

beam on the first half, one gets a spatial velocity modulation in the electron beam. Because the more energetic electrons are subsequently less bent, and hence traverse a shorter path in the dispersive mid-section, the velocity modulation is efficiently converted into a spatial density modulation (the desired bunching) in the downstream half of the undulator. (A klystron tube does much the same thing—converting a velocity modulation into a density modulation.)

With the 1.06-micron external laser beam focused on the upstream section of this optical klystron, the ACO group promptly observed coherent third harmonic output at 3550 Å, with an intensity 3000 times that of the spontaneous, incoherent, third-harmonic signal. The energy of this harmonic generation comes from kinetic energy loss of the 166-MeV electron beam circulating in the storage ring, *not* from the pumping pulsed laser. The repetition rate of the external laser—20 Hz—is, in fact, limited by the time required for synchrotron radiation in the storage ring to damp away the disruption engendered in the circulating beam by the intense laser pulse. In a linac-based FEL one would not have this problem, because the electron beam is discarded after every pulse. But on the other hand, the synchrotron radiation

damping in a storage ring greatly facilitates FEL operation at short wavelengths by keeping the electron beam's energy spread small.

Although the demonstration of coherent third-harmonic generation at ACO came very soon after the experiment was set up, Petroff told us, the technical difficulties were not trivial. Coherent harmonic generation, he explained, requires very precise superposition of the external beam with the electron beam in the undulator. This problem has in fact delayed the achievement of harmonic generation in a similar experiment currently being attempted by a Bell Labs-Brookhaven collaboration at the Brookhaven synchrotron light source. Richard Freeman (Bell Labs) told us that this problem should be solved by next summer with the installation of a new optical klystron that will permit the Brookhaven vuv storage ring to run at a higher energy with consequently greater electron-beam stability.

Petroff believes that the harmonic frequency multiplication technique demonstrated at ACO will prove an eminently practical source of coherent vuv and xuv light. The necessary external lasers are modest and commercially available. Even when the new storage rings eventually provide room for undulators long enough to

permit self-contained FEL oscillation at vuv wavelengths, he argues, the amplifier technique will still have the great advantage of avoiding the problems one has with mirrors in the ultraviolet. Furthermore, the extra optical power density supplied by external lasers should assure strong harmonic generation, providing bright coherent sources well down in the extreme ultraviolet.

Harmonic generation in pulsed gas jets has in fact already produced coherent xuv light at 355 Å (PHYSICS TODAY, November 1983, page 19). But with a gas serving as a passive nonlinear harmonic generator, as distinguished from the relativistic electron beam, which functions as an active nonlinear medium, the harmonic power must come from the pumping laser. In such schemes the conversion efficiency becomes extremely small as one goes to higher-order harmonics. —BMS

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Infrared free-electron laser uses electrostatic accelerator

From the near ultraviolet to the near infrared—2000 Å to 25 microns—we have access to an abundance of coherent sources, some of them tunable over limited ranges. For the outer reaches of the optical spectrum—the far ultraviolet and the far infrared, where conventional laser sources offer very little—free-electron lasers present a unique opportunity. The preceding story describes the promise of FEL harmonic frequency multiplication for the vacuum ultraviolet and extreme ultraviolet. At the other end of the spectrum, a novel, electrostatic-accelerator-based, broadly tunable, far-infrared FEL at the University of California, Santa Barbara, began lasing at 400 microns two months ago.

The Santa Barbara project, headed by Luis Elias, is unique among free-electron lasers in that the source of its electron beam is an electrostatic accelerator similar to a Van de Graaff generator, rather than the usual high-energy accelerator. Most free-electron lasers employ rf linacs or storage rings, producing electron energies on the order of 100 MeV. The lasing frequency of an FEL increases as the square of the electron-beam energy. Operating at very long wavelengths, the Santa

Barbara laser requires electron energies of only a few MeV. Such modest energies are easily supplied by old-fashioned electrostatic accelerators like the Van de Graaff.

With a maximum electron energy of 6 MeV, the Santa Barbara FEL will soon be continuously tunable over an extraordinarily broad far-infrared wavelength range—from 100 to 1000 microns. One tunes the laser simply by varying the accelerating voltage. Although this project has been funded by the Office of Naval Research primarily to study the operation of FELs using electrostatic accelerators modified to exploit electron-beam recovery, there will also be a strong emphasis on using the new instrument as a high-power, broadly tunable research tool for spectroscopic and condensed-matter investigations. The plan is eventually to turn the laser into a user facility for the general community of far-infrared experimenters. Placing similar emphasis on far-infrared experimentation, Earl Shaw, Kumar Patel and their colleagues at Bell Labs are developing a microtron-based FEL with a maximum wavelength of 400 micron.

The far-infrared is of particular interest to condensed-matter experi-

menters. "Almost all the collective excitations of solids—phonons, magnons and the like—occur at these wavelengths," we were told by Vincent Jaccarino, a Santa Barbara physicist particularly interested in exploiting the new laser to investigate such phenomena. Carbon dioxide lasers operate at a fixed wavelength of 10.6 microns, and high-energy accelerator-based free-electron lasers have also been limited to the near infrared. For longer-wavelength studies, very little is available. Alcohol lasers, exploiting transitions between rotational levels of various alcohol molecules, provide coherent radiation at a discrete set of longer wavelengths; but they are limited to milliwatts of output power. What the experimenters want is continuous tunability and much higher power levels, especially for the study of nonlinear excitations and chemical reactions.

Recirculation. Electrostatic accelerators are simple, extremely stable and relatively cheap sources of high-quality charged-particle beams of modest energy. But in conventional use they offer only very limited beam current—on the order of a few hundred microamps. For high-power FEL operation, one requires a much higher electron cur-

rent. One could run a conventional Van de Graaff with an ampere of current, but only for unacceptably short pulse durations. In high-current operation, the accelerator's high-voltage terminal discharges much more quickly than it can be recharged; one could not maintain a monoenergetic 1-amp current for more than a microsecond.

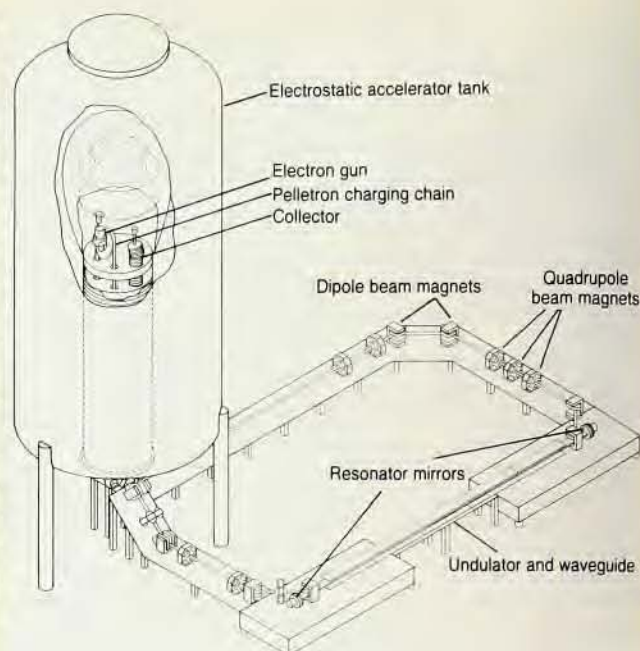
A microsecond is, however, not long enough to achieve lasing saturation in the FEL undulator. Saturation in a free-electron laser oscillator typically requires that the light bounce back and forth in the resonator on the order of a hundred times. Thus, in the 5.6-meter-long Santa Barbara FEL undulator, one needs a current pulse duration of at least 5 μ sec to reach saturation.

Devising a technique to provide a high-current pulse persisting for tens or even hundreds of microseconds would not only permit the FEL to reach saturation. It would also be of considerable interest to condensed-matter experimenters. The output of FELs based on high-energy accelerators or microtrons comes in trains of picosecond micropulses. While this has the virtue of permitting the study of fast processes with high temporal resolution, it exacts a cost in frequency resolution. The Fourier transform of a much longer optical pulse has, of course, a far narrower frequency spectrum, permitting spectroscopic studies with very high energy resolution. Furthermore, the longer the optical pulse, the greater is the time-averaged power delivered to the experimental sample.

To lengthen the pulse duration of the electron beam by one or two orders of magnitude, Elias and his colleagues have devised the innovative trick of *recirculating* the electron beam—returning it to the accelerator's high-voltage terminal after it has made its lasing pass through the undulator. If one could return 99% of the electrons to the polished aluminum ball atop the accelerator whence they began their 3-megavolt descent to the undulator, Elias expects, one could lengthen the current pulse to perhaps 100 microseconds. The first lasing was achieved on 21 August with 95% beam recirculation yielding a current of 1.25 amps lasting 11 μ sec. Having earlier achieved 99.4% recirculation before the free-electron laser undulator was installed in the beam path, the group is confident that they can eventually achieve 99% recirculation during FEL operation. Continuous (cw) operation of the Santa Barbara laser would require a recirculation rate of about 99.9%; but this fond hope may well be undermined by small, insidious effects.

The history of electron recirculating goes back 20 years to Gersh Budker's 1964 proposal to recapture the energy

The far-infrared free-electron laser at UC, Santa Barbara, consists of an electrostatic accelerator producing electron energies up to 6 GeV, a 5.6-meter-long undulator surrounded by a hybrid mirror-waveguide resonator, and the electron-beam magnets required to steer the beam through the undulator and back up the accelerator for recirculation. By recovering more than 95% of the electrons in this way, one can lengthen the duration of the high-current electron pulse by one or two orders of magnitude.



of electron beams used to "cool" colliding high-energy proton beams at Novosibirsk. A decade later, John Madey (Stanford) suggested that one might exploit electron beam recirculation to render electrostatic accelerators suitable for FEL operation.

Optical power. No rf-accelerator-driven free-electron laser has as yet produced continuous optical pulses longer than a few picoseconds. The present configuration of the Santa Barbara system can produce 50- μ sec optical pulses with a peak power of 3 kW at a repetition rate up to 10 Hz. This yields a time-averaged power level on the order of 100 watts. With the replacement of the present undulator by one of helical design next spring, the system should be producing megawatts of peak power.

For many experimental applications—for example, the modification of chemical reactions—high average power with long pulse durations is at least as important as high peak power. With kilowatt average power levels an immediate prospect, the question of efficiency becomes important. In the absence of recirculation, the lasing efficiency of the Santa Barbara FEL is only about 0.3%. That is to say, in a single pass through the undulator only 0.3% of the electron beam energy is converted to coherent radiation. If one multiplies this single-pass efficiency by the intrinsic efficiency of the electrostatic accelerator itself, one gets a distressingly low overall efficiency on the order of 10^{-6} . One would need a megawatt of input power for every watt of average-power output.

Here again, recirculation of the elec-

tron beam comes to the rescue. As the same electrons are used again and again, the efficiency of the electrostatic-accelerator-FEL system increases dramatically, reaching levels that become interesting for such high-power applications as fusion plasma heating and submarine communication. Elias is in fact spreading the word among tokamak researchers, who are always on the lookout for efficient, high-power auxiliary heating sources for their fusion plasmas.

The picosecond microbunch length inherent in rf linacs limits FEL operation to wavelengths shorter than 200 microns. The Bell Labs microtron-based FEL, with a similar time structure, is designed to go as far as 400 microns, but it cannot achieve the millimeter wavelengths envisioned for the Santa Barbara facility.

The Pelletron. The National Electrostatics Corporation's variant of the Van de Graaff accelerator employed at Santa Barbara is called a Pelletron. The principal difference between the Pelletron and the conventional Van de Graaff is that the conveyor carrying the electrons to the high voltage terminal is a chain of metal pellets rather than the usual rubber belt. The basic accelerating scheme, however, is the same. Electrons deposited on the conveyor at ground are mechanically transported to a hollow, polished metal ball sitting atop an insulating column. As it accumulates charge, this terminal acquires high voltage, providing a strong, accelerating electrostatic gradient back to ground. The work is done by the mechanical conveyor, which carries the charges uphill against the



The Santa Barbara FEL produced its first laser output at 400 microns at the end of August. One sees the base of the tall, yellow electrostatic accelerator tank at the back, filled with 6 atmospheres of SF_6 gas. The beam loop on the floor passes the electron beam through the FEL (left) and recirculates it back to the accelerator (see drawing opposite).

gradient. An electron gun in the high-voltage terminal then injects the electron beam back downhill into the accelerating column.

In the Santa Barbara scheme, the accelerated electron beam, after passing through the FEL undulator, is sent back uphill against the electrostatic gradient, giving up its kinetic energy to climb back to the high-voltage terminal. Having lost a small fraction of their energy in the process of lasing in the undulator, the electrons require a slight boost to get back to their starting voltage.

High-power FEL operation requires an electron beam of very good optical quality, with minimal "emittance" (phase-space spread). This requirement is particularly demanding when the recirculation scheme sends the beam repeatedly through the disruptive undulator and the dozens of bending and focusing magnets that steer it back up the accelerator. The Santa Barbara group has therefore been at pains to develop a novel electron-gun design that minimizes beam aberrations. "By eliminating the conventional gridded structures that introduce diffractive aberrations, we've been able to generate an electron beam with transverse emittance nearly 20 times better than what one can achieve with an rf accelerator," explains Jerry Ramian, chief engineer of the Santa Barbara project. Approaching the thermal emittance limit, "we now have the highest-quality electron beam available at any accelerator that employs electron-gun injection," Elias told

us with some pride. This is all the more impressive when one considers that Van de Graaff generators are used almost exclusively to produce ion beams. Elias's suggestion that one could produce a high-quality electron beam in this way had met with some skepticism.

Short-wavelength free-electron lasers generally use spherical mirrors to keep the lasing optical field away from the walls of the resonator cavity. Such "free-mode resonators," however, become impractically large for long-wavelength operations. Infrared lasers, therefore, frequently employ waveguide cavities to contain the optical field. In high-power operation, however, the losses in the metal waveguide walls become severe. To reduce waveguide propagation losses and to increase long-wavelength gain, Elias has introduced a novel hybrid resonator design for the Santa Barbara FEL, with waveguide walls containing the optical field vertically while cylindrical mirrors, located where waveguide losses would have been worst, serve horizontally as a free-mode resonator.

Plans. Now that lasing has been demonstrated, Jaccarino has begun casting about for funding to build a modest user facility around the Santa Barbara laser. With kilowatts of tunable far-infrared power, he anticipates that one will be able to excite collective excitations in a nonlinear fashion. "At low power, we've been restricted to exciting phonons and magnons with wave numbers near zero," Jaccarino told us. "Now we'll be able to explore

the entire Brillouin zone." Among the nonlinear excitations that now become accessible to detailed study are the lattice instabilities that are thought to generate the ferroelectric transition and excited DNA modes that may play a role in replication.

For high-resolution spectroscopy one wants a very well-defined laser output frequency. To this end, the unique stability of electrostatic accelerators is a great boon, together with the long pulse duration that narrows the Fourier spread of the laser output.

In its present configuration, the Santa Barbara FEL will operate only at far-infrared wavelengths longer than 100 micron. But the next step is to attempt to turn the system into a "two-stage FEL," permitting the laser to operate over the full range from millimeter wavelengths down into the ultraviolet. For a given electron energy, the lasing wavelength of an FEL is proportional to the undulator period—typically a few centimeters. The two-stage trick for producing short wavelengths is to generate an optical field of such intensity in the undulator that the radiation field itself serves effectively as a second undulator of much shorter periodicity.

Demonstrating the feasibility of this novel two-stage scheme is an important part of the Santa Barbara FEL development program. With a new undulator soon to be installed, the Santa Barbara FEL should be able to generate optical intensities on the order of 10^8 W/cm^2 . At this point, the magnetic intensity of the radiation field becomes comparable to that of the magnetostatic undulator, and one has, in effect, an auxiliary undulator with a period of a fraction of a millimeter. Thus, without increasing the maximum beam energy, one has an infrared FEL that can also generate laser light in the ultraviolet.

This great expansion of tunable wavelength range is, however, purchased at the expense of output power. A two-stage FEL is far less efficient than a one-stage system. With an eye toward the eventual production of very high power in the near infrared, the Santa Barbara group envisions the employment of the 40- or 50-MeV electrostatic accelerators that are currently under development at NEC, and the use of "microwigglers"—undulators with periods of a few millimeters. Such high-power visible FELs could have important military applications. The gigantic lasers now employed in inertial-confinement fusion research (Nova and Antares) have, of course, much higher peak powers than one could anticipate with such a device; but an FEL based on an electrostatic accelerator would generate much longer pulses and hence higher average power.

—BMS □