Free Electron Laser Success Explained

A Livermore-Berkeley group finally publishes an account of the tapered-undulator experiment that has focused so much interest on high-power free electron lasers for missile defense

PARTLY because of a reported "breakthrough" at the Lawrence Livermore National Laboratory almost 2 years ago, the free electron laser has become a leading candidate among the directed-energy alternatives being considered for missile defense by the Strategic Defense Initiative Organization and has attracted considerable media attention in the process. After a lengthy delay because the results were initially classified, an account of part of that breakthrough has now been published.

With the help of a special magnet called a tapered undulator to effect the energy transfer, a group of 11 researchers from Livermore and the Lawrence Berkeley Laboratory has converted up to 40%* of the energy of the electron beam in an accelerator at Livermore into microwave laser radiation. "This is the first time that high-efficiency transfer of energy from an electron beam into long-wavelength laser radiation has been demonstrated," says Andrew Sessler of Berkeley, one of the project leaders along with Donald Prosnitz, Thaddeus Orzechowski, and Ted Scharlemann of Livermore. Energy efficiency is essential if high-power free electron lasers are to be affordable because the capital cost grows with the electron beam power, agrees Charles Brau at the Los Alamos National Laboratory, where a competing project is in progress.

For missile defense, the Army's Strategic Defense Command, which is managing the Star Wars free electron laser program, is interested in near-infrared wavelengths near 1 micrometer. A second important ingredient of the Livermore demonstration is therefore the development of a detailed theory of free electron laser operation. The close agreement between experiment and theory now provides a guide for the considerably more difficult feat of moving to shorter wavelengths. In fact, a new round of experiments with a higher energy accelerator is under way aimed at achieving efficient energy transfer at 10.6 micrometers. As part of a large defense project involving hundreds of people, these experiments fittingly have a code name—Paladin.

Last summer, the Army announced its intention of building a large facility at its White Sands Missile Range in New Mexico to explore unresolved questions about free electron lasers. Because free electron lasers of the requisite power for missile defense may be too large to boost into space, one scenario that has been discussed is to have a number of geographically dispersed ground-based centers, each housing several free electron lasers. Each laser beam would be bounced off one or more orbiting mirrors and targeted at a missile still in its boost stage.

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Livermore is not the only entrant in the competition now under way for the right to construct a large free electron laser at White Sands, but it is taking its own approach. The two other major players, Los Alamos and a Boeing Aerospace–Spectra Technology collaboration, build their free electron lasers around radio-frequency electron linear accelerators of the type familiar in physics laboratories. Livermore is using an induction linear accelerator, which operates by a different principle and produces an electron beam with different properties.

An important difference between the induction and radio-frequency linear accelerators is that the former generates, comparatively speaking, a beam comprising a small number of intense pulses, whereas the beam from the latter consists of a large number of so-called micropulses. The free electron laser radiation mimics the characteristics of the accelerator beam from which it was born. For missile defense, the time-average laser power rather than the instantaneous or peak power in one pulse may be what counts, so the two kinds of sources may be in principle comparable.

Free electron laser researchers distinguish between a laser oscillator and a laser amplifier. In a laser oscillator, spontaneous radiation is amplified and converted into coherent laser light upon being reflected many times through the laser medium (in this case, the electron beam) by mirrors forming an optical cavity. Without mirrors, a single pass through the laser medium is sufficient for a laser amplifier to boost the power of coherent radiation from another source.

The Livermore experiment involved a free electron laser amplifier because the pulse structure of the laboratory's induction linear accelerator was incompatible with a laser oscillator. In brief, since the electron beam pulses are short but widely spaced in time, there would be electrons in the undulator for only one pass of the nascent optical pulse through the cavity and, hence, no laser action. With its radio-frequency linear accelerator, Los Alamos has built a free electron laser oscillator that operates at 10.6 micrometers. The short temporal spacing between the electron micropulses matches the travel time of the optical pulse in the cavity.

Among other factors, however, the presently low beam current in the radio-frequency accelerator and the inability of the mirrors to handle high optical power loads limit the power output of an oscillator. In an experiment with a tapered undulator, Los Alamos researchers obtained only a 2% energy transfer. While this was the highest ever achieved with an oscillator, it was less than the 4% estimated to be achievable with perfect mirrors. Moreover, even with a higher beam current, significantly higher efficiencies will not be possible until a way of handling the mirror problem is found, says Brian Newnam of Los Alamos. One such strategy involving grazing-incidence mirrors to spread the beam over a large area is undergoing testing.

Despite the encouraging results at Livermore, it is by no means certain which, if either, of the two types of machines will be the first to succeed in producing enough high-power, short-wavelength laser light to destroy ballistic missiles in flight. In the past year, for example, Los Alamos has demonstrated an energy recovery scheme that could effectively boost the efficiency of its free electron laser to as much as 20% by

*The published efficiency is 35%, but subsequent experiments reached 40% and almost doubled the power output from 1 to 1.9 gigawatts, according to Thaddeus Orzechowski of Livermore.

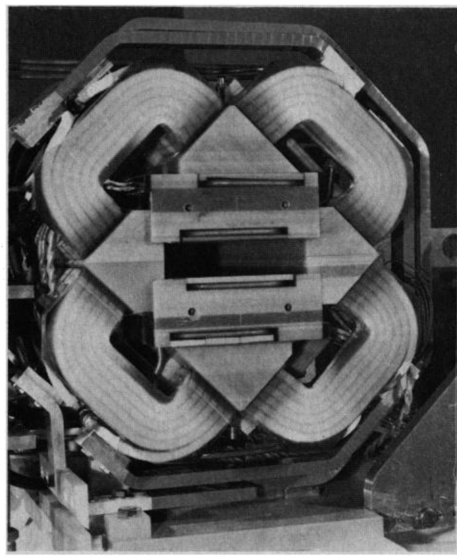
decelerating electrons after they have passed through the undulator and using the energy to help accelerate a new pulse.

At Livermore, the source providing the coherent radiation to be amplified was a device called a magnetron that emitted pulses of microwaves at a wavelength of 8.7 millimeters (34.6 gigahertz). The microwaves then passed through the undulator together with a 3.5-megaelectron-volt (MeV) electron beam from Livermore's Experimental Test Accelerator (ETA). Energy extracted from the electron beam while it was in the undulator was converted into radiation, thereby boosting the peak power of the microwave pulses from 50 kilowatts to nearly 1.9 gigawatts in the most recent experiments. Because the ETA can fire only once a second, the average power was much lower, although Livermore's "State of the Laboratory" report for 1985–1986 reported that researchers are testing prototype components for a future accelerator that can operate at rates up to 5 kilohertz.

Energy transfer occurs in the undulator (sometimes also called a wiggler) because of the interaction between the radiation wave and the electrons, which are also undergoing an oscillatory motion. An undulator comprises a linear array of vertical dipole (north-south) magnets of alternating orientation. The periodic dipole array bends the electrons into an approximately sinusoidal trajectory in the horizontal plane, so that they emit synchrotron radiation. If the electron beam energy, the dipole period, the undulator magnetic field flux, and the wavelength of the input radiation satisfy a resonance condition, the electrons within a pulse are in effect stimulated to congregate in so-called microbunches that have the periodicity of the input radiation wave. The resulting coherent radiation amplifies the input wave with maximum energy transfer.

The amount of energy transferred depends on the number of electrons in the beam, that is, on the beam current. The ETA accelerated a pulsed beam with a current of 4000 amperes. For efficient energy transfer, the electron beam must be bright; that is, it should have a narrow cross section and should not diverge. The ETA was not designed with free electron lasers in mind, and its beam was not of the best quality for this purpose. Accordingly, the Livermore researchers stripped away the outer layer of the ETA beam and kept only a dense core of 850 amperes. The energy transfer efficiency of 40% is referenced to this dense core; the overall efficiency was lower by a factor of 850/4000.

In an experiment reported 2 years ago, the Livermore researchers obtained an energy transfer efficiency of 5% while obtaining a peak output power of 80 megawatts. This result was obtained with a conventional undulator in which the magnetic field flux of the constituent dipoles was constant along the length of the 3-meter-long device. However, because the electrons lose energy as radiation is generated during their flight through the undulator, the resonance condition for maximum transfer of energy changes. To maintain the resonance condition, one can progressively decrease either the dipole period or the magnetic field flux along the undulator, a strategy known as tapering.



End view *of tapered undulator used in the Livermore free electron laser amplifier. A linear array of pulsed, air-core electromagnets generates the alternating vertical dipole fields in the 3-meter-long undulator.*

For the recently reported experiments, the investigators used the same undulator but varied the current powering each of the electromagnet dipoles, thereby tapering the magnetic field flux. In one test, they created a variable-length undulator by fully powering only some of the dipoles. They found that the power output increased exponentially with undulator length, reaching 180 megawatts at 1.3 meters, but it did not increase thereafter because the resonance condition was too badly violated. After using a detailed computer model of the free electron laser to determine the optimum tapering profile, they observed a further but slower increase of output power with undulator length, reaching a maximum of 1 gigawatt at 2.3 meters, in close agreement with the computer model.

According to the resonance condition for maximum energy transfer, the laser wavelength is approximately proportional to the undulator period divided by the electron beam energy squared. The most practical way to reach the near-infrared wavelengths of interest for missile defense is therefore to raise the electron beam energy. As it happens, Livermore is also the site of the 50-MeV successor to the ETA, the Advanced Test Accelerator or ATA. Like its predecessor, the ATA was not built with a free electron laser in mind, but the highly encouraging ETA results have made that application the number one priority.

The Paladin experiments now under way have as their first goal testing the performance of a tapered wiggler in amplifying 10.6-micrometer radiation from a carbon dioxide laser. The choice of 10.6 micrometers is dictated primarily by the energy of the ATA, in accordance with the aforementioned resonance condition, and by the ready availability of high-power carbon dioxide lasers. The state-of-the-laboratory report asserts that "[t]he Paladin experiment . . . will test the remaining physics issues for the visible/near-infrared lasers considered suitable for ballistic-missile defense applications." The Boeing–Spectra Technology collaboration is also close to beginning a test of a low-peak-power free electron laser oscillator emitting visible light at 0.5 micrometer. If it is successful, the investigators will attempt to raise the average power by increasing the number of pulses, according to Jack Slater of Spectra Technology.

Moving from microwave to infrared wavelengths involves much more than a higher energy accelerator. For one thing there is a more stringent requirement on the brightness of the electron beam. All lasers, whatever the type, require that a quantity called the gain exceed losses if lasing is to occur. For free electron lasers, the beam brightness required to maximize the gain works out to be proportional to the beam current divided by the lasing wavelength.

The brightness of the dense core of the ETA beam was 2×10^4 amperes/(centimeter-radian)^2. According to a paper presented at an accelerator conference last year by William Fawley of Livermore, the comparable figure for the ATA will be ten times this value. The state-of-the-laboratory report estimated still another increase by a factor of 5 or more to reach the visible/near-infrared range.

Evidently, the electron beam brightness increase of 10^4 needed to keep the gain constant while going from the microwave to the visible/near-infrared is not in the cards, which suggests that high gain will be more difficult to achieve at shorter wavelengths. To test ways of increasing the brightness to the value Fawley cited for the visible/near-infrared laser, Livermore scientists are assembling a new machine, ETA II. One advantage of the radio-frequency linear accelerator is that its the beam is already of good quality. None of the beam is thrown away, for example. Moreover, Los Alamos has recently constructed an advanced electron injector with a significantly increased brightness. The accelerator cannot be brighter than its source.

There is also an unfortunate trade-off between the efficiency of energy transfer from the electron beam to the laser wave and the gain. As the efficiency increases as a result of tapering, the gain achievable at a fixed beam brightness and undulator length drops, plainly putting a constraint on the maximum efficiency allowed before the laser shuts off. This constraint becomes increasingly severe as the wavelength decreases. For this reason, no one expects anything like a 40% energy transfer efficiency in the first Paladin experiment, which will use a new undulator that is 5 meters long. The paper by Fawley discussed a modest 2% efficiency with a mildly tapered undulator.

To boost the overall energy transfer efficiency back up to a useful value, the strategy that is being adopted is to use a very long undulator. Since the gain is proportional to the undulator length, more energy can be extracted from the beam in a long undulator without shutting off the laser. Fawley mentioned a follow-on Paladin experiment with a 25-meter-long undulator. A visible/near-infrared free electron laser amplifier may require an undulator many tens of meters in length.

There are other physics issues that arise at short wavelengths. Microwaves travel through a wave guide, so there is no difficulty in keeping the radiation from diverging away from the electron beam and limiting the energy transfer, but there are no wave guides for the shorter wavelength radiation. As it happens, a theoretically predicted effect known as optical guiding may provide a solution. In short, as calculated by Scharlemann, Sessler, and Jonathan Wurtele of the Massachusetts Institute of Technology and by Gerald Moore of the University of New Mexico, the interaction between the electron beam and the radiation wave can generate a lens-like effect that focuses the wave.

Results from both the Livermore Paladin and Boeing Aerospace–Spectra Technology visible oscillator experiments should be in during the coming year. When details will be published is quite another matter. ■

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ADDITIONAL READING

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Planetary Scientists Are Seeing the Unseeable

Scientists who gathered last November in Paris at the 18th annual meeting of the Division of Planetary Sciences of the American Astronomical Society learned just how innovative their colleagues could be in times of fiscal restraint. Some researchers reported on mapping the unseen surface of Pluto while others told of charting the interior of the moon Mimas using ordinary images of its surface. Another group piggybacked on a project run by galactic astronomers. Others argued against the advisability of the separate simultaneous sessions on comets and asteroids, seeing as how some asteroids may be comets in disguise.

More Clues to Asteroid–Dead Comet Connections

Planetary scientists reported on two more lines of evidence supporting the proposal that some asteroids of the inner solar system are actually burned out comets and not escapees from the asteroid belt. One group of researchers found that asteroids that have orbits suspiciously like those of comets also have the same color as comet nuclei. From another study, it appears that a cometary source for some asteroids would make sense of the abundance of inner solar system asteroids and their orbits.

William Hartmann of the Planetary Science Institute in Tucson and David Tholen and Dale Cruikshank of the University of Hawaii examined ten asteroids that others had proposed as possible burned out comets, ones that could no longer release the dust and gas typical of comets. These asteroids had been singled out because they have peculiar orbits. Comets of the inner solar system show less preference for orbiting near the orbital plane of the planets than asteroids. In addition to larger inclinations, comet orbits tend to be elongated and oriented in special relations to Jupiter, whose gravity can be responsible for keeping comets from escaping from the solar system after their arrival from orbits far beyond Pluto.

Another characteristic of burned-out comets, originally proposed by Hartmann and his colleagues, is a dark neutral or brownish black color. They found such colors in the outer asteroid belt, in the dust around comets, and apparently on the surface of nearly inactive comets. When spacecraft arrived at Halley's nucleus, it too was found to be coal black.

When Hartmann checked on the color of the ten asteroids with cometlike orbits, he found that all ten had cometlike colors, or at least the color typical of outer solar system objects. Among a control group of 13 asteroids having typical asteroidal orbits, only one was dark-colored. Thus, at least among the chosen examples, all asteroids that orbit like comets are colored like comets, and almost all asteroids that have typical asteroid orbits are not colored like comets.

George Wetherill of the Carnegie Institution of Washington reported that burned-out comets in the inner solar system would also help explain the number of asteroids there. Celestial mechanicians have always had a problem explaining the presence of the roughly 1000 asteroids larger than 1 kilometer thought to pass inside the orbit of Earth, called Apollo objects, and the several thousand asteroids presumed to pass inside the orbit of Mars, called Amor objects. Only recently had a second means been proposed of bringing them in from the asteroid belt lying between Mars and Jupiter. Wetherill recently modeled these two known mechanisms by which Jupiter's gravity, with or without the help of Mars' gravity, can send objects in the asteroid belt into Apollo or Amor orbits. The modeled mechanisms could support a population of 361 Apollo objects and 1430 Amor objects, he found.

That more or less explains for the first time a deficiency that dynamicists, for lack of more productive sources in the asteroid belt, had attributed to dead comets. But do dynamicists still need a cometary source? Wetherill thinks so, if only to provide an explanation of observed objects with orbits inclined 50° to 70° or elongated and passing inside Earth's orbit but also near Jupiter. As a test of the reasonableness of a cometary source, he takes Comet Encke as an example. It is in an Apollo-type orbit and looks to be a comet in its old age. It has probably been