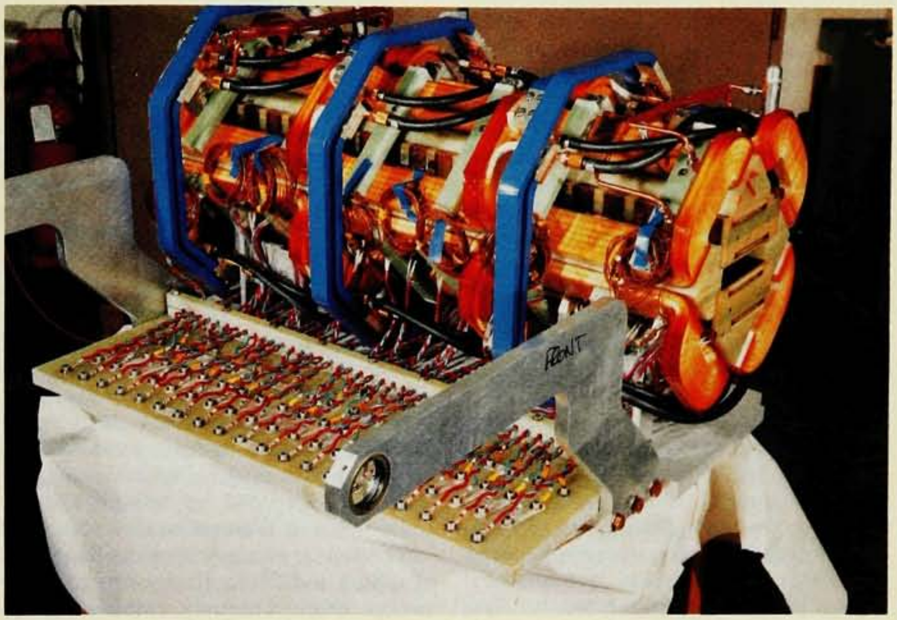
Free-electron lasers achieve high microwave power



The wiggler of the Livermore-Berkeley free-electron laser amplifier is 3 meters long. Seen here is a 1-meter-long module before installation. The prominent external windings provide the quadrupole field needed to keep the beam focused in the absence of an axial magnetic field in this experiment. The electron beam and microwave radiation traverse the wiggler through the rectangular interaction waveguide along the axis. Wiggler-magnet pole faces of alternating polarity line the waveguide with a periodicity of 10 cm, causing the electrons to wiggle their way through the interaction region.

The output wavelength of a free-electron laser varies as the inverse square of the energy of the electrons whose undulation through the FEL generates the laser light. Accelerators and storage rings of the kind one uses for high-energy physics have provided FEL researchers with electron beams of sufficient energy to yield laser output in the near infrared and even in the visible (see PHYSICS TODAY, December 1983, page 17). But such rf linacs and storage rings are typically limited to rather low electron currents, thus seriously limiting the peak output power of the free-electron lasers that depend on them.

At longer wavelengths—from infrared to microwaves—where one can make do with electron energies on the order of an MeV, one can hope for much higher power laser output by availing oneself of the very-high-current accelerators capable of operating at these modest electron energies. In recent months two groups have in this way demonstrated high-efficiency, high-gain FEL amplifiers, producing millimeter-wave pulses with peak power approaching 100 megawatts.

Last summer, a Livermore–Lawrence Berkeley Lab collaboration[1] employing Livermore's Experimental Test Accelerator, a 4.5-MeV induction linac, as the beam source for its 3-meter-long free-electron laser, was able to amplify 30-kilowatt (peak power) pulses of 8.7 mm (35 GHz) microwave input to 80 *mega*watts, with an extraction efficiency of 5%. The previous autumn, a group at the Naval Research Lab[2] had produced 17-MW pulses at the same microwave wavelength with 3% efficiency, using an FEL amplifier whose 900-keV electron beam came from NRL's VEBA pulse-line accelerator.

These extraction efficiencies are one to three orders of magnitude higher than those achieved in earlier efforts to produce far-infrared and millimeter-wave FEL output during the past decade. "Long-wavelength free-electron lasers are coming of age," says Steven Gold, leader of the NRL group. It is not just that the present efforts are producing unprecedented gain, power and efficiency, he points out, "We're also seeing the convergence of theory and experiment."

The success of the theoretical models in accounting for the experimental results of both groups is of considerable practical interest—not only for microwave applications, but also for extrapolation to much shorter wavelengths, where other intriguing applications are envisioned. For high-power microwave applications, such as radar, communications and fusion-plasma heating, a good understanding of the physics of these high-power free-electron lasers is essential for optimizing the design of a practical device. But the Livermore–Berkeley group, in particular, is also very much interested in near-infrared and visible applications.

The Livermore–Berkeley FEL, intended as a first step toward high-power devices at short wavelengths, was designed to operate *without* an axial magnetic field. At the very high beam currents (half a kiloamp, with very small phase-space spread) passing through the "wigglers" of these high-power FELs, an axial magnetic field would serve several useful functions. Magnetic field lines parallel to the nominal electron beam direction would help to focus the beam and counter the dispersive tendency of Coulomb repulsion. Furthermore, by judicious adjustment of parameters, one can make the helical motion of electrons around these axial field lines resonate with the oscillating motion of the beam in the spatially periodic, *transverse* magnetic field of the wiggler, thus significantly enhancing the gain of the FEL.

Nonetheless, the Livermore–Berkeley group chose to make do without an axial magnetic field. They were seeking to understand the physics of a high-power FEL that could be extrapolated all the way down to visible wavelengths. An FEL at such short wavelengths requires an electron beam so energetic that no practicable axial magnetic field would be strong enough to do much good. Furthermore, the complex electron trajectory resulting from the combined effects of the trans-

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verse wiggler field and an axial field makes the physics much more difficult to analyze. "We were happy to forgo the extra gain an axial field might provide in order to have a model of the physics good enough to get us to the visible," explains Donald Prosnitz, leader of the Livermore contingent.

The Berkeley contingent is headed by accelerator theorist Andrew Sessler. Sessler is particularly interested in using high-power FEL output in the 1-cm wavelength regime to drive miniature versions of conventional rf linacs (see PHYSICS TODAY, February 1983, page 19). The large rf linacs now used for high-energy physics are driven by 10-cm rf input from powerful klystron tubes. The Stanford Linear Accelerator, for example, requires two miles of rf cavities to accelerate electrons to 50 GeV. Reducing the driving wavelength by an order of magnitude, Sessler hopes, could give us a miniature SLAC-type linac with an accelerating gradient of several hundred MeV per meter. A two-mile linac of such design could then accelerate electrons to perhaps TeV (1000 GeV).

But klystrons and other conventional microwave tubes become rather feeble power sources at wavelengths as short as a centimeter. What Sessler envisions for the new generation of high-energy-physics electron accelerators is, in effect, a "two-beam accelerator," with a low-energy, high-intensity electron beam, much like that produced by the ETA, running alongside the miniaturized accelerating linac. This low-energy beam, undulating its way through a magnetostatic wiggler structure, would serve as a free-electron laser source of 1-cm radiation that would be fed across by waveguides to the parallel accelerating structure, driving the second, low-intensity beam to hundreds of GeV. With such high-gradient accelerators, he points out, one could achieve 600-GeV e^+e^- collisions with a pair of head-on colliding linacs, each about a mile long, without spilling over the modest confines of the Stanford Linac Accelerator Center. Compare this to the LEP storage-ring collider now under construction at CERN, which aspires ultimately to achieve 200 GeV e^+e^- collisions with a gargantuan underground ring that circumnavigates more than a dozen villages on the Swiss–French frontier.

The ETA, the Experimental Test Accelerator operating at Livermore since 1979, is a prototype of the much larger induction linac—the Advanced Test Accelerator—completed at Livermore three years later (see PHYSICS TODAY, February, page 58). The 80-meter-long ATA can generate repeated 10-kiloamp pulses of 50-MeV electrons at high repetition rates. Such high currents are far beyond the capacity of rf linacs, where electrons effectively ride an electromagnetic wave down a series of resonant cavities. In an induction linac, by contrast, the electrons pass through a sequence of nonresonant cavities, each of which presents the electrons with a quasi-electrostatic accelerating gap fed by a high-voltage pulse from a transmission line.

The extraordinary current densities of which induction linacs are capable makes them uniquely interesting as beam sources for high-power free-electron lasers. One can understand the name "induction" linac by thinking of each of the linac's accelerating modules as a one-to-one, single-turn transformer. The transmission line serves as the primary loop and the electron beam is, in effect, the secondary.

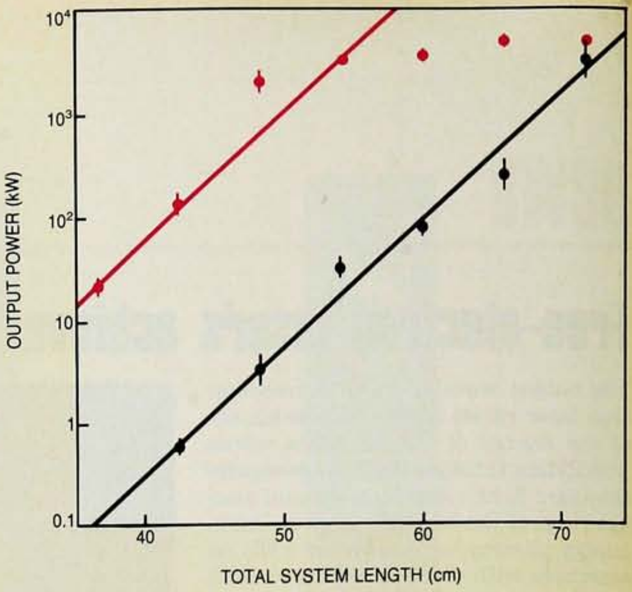
Prosnitz and his colleagues plan in the near future to use the ATA as an FEL beam source of 50-MeV electrons, thus getting down to wavelengths as short as 10 microns. To maintain adequate electron-beam quality for FEL operation at the high energy and current levels of the ATA, the group has developed a technique of "laser-guided particle-beam focusing." One fills the beam pipe with low-density benzene vapor and creates an electrostatic focusing channel by means of an ionizing auxiliary laser beam. The group has already demonstrated that one can in this way avoid the beam-breakup instability modes that plague high-current electron accelerators. The lid of secrecy having only recently been lifted, these ATA results will soon be submitted for publication.

With a higher-energy, high-current electron accelerator, the Livermore group anticipates that this approach would work in the visible. A high-peak-power FEL operating at submicron wavelengths with an efficiency exceeding 10% would be of considerable interest for military applications such as the Strategic Defense Initiative ("Star Wars").

Amplification. The electron beam pulses of both the Livermore–Berkeley and NRL experiments last only on the order of 10 nsec, much too short a time for the FEL to act as a free-standing laser oscillator. A laser oscillator would require reflectors at both ends of the wiggler and a beam pulse long enough for the radiation generated by the undulating electrons to bounce back and forth many times before the beam disappears. These devices were in fact single-pass laser amplifiers. Low-power 35-GHz radiation pulses from a microwave tube were directed into the upstream end of the wiggler along the electron beam path. With the beam energy and the wiggler's transverse magnetic field strength tuned to resonate with the wavelength of the input radiation, the radiation is amplified during a single pass through the wiggler by coherent stimulated emission of radiation at the same wavelength from the undulating electron beam.

In this configuration, Thaddeus Orzechowski and his Livermore–Berkeley colleagues observed saturation of their 3-meter-long wiggler with an input signal of 30 kW and a beam current of 500 amps. The signal was amplified to 80 MW, a gain of 34 dB. This almost 3000-fold increase in the energy of the input radiation comes from a 5% loss of kinetic energy by the 3.3-MeV electrons—the "extraction efficiency" of the FEL.

The NRL experiment, with an effective wiggler length of only 63 cm, would have achieved significantly lower gain had it not been for the gyro-resonant enhancement provided by the experi-



Output power of the NRL 35-GHz free-electron laser amplifier as a function of wiggler length. For 40-watt input (black), the data fit an exponential, $P_{out} = P_{in} \exp[(0.28\ \mathrm{cm}^{-1})(L - 32\ \mathrm{cm})]$ all the way out to 70 cm, indicating a small-signal gain of 1.2 dB/cm. For higher-power input (8 kW, color), the output follows the same 1.2-dB/cm exponential until saturation sets in at about 55 cm.

ment's 20-kilogauss axial magnetic field. With the aid of this axial field—eschewed by the Livermore experiment—the group was able to amplify a 7-kW input radiation pulse to 17 MW with an electron beam energy of only 0.9 MeV, just about the same 34-dB gain achieved a few months later at Livermore.

The NRL group, including participants from the Universities of Utah and Maryland, took its 600-amp electron beam from a pulse-line accelerator—essentially a single-shot device coupled to a large capacitor bank through a pulse-forming transmission line. The extraction efficiency with which energy was transferred from the electron beam to the radiation was observed to be about 3.2%.

Like the Livermore–Berkeley collaboration, the NRL group has achieved even higher gain levels with lower-power radiation input (subsaturation signals) and, indeed, with no radiation input at all ("superradiant" experiments). In these superradiant experiments, one begins not with input from a magnetron tube, but rather "from noise." As the electron beam undulates between the alternating-polarity magnet poles of the wiggler, it emits incoherent synchrotron radiation with a broad spectrum that peaks at the wavelength at which the FEL will eventually lase. This incoherent noise is sufficient to get the process of coherent laser amplification started even in the absence of radiation input or reflectors. In such superradiant experiments, however, it is more difficult to pin down the performance characteristics of the FEL system.

Gold stresses the potential usefulness of free-electron lasers as broadband high-power amplifiers in the millimeter-wave regime. Although conventional microwave generators such as klystrons, magnetrons and traveling-wave tubes can put out very high power levels at wavelengths near 30 cm, this power falls off rapidly with decreasing wavelength. Gyrotron tubes, Gold suggests, could in principle be designed to deliver high pulsed power efficiently at wavelengths below a centimeter, but to date they have served primarily as narrow-band amplifiers or fixed-frequency oscillators. For fusion-plasma heating with millimeter-wave radiation, for example, a Gyrotron oscillator would be the FEL's principal competitor.

The great virtue of the free-electron laser at these wavelengths, aside from its tunability, Gold suggests, is its broad bandwidth. "Without turning a knob," he told us, "one can amplify millimeter-wave signals containing a very wide spectrum of frequencies. "This would be particularly useful for radar and communications," he argues. One would shape a desired signal waveform on a low-power device and then amplify it to very high power with a free-electron laser.

"With its axial magnetic field, our experiment is principally relevant for high-power microwave and millimeter-wave applications," Gold explains. The Livermore–Berkeley experiment, on the other hand, looks primarily toward extrapolation to much shorter wavelengths. Another FEL group at NRL, led by John Pasour, has been using an old National Bureau of Standards induction linac to do superradiant experiments[3] at a wavelength of 1 cm. Because their induction linac has much longer beam pulse lengths (2 μsec) than the other groups, Pasour and his colleagues are looking toward the possibility of a free-standing high-power microwave laser oscillator. —BMS

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Stellar companion appears to be giant planet

Is Jupiter as large as a planet can be? Are the Sun's faint neighbors, with roughly 10% of its mass, the smallest stars? There is no apparent physical reason that objects in the mass range of 5 to 50 times the mass of Jupiter should not exist, and although the properties of such objects have not been well explored theoretically, their existence has important implications for a number of fields in physics and astronomy.

Now astronomers at the University of Arizona (Steward Observatory) and the Kitt Peak National Observatory have identified a companion to a nearby star named VB8 that appears to have a mass in this range—a mass below that at which hydrogen fusion reactions can occur in its core. In a paper published in the March issue of the *Astrophysical Journal*, David McCarthy (Arizona), Ronald Probst (Kitt Peak) and Frank Low (Arizona) argue[1] that they have identified a "substellar brown dwarf," or, to those uninitiated into astronomical jargon, a planet.

The existence of planetary systems beyond our own has been a topic of speculation for at least four centuries, since Copernicus displaced the Earth from its central position in the universe. Systematic searches have been conducted for nearly 100 years, using the techniques of classical astrometry to obtain precise positions for the nearby stars and then to follow their motions across the sky over several decades in an attempt to detect periodic deviations from a rectilinear trajectory caused by orbital motion about a stellar–planetary barycenter. In 1962, Peter van de Kamp of the Sproul Observatory published data indicating that Barnard's star (one of the ten nearest stars to the Sun, at a distance of 6 light-years) exhibited such motion, suggesting a companion with a mass several times that of Jupiter in a highly eccentric orbit. Subsequent work by several other astrometrists casts serious doubt on this claim, although a few additional examples of such nonlinear motion were subsequently uncovered.

One of the largest currently active astrometric programs is conducted by the US Naval Observatory with its 61-inch telescope at Flagstaff, Arizona. One of the Naval Observatory's major activities consists of determining the distances of some 1000 nearby stars using trigonometric parallax (observing the displacement of these foreground objects against the background of distant, fixed stars as the Earth describes its annual solar orbit). The stars for this program were selected as exhibiting large secular angular displacements on photographic plates taken several decades apart (which, for the relatively narrow range of intrinsic stellar velocities, implies relative proximity to the Earth). Robert Harrington (USNO) told us that VB8 was added to this program a decade ago, and that within a few years it showed a scatter about the expected parallactic curve that was larger than that of other program stars. Only about a dozen of the 1000 stars being monitored showed such deviations. Harrington and his collaborators drew attention to the possibility of a companion for VB8 about two years ago.

McCarthy and Low, meanwhile, have been interested in developing high angular resolution techniques for use in infrared astronomy for nearly a decade. The most promising of several methods to emerge was an adaptation of a technique employed for some time by optical astronomers: speckle interferometry. The image size of stars recorded by ground-based telescopes is determined principally by the amount of refraction—from turbulent cells in the atmosphere—suffered by the in-