

for this initial launch will get the first two months of their guaranteed observing time. However, it will actually take five months to get these observations, because time will be shared with tests to verify the performance in orbit of the observatory and science instruments. Following the 100% guaranteed observing time, the hardware developers will be allowed 50% guaranteed observing time for the next six months, with the fractions decreasing to zero 33 months after launch.

Some astronomers have already been working toward those first results from Space Telescope for a decade or even longer. In its earliest phase, it was called the Large Space Telescope, and not tied to the Space Shuttle. Now, 13 years and two name changes later, it appears almost ready for launch. C.

Robert O'Dell (Rice University), who was project scientist from 1972 through 1983, wryly observed, "We'll soon know if we developers get the best science out of the observatory or if that distinction falls to those who stayed home doing good science instead of attending reviews for ten years."

The Space Telescope Science Institute, whose building on the Johns Hopkins Homewood campus was formally dedicated last year, has established five working groups that will identify key projects for Space Telescope. The groups are: solar system studies; stars and star clusters; interstellar/intergalactic medium and supernovas; galaxies and clusters of galaxies; and quasars and active nuclei. Next June the Institute will issue a call for proposals. Selection will be made

by peer review. The Institute estimates about 30% of the observing time might go to the key projects identified by the working groups.

Second-generation instruments for Space Telescope may exploit Space Telescope's capability for two-dimensional spectroscopy and studies in the near-infrared. To that end, this month NASA expects to issue an Announcement of Opportunity for second-generation instruments to replace one or two of the first-generation instruments in 1990 and 1991. Meanwhile, if one of the first-generation instruments failed, some replacement might be possible. There will be a back-up Wide Field/Planetary Camera available two and a half years after launch, and almost a complete replacement of the Faint Object Camera, if needed. —GBL

Orsay free-electron laser demonstrates uv harmonic generation

Coherent sources of vacuum-ultraviolet and extreme-ultraviolet radiation are hard to come by. The selection of lasers emitting in the vuv (wavelengths below 2000 Å) is very limited, and the first clear observation of laser emission in the xuv (below 1040 Å) is only a year old (PHYSICS TODAY, November 1983, page 19).

Coherent vuv and xuv sources are much sought after for a broad range of uses in pure and applied physics. With the advent of a new generation of dedicated electron storage rings comes the prospects of free-electron lasers operating in the vuv. But this is still some years off. No existing storage ring is suitable for *direct* FEL operation at vuv wavelengths.

It is therefore with considerable enthusiasm that the community of prospective users hears¹ of the recent demonstration of an *indirect* free-electron-laser technique by Yves Petroff and his colleagues at the 20-year-old ACO storage ring at Orsay, south of Paris. In July they demonstrated the feasibility of exploiting a free-electron-laser undulator to generate coherent ultraviolet harmonic output from a longer-wavelength external laser source.

Focusing the 1.06-micron output of a high-power, pulsed Nd:YAG laser on the upstream section of a free-electron-laser undulator through which the 166-MeV electron beam of the storage ring was wending its serpentine way, the ACO group observed a strongly enhanced, coherent, third-harmonic output at 3550 Å in the near ultraviolet. This is not yet the vacuum ultraviolet, but Petroff sees no impediment to doing the same thing starting with a 2480-Å excimer laser, in which case the third-harmonic output (827 Å) will be well

into the extreme ultraviolet.

This is the group's next order of business. They chose to do the proof-of-principle demonstration at longer wavelengths, Petroff explained, because the detection of xuv output requires a complex vacuum monochromator. (Below 2000 Å, water vapor renders air opaque to vuv beams, and below 1040 Å, all materials are opaque to xuv radiation.) This extra effort is only justified, he points out, after one has demonstrated success in the near ultraviolet, where detection is more straightforward.

The Orsay group stresses its debt to Francesco DeMartini, a theorist at the University of Rome, who has for the past five years championed and calculated the details of harmonic frequency multiplication in free-electron lasers.

Free-electron lasers and laser amplifiers function by transferring energy from a beam of relativistic electrons to an electromagnetic optical field traveling with the beam. This energy transfer requires two essential conditions: ▶ Because the optical field is purely transverse, the electron beam must be made to undulate so that it acquires a transverse velocity component.

▶ Because the electrons will be *accelerated* as well as decelerated by different phases of the optical field, nonzero net energy transfer requires that the electrons be nonuniformly distributed along the beam; they must be bunched into packets concentrating in the decelerating phases of the optical field.

The electron beam in an FEL acquires an undulating trajectory by passing between the alternating, periodically spaced poles of a magnetostatic undulator. As a result of this periodic bending, the electrons emit spontaneous, incoherent synchrotron radiation,

peaked at a resonant wavelength given approximately by $\lambda_u/2\gamma^2$, where λ_u is the spatial periodicity of the undulator and the Lorentz factor γ is the electron energy divided by $m_e c^2$. If this spontaneous incoherent radiation is strong enough and the electron beam is of sufficient density, one need only put mirrors on either end of the undulator to have a self-sufficient free-electron-laser oscillator; no external laser source is required. The repeatedly reflected synchrotron radiation will intensify and become coherent as it stimulates the electrons to emit at the resonant wavelength. The relation between the resonant wavelength and the electron energy is such that an observer riding the electron beam sees the undulator periodicity (typically several centimeters in the lab frame) and the optical wavelength as the same.

The requisite bunching action is accomplished by the optical field. Electrons accelerated in one phase region move ahead of the mean beam velocity; electrons decelerated in an adjacent phase region fall behind. The result is a gathering of the electrons into microbunches whose length is comparable to the resonant optical wavelength.

Harmonic generation. This spatial bunching of the electron beam at the resonant optical wavelength of the FEL will, in general, also contain higher Fourier components. This will be reflected in the appearance of higher harmonics in the incoherent synchrotron radiation from the electron beam traversing the undulator. If the bunching is sufficiently pronounced at these harmonic frequencies, one will also see the higher harmonics in the coherent optical output of the system.

Such coherent harmonic output has

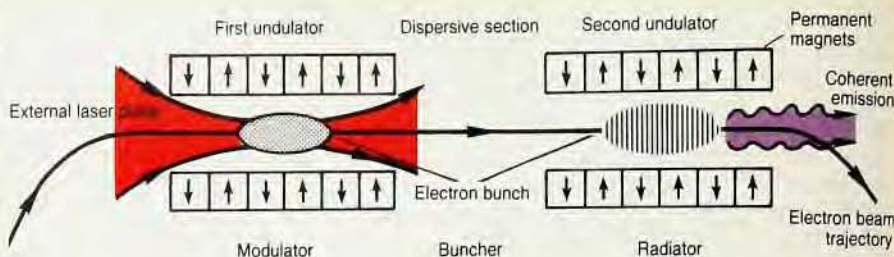
already been seen at three free-electron-laser oscillators: John Madey's Stanford group observed 2nd and 4th harmonic output from the original 3-micron FEL in 1976; Charles Brau and his Los Alamos colleagues last year saw² the fifth harmonic in the output of their 10-micron FEL oscillator; recently a TRW-Stanford collaboration observed the first such coherent harmonic generation in the visible—their 1.6-micron FEL oscillator at the Stanford superconducting linac was seen to lase in the green (3rd harmonic). The higher the harmonic, of course, the weaker the output. Symmetry considerations restrict the output of the usual linear undulator configuration to the odd harmonics. Madey's original undulator had an atypical helical geometry designed to suppress the odd harmonics. Thus they were able to see the second and fourth harmonics.

With coherent ultraviolet sources being so ardently sought after, can one not extend this harmonic-generation scheme to shorter wavelengths, or simply build an FEL oscillator with a vuv resonant wavelength? These short wavelengths pose special problems. Quite generally, the higher the frequency of the FEL one wants to build, the more difficult it is to achieve adequate gain; the gain decreases as $f^{-3/2}$. The gain does, however, increase as the cube of the undulator length. "If we could put a 5-meter-long undulator in ACO," Petroff told us, "we'd have a 2000-Å free-electron-laser oscillator immediately."

There is, however, no room for a 5-meter undulator in ACO, or for that matter, in any other suitable storage ring. The undulator used by Petroff's group is 1.3 meters long, the maximum length that can be accommodated by the straight sections of the ACO ring. Things should get better in a couple of years, when the new "Super ACO" storage ring is completed at Orsay. The ten-year-old DCI ring will then be entirely at the disposal of the FEL researchers, who will then be able to modify it to accommodate a 5-meter undulator. Super ACO, which is also intended as a synchrotron-radiation source, will be able to accommodate several undulators as long as 3.4 meters.

Mirrors also present a special problem at short wavelengths. Ultraviolet radiation tends to degrade the reflectivity of laser mirrors and, as one goes to lower wavelengths, it becomes increasingly difficult to obtain the "half-silvered" mirrors necessary to pass light out of the laser. In the xuv region—below 1040 Å—all solid materials are completely opaque.

Laser amplifiers. An FEL undulator can serve as a source of coherent light at the fundamental resonant frequency



The optical klystron of the Orsay free-electron laser, shown schematically, is a conventional FEL undulator split into two halves separated by a dispersive midsection. The electron bunch (grey oval) from the ACO storage ring, passing through the array of alternating permanent magnets, acquires the serpentine motion that couples it to the focused optical field from the external laser. In the upstream (modulator) section, this coupling produces a velocity modulation, which the dispersive (buncher) midsection converts to a strong spatial modulation that breaks the bunch into microbunches as short as the external laser wavelength. In the downstream (radiator) section, this pronounced microbunching produces coherent radiation not only at the external laser frequency, but also at its third harmonic.

or its harmonics in two distinct ways: either as a self-contained laser oscillator or as a laser amplifier of coherent light from an external laser. Historically, in any given wavelength regime, FEL amplification has been demonstrated before free-standing FEL oscillation has been achieved. An FEL amplifier does not use mirrors to create an oscillator cavity. The beam from an external laser with the same wavelength as the undulator's resonant wavelength is propagated along the electron beam traveling through the undulator. The resulting stimulated emission from the undulating electrons amplifies the incident laser beam at the expense of the electron's kinetic energy.

The Orsay group, collaborating with John Madey, David Deacon and their Stanford colleagues, last year demonstrated the first FEL oscillator operating at visible wavelengths—using the same 1.3-meter undulator employed in their present harmonic-generation experiments (PHYSICS TODAY, December 1983, page 17). In last year's visible-oscillator experiment, ultraviolet harmonics were a plague rather than a boon. They caused serious mirror damage that took months to overcome.

Unlike the harmonics observed in the various infrared FEL oscillators operating at rf linacs, the ultraviolet harmonics seen in the Orsay-Stanford visible FEL oscillator were incoherent synchrotron radiation. Coherent harmonic generation from self-contained laser oscillators has only been demonstrated in oscillators operating in the "strong-signal" or saturated regime. The linac-based infrared FEL oscillators have sufficiently high electron current densities to operate in the strong-signal regime. The storage-ring-based ACO oscillator was restricted to the weak-signal regime by its shorter wavelength and the much smaller current density available in a

storage ring. On the other hand, the excellent beam quality available at ACO made possible FEL oscillations in the visible—a feat not yet accomplished at any linac.

External laser source. Operating in the weak-signal regime, the ACO free-electron-laser oscillator simply does not supply sufficient optical power density to produce coherent harmonic generation by itself. The generation of coherent harmonic radiation requires enough optical power to yield strong electron bunching. This the Orsay group supplied by focusing on the undulating electron beam the 1.06-micron output of a commercially available 15-megawatt (peak power) Nd:YAG laser with a pulse duration of 15 nanoseconds.

With the ACO storage ring providing an electron beam energy of 166 MeV, the resonant wavelength of the undulator was also 1.06 microns. Thus the undulator and the electron beam were operating as an FEL amplifier for the external laser source. The mirrors used in the earlier visible FEL oscillator experiments are no longer necessary. This mirrorless configuration circumvents all the problems attending the use of mirrors with ultraviolet radiation.

Optical klystron. An innovative trick used by the Orsay-Stanford collaboration to achieve lasing last year was to convert the 1.3-meter undulator into an "optical klystron"—a configuration suggested in 1977 by N. A. Vinokurov and Alexander Skrinisky (Novosibirsk) for enhancing the gain of free-electron lasers. One converts a conventional undulator into an optical klystron by removing a pair of poles from the middle of the periodic array of magnets and imposing a higher magnetic field in the resulting gap. Thus the undulator is effectively divided into two halves with a dispersive section between them. Focusing the external laser

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-