Free-electron lasers take small steps toward distant goal

Until recently, no free-electron laser was able to convert more than 5% of the energy from an electron beam into microwave radiation. Last fall, however, a team from Lawrence Livermore National Laboratory and the University of California at Berkeley published a (previously classified) report that they had operated a free-electron laser with an unprecedented 40% efficiency at a wavelength of 8.6 mm. The peak power exceeded 1 gigawatt. Meanwhile, researchers at Los Alamos National Laboratory who operate a free-electron laser of different design at a shorter wavelength (10 microns) have reported a modest increase in efficiency from 1.3% to 2% with peak power output of 20 MW, as well as development of several promising enhancements of their laser operation. In yet another experiment, a Stanford–TRW team has operated an FEL in the visible region of the spectrum (525 nm) with a peak power as high as 170 kW.

Each of these steps moves FELs a bit closer to some of their anticipated applications in medicine, electronics and basic research. Still, they remain orders of magnitude away from the the most publicized of applications—defense against ballistic missiles. The APS Study Group on Directed Energy Weapons (see PHYSICS TODAY, May, page S1) estimated that FELs for strategic defense applications might need to reach average power outputs in the GW region at wavelengths of about 1 micron. To explore whether FELs can scale to the required performance levels, the Army is building a ground-based FEL facility at White Sands Missile Range, New Mexico. In the next year, they will choose which of two competing FEL concepts will be the basis for the large-scale experiment: an FEL whose electron beam is accelerated by an induction linac, such as the facility operated at Livermore, or one based on a radiofrequency linac, like that at Los Alamos.

In any free-electron laser, an accelerator generates an energetic electron beam, which then travels down a wiggler or undulator, a region subjected to a spatially periodic, transverse magnetic field. (In an undulator the radiation from successive bends is coherent, whereas in a wiggler it is not. Nevertheless, "wiggler" has become a common term to describe either situation.) As the relativistic electrons oscillate in this wiggler, they can radiate coherently with an imposed (or spontanteously emitted) radiation field provided the radiation field maintains the right phase with respect to the electrons. The resonant condition is essentially that the optical wave travel one optical wavelength further than an electron during the time that the electron travels one wiggler period. If λ_s is the wavelength of the radiation and λ_w is the "wavelength" of the wiggler, then

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{a_w^2}{2}\right)$$

Here γ is the electron's Lorentz factor and a_w is a term that varies directly with the product of the wavelength and magnetic field of the wiggler. Note that the wavelength of the signal output varies as the inverse square of the electron energy. The two main types of FELs differ in the design of the linear accelerator that provides the electron beam. From the different beam characteristics stem important differences between the two laser types. An induction linac typically produces widely spaced beam pulses with high current in each pulse. Because the interval between pulses is so long, an induction FEL must operate as an amplifier, increasing the power of an applied radiation field in one pass. The relatively high currents of the induction linacs at Livermore have enabled FELs there to operate at powers in the GW region, but the moderate energy ofthe linac on which Livermore did its first FEL work restricted their operation to wavelengths of about 1 cm.

By contrast, the rf linacs that have been available for FEL work to date have higher energies and lower currents than induction linacs. Thus the FELs they power typically operate now at shorter wavelengths but lower power levels. The electron beam consists of packets of thousands of micropulses, with each of the micropulses lasting perhaps tens of psec. Existing rf FELs are operated as oscillators, building up the spontaneously emitted radiation by successive reflections off mirrors in optical cavities. The output approaches that of a continuous wave laser.

The induction and rf technologies being considered for the ground-based FEL face distinctly different problems as they scale up. To tackle these problems, the Army has directed Livermore Lab to have its industrial partner, TRW, develop a proposal for an induction FEL at the White Sands facility. This month the Army will select a firm to collaborate with Los Alamos in preparing an rf FEL proposal.

Colonel James McNulty, director of the GBFEL program, sáid that the Army will monitor progress by technical milestones between now and early spring 1988, at which time the industrial firms must submit specific design proposals. The Army will make its final selection by 1 June 1988. It plans to have the facility operating in the early 1990s.

McNulty could not comment on some of the specific design criteria such as power, but he did say that the wavelength would have to be in the range from 0.8 to 1.6 microns. (The wavelength is dictated in part by requirements of atmospheric transmission.) The Army requires that the device be tunable over a small region near the selected wavelength, even while lasing. And the selected FEL technology would have to be scalable to a weapons class system.

Induction FELs. The Livermore–Berkeley FEL collaboration has been using

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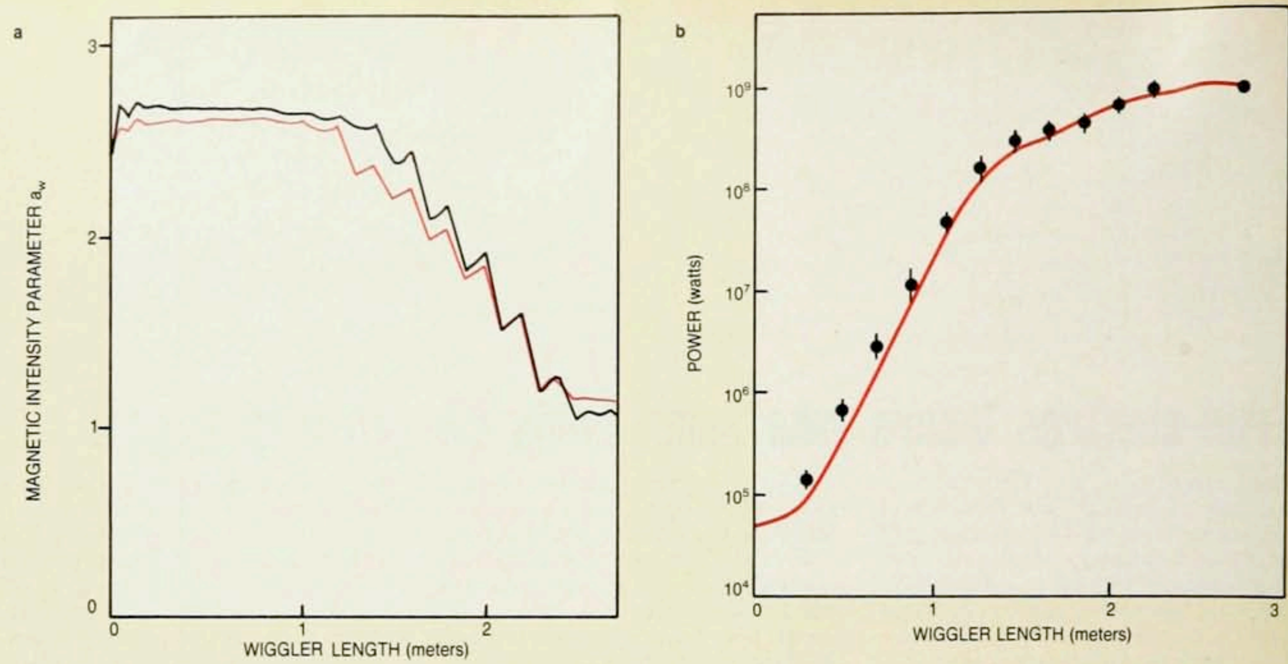

Wiggler field profile (**a**) and power output (**b**). Decreasing the magnetic field strength of the wiggler in their free-electron laser enabled a Livermore–Berkeley team[1] to reach efficiencies higher than 40%. The magnetic field intensity, measured by parameter a_w, is constant for about 1 meter, then decreases to maintain resonance as the electrons lose energy. As a result, power grows along the wiggler length. Red curves are numerical evaluations. Experimental results are shown as black curve and data points.

the 5-MeV Experimental Test Accelerator at Livermore to generate microwave radiation with efficiencies of about 5%. (See PHYSICS TODAY, April 1985, page 17.) Last fall, they reported[1] achieving much higher efficiencies by tapering their wiggler—a technique pioneered by the Stanford–TRW group and followed in other FELs as well. In a tapered wiggler, either the strength or the period of the magnetic field is decreased along the wiggler length to maintain the resonance condition given above as the electrons lose energy. In the Livermore experiment, the ETA operated at 3.5 MeV to match the 34.6-GHz resonance in the operating range of the wiggler. With a uniform magnetic field in the 3-m-long wiggler, the researchers found that the output signal saturated at 180 MW after a length of 1.3 m. Once they tapered the field strength in the last 1.7 m of the wiggler down to 45% of its initial value, they got a peak output power above 1.0 GW, corresponding to a 40% efficiency in extracting energy from the electrons. The graphs above show the wiggler field profile and the amplified signal output as a function of wiggler length in their experiment.

The challenge will be to maintain a high efficiency as the group moves toward shorter wavelengths. Meeting it will require an accelerator that provides a beam with high brightness, that is, one with both high current and low transverse spread of electron velocities, even at the higher energies needed to yield shorter wavelengths of radiation. The Livermore–TRW team is researching improvements in several features of an induction accelerator. One such feature is the electron injector. Existing field-emission cathodes produce beams of sufficient brightness but do not operate at the required duty factor of 10^{-4}. The Livermore group has tested a dispenser cathode that has provided almost the required brightness at 1 kiloamps and which, they feel, should work well at higher currents.

The Livermore–TRW team is also exploring an accelerator design with a higher gradient and a pulse repetition rate much higher than the current 1 Hz. To produce adequate average power for an FEL for weapons applications, the induction linac would have to operate at rates of thousands of pulses per second. For this reason, Livermore has designed a nonlinear magnetic pulse compressor. This device relies on a very rapid change of permeability in ferromagnetic materials to produce a sudden pulse of current.

Another requirement is to maintain the horizontal focus of the electrons as they are focused vertically by the wiggler field. The external quadrupole magnets used in the 3-m wiggler will not preserve velocities over longer wigglers, so the Livermore experimenters are shaping the wiggler magnets to provide the required focusing.

One of the most severe problems for the induction FEL, however, will be to prevent divergence of the radiation down the length of a wiggler that may have to be as long as 100 m to give the required amplification. Many hopes rest on a theoretical prediction that optical guiding occurs in the wiggler: The electron beam may act as an optical fiber along which the radiation is guided without diverging outward. So far this crucial prediction has not been experimentally verified. Livermore is now conducting a series of tests called the Paladin experiments to measure the divergence of the laser beam as the length of a tapered wiggler is increased in stages from 5 m to 25 m by adding more 5-m wiggler sections. Donald Prosnitz (Livermore) told us the Livermore researchers are already seeing some gain in the amplifier with a 5-m wiggler. For this experiment, they are using the 50-MeV Advanced Test Accelerator at Livermore and operating at a wavelength of 10.6 microns with a CO_2 laser as the input.

Radiofrequency FELs. A team at Los Alamos led by Roger Warren has recently made several improvements in their FEL to help overcome some barriers to scaling to higher power levels.[2] By modifying their accelerator, they increased the beam current to 300 A and raised the FEL efficiency from 1.3% to 2% for operation with a tapered wiggler at a wavelength of 10 microns. The corresponding intracavity peak power level and output were

2000 and 40 MW, respectively. At efficiencies of just a few percent, it pays to recover the unspent energy in the electron beam. So Los Alamos installed an energy recovery loop that circles the electron beam back to the linac, where deceleration of the electrons pumps up to 70% of their energy back into the rf cavities. Charles Brau of Los Alamos told us the design goal had been 50% recovery. This loop functioned stably even while the FEL was lasing.

Last fall Los Alamos operated a new type of injector based on photoemission technology, which uses a laser to generate very short pulses of electrons that give a high-quality beam. Their current injector produces a long pulse which must then be compressed, with subsequent degradation of the beam quality. The new injector has produced a peak current of 400 A for an 80-psec pulse with an energy of 1 MeV. (The average current over a 10-μsec burst of pulses was 3 A.) The brightness at a peak current of 120 A exceeded the specifications for the White Sands demonstration. Brau emphasized that the injector may be of potential interest for many accelerator applications.

Perhaps the major limitation on rf FELs is the capability and survivability of the optical resonator at high power levels. The high-reflectivity mirrors at either end of the cavity are readily damaged by intense radiation. Such damage has so far prevented the Los Alamos team from operating at the design point of the wiggler. The group plans to try copper mirrors with increased cavity length. In a separate experiment with an argon ion gain medium, the Los Alamos team has shown that they can fabricate and align a 64-m-long optical resonator with 4° grazing incidence mirrors.

Another obstacle to high-power rf FEL operation has been the low power available from existing accelerators. The Boeing Aerospace Company has just finished constructing a 120-MeV rf accelerator designed to operate with a short-wavelength (0.5 micron) FEL. They hope to produce average currents as high as 100 A and increase power output by generating more closely spaced packets of micropulses. Spectra Technology and Rockwell's Rocketdyne division have provided the 5-m wiggler and the optical resonator, respectively. Boeing project director Donald Shoffstall told us the company hoped to get the device to lase by late May and would gradually work toward high-power operation. Boeing is competing for selection as the contractor to work with Los Alamos to develop an rf FEL design for the White Sands facility.

More FEL work. While the efforts just described focus on defense applications, other FEL work is directed more toward such applications as medicine or materials science, where average power levels of a few watts suffice. A Stanford–TRW collaboration has recently reported operation of an FEL at a wavelength of 525 nm. The Stanford FEL uses the electron beam from Stanford's superconducting linear accelerator, whose energy is 60 MeV. To get wavelengths in the visible, the Stanford–TRW team needed an electron beam energy above 100 MeV. Thus they extracted the beam emerging from the linac at 60 MeV and piped it back for a second pass through the linac to boost its energy to 115 MeV. Only one other FEL—at Orsay, France—has operated in the visible before and it did not achieve the power obtained in the experiment at Stanford, where the peak power output was 170 kW. The collaborators on this experiment are Todd Smith and Alan Schwettman of Stanford and George Neil, John Edighoffer and Steven Fornaca of TRW.

Smith said they are now refurbishing the laser and hope to push for ultraviolet wavelengths when it is running again in October. The group has also developed an energy recovery scheme in which they take the electron beam from the wiggler exit and feed it back into the linac 180° out of phase with the field. As the electrons are decelerated they give their energy back to the radiofrequency field for acceleration of a fresh bunch of electrons.

The White Sands GBFEL program will explore whether ground-based FELs can direct high levels of radiant power to mirrors in space, which would in turn direct that energy toward enemy targets. The program must evaluate not only the potential for high-power FEL operation but also the performance of beam control systems and problems of atmospheric transmission.

The Army has asked a team of experts called the Technical Advisory Group to recommend which of the two FEL concepts—induction or rf—should be chosen. The group is headed by Lieutenant Colonel Tom Johnson of the US Military Academy (West Point). Because they must consider not only which laser is most feasible but which will give the beam with the most promise for atmospheric transmission, the 14 members and 5 consultants on the advisory group include not only experts on accelerators, FEL physics and optics but also experts on atmospheric propagation. Five of these experts, including Johnson, participated in or reviewed the APS DEW study. Johnson said his group would be looking at FEL technologies now in even greater detail.

The APS DEW study group stated in its report that "FELs suitable for strategic defense applications, operating near 1 micron, require validation of several physical concepts." Among those they cited were the demonstration of optical guiding and transverse sextupole focusing for the induction FEL, and control of sideband instabilities and harmonic oscillations for the rf-type FELs. Andrew Sessler (University of California at Berkeley), a member of the DEW panel, feels it is unlikely that enough technical information will be developed for a proper choice to be made between the two approaches by June 1988.

While recognizing that the Army might have to make a decision before all the questions are completely answered, McNulty nevertheless feels it is necessary to take some risks and set challenging goals to move the FEL time schedule ahead. Asked which type of FEL now held the edge, McNulty said that he felt they were tied at this point. He cited optical guiding as the critical issue for induction FELs and optical resonators as the challenge for rf FELs.

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Astronomers seek high resolution

Astronomical advances often depend upon technological advances. In recent years charge-coupled-device detectors on existing telescopes have reached photon efficiencies approaching 100%, significantly better than those of photographic detectors. (See PHYSICS TODAY, March, page 19.) "The 5-meter Hale telescope with a charge-coupled-device detector is equivalent to a 50-meter diameter telescope equipped with 1948 photographic plates," says Peter Waddell (University of Strathclyde, Glasgow), who is trying to develop large