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Free electron lasers: scientific challenge for military and civilian development

by Charles B. Stevens

Both classified and unclassified experiments throughout the world, most recently at France's Orsay Laboratory for the Utilization of Electromagnetic Radiation, show that the energy of high-quality electron beams can be directly converted to laser radiation.

Theoretical and computer studies based on these experiments indicate that this conversion of "free electron" energy into laser beam energy can be scaled to high power levels and readily tuned to a wide variety of wavelengths with extremely high efficiencies compared to conventional lasers. This free electron laser (FEL) promises to be a most versatile tool for laser applications—such as optical communications, isotope separation, metal cutting and finishing, photochemistry, anti-missile beam weapons and inertial confinement fusion—and for making feasible entirely new ones such as intercontinental transport of power and laser beam propulsion of satellites.

Thus, the FEL promises to be the "electric motor" of the emerging laser industrial revolution.

As announced in the June 24 *Le Monde*, scientists at the Orsay Laboratory for the Utilization of Electromagnetic Radiation reported that on June 22 that they were able to extend the operation of their FEL, which is based on an electron beam storage ring, to the shorter "red" wavelength—about 0.6328 micrometers—at low beam power levels of about 50 microwatts. The previous short wavelength record for an FEL was held by Stanford University which achieved outputs in the multimicrometer infrared range. The French team which is led by Dr. Yves Petroff who has been collaborating with Stanford's Dr. John Maddy, the inventor of the FEL concept, for the last several years. This most recent FEL breakthrough demonstrates the increasing progress of FEL technology in general and will have immediate applications in the full range of laser photochemistry and spectroscopy research.

Ordinary lasers

Light amplification through the stimulated emission of radiation—or the laser, as the process is abbreviated—has existed only since 1960. In the simplest terms, the laser is a machine that converts incoherent energy (light or heat or other electromagnetic energy) into coherent energy, where the wavelengths are the same and the wave patterns are all traveling in step (in phase).

The first systems to generate coherent electromagnetic radiation (see **Figure 1**) consisted of alternating current generators and electronic devices like vacuum tubes and magnetron devices like the gyrocon and klystron. To achieve the shorter wavelengths found in ordinary lasers, scientists had to manipulate electron motions on an atomic scale and within an atom or molecule. This, in general, has limited lasers based on specific atoms or molecules to one or at most a few specific wavelengths. And while tunable dye lasers, which can be varied continuously throughout a range of output wavelengths, have been developed, they are both inefficient and limited in terms of range and power level achievable.

Because of this specific dependence on particular atoms and molecules, the ordinary laser is generally quite inefficient at high power outputs. The FEL represents the *return to coherent electromagnetic radiation based on free electron motions*.

All lasers consist of three elements: an *energy pump*, a *lasing medium* that the energy pump excites into activity, and a *host material* that maintains the lasing medium in a desired configuration during the lasing process. In ordinary lasers, energy pumps can be flash lamps, particle beams, neutron beams, or even a laser beam itself—all external to the lasing medium. These pumps direct their energy into the lasing medium, which can be a gas, a liquid, or a solid (such as glass doped with a specific atom or molecule). For gas lasers, the host can simply be a bottle to hold the lasing gas.

One reason for the greater efficiency and versatility of FELs is that the energy pump and the lasing medium are the same—an intense beam of monoenergetic electrons. For the FEL, the host consists of a magnetic field.

Existing free electron devices (i.e., electrons not tied to a specific atom or molecule), such as the gyrocon, klystron and traveling-wave tube, achieve the generation of coherent electromagnetic radiation with efficiencies ranging from 20 to 90 percent with wavelengths ranging from 1,000 to 10 million microns. The FEL is expected to eventually extend the operation of free electron devices to shorter wavelengths ranging over the far infrared, the infrared, visible, and ultraviolet-soft x-ray, which respectively range from 1000 to .1 microns in wavelength, with efficiencies ranging from 20 to

40 percent. This is the range in which ordinary atomic and molecular lasers operate at maximum efficiencies from 0.1 to 5 percent at high power outputs. The FEL would thus operate at more than an order of magnitude of greater efficiency and with the ability to tune in on any of these specific wavelengths.

The FEL can be operated either as a oscillating cavity which generates a coherent laser beam, or as an amplifier which vastly increases the power level of an input laser beam. A pure FEL could consist of one module acting as a oscillating cavity to create the initial beam and a second module utilized to amplify the beam to high power levels. The workings of the FEL are more readily demonstrated in the case of the amplifier stage.

The FEL amplifies the intensity of an input laser beam through resonance with the radiation emitted from high-energy (high-velocity) electrons. For simplicity consider a single electron as shown in **Figure 2**. The input laser beam and single electron propagate from right to left along the z-axis. Wiggler magnets above and below the input beams cause the electron to oscillate back and forth in the y-direction. The wiggler field polarizes the input laser beam—which is also traveling in the z-direction—so that its electric field (E_S) is in the same plane as the wiggling electron. The oscillating electric field of the laser beam interacts with the wiggling electron such that it retards the electron's motion. This deceleration of the wiggling electron generates electromagnetic radiation. If the spacing (or rather period) and strength of the wiggler magnetic field, the velocity (energy) of the electron, and the wavelength of the input laser beam maintain a precise harmonic relationship, then the radiation emitted by the decelerating electron will be "in tune with" the input laser beam. The result will be an increase in the input laser beam's total energy exactly by the amount lost by the decelerating electron.

The harmonic relationship, otherwise known as the synchronism condition, specifies that the spacing of the wiggler field must be approximately the same as the wavelength of the laser field for electrons with velocities much less than the speed of light, i.e., nonrelativistic electron velocities.

Because of the technical difficulties of fabricating very small magnets, the radiation that can be amplified by nonrelativistic electrons is limited to wavelengths longer than several thousand microns. To overcome this difficulty and get to wavelengths commensurate with lasers—between 0.1 to 10 microns—relativistic electron beams must be utilized, i.e., electrons traveling near the speed of light.

Relativistic electron beams can overcome this problem of the large spacing of the wiggler magnets because of two effects predicted by the theory of special relativity. First, from the standpoint of the electron moving at near the speed of light, anything stationary, such as the wiggler magnets, appears to be contracted in the z-direction of **Figure 2**. This relativistic "Lorentz" contraction shrinks the spacing between the wiggler magnets in the z-direction.

Simultaneously, from the standpoint of stationary objects, the wavelength of radiation emitted by the decelerating electron appears to be "Doppler" shifted to shorter wavelengths. (This phenomenon is similar to the change in pitch of a train's whistle when it passes by us.)

Because of these two relativistic effects, with careful adjustment of the electron's initial velocity, the electron will emit radiation at a wavelength corresponding to that of the wavelength of the input laser beam, thereby amplifying the intensity of the laser beam.

These relativistic effects diminish with decreasing velocity of the electron. This can be countered by progressively by the electron will change. This can be countered by progressively tightening the spacing between the wiggler magnets and/or increasing the strength of the magnetic field.

Extending the above concepts to a beam of relativistic electrons involves many technical and theoretical difficulties. All of the electrons must have the same velocities. This is extremely difficult to achieve in high-current, high-energy electron beam accelerators. But as part of the strategic defense effort, electron beam guns for shooting down incoming warheads with the requisite quality beams are being developed at the U.S. National Laboratories. The Advanced Test

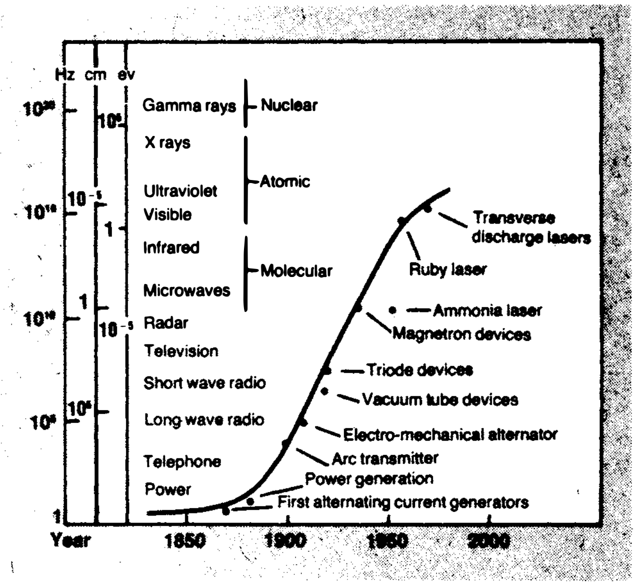

Figure 1

The points on the graph show the date of the first development of devices for generating coherent radiation in the range described in the list to the left of the graph line. The vertical axis, in three columns, shows the frequency (in hertz), the wavelength (in centimeters), and the photon energy (in electron volts). The development of infrared, visible light, and ultraviolet lasers increased the range of available frequencies of coherent radiation exponentially. The free electron laser will duplicate this accomplishment and extend it to shorter wavelengths.

Adapted from Baldwin, et al, *Review of Modern Physics,* October 1981.

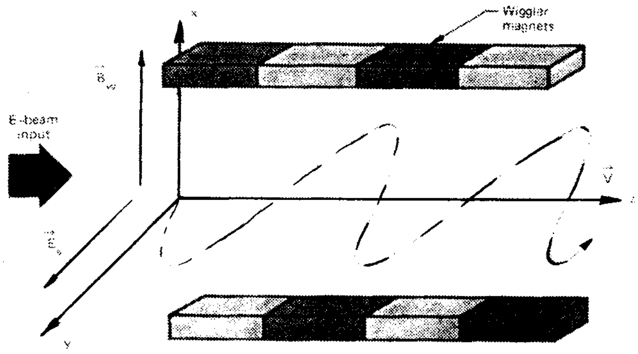

Figure 2

Mechanism of energy transfer in the FEL. An electron is injected in the z direction into the field, B_w, whose field lines lie along the direction of the x axis, of a periodic array of magnets (the "wiggler"), which imposes a transverse oscillatory motion on the electron (in the y direction) as it traverses the array. This oscillatory motion causes the electron to emit electromagnetic radiation. The kinetic energy lost by the electron is transferred to a co-propagating laser beam which has an electric field, E_s, associated with it. It should be noted that the angle at which the trajectory of an electron is bent when it crosses a magnetic field is proportional to the product of the electron's velocity and the strength of the magnetic field. Therefore, both the magnetic field strength and the velocity of the electron together determine the "period" of the oscillatory motion of the electron in a wiggler field. By increasing the strength of the magnetic field while the electron velocity decreases, this period can be kept constant.

Accelerator (ATA) facility at Lawrence Livermore National Lab in California is an outstanding example. This electron beam gun generates a 10,000-ampere high quality beam of 50 million-volt electrons. For an inertial confinement fusion free electron laser, we would need an electron gun generating a 1.1 billion volt, 20,000-ampere high quality beam; this would involve significant advances in electron beam accelerator technology.

Secondly, with a simple monoenergetic beam of electrons which are evenly spaced along the line of propagation of the beam, only a minute fraction of the electrons would be in synch with the electric field of the input laser beam. This problem could be overcome if the electron beam consisted of shockwave-like clusters or clumps of monoenergetic electrons.

Happily, according to recent theoretical studies, there already exists a mechanism which transforms the uniform beam into a series of electron clusters. This occurs if the input laser beam is quite strong; any electron with an energy close to the synchronous energy will, on the average, lose energy at the same rate as a synchronous electron. In effect, the input laser beam selects electrons with the proper phase relationship. As a result, entire ensembles of electrons may then interact coherently with the input laser beam, permitting high energy-extraction efficiencies.

Figure 3 shows the general layout of a typical FEL device.

To create a laser beam from scratch—i.e. without an input beam—the FEL must be transformed into an oscillating cavity. This is done by placing partially silvered mirrors at either end of the wiggler cavity. Over a period of time a coherent laser beam will be formed and reflected back and forth in the cavity. Once formed the beam will build up in intensity in the manner described for the FEL amplifier. The wavelength of the FEL generated laser beam can be tuned to a desired wavelength by either changing the spacing of the wiggler fields or by changing the input energy of the electron beam. Such FEL oscillating cavities are capable of only generating laser beams of minute power levels since optics, such as mirrors, must be placed in line with the electron beam and thus are very susceptible to beam damage.

The first generation FELs will probably consist of a FEL amplifier combined with a conventional laser. A FEL module can be tuned to amplify any wavelength of conventional laser beam input by either changing the initial energy (velocity) of the input electron beam or by changing the physical spacing of the wiggler magnetic fields. Eventually, FEL oscillating cavities will be combined with FEL amplifiers to produce a fully tunable high power FEL.

Prospects and applications

With the near-term prospect of scientific and technological spin-offs from the new beam weapons defense policy announced by President Reagan on March 23, the United States is on the verge of a new industrial revolution. And this revolution will be most generally characterized by technologies based on plasmas and directed energy beams. In this context, the free electron laser will play the same role as the electric motor did in the electricity industrial revolution at the turn of the 19th century. Eventually the various components of the FEL will be generated with self-organized plasma structures, making FELs both more efficient and capable of attaining extremely intense beam outputs at even shorter wavelengths.

In the most general sense, the FEL is simply the structured interaction of three electrical currents. First, the current in the wiggler magnetic coils interact with the free current represented by the electron beam. This interaction generates a potential—the laser beam—which propagates at the speed of light. Depending on the wavelength of the output laser beam, this potential will interact with various types of electrical circuits. For example, at long wavelengths this potential will simply generate electrical currents the same way that radio waves do in antennas. At shorter wavelengths this potential will interact with the electrical "circuits" found in molecules and atoms—the electron orbits. At even shorter wavelenghts this potential will even transform the electrical circuits found within the nucleus—i.e., generating nuclear transmutations.

Experts in the field say that given a crash program, tunable FELs with efficiencies ranging from 20 to 40 percent and continuous power outputs from 10 to 100 megawatts can be achieved within the next five years. Much of the U.S. FEL program is already part of the classified beam weapons effort. FELs placed on mountaintops and connected to the utilities' electric power grid could be utilized both as direct line of sight terminal defense beam weapons and indirect, long range systems making use of orbiting mirrors for retransmission of the FEL beams to intercept ICBMs in both the launch and mid-course phases of their trajectories.

The same FEL strategic defense system could alternately be utilized in a number of civilian areas, including intercontinental electric power transmission; satellite and spaceship propulsion, and even the propulsion of jet aircraft when they are above the clouds; communications; remote sensing; and round the clock farming.

Power transmission: At the present time base-line electric power plants are utilized most inefficiently. They are run full steam during the peak electric load periods of daylight hours and virtually shut down at night. Furthermore, peak daytime loads are often met with small (and therefore high-cost) backup power generators. Given a network of FELs and orbiting mirrors, electricity generated by power plants on the nighttime side of the world could be transmitted at 20 percent efficiencies to the daytime side, in the form of laser beams, and be reconverted into electricity with solar cells at the receiving sites. But unlike solar radiation, conversion of FEL laser beams to electricity would be extremely efficient and economic, because the beam radiation is both coherent and at a much higher energy flux density. Only a few square meters of solar cells could generate megawatts of electrical output utilizing FEL beams. Existing optical technology would make the transmission of these beams completely safe.

In the case of developing countries, the FEL power transmission system would make possible the instant electrification of the remotest areas in an economic fashion. For example, a small megawatt solar cell grid could be placed by helicopter on a remote farm. Farm machinery could then be directly connected to the solar cell module. As the history of U.S. rural electrification demonstrates, this system alone could rapidly increase Third World agricultural productivity by more than an order of magnitude.

Energizing and propelling satellites and spaceships: Jet aircraft when cruising above the clouds could be directly powered by FEL laser beams employed by the same power transmission system. Lenses carried above the aircraft would focus and transmit the FEL beams into the jet engines to provide the heat which is usually generated by burning kerosene. This would vastly increase the cargo carrying efficiency of aircraft, since existing long-haul jets are primarily

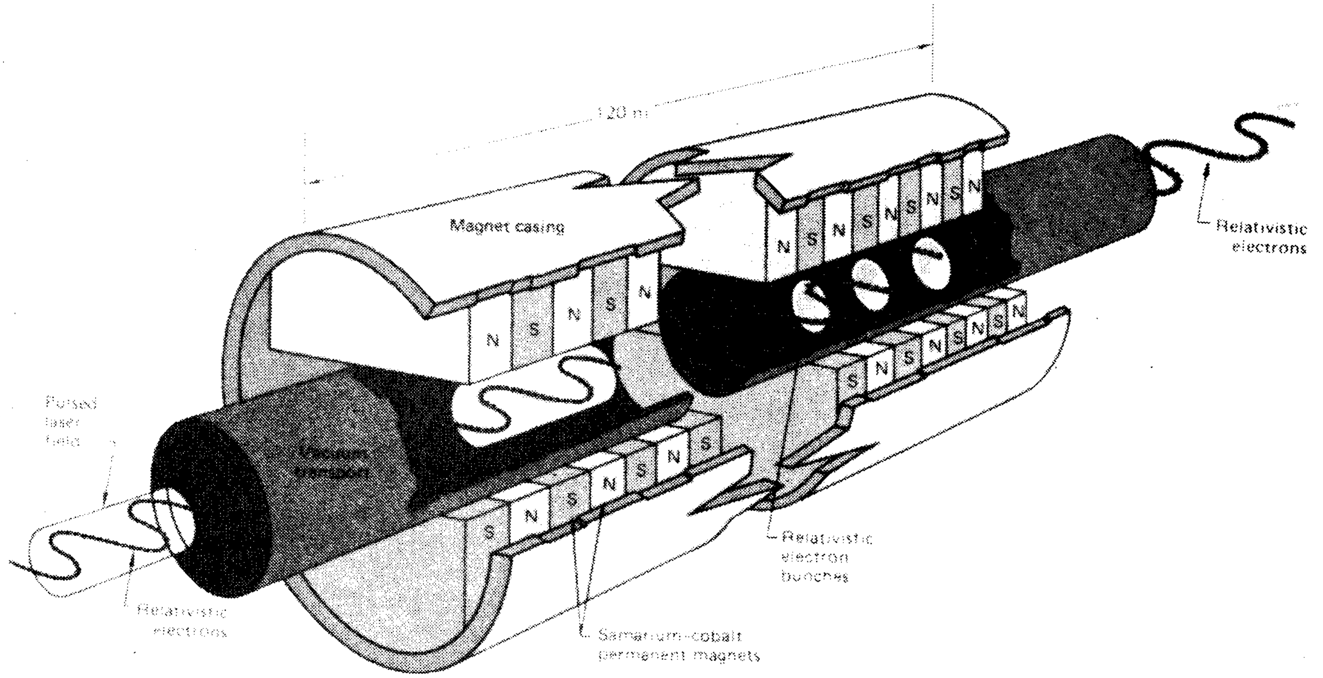

Figure 3

Artist's conception of a typical FEL device. The wiggler consists of a series of magnets 120 meters long. A beam of high-energy (relativistic) electrons enters the device together with a pulsed laser field. At a certain distance along the wiggler, the kinetic energy of the electrons (now bunched as described in Figure 2) is transferred to the input laser beam. Figures 2 and 3 were adapted from "The Free-Electron Laser Amplifier," by Donald Prosnitz and James C. Swingle, Energy and Technology Review of Lawrence Livermore National Lab, Jan. 1982.

loaded with kerosene fuel which is consumed during the flight. Extremely large jet liners capable of in-flight repair and maintenance would be kept in continuous flight for months at a time, off-loaded in the air by helicopters and other vertical take-off aircraft. Large space shuttles could be accelerated via FEL-powered jet engines within the atmosphere to orbital velocities and therefore be propelled into space without the use of inefficient booster rocket engines.

Laser light transmission of information: As is currently being demonstrated by optical fiber transmission of telephone calls in parts of the United States, this technology is extremely efficient and economic. Tunable high power FEL beams will extend this optical transmission capability to open links between the ground and orbiting satellites. (Laser beams are already utilized for communication between satellites in orbit.) Long distance communication costs could be decreased by several orders of magnitude and extended to the remotest regions with minimal infrastructural prerequisites, as in the case of electric power transmission discussed above.

Detecting targets and remote sensing: As Dr. Edward Teller of Lawrence Livermore National Lab most recently pointed out in the June issue of *Laser Focus*, laser beams are most efficient systems for this purpose. Laser beams can be utilized as an extremely short wavelength radar—ladar. Tunable 10- to 100-megawatt FEL beams would be quite capable of detecting the most indiscernible type of targets such as low-flying cruise missiles and submarines; given the tunability of the FEL, beams directed from orbiting mirrors would even be able to detect the chemical make-up of the exhaust of various types of aircraft. In the same manner all types of chemical emissions could be detected and located from space. This would be a powerful tool for understanding and controlling industrial and "natural" pollution. Laser remote sensing from space could also be extended to geological and oceanographic mapping.

Night-time irradiation of specific crop fields: The same FEL-orbiting mirror system could be utilized, not just to increase the rate at which various agricultural crops could be grown; round-the-clock hot-house experiments have already shown that constantly irradiated plants grow exponentially faster and a larger and healthier plant results. These effects are enhanced by shining specific wavelengths of light on specific types of plants.

Other major applications of FELs include industrial level photochemistry and isotope separation; lithography for electronic microchip production; x-ray microholography of living cells; materials preparation and research; smog, fog and cloud dispersal; and metal cutting and heat treating.

Given that President Reagan's March 23 initiative will result in a crash effort to develop the FEL, all of the above peaceful applications could be fully realized before the end of this century.