The peak power output of 60 milliwatts could be raised somewhat if lasing could be achieved with the undulator rather than the optical klystron. Somewhat paradoxically, the undulator more efficiently transfers energy from the electrons to the laser beam than the optical klystron does, even though the gain is lower. The use of positrons rather than electrons in the storage ring would also help. The negatively charged electrons tend to attract residual ions in the evacuated beam pipe, and this has deleterious effects on the stored beam. Finally, the lack of ultraviolet-resistant mirrors limits laser wavelengths. Petroff hopes eventually to be able to generate laser light over the range from 3500 angstroms to 1 micrometer. And the physics of the device can also be explored in detail.

Elsewhere, Claudio Pellegrini, Alfredo Luccio, Arie van Steenbergen, and Lihua Yü of Brookhaven National Laboratory are in the midst of a free electron laser project using the 800-MeV storage ring of the National Synchrotron Light Source. With a longer undulator (2.5 meters) and a higher beam current density than at LURE, the gain could reach a few percent. Subject to the availability of mirrors, an ultraviolet free electron laser is also a possibility. And, at the Frascati National Laboratory of the National Institute of Nuclear Physics near Rome, a Frascati–University of Naples collaboration is well along on a visible free electron laser in the ADONE storage ring.

At Stanford, Madey has begun building a dedicated storage ring for free electron laser research. The new ring will reach an energy of 1.0 billion electron volts (GeV) and have a very high current density. Lasing in the soft x-ray region down to about 50 angstroms could be achieved, if mirrors can be developed that reflect x-rays and that resist radiation damage. With a 20-meter space for the undulator, the gain would be high enough that the mirrors would not have to be nearly as good as those at LURE; a 40 percent reflectance would do. An expensive part of all storage rings is the accelerator that injects the electrons. Madey is fortunate that Stanford's mothballed Mark III electron linear accelerator can be refurbished for that purpose. The ring itself will go in an empty Mark III experimental hall. All in all, the project will take 3 years to complete and will cost $6.3 million.—**Arthur L. Robinson**

Additional Reading

1. *IEEE Journal of Quantum Electronics* **QE-19**, 271 (March 1983). This is a special issue on free electron lasers.