Free Electron Lasers Show Their Power

The efficiency of millimeter-wave lasers that convert energy from high-current electron beams into intense radiation is growing

Free electron lasers tend to fall into long- and short-wavelength categories. In the last few months, several groups have demonstrated what might be called second-generation lasers of the long-wavelength type. In contrast to the first such lasers in the 1970's, which were inefficient and poorly characterized, these efficiently convert electron beam energy into pulses of millimeter-wave radiation having instantaneous or peak power up to 80 megawatts, and their performance closely matches theory.

Free electron lasers offer several benefits that make them worth perfecting. In contrast to conventional lasers, they are in principle continuously tunable from microwaves to x-rays. Although one device would not cover the entire spectrum, an easily tunable free electron laser would clearly be a marvelous research tool, especially in wavelength regions that are now without tunable lasers. They, also in theory, promise a high overall or "wall plug to light" energy efficiency. This is an essential feature if the devices are to play a role in industrial or defense applications, almost all of which require high-power radiation that is not too expensive to generate.

Advancing accelerator technology is the driving force behind free electron lasers. "If you can make a good accelerator, the free electron laser easily follows," paraphrases the sentiments of many researchers. But a dichotomy in existing accelerator technology is the main reason why free electron lasers divide into long- and short-wavelength categories.

Accelerators of the type used by elementary particle physicists generate beams of high energy but low current, while pulsed power accelerators developed for defense-related research produce beams of high current but low energy. However, the wavelength of the light emitted by a free electron laser decreases with the inverse square of the beam energy, while the amplification (gain, in laser jargon) increases slowly with the current. Researchers therefore have to choose between sources with high gain but long wavelength and those with short wavelength but low gain.

This choice may not always have to be made. Since directed energy beam (star wars) weapons require both high energy and high current, the technology is heading in this direction. The Advanced Test Accelerator (ATA) at the Lawrence Livermore National Laboratory, which will also be used for free electron laser experiments, is the most recent example.

Most free electron laser research is, in fact, supported by the Department of Defense, with directed energy weapons, which might operate in any of several spectral regions, partly in mind. Apart from star wars, millimeter waves are candidates for other military applications. Because of the narrow line width, short (compared to microwaves) wavelength, and high power of millimeter-wave free electron lasers, high-resolution, high-power, or compact radars, telecommunications transmitters, and electronic warfare systems (such as jammers) are mentioned frequently.

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On the civilian side, fusion energy researchers are giving substantial attention to heating magnetically confined plasmas by electron cyclotron resonance absorption of millimeter-wave radiation. And future ultrahigh-energy particle accelerators may be powered by millimeter-wave devices in place of the lower frequency klystron tubes now used.

Free electron lasers are not, however, the only possible source of high-power millimeter waves. They face stiff competition from such alternative devices as gyrotrons, which are becoming commercially available.

Millimeter-wave technology is more familiar to microwave engineers, who only have to adjust their thinking a notch, than to optical scientists. The histories of the two branches of free electron laser research differ, as well. Some observers credit Robert Phillips, then at the General Electric R&D Center in Schenectady, with the first significant millimeter-wave experiment. (See *Science*, 2 September 1983, p. 937 for a review of short-wavelength free electron laser research.)

Starting in the late 1950's, Phillips constructed several devices that he called ubitrons and that produced radiation with wavelengths as short as 6 millimeters. The radiation was generated by passing a 100-kilovolt electron beam through a device called a magnetic undulator, which had been introduced even earlier by Hans Motz, then at Stanford University. The undulator impresses a spatially periodic magnetic field perpendicular to the electron beam; this causes the electron trajectories to oscillate.

For amplification of radiation (either that introduced from an external source or that emitted as synchrotron radiation by the oscillating electrons), the electrons must be decelerated by the electric field of the radiation wave, which then gains the lost kinetic energy. If the beam energy, the undulator period and field, and the radiation wavelength satisfy a resonance condition, after a short distance in the undulator, the electrons congregate in tiny microbunches that have the periodicity of the radiation wave and are decelerated in concert.

When the Department of Defense ceased its funding of Phillips' largely classified work, the ubitron experiments were discontinued. With the availability of higher energy and higher current accelerators in the 1970's, the ubitron was reborn as the free electron laser in several experiments, such as that in 1978 by David McDermott (now at the University of California at Los Angeles), Thomas Marshall and S. Perry Schlesinger of Columbia University, and Robert Parker and Victor Granatstein (now at the University of Maryland) of the Naval Research Laboratory (NRL). The term "free electron laser" was originated by John Madey of Stanford, who headed the group that built the first short-wavelength devices 2 years earlier.

With a 25-kiloampere, 1.2-million-electron-volt (MeV) electrostatic accelerator, the group generated 20-nanosecond-long pulses of 0.4-millimeter radiation having a peak power of 1 megawatt. In contrast to the ubitron, where the wavelength of the radiation and the period of the undulator are comparable, the relativistic electron beam energy in the free electron laser makes the radiation wavelength considerably shorter, in accordance with the $1/E^2$ relationship already mentioned.

In comparison with the 30-gigawatt peak power of the pulsed electron beam, the 1-megawatt output pales. One direction of subsequent research was therefore to increase the efficiency of the free electron laser toward the theoretical value of 10 percent or greater. Early in 1982, Parker, Robert Jackson (now at Mission Research Corporation, Alexandria, Virginia), Steven Gold, and several NRL co-workers reached the 2.5 percent efficiency level in generating pulses of 4-millimeter radiation with 35-megawatt peak power. Although the beam energy was the same as in the Columbia-NRL experiment, the period of the undulator was much longer, which accounts for the longer wavelength of the emitted radiation.

The advance came after considerable analysis and computer modeling by inserting an aperture between the accelerator and the undulator, which scraped off more than 90 percent of the electrons in a 4.5-centimeter diameter beam, leaving a 1.5-kiloampere beam of 6-millimeter diameter. The important effect of this action is the creation of a beam with a spread in electron axial velocities of less than 0.1 percent, as compared to several percent previously, which makes the bunching process and hence the production of radiation more efficient.

Since then, the NRL group, which is now headed by Gold, has upped the efficiency to 6 percent and power levels to 75 megawatts (*1*). In one experiment that shows the power density of the free electron laser beam, the researchers created an atmospheric pressure air plasma by letting focused millimeter-wave beam pass into the air of the laboratory.

Most recently, Gold, Delbert Hardesty, and Allen Kinkead of NRL, Larry Barnett of the University of Utah, and Granatstein at Maryland teamed up to demonstrate a free electron laser amplifier (*2*). The experiment used 8.6-millimeter radiation from a very monochromatic source (a magnetron) as the input. With an input power of 7 kilowatts, the NRL free electron laser amplifier put out a maximum of 17 megawatts.

Electrons repel one another, so keeping a 1.5-kiloampere current confined to a narrow beam in the undulator required the addition of a second, solenoidal magnetic field, somewhat in the spirit of magnetic confinement of ions and electrons in fusion energy plasmas.

Electrons traveling in a purely solenoidal field will spiral around the field lines at a characteristic cyclotron frequency. As it happens, the gyration has effects somewhat like the oscillation in an undulator: bunching occurs, and coherent radiation is emitted (cyclotron maser). The presence of the solenoidal guide field therefore raises the possibility of two kinds of radiation being emitted, which must be distinguished. Some observers now speak of the Columbia-NRL experiment as "probably a free electron laser," since a complete set of diagnostic tests was not made.

ATA

Beam physics experiments began on the Lawrence Livermore National Laboratory's $55-million Advanced Test Accelerator in the late summer of 1983. The photo looks from the end of the accelerator toward the chamber where beam propagation and free electron laser experiments take place. The vertical black pipes are transmission lines, which deliver 250-kilovolt pulses lasting 70 nanoseconds five times a second to each of the 190 induction modules, a few of which are in the foreground. The 256-foot accelerator boosts electrons injected at 2.5 MeV to a final energy of 50 MeV.

Lawrence Livermore National Laboratory

The later NRL experiments made use of a synergy between the electron motions due to the solenoidal and undulator fields. When the period of the cyclotron gyration and the transit time through one period of the undulator are comparable, a resonance effect greatly enhances the output of radiation. However, the detailed theory of the free electron laser is made even more complicated.

At the Massachusetts Institute of Technology (MIT), Joel Fajans, George Bekefi, Yuan-Zhao Yin (visiting from the Institute of Electronics, Academica Sinica, Beijing), and Benjamin Lax backed off from producing very high power levels in favor of a careful comparison of theory and experiment (*3*). To accomplish this, they operated at a comparatively low beam energy (0.2 MeV) and current (5 amperes), where nonlinear effects are not large. Their free electron laser produced about 100 kilowatts peak power for 0.5-microsecond pulses of radiation in the range 1.6 to 4.2 centimeters. However, they achieved a conversion efficiency of 12 percent, close to the theoretical maximum for their operating conditions of 16 percent.

In work just submitted for publication, the MIT physicists studied free electron laser amplifier behavior when a few watts of monochromatic radiation was injected into their device. For both laser and amplifier configurations, observed properties agreed closely with theoretical work by Lazar Friedland, now at the Hebrew University in Jerusalem, by Henry Freund and Adam Drobot of Science Applications, Inc. (McLean, Virginia), and by Freund and Achintya Ganguly of NRL.

From a practical point of view, the solenoidal guide field solves only part of the efficiency problem, in the view of some researchers. It is partly responsible for the need to scrape off 90 percent of the electrons in the initial beam. While this stratagem enhances dramatically the conversion efficiency to radiation from that part of the beam in the undulator, the overall efficiency does not increase concomitantly because so much of the accelerated beam is not used.

Bekefi and his colleagues are planning a new free electron laser that will have high energy (2 Mev) and high current (1.1 kiloamperes) but no guide field. Preliminary experiments with a new electron gun suggest that device will work out. However, a second free electron laser group at NRL has already reported some success with a similar scheme that depends on a small-scale ancestor of Livermore's giant ATA.

John Pasour, Robert Lucey (of Pulse Sciences, Inc., San Leandro, California), and Christos Kapetanakos have operated a linear induction accelerator with an energy of 0.7 MeV and a current of 0.6 kiloampere (of which 0.2 could be focused into the undulator) to generate pulses of radiation in the range 6 to 15 millimeters having peak powers of 4 megawatts (*4*).

A major goal of this NRL project is the demonstration of longer pulses than previously achieved. The distinction is that between the average power emitted and the peak power. The average power can be quite low, even for very high peak power, if the pulse length is short and if the pulses are not produced often.

The accelerators used previously were of a type that stores up a large quantity of electrical charge in a bank of capacitors and applies it quickly to a structure called a field emission diode. The voltage between the cathode and anode of the diode forms a plasma and draws electrons from it, forming the accelerated beam. However, the expanding plasma in the diode quickly shorts it out, so the pulse length is usually of the order of 50 nanoseconds.

The linear induction accelerator used by Pasour and his colleagues was built at the National Bureau of Standards. It does have a diode-type injector that generates the initial beam of about 0.4 MeV, but a much larger space between the cathode and anode hinders any shorting due to plasma formation. Two induction modules comprise the remainder of the machine, with each giving additional energy to the beam.

Induction refers to the method of applying the accelerating voltage to the electron beam. The walls of a module and the beam play the roles of the two coils in a transformer. A voltage pulse arrives at a module in synchronism with the electron beam, generating a current in its inner walls. The wall structure is designed to have a considerable inductance, so that the current varies with time. As in a transformer, the magnetic field generated by the current, transfers the voltage to the secondary coil, in this case the electron beam. The NRL machine was able to produce 2-microsecond-long pulses.

The key to omitting the solenoidal guide field is the absence of the customary magnetic field at the location of the electron gun. This focusing field is ordinarily continued outside the accelerator past the undulator as the guide field. Apparently the rule is that beams born in a magnetic field must subsequently live and die in one. In the NRL machine, the undulator is of a type that provides a certain amount of focusing of its own. Pasour estimates the scheme will work for currents up to approximately 1 kiloampere.

Linear induction accelerators may provide the bridge between the high-current/low-energy and low-current/high-energy technologies of the present. Because they are less susceptible to certain current-limiting instabilities found in the radio-frequency linear accelerators common in high-energy physics, they are able to handle higher currents. And by adding induction modules, the energy can be increased over that of diode-type accelerators.

This prospect, along with the absence of the solenoidal guide field, makes linear induction accelerators of interest to researchers who would like to scale free electron lasers that are known to work in the millimeter-wave range to shorter wavelengths, such as the near infrared and visible. Modeling a free electron laser at the high currents and energies where nonlinear effects are rampant is difficult enough without the added complication of the guide field and its effect on electron trajectories. And because the strength of the solenoidal field needed to operate the free electron laser near the cyclotron resonance increases inversely with the wavelength, taking advantage of the synergy between the two is increasingly impractical as the wavelength decreases.

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A collaboration comprising Thaddeus Orzechowski and Donald Prosnitz of the Lawrence Livermore National Laboratory, Andrew Sessler of the Lawrence Berkeley Laboratory, and several co-workers from both institutions has used the predecessor to Livermore's ATA, the Experimental Test Accelerator or ETA, to make a free electron laser amplifier without a solenoidal guide field. Their goal was to demonstrate a physical system that is simple enough to model accurately and which is scalable to shorter wavelengths (*5*). This group is the largest in size and budget of those working in long-wavelength, high-power free electron lasers, although a rival team of comparable capability at the Los Alamos National Laboratory is exploring another route to high-power infrared devices.

Because of their extensive computer resources, the two weapons laboratories have always had a strong hand in numerically simulating complex physical systems. The free electron laser is no exception, and the Livermore-Berkeley collaboration has been able to model details in the high-current/high-energy regime that had not been treated before.

Armed with these results, the group began experiments with the ETA, a linear induction machine that put out a beam with an energy of 3.3 MeV and a current of 6 kiloamperes. However, this was reduced to 600 amperes in the interests of having a good beam. With pulses of 8.6-millimeter radiation from a magnetron having a peak power of 23 kilowatts as input, the laser amplifier boosted the radiation to 80 megawatts. The conversion efficiency of electron beam energy to radiation was 5 percent.

These results are so encouraging that the group has obtained funding for an even larger experiment. As part of the directed energy beam weapon research program, the ATA, has been built at Livermore, which has an energy of 50 MeV and currents up to 10 kiloamperes. The group is gearing up to make an infrared (10 micrometers) free electron laser using this machine, as it believes it has the information needed to scale to the shorter wavelength. According to Sessler, after the first round of experiments, the behavior of the amplifier is quite consistent with theory, although there are some small quantitative disagreements.

The physicists have also begun a second round of ETA experiments. These involve a so-called tapered undulator. Because the electrons lose energy as radiation is generated, the resonance condition for maximum transfer of energy from the electron beam to the radiation wave changes over the length of the undulator. To enhance energy transfer, the undulator magnetic field is decreased along its length and thereby maintains the resonance. Tapering has been demonstrated at low currents by a TRW-Stanford collaboration (*Science*, 20 July, p. 305), but successful operation at the high currents of the ETA is a prerequisite to beginning ATA experiments.

—**Arthur L. Robinson**

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