Far IR Free Electron Laser at Santa Barbara

An electrostatic accelerator whose beam recirculates helps make a high-power tunable laser for an underdeveloped spectral region

The latest entry in a gradually lengthening list of free electron laser demonstrations comes from the Quantum Institute of the University of California at Santa Barbara, where on 21 August physicists operated for the first time a unique far infrared laser. Unlike previous machines, which were put together to test free electron laser concepts, Santa Barbara's will be used quite quickly by in-house and visiting scientists interested in exploiting its high-power and tunable far infrared radiation.

In its first three tests, the laser operated at a wavelength of 400 micrometers, putting out 11-microsecond-long pulses of 3000 watts peak power at a rate of 1 per second. The design specifications, which should be approached as the machine gets broken in, call for a peak power up to 18,000 watts, pulse lengths as long as 200 microseconds, and a repetition rate of 20 per second. Moreover, further improvements are already scheduled, which will double the peak power output and raise the maximum value of the time-average laser power to 3000 watts from the present 100 watts.

With a planned wavelength range from 100 to 500 micrometers, the Santa Barbara free electron laser is in the midst of the far infrared, which the International Union of Pure and Applied Chemistry defines as extending from 50 to 1000 micrometers. Some prefer to call these long wavelengths the submillimeter region. In either case, there have never been sources of this radiation that emit intensely and over a broad range of wavelengths, notes Vincent Jaccarino of Santa Barbara, who will be one of the first users.

Free electron lasers convert the energy of relativistic electrons in an accelerator to electromagnetic radiation. The conversion takes place when the electrons pass through a magnetic structure called an undulator that impresses, depending on the design, either a sinusoidal or helical motion on top of the normal trajectory, which generates synchrotron radiation mainly in the direction of the electron beam. As in any laser, this spontaneous emission then stimulates further radiation, in this case from the wiggling electrons. Reflecting mirrors at each end of the undulator form an optical cavity for the build up of coherent laser radiation.

The wavelength of the laser radiation is dictated primarily by the periodicity of the undulator (usually a few centimeters) and by the electron beam energy and secondarily by the strength of the magnetic field in the undulator, as expressed in a resonance condition. Since the undulator period is fixed, the wavelength range of the free electron laser depends mainly on the maximum and minimum energies of the accelerator.

That much is common to all free electron lasers. Santa Barbara's is different in several respects. Most laser optical cavities or resonators consist simply of reflecting mirrors at each end and are otherwise open. Because of the long wavelengths in the far infrared, it is difficult to keep the laser beam squeezed down to a small diameter in a resonator with no confining walls. If the beam is too large, the magnetic field in the undulator drops, reducing its effectiveness. A waveguide could contain the beam but introduces losses in intensity that make lasing more difficult. Project director Luis Elias and his colleagues have designed a metallic waveguide with confining top and bottom strips but open sides that minimize the losses.

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A more substantial difference is in the accelerator itself. Santa Barbara's free electron laser uses an electrostatic (Van de Graaff) electron accelerator with a maximum beam energy of 3 million electron volts (MeV) now and 6 MeV when upgraded next year. Previous free electron laser demonstrations used radiofrequency electron linear accelerators or electron storage rings with energies up to 160 MeV. According to Gerald Ramian, who came with Elias from Stanford University, where the very first free electron laser was demonstrated 8 years ago, the choice was dictated by the superior properties of electrostatic accelerators when low energy beams are of interest.

In particular, the accelerator permits an uncommon wrinkle that has turned out to be essential for Santa Barbara's laser operation—it both accelerates the initial electron beam and it decelerates the beam after it has passed through the undulator. The overall path outside the accelerator is rectangular with the undulator and optical cavity in one leg. The undulator is an array of samarium-cobalt permanent magnet dipoles of alternating up and down field direction. Once back in the accelerator and decelerated, the electrons are collected for reuse.

Recirculation of the beam has at least two benefits. The first is efficiency. An overall efficiency (wall plug to light) of 50 percent has been speculated upon but not yet demonstrated. With ordinary undulator designs, only a fraction of 1 percent of the electron beam energy gets converted into light per pass through the undulator, plainly an inefficient process if the beam is used once and then lost.

The key to energy efficiency is the deceleration process. In an electrostatic accelerator, electrons are generated and transported on a belt or chain to a terminal, where the collected charge creates a high voltage. The voltage accelerates electrons from a "gun" in the high-voltage terminal down a column, thereby generating the electron beam and also discharging the terminal. Deceleration is just the reverse process. The electrons travel up a second column in the accelerator toward the high-voltage terminal, which they recharge. They need only a slight energy boost from a power supply to replenish that lost as laser light, and they are ready to be reaccelerated.

The second benefit of recirculating the electrons is the ability to maintain a higher average beam current because the high-voltage terminal in the accelerator begins to be recharged even before it is significantly discharged. Without beam recirculation, it would be necessary to wait for the slow recharging by the small electron current coming up the belt or chain. The higher beam current translates into an increased average laser power.

Santa Barbara's accelerator was built by National Electrostatics Corporation (NEC), Middletown, Wisconsin. Tests of the recirculation scheme last year, when the machine was at the factory being modified for free electron laser use, demonstrated an average beam recovery of 97 percent. Moreover, the accelerated beam current reached 1.2 amperes, as compared to the tens of microamperes typical of this kind of accelerator.

With the undulator and other elements of the free electron laser at Santa Barbara, beam recovery is currently 83 percent, according to Ramian. "We are hoping for the upper 90's, when everything is working properly," he says. Unexpected was the observation of a recirculation threshold for lasing, as it was originally thought that recirculation was not necessary. So far, at least 70 percent beam recovery is needed before lasing begins.

One limitation of using the electrostatic accelerator is that the low beam energy confines the laser radiation to the far infrared. This is not necessarily a disadvantage, as there is much interest among physicists, materials scientists, chemists, and biologists in this wavelength region. Another free electron laser project that has been under way at AT&T Bell Laboratories for some time is designed explicitly for this purpose.

However, Elias proposed some years back a way to reach the near infrared without a high-energy accelerator. With the upgraded free electron laser system, including the 6-MeV accelerator and a higher capacity power supply, the idea will be tested next year.

Elias calls his plan a two-stage free electron laser. The first stage operates in the ordinary way, producing far infrared radiation. The second stage does not use an external undulator. Instead, it uses the electromagnetic field of the far infrared radiation as an extremely short-period undulator that interacts with the electron beam to generate near infrared. A new undulator is under construction for this demonstration.

A crucial aspect of the two-stage free electron laser is the quality of the electron beam, which is expressed by the spread in energy of the electrons and by a quantity called the emittance. Both should be as low as possible. In particular, the emittance, which is a measure of the diameter of the electron beam and of the velocity component of the electrons normal to the beam direction, should be close to the theoretical minimum value. Measurements last year at NEC indicate that this is indeed the case.

Eventually, Santa Barbara would like to operate the free electron laser as a user facility, where visiting scientists could come to do experiments, as at national synchrotron radiation centers. The present hope is to acquire a $2-million building with laboratory and office space that would be adjacent to that housing the free electron laser, for which Santa Barbara spent $5.5 million over 5 years.

In the meantime, the first experiments will begin as soon as the laser quality is better characterized. One of the first studies, by Jaccarino and his associates, will be to investigate nonlinear lattice vibration effects in the semiconductor indium antimonide. As there is room in the laser building for only one experiment at a time, there will be limited opportunities for outside collaborators at first.—ARTHUR L. ROBINSON

The Paleoclimatic Magic Numbers Game

Examination of major events in the climatic and faunal records begins to identify environmental change as an engine of evolution

There is a widely held belief among biologists that the environment—specifically environmental change—drives evolution. This very reasonable assumption has, however, been only little tested in any systematic, large-scale manner. Individual researchers have, of course, noticed apparent correlations between assumed climatic events and evolutionary pulses in many different faunal groups. The first attempt to bring together such examples and to see how they match up with data on global climatic history was held recently at the Lamont-Doherty Geological Observatory, New York.* The meeting concentrated on the faunal record in Africa and southern Eurasia from the beginning of the Neogene Period, which started 25 million years ago, onwards.

The gathering illustrated the very different nature and quality of data available to those who would reconstruct climatic history and those who seek to track the history of life, even over relatively short time intervals. Drawing on the fruits of the National Science Foundation's Deep Sea Drilling Program, it is possible to obtain rather detailed and continuous records of putative temperature changes over many millions of years. By contrast, a move onto the continent offers a faunal record that at present is at best fragmentary and at worst misleading.

For instance, one can easily be seduced into recording a pattern of apparent first and last appearances of a faunal group that in reality reflects just a restricted window onto the group's history offered by a single, temporally limited site. The mood of the meeting was, however, one of optimism, as it became apparent that individually these windows may in some cases expand and collectively may eventually be coalesced to offer a relatively uninterrupted view of the major features of faunal history during the Neogene.

Nevertheless, even with the continental evidence so far available it proved possible to identify times of apparent evolutionary activity since the beginning of the Neogene that coincided with strong signals of global cooling in the climatic record. The most striking correlations were at around 15 million and 2.4 million year ago, with something clearly happening at around 5 million years before present too. One proposal that might eventually allow a much finer grained pattern to be perceived was that when the deep-sea drilling ship is next in the Indian Ocean, some time in 1987, a core should be taken close to the East African coast.

A long core taken in this locality with the new hydraulic piston technology would provide an unparalleled opportunity for tying in the detailed chronology and temperature record from the deep sea with the volcanic ash–layered, fossil-

*Workshop on Neogene Paleoclimates and Evolution, Lamont-Doherty Geological Observatory of Columbia University, 11 to 13 September 1984.