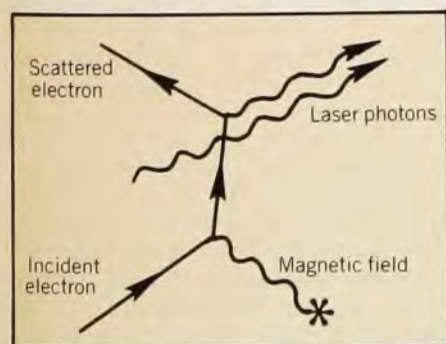


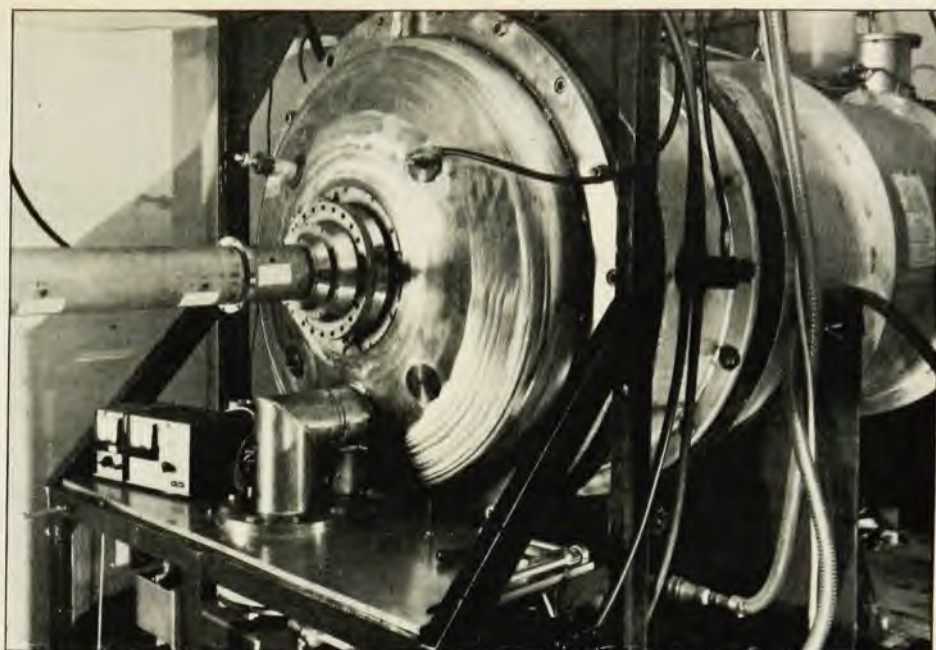
Update on free-electron lasers and applications

Lasers whose operating frequencies are not determined by energy levels in atoms or molecules have long been a goal of researchers in the field. Stimulated scattering by free electrons passing through spatially varying magnetic fields promises to meet that goal. Two years ago, a group at Stanford reported laser action from stimulated bremsstrahlung,¹ and a collaborative effort of the Columbia University Plasma Lab and the Naval Research Lab has produced a laser based on stimulated Raman scattering by free electrons.² These results have encouraged many other laboratories to investigate the construction and potential uses of free-electron lasers. Active research is now going on at Bell Labs, Los Alamos, The University of Trento, Frascati, Brookhaven, and the Lawrence Livermore Labs, among others. Much of the excitement is due to these lasers' promise of exceedingly high power levels at a low enough cost to make them useful suppliers of industrial process energy.

Principles of operation. The purpose of a laser is, of course, to produce a large number of coherent photons—what can, in effect, be called a collective mode of the electromagnetic field. In the free-electron lasers now in operation, the coherent radiation arises in a stimulated scattering process in which a high-energy free electron is scattered by a spatially varying magnetic field. The upper laser state consists of a fast electron together with a virtual photon from a rippled magnetic field; the lower state has a scattered photon together with a low-energy electron. One can represent the process in a Feynman-type diagram as shown:



With enough scattering events, the scattered radiation can build up to sufficiently high levels to stimulate further scattering, ultimately raising the intensity above the laser threshold. A classical point of view can equally well be used to understand the process: The combined action of the rippled magnetic field and the signal field



The VEBA pulsed high-energy diode at the Naval Research Laboratory. The large tank is a transmission line that forms the pulse; the electron beam propagates along the tube to the left. In the free-electron laser the tube is surrounded by a solenoid that produces a rippled field.

produces longitudinal forces that cause bunching of the electron beam, and the oscillation of these bunches in the field in turn produces radiation at the laser, or signal, frequency. The basic principles are not new, and have been in use in the microwave region since the early 1950's, in devices such as the "ubitron." In fact, the new devices could just as well be called "relativistic ubitrons" as "free-electron lasers," Norman Kroll, a theorist at the University of California at San Diego, told us.

The two free-electron lasers differ in whether the electrons also exhibit collective oscillations. In the Stanford work, the electron beam has a relatively low intensity (2.6-A peak current) and does not exhibit collective oscillations; each electron scatters individually. In the laboratory frame the process can be described as stimulated bremsstrahlung. In the electron's rest frame the scattering process looks very much like stimulated Compton scattering, except that the incident photon is a virtual one. The Stanford group obtained stimulated emission amplifying an external beam three years ago (PHYSICS TODAY, February 1976, page 17), and was able to obtain laser operation soon after. In their apparatus a 43-MeV beam, from the Stanford superconducting linac, passes through a helical magnet coil that produces a field whose direction varies along the beam axis with a 3.2-cm period. The output laser beam has a wavelength of roughly 3.4 microns.

In their subsequent investigations the group, which includes Luis R. Elias, John M. J. Madey, H. Alan Schwettman, Todd I. Smith, and various other faculty, postdoctoral fellows and graduate students, has been investigating the structure of the

optical pulse in the time and frequency domains. Madey told us that they are particularly interested in relating properties of the optical pulse to parameters of the electron pulse and of the cavity.

The Columbia-NRL laser, which was built by David B. McDermott, Thomas C. Marshall and S. Perry Schlesinger (all at Columbia), and Robert K. Parker and Victor L. Granatstein (at NRL), involves a lower energy beam (1.2 MeV), but with a much higher intensity (25-kA peak current) and, more importantly, much higher current density. The electron beam is produced by field emission from the cathode attached to the VEBA pulsed-high-voltage diode at the Naval Research Lab. (It resembles the Aurora device at the Harry Diamond Laboratories.) After emerging from the accelerator the beam passes through a region in which a strong longitudinal field has a spatially periodic ripple imposed on it. (The ripple is produced by inserting, within the main solenoid, a set of aluminum rings that carry currents in alternate directions.) Light emitted while the electrons are in the "undulator" is reflected by annular mirrors, which serve to define an optical cavity. The cathode that emits the electron beam is inserted through the hole in one mirror, and the laser beam leaves via the other. The wavelength reported for the initial experiments is about 400 microns.

The nonlinear interaction of the rippled field and the signal wave in the electron plasma produces a disturbance that propagates as a collective wave along the beam. This plasma wave reinforces the scattering into the laser mode and produces a high-gain system. The process is, essentially, stimulated Raman scattering from the electron beam. The virtual

photons of the magnetic field, whose wavelength is relativistically contracted, serve as the high-energy "pump" mode in this three-mode process; the plasma wave is the "idler" mode that absorbs the energy remaining from the inelastic Raman scattering, and the scattered light, whose frequency is less than that of the pump, is the "signal" mode. The laser is thus analogous to the well-known parametric amplifier.

The Columbia-NRL group has been working to upgrade their apparatus. They have also been investigating ways to reduce the effect of second-order Stokes (two inelastic scattering events) and of anti-Stokes (inelastic scattering to higher frequency) processes, Marshall told us. Such processes detract from the growth of the laser intensity, and are therefore undesirable.

Both the Stanford and NRL lasers are tunable by adjusting the electron-beam energy. One can also vary the period of the rippled magnetic field and thereby change the frequency of the output, but that is a more complicated procedure. Most lasers are restricted to fairly narrow ranges, whose wavelengths are determined by atomic or molecular energy levels. Even dye lasers are limited by the absorption bands of available dyes. The energies of free electrons are not so constrained. In fact, Madey told us, it should be possible to reach the ultraviolet with storage-ring devices. The Stanford group is investigating a number of possibilities for improving the performance of the lasers; Madey and David Deacon, a former graduate student of his, have, for example, suggested using isochronous electron optics to keep the electrons bunched, which should permit much higher power levels. The absence of a medium (fluid or glass, say) in which the laser action takes place provides a further advantage for high power levels: Conventional lasers are often limited in power or spatial resolution by nonlinear optical effects in the lasing medium; again, free-electron lasers are not subject to these problems.

The field is an actively developing one, and some of its earlier history is obscured by security classifications. Our earlier report, a recent report in *Nature*³ and the latest volume (5) of *Physics of Quantum Electronics* all contain accounts of the development of the idea. In 1951 Henry Motz⁴ built the "undulator" to produce spontaneous radiation from an electron beam in a periodic transverse field, and the ubitron was invented in 1960 by R. M. Phillips.⁵ In 1968 Richard Pantell and his collaborators⁶ in the Electrical Engineering department at Stanford and, Madey,⁷ independently in 1971 suggested using relativistic beams to produce the scattering. Elias has proposed⁸ using a high-intensity pump wave at far-infrared frequencies together with a recirculating beam, accelerated electrostatically, to obtain continuous radiation, tunable from

infrared to ultraviolet frequency. His proposal will be funded by the Office of Naval Research, Elias told us, and he expects the machine to be ready in the early 1980's.

Potential applications. Now that the feasibility of at least two varieties of free-electron laser has been demonstrated, their potential applications are being investigated. Charles Brau, who is heading a group working on the subject at Los Alamos, told us that he foresees high-efficiency, high-power, low-cost lasers that would be useful for large-scale industrial processes. This would happen, Brau said, when the device produces photons at about one cent per mole of photons, or a capital cost of a few dollars per watt. He expects that the overall efficiency of the free-electron lasers will approach about 40% (total ac input to light output) with the electron-beam-energy recovery techniques being developed at Los Alamos. Although not everyone we talked to shares Brau's optimism, they do agree the laser will be a very good capital investment for producing photons even if it does wind up being somewhat more expensive than traditional lasers. And Granatstein told us that recent theoretical calculations at NRL also gave efficiencies in the 40% range. (For comparison, the CO₂ laser, which is one of the most efficient currently available, has a demonstrated overall efficiency of 15–20%.)

One obvious use of such a high-power source of relatively narrow-band radiation is in industrial chemistry, to supply energy to specific reactions. For example, Brau told us, one could use such a source to clean the exhaust gases from combustion by selectively decomposing noxious substances. Similarly, one could purify the feedstocks for chemical processes by selective destruction of contaminants. That process has already been investigated, using an argon-fluoride laser, for silane gas. Coal gasification is another potential application.

Kumar Patel of Bell Labs told us that the high-intensity, short pulses of radiation enable one to do time-resolved studies of transient phenomena, as well as more usual sorts of spectroscopy. Bell Labs is building a free-electron laser tunable over a broad range of frequencies, which they intend to use for analytic studies, at least initially.

A further type of application, particularly of the sub-millimeter radiation produced by the Columbia-NRL laser, is for radar, an application that clearly interests the Air Force and Navy, which are supporting much of the Columbia-NRL work. Marshall told us that the coherence and high peak power of the radiation make it very attractive for this use.

The line width ($\Delta\lambda/\lambda$) of the lasers is about 2% for the Columbia-NRL experiments and somewhat less than 0.2% in the Stanford experiments. The latter ap-

proaches the width of pulsed dye lasers. For most of the applications that are foreseen, including the industrial photochemistry applications, one does not need particularly narrow emission lines, Madey told us. The high power, coherence, and tunability are already very attractive properties. The Trento and Frascati groups have organized a conference that was to be held near Trento in June, to explore the potential for applying free-electron lasers to chemistry. —TVF

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High-energy astronomers take a look at x-ray sky

The second orbiting High Energy Astronomy Observatory started its normal operations on 7 January. It has already produced more than a thousand x-ray images, many of them spectacular pictures of supernova remnants, quasars, galaxies, clusters of galaxies, stars and clusters of stars. It has also produced a number of puzzles, most notably for theories of pulsar formation.

The pictures are produced with a high-resolution grazing-incidence reflecting telescope that can be focused on one of four interchangeable instruments, including a television-like multichannel system with a roughly 5-arc-sec resolving power and an imaging proportional counter with a one arc-min resolving power and very high sensitivity. These instruments provide an increase in sensitivity of a factor of 1000 and an increase in spatial resolution (in one measure) of a factor of 40 000 over earlier instruments. As Riccardo Giacconi, principal scientific investigator of the project, put it, in the twenty-odd years since its beginning, x-ray astronomy has evolved as much as optical astronomy did in the years from Galileo to Palomar.

The rate at which data are being received has so far permitted only preliminary investigations; more than a thousand new x-ray sources have already been found in the pictures, for example, and other data are coming in at a comparable