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Free-Electron Lasers

Charles A. Brau

Free-electron lasers are tunable, potentially powerful sources of coherent radiation over a broad range of wavelengths from the far-infrared to the far-ultraviolet regions of the spectrum. These unique capabilities make them suitable for a broad variety of applications from medicine to strategic defense.

Free-electron lasers represent a complete departure from conventional lasers, with properties and problems all their own. Making use of a simple and elegant gain medium—an electron beam in a magnetic field—they have already demonstrated broad tunability and excellent optical-beam quality. In the future they may generate the greatest average power ever achieved by a laser.

"Free" electrons are electrons that are not "bound" into atoms or molecules. The electrons in a free-electron laser form an electron beam in a vacuum, much like the electron beam in the picture tube of a television set except with much higher energy and intensity. Electrons bound to atoms and molecules vibrate only at specific frequencies. Thus, the laser light from conventional lasers, which make use of bound electrons, appears only at the frequencies specific to the atoms or molecules of the laser. On the other hand, the electrons in free-electron lasers are forced to vibrate by their passage through an alternating magnetic field. The vibration frequency, and hence the laser wavelength, can be adjusted by altering the construction of the magnetic field or by changing the speed (or energy) of the electrons passing through the magnetic field. There is great interest directed to free-electron lasers because of their broad tunability from the far-infrared to the far-ultraviolet. Recently, it has been recognized that free-electron lasers are uniquely suitable for operation at very high average power levels, and this has made them attractive for military applications.

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Historical Overview

Because they depend on an electron beam in a vacuum magnetic field, free-electron lasers actually have as much in common with microwave devices as they do with conventional lasers. For this reason, they can be regarded as an extrapolation of microwave technology to optical wavelengths. In fact, the first device to have the characteristics of a "free-electron laser" was operated in the microwave portion of the spectrum. It was not known as a free-electron laser, since at that time lasers had not yet been invented.

Free-electron lasers as we know them today were actually developed independently, as an extension of synchrotron radiation research. Synchrotron radiation is the short-wavelength radiation that is given off by electrons in synchrotrons and storage rings. This radiation can be enhanced by adding magnets to a storage ring to wiggle the electrons, with the magnets arranged in the same configuration now used for free-electron lasers. The synchrotron radiation from such wigglers (or undulators) is identical to the incoherent, spontaneous radiation observed from free-electron lasers before they begin to lase.

The earliest work on wiggler or undulator radiation dates back to 1951 when Motz (*1*) demonstrated incoherent radiation from such devices in both the millimeter and optical regimes (*2*). After this work, Phillips, then at General Electric, developed a device he called

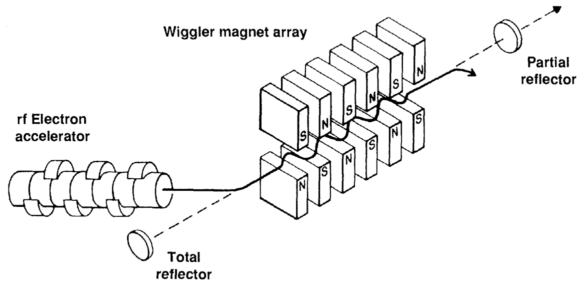

Fig. 1. Schematic diagram of a free-electron laser. The beam of electrons is directed through an alternating magnetic field called a wiggler. As they pass through this field, the electrons oscillate back and forth and radiate. This radiation is Doppler-shifted to optical frequency by the high velocity of the electrons and forms laser radiation.

the "ubitron," which would now be called a low-voltage free-electron laser (*3*). High power (>1 MW) and high efficiency (>10%) were obtained at wavelengths from 10 cm to 5 mm, but other devices such as traveling-wave tubes offered higher gain and other advantages, and the ubitron was not actively pursued.

Then, in 1970, Madey, of Stanford University, independently proposed what he called the free-electron laser (*4*). Influenced by research on synchrotron-radiation sources, Madey conceived his device for the optical region, using a beam of highly relativistic electrons. In his original proposal, Madey actually described his device with a quantum-mechanical theory. This made it immediately clear that the new invention was a laser, a device that operates on the basis of stimulated emission from an inverted population of quantum states. It was subsequently discovered that the device could be accurately described with classical mechanics (*5, 6*). This made it possible to develop much more powerful descriptions of free-electron laser performance.

In 1975, Madey and his co-workers at Stanford succeeded in demonstrating gain with a free-electron laser, using a 24-MeV electron beam and a 5-m-long wiggler to amplify the optical beam from a CO_2 laser (*7*). A year later, they added mirrors to the system and operated the accelerator at 43 MeV to demonstrate laser oscillation at a wavelength of 3.4 μm, in the near-infrared part of the optical spectrum (*8*). Although the power (300 mW) and efficiency (0.01%) were small, there could be no doubt that the device had lased. Because of the obvious potential of the device for high power and broad tunability, these results immediately attracted a great deal of interest. Theoretical work on free-electron lasers accelerated, and experimental work began at several laboratories that already had suitable accelerators.

Up to the present, about eight free-electron lasers have been successfully operated in the short-wavelength region, and a number of others have been operated in the microwave region. Several types of accelerators have been used, including radio-frequency linear accelerators (rf linacs), storage rings, microtrons, induction linacs, and electrostatic accelerators. Since Madey's original demonstration, the performance of free-electron lasers has expanded in all directions. The shortest wavelength (525 nm) has recently been achieved with an rf-linac free-electron laser built by TRW, Incorporated, and tested on the superconducting accelerator at Stanford (*9*). The highest power (1 GW) and gain (40 dB) have been achieved with the induction linac ETA at Livermore, at a very long wavelength (9 mm) (*10*). In between these two lasers lies a variety of devices of intermediate power and wavelength. In addition, about six more devices are currently under construction.

Of the free-electron lasers that have been constructed thus far, considering only those built to operate in the optical regime, only about half have worked. The reason, in most cases, has been that the available electron accelerator was not satisfactory for free-electron laser experiments and could not, within time and budget restrictions, be suitably modified. One or two of these lasers may yet be brought into operation, but free-electron lasers remain subtle, expensive devices.

Basic Principles

Conceptually, free-electron lasers are rather simple. The configuration of the electron beam and wiggler magnets is shown in Fig. 1 (*11*). The magnets are arranged with their poles alternating so that the magnetic field reverses every few centimeters. The overall length of the wiggler is typically a few meters, which corresponds to about 100 periods. The electron beam is injected into the end of the wiggler and travels down its length.

As the electrons proceed down the wiggler, they are deflected alternately left and right by the magnetic field and follow a wiggly path. The motions are simple forced oscillations; no subtle resonant effects are involved. If we place ourselves in a frame of reference moving down the wiggler at the mean velocity of the electrons, we observe the electrons oscillating back and forth in a straight line perpendicular to the wiggler axis (*12*). The situation is similar to that of an electric current running up and down an antenna, and, like the antenna, the electrons radiate energy at the frequency with which they are oscillating.

When observed from within the moving frame, the radiation from the electrons goes in all directions, like the radiation from the antenna. However, when observed from the stationary frame of the laboratory, the electrons are moving at nearly the speed of light and the radiation appears to be moving almost entirely in the forward direction, parallel to the electron beam. To an observer standing in the laboratory and looking at the oncoming radiation, the frequency is Doppler-shifted to a higher frequency, which corresponds to a shorter wavelength. This wavelength is given by the formula

$$\lambda_L = \lambda_w[1 + (eB_w\lambda_w/2\pi m_0 c)^2]/2\gamma^2 \qquad (1)$$

where λ_L is the laser wavelength, λ_w is the period of the wiggler (the distance over which the magnetic field undergoes a complete cycle), e is the electron charge, B_w is the average magnetic induction, m_0 is the rest mass of the electron, c is the velocity of light, and γ is the energy of the electron in units of its rest energy (0.511 MeV).

Typically, the magnetic field is made as large as possible to maximize the wiggle motion and electron radiation, subject to the constraint that the wavelength not become too long. This means that the magnetic field term in Eq. 1, $eB_w\lambda_w/2\pi m_0 c$, is generally of the order of unity. For available permanent magnet material, the average magnetic field strength is typically of the order of 0.5 T for a wiggler period of the order of 2 cm. For an electron energy of 100 MeV, corresponding to $\gamma \approx 200$, the laser wavelength is $\lambda_L \approx 0.5$ μm, in the green portion of the visible spectrum. Thus, for convenient values of the wiggler period and the electron energy, we obtain a very useful wavelength.

When a laser beam is traveling down the wiggler with the electrons, the electrons behave in a very interesting fashion. When the wavelength of the laser satisfies the resonance condition, Eq. 1, the electrons interact with the laser beam and move from their random positions to form bunches spaced at the laser wavelength. Then, instead of emitting their radiation at random, they radiate in phase with the laser beam. By adding their radiation coherently to that of the laser beam, the electrons amplify it. Thus, the laser beam emerges from the wiggler stronger than when it entered.

The source of the optical beam incident on the free-electron laser can be either external, from a separate laser, or regenerated from the output of the free-electron laser itself. If the source is external, then the free-electron laser is referred to as an amplifier, and the source is called the master oscillator. In this case, the wavelength of the output beam is the same as that of the master oscillator, and the electron energy and magnetic field must be adjusted to satisfy Eq. 1.

Alternatively, the input beam may be obtained by taking part of the output beam from previous electrons and returning it to the input end of the free-electron laser. This is illustrated in Fig. 1, where a partially reflecting mirror is used to split the beam coming out of the wiggler into the output beam and the return, or feedback beam, which is reflected back through the wiggler. In this configuration the free-electron laser is referred to as an oscillator. In this case the wavelength can have any value and will correspond, in general, to the wavelength for which the laser gain, or amplification, is a maximum. This wavelength is given by Eq. 1.

Compared with conventional lasers, free-electron lasers offer a number of important advantages. The first and most obvious is the degree to which free-electron lasers can be tuned. Wavelength tuning can be accomplished initially by the construction of the wiggler and the electron accelerator, and various devices have already been operated at wavelengths from the far-infrared to the visible portions of the optical spectrum, as shown in Fig. 2. In addition, it is possible to tune a given device over a substantial range by varying the electron energy around the design point. Most accelerators can be operated over a range of electron energy exceeding a factor of 2, which corresponds to a variation of more than a factor of 4 in the optical wavelength. The wavelength ranges achieved in the experiments at Los Alamos and Santa Barbara, shown in Fig. 2, represent the broadest tuning range ever achieved by any laser of any type (*13, 14*).

An equally important advantage of free-electron lasers is the high power to which their output can be scaled. There are two reasons for this scalability. In the first place, free-electron lasers are able to reject enormous amounts of waste heat. In all lasers, including free-electron lasers, most of the input energy is converted into waste heat. This waste heat must be removed by cooling the laser medium or, in the case of gas lasers, by allowing the hot laser gas to flow out of the laser at very high speed. Because heat removal is much faster when the laser medium flows out of the laser, gas lasers are currently the most powerful lasers. In the free-electron laser, the waste heat is in the electron beam, which is moving at nearly the speed of light, about a million times faster than a high-speed flowing gas. The electron beam exits the laser in a few billionths of a second, carrying the waste heat with it. In fact, recent experiments at Los Alamos have shown that the spent electron beam from the laser can be decelerated to recover as much as 70% of the leftover energy, thereby increasing the overall efficiency (*15*). Likewise, 90% of the electron beam from the free-electron laser at the University of California, Santa Barbara, is recovered and the energy reused (*16*). The second reason why free-electron lasers can be scaled to high power is the availability of high-power accelerators. Although research must be continued to develop electron beams with the high quality that is required for free-electron lasers, beams of high power already exist. For example, the Stanford Linear Accelerator Center has a 200-kW electron beam that operates 24 hours a day, and the Los Alamos Meson Physics Facility has an 800-kW proton beam that likewise operates 24 hours per day.

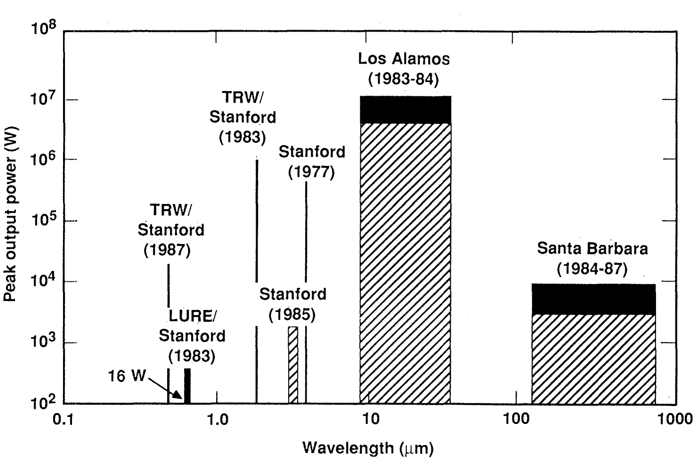

Fig. 2. Free-electron lasers have been operated at a variety of wavelengths from the visible to the millimeter region of the spectrum. Several devices have been tuned over broad wavelength ranges.

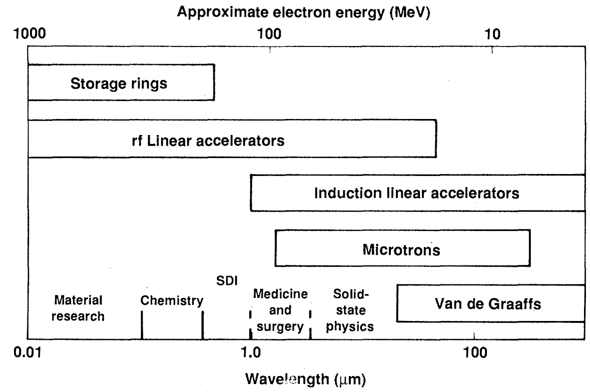

Fig. 3. Various types of accelerator technology are useful for different electron-energy ranges and, accordingly, different laser wavelength regions (SDI, Strategic Defense Initiative).

These advantages do not come without disadvantages, however. The single, most important disadvantage of free-electron lasers is their high cost. Electron accelerators are expensive, costing several million dollars even for a small one, so free-electron lasers are not economical for small devices. However, in very large sizes the unit cost becomes quite competitive, and it may be possible, some day, to build free-electron lasers of 100 kW and larger at unit costs of less than $500 per watt. In the meantime, applications will be limited to those specialized circumstances that can bear the high cost. Fortunately, there are some important applications that can do this.

Laser Experiments

The broad wavelength range spanned by the various free-electron lasers shown in Fig. 2 corresponds not only to a broad range of electron energy but to a variety of accelerator technologies as well. Because almost all wigglers have a period of the order of a few centimeters, the wavelength of a free-electron laser is largely determined by the electron energy. As a result, since each type of accelerator is most useful over a certain energy range, it is possible to correlate each type of accelerator with a wavelength range over which it is most useful. This correlation is shown in Fig. 3, where the spectral regions of interest to a number of applications are also indicated. The relation between energy and wavelength is approximate, since the wiggler period and magnetic field are somewhat variable, and the spectral regions of interest for the various applications are fuzzy and in some cases overlap. Most importantly, the operating regions for the various types of accelerator technology should not be regarded as well defined. In particular, the boundaries continue to expand as the technology improves.

The electron energy is not the only factor determining the useful wavelength range for each type of accelerator. Both induction linacs and rf linacs can be operated at electron energies sufficient to achieve much shorter wavelengths than indicated in Fig. 3. However, as the wavelength becomes shorter, it is necessary to focus the electron beam more carefully inside the laser beam, and this requires a better electron beam quality. New developments in accelerator technology will extend the wavelength range of these accelerators to much shorter wavelengths than are indicated in Fig. 3.

Because of their simplicity and reliability, electrostatic accelerators are ideal for the far-infrared spectrum. The first such device is now operating at the University of California at Santa Barbara, where it is already in use not only for free-electron laser research but also for research in solid-state physics and biophysics (*16*). The operating range of the accelerator is approximately 2 to 6 MV, which corresponds to wavelengths in the range from 100 to 800 μm. The laser operates in pulses 3 to 30 μsec in duration, with a linewidth estimated to be as narrow as one part in 10^8 (*17*).

Induction linacs are another type of accelerator that has been used for free-electron laser experiments. The outstanding feature of induction linacs is the very large current that they can accelerate, typically as much as 10 kA in pulses lasting about 50 nsec. The Experimental Test Accelerator at Lawrence Livermore National Laboratory operates at 3.5 MeV, which corresponds to a wavelength of about 9 mm, in the microwave part of the spectrum (*10*). As much as 40% of the electron energy has been converted into

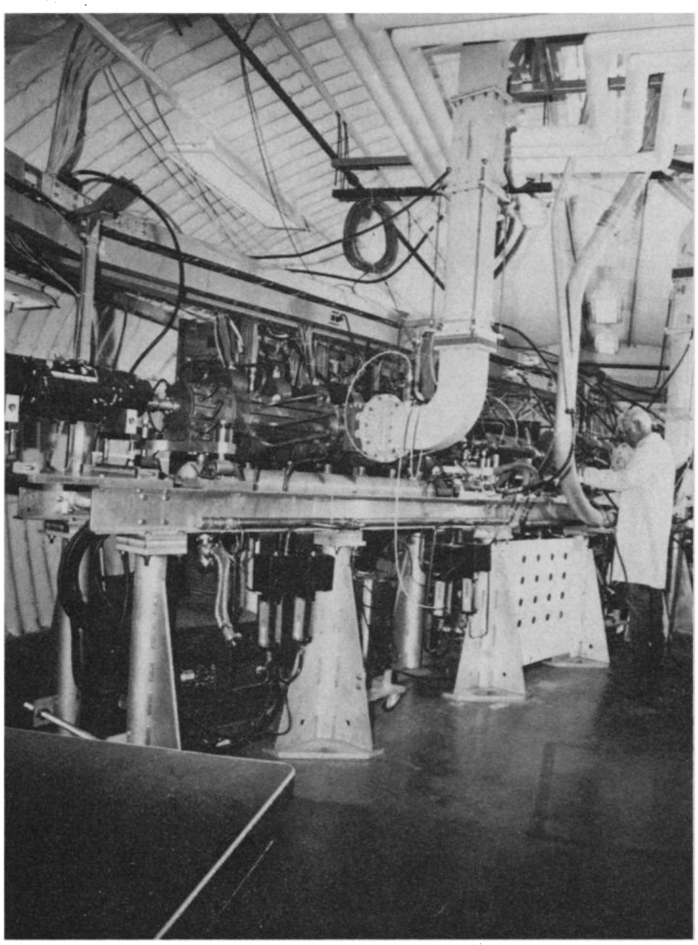

Fig. 4. The rf linac used in the Los Alamos free-electron laser experiments is of conventional design and typifies accelerators of this type used in free-electron laser experiments at several laboratories. The electrons are accelerated to 20 MeV in the two copper structures, each about 1.5 m long. The rf power to accelerate the electrons is carried by the waveguides coming down from the ceiling, and the electron beam exits the accelerator through the vacuum pipe at the left. The wiggler and laser optics are located to the left of the photograph.

microwave radiation, which corresponds to a peak output power of 1 GW (*18*).

Since the original free-electron laser experiment of Madey and his co-workers at Stanford, several free-electron lasers have been operated with rf accelerators. These accelerators are characterized by high energy and low current, but improvements in electron injector technology have increased the current and electron beam quality for free-electron laser applications. The rf linac used in the experiments at Los Alamos (Fig. 4) is typical. The accelerator has an active length of 3 m and accelerates electrons to an energy of 21 MeV with a peak current of more than 100 A. The shortest wavelengths achieved with a free-electron laser, 525 nm, were obtained recently by a collaboration between teams from TRW, Incorporated, and Stanford University (*19*). A photograph of the 5-m wiggler used in these experiments is shown in Fig. 5. Free-electron lasers of this type also produce extremely good optical-beam quality. In experiments at Los Alamos the collimation of the laser beam was observed to be within 4% of the physical limit of diffraction, in spite of deliberate misalignment of the optical system and electron beam (*13*).

Microtrons are similar to rf linacs except that instead of running the electron beam through many accelerator sections to achieve high energy, microtrons pass the beam through the same accelerator section many times. In principle, this can greatly reduce the cost and size of the accelerator: a 20-MeV accelerator can fit into a few square meters of space. Several free-electron lasers have been constructed with microtrons for operation in the far-infrared. None have shown more than slightly enhanced spontaneous emission thus far, but continuing work on these devices should result in successful operation in the near future (*20–22*).

Storage rings offer the most elegant approach to free-electron laser technology. In operation, storage rings circulate a "stored beam" of electrons around a ring that is typically several meters in diameter. In modern storage rings the electron beam may be stored for many hours. Because of the natural damping properties that occur in electron storage rings, the electrons cool to a small energy spread and become well collimated. Because they work best at high electron energy, over 100 MeV, and have good electron-beam quality, storage rings are well suited to free-electron laser operation at short wavelengths.

The first such laser is in operation at the Laboratoire pour l'Utilisation du Rayonnement Electromagnetique (LURE) in Orsay, France. Operating at an electron energy of 220 MeV, the laser produces radiation tunable over the range from 570 to 640 nm, in the red portion of the spectrum (*23*). Although the laser beam is of rather low power, about 3 mW, it continues for several hours at a time, which corresponds to the storage time of the electron beam in the ring.

In the future, free-electron lasers will be extended to much higher power and shorter wavelengths. Higher power will depend in part on the development of higher current accelerators, but even more important will be the development of optics capable of operating at high power without damage. Damage to optical coatings has already been observed in free-electron laser experiments at several laboratories, resulting from the optical beam being narrowly confined in the optical resonator and becoming quite intense. However, new optical resonator configurations with grazing-incidence mirrors are being developed, and with improved coatings and higher laser gain it should be possible in the future to achieve power levels exceeding those of any other lasers.

Shorter wavelength lasers will depend on the development of improved electron injectors as well as better mirrors. Mirrors have been developed for use in parts of the extreme ultraviolet and soft x-ray regions with reflectance exceeding 50%, but for other spectral regions no mirrors exist. For those regions where mirrors exist, this reflectance is good enough to lase if the gain is more than a factor of 4 per pass. This appears quite possible, but better mirrors will help. Alternatively, it may be possible to build a high-gain wiggler that can amplify the spontaneous radiation produced at the beginning of the wiggler and produce a coherent optical beam without any mirrors at all (*24*).

To be available for a broader variety of applications in research, medicine, and industry, free-electron lasers must also become much cheaper. Anticipated improvements in the power and efficiency will serve to bring down the unit cost of large, high-power devices, but it will also be necessary to develop economical small devices. Promise for this lies in two areas of technology. The first is the development of two-stage free-electron lasers, in which the long-wavelength beam from a low-energy free-electron laser is used as the wiggler for a short-wavelength free-electron laser using the same, low-energy electron beam (*25*). This approach depends on extremely good electron-beam quality, which can be achieved in electrostatic accelerators. The second promising technology for less expensive free-electron lasers is that of microtrons. At present, the difficulty with microtrons is their poor electron-beam quality. It should be possible in the future to use more elaborate injection schemes and improved accelerator design to achieve better electron beam quality and useful free-electron laser performance.

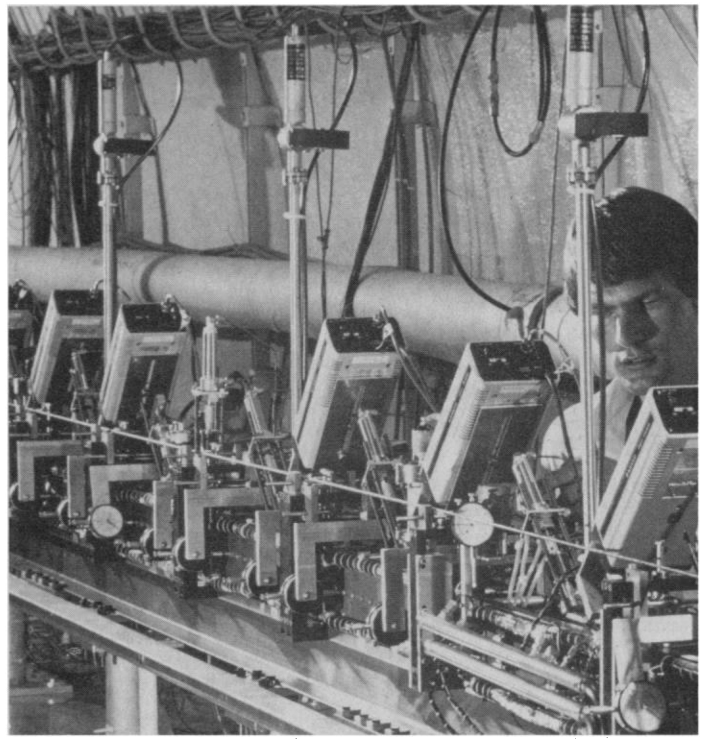

Fig. 5. The wiggler used in the TRW and Stanford experiments uses a permanent magnet structure that is 5 m long and contains about 1200 small, samarium-cobalt magnets. The television cameras located on the top of the wiggler are used to align the electron beam to the center line of the wiggler and the laser beam, which has a diameter of about 2 mm in the wiggler.

Applications

As has been the case with most new, technological advances born in research laboratories, the first applications of free-electron lasers will be in research itself. Compared with alternative light sources, free-electron lasers offer several advantages for research applications. Foremost among these are their tunability and high peak power and intensity. Among lasers, free-electron lasers are uniquely able to tune throughout previously inaccessible regions of the spectrum, especially in the far-infrared, beyond about 20 μm, and (someday) in the far-ultraviolet, beyond about 200 nm. Although conventional lasers have already been designed for use in the far-infrared and far-ultraviolet spectral regions, none are continuously tunable and only a few have very high peak power. Besides lasers, other sources of light are also available in these spectral regions. Some, like synchrotrons in the far-ultraviolet and thermal sources in the infrared, offer continuously tunable radiation, but none offer the coherence and high intensity (focused power) of free-electron lasers (or other lasers, for that matter).

High intensity is necessary for opening up a whole new class of phenomena—called nonlinear phenomena—that have become accessible only since the development of the laser. Nonlinear phenomena, such as explosive ablation of surfaces and multiphoton absorption by molecules, are phenomena that occur only at extreme values of the optical intensity. Such nonlinear phenomena tell us a great deal about the properties of matter. More important, however, they also form the basis for many new and exciting technologies from laser medicine to optical computers.

Biology and medicine. For example, a laser has recently been used to remove a selected segment as small as 0.25 μm from a chromosome. This was accomplished by tuning the laser to a wavelength at which the segment absorbs the laser light (*26*). It is believed that under certain circumstances the process takes place by the simultaneous absorption of two photons. This nonlinear phenomenon is one of the first illustrations of a "laser scalpel," with which it may someday be possible to make local surgical alterations in large molecules. In other experiments, tunable lasers may be used to unravel the spectroscopy of the genetic material DNA in the far-infrared spectral region (*27*).

Medicine offers a large number of other opportunities for free-electron lasers. The interaction of laser radiation with mammalian tissue produces a wide variety of effects (*28*), which can be used for a broad spectrum of medical and surgical applications (*29*). The nature of the tissue effect depends on both the wavelength and the pulse length of the laser radiation. For example, light in the red portion of the spectrum can penetrate millimeters through tissue, whereas near-infrared radiation is absorbed in less than a micrometer. Similarly, for pulses longer than 1 second, the heat deposited in the tissue by the laser can diffuse more than a millimeter, whereas the heat from microsecond pulses is localized to dimensions on the order of a micrometer. Diffuse heating of tissue is observed to produce burning, cauterization, coagulation, and, in special cases, chemical reactions. On the other hand, intense local heating of very small volumes leads to instantaneous vaporization of the tissue or even to plasma formation and shock wave effects.

These various types of tissue interaction can be used to effect a variety of surgical procedures (*30*). For example, continuous or long-pulse Nd:YAG (yttrium-aluminum-garnet) lasers operating at a wavelength of 1 μm have been used to actually "weld" arteries together long enough to allow healing to occur (*31*). Continuous-beam argon lasers operating at a wavelength of 0.5 μm are used for removing plaque that is obstructing blood flow through arteries (*32*). Pulsed CO_2 lasers, which deposit their energy in very small, well-defined volumes, are used to remove tumors in the central nervous system by vaporizing them (*31*). Intense pulses from Nd:YAG lasers have been shown to fracture kidney stones by means of the shock produced at the surface of the stone, so that the fragments can be passed from the body (*33*).

Given the diversity of tissue effects and procedures that are possible, the advantages of a free-electron laser become clear. Not only are free-electron lasers able to provide wavelengths and pulse lengths unavailable from any other laser—or combination of lasers—but they can also be adapted to the requirements flexibly and in real time. The flexibility will make it possible to get combinations of laser parameters that not only achieve the desired result but that adapt to the limitations of the surgical environment, such as the need to propagate the radiation through an optical fiber to the site of the operation. The real-time adaptability could be used to vary the laser parameters while the surgical procedure is in progress, and feedback from the operation could be used to control the laser by means of an expert system. For example, the fluorescence from the laser-produced vapor and plasma could be used to control a laser operating on plaque near the arterial wall. If the arterial wall were punctured, the laser wavelength and pulse length could be adjusted to cauterize the wound and seal the perforation.

Solid-state physics. This is another research area rich in applications for free-electron lasers. Two free-electron lasers have already been built specifically for research in this spectral region. The first, at Santa Barbara, is already in active use for research (*34*). The second, at AT&T Bell Laboratories, is still under development (*21*).

Industrial applications. Free-electron lasers can also be used in the industrial sector. One of the most promising uses is in the microfabrication of semiconductor circuits. In the conventional process, the circuit is imaged from a mask onto the surface of a silicon chip covered with a layer of photoresist. When the photoresist is exposed to light it is either hardened or softened by the photochemical effect of the light and can be selectively removed by a chemical bath to form the image of the microcircuit on the silicon chip. In the future, however, this process is likely to be replaced by new technologies that are just now emerging. For example, it is possible to use a scanning laser to print the pattern on the photoresist by direct writing, the way a laser prints the pattern in a computer laser printer. With sufficient laser intensity, the resist can be removed directly by the laser without the need for chemically developing the image (*35*). It is even possible to use an ultraviolet laser to initiate chemical reactions in a gas or liquid over the surface of the silicon chip to deposit the microcircuit on the chip (*36*). By tuning the laser wavelength or varying the composition of the gas or liquid, or both, it should be possible to construct various features of the microcircuit. The potential advantages of free-electron lasers in terms of high intensity and tunability at short wavelengths for applications of this type are manifest.

Chemical applications. The power and wavelength tunability of free-electron lasers makes them intrinsically well suited to large-scale chemical processing as well. The issue is generally one of the cost of a laser photochemical process compared with that of the conventional process (*37*).

Two important classes of processes have been identified in which a large quantum yield (many molecules of chemical product for each laser photon) is possible. In the first process, a laser is used to purify chemical compounds by removing a few impurity molecules from a large number of desired molecules. A good example is the purification of silane (SiH_4) (*38*). High-purity silane is the starting material for the production of certain types of semiconductors and optical materials. Experiments with an excimer laser at 190 nm have demonstrated that this method produces extremely pure product material with high quantum yield.

A second class of photochemical processes having high quantum yield is that of laser-initiated chain reactions. In this case, a single photon is used to initiate a chain reaction that may yield thousands of molecules of product before the chain is broken. A good example of such a process is the synthesis of vinyl chloride (*39*), the starting material for the production of polyvinyl chloride (PVC). In experiments with ultraviolet lasers the quantum yield has been observed to be as high as 20,000, and pilot plants are now under construction in several countries.

Defense needs. In the end, military applications may present the most demanding and challenging opportunities of all. The ability of lasers to transport energy over long distances in almost no time makes them attractive for strategic defense against missiles. The unique ability of free-electron lasers to operate at high power and short wavelength has made them a leading candidate for this application, and plans are being made to construct and test a large device for this purpose at White Sands Missile Range (*40*). However, tremendous amounts of laser power are required to defend against a large number of simultaneously launched missiles, and even free-electron lasers do not offer a near-term solution (*41*). However, it may not be necessary to defend against large numbers of simultaneously launched missiles. As part of a broad disarmament program, relatively small defensive systems might make it safe to negotiate the complete elimination of nuclear missiles by protecting each side against the possibility of being held hostage by a few missiles kept hidden by the other side.

Conclusions

Free-electron lasers represent a complete departure from conventional lasers, and they offer performance not available from other sources. By varying the electron energy, it is possible to tune the wavelength over a broad range and to operate at wavelengths where no other lasers exist. Equally important, by avoiding the cooling problems associated with conventional lasers and using high-power accelerator technology, it is possible to operate free-electron lasers at extreme power levels. Clearly, there are manifold applications for lasers with these qualifications, and two new free-electron lasers for the near-infrared and visible spectrum are being developed at Vanderbilt University (*42*) and the National Bureau of Standards (*43*) to support research in medicine and materials science. These will supplement the user-oriented facilities at Santa Barbara and Stanford.

Unfortunately, free-electron lasers are expensive, especially in small sizes, and, until cheaper free-electron lasers are developed, only a limited subset of the possible applications can be addressed. Nevertheless, it is clear that free-electron lasers are developing rapidly. As they do so, they will play an increasingly important role in a broad variety of fields.

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Research Articles

Insertional Mutagenesis of the *Drosophila* Genome with Single P Elements

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A versatile genetic method for identifying and cloning *Drosophila melanogaster* genes affecting any recognizable phenotype is described. Strains are constructed in which the insertion of a single P transposable element has caused a new mutation, greatly simplifying the genetic and molecular analysis of the affected gene. Mutagenesis is initiated by crossing two strains, each of which contains a specially designed P element. One element (jumpstarter), encoding P element transposase, efficiently mobilizes the second nonautonomous transposon (mutator), whose structure facilitates selection and cloning of new insertion mutations. Random mutator transpositions are captured in individual stocks that no longer contain jumpstarter, where they remain stable. This method was used to construct 1300 single P element insertion stocks which were then screened for recessive mutations. A library of single-element insertion strains will allow the structure and function of *Drosophila* genes to be readily correlated, and should have many other applications in *Drosophila* molecular genetics.

IN BACTERIA, GENETICALLY MARKED TRANSPOSABLE ELEMENTS are very useful for genetic manipulation in vivo (*1*). Strains containing single, marked transposons allow highly efficient insertional mutagenesis, genetic mapping, and the construction of specific chromosome rearrangements. In contrast, the potential of transposable elements as genetic tools in higher organisms has been less fully realized. Transposon insertion mutations have occasionally allowed the isolation of specific genes in organisms as diverse as *Drosophila*, maize, nematode, and mouse (*2*). However, the high copy number and low transposition rate of most eukaryotic transposons have limited the general applicability of this approach.

An exception is the family of small nonretroviral *Drosophila* transposons called P elements (*3*). Several properties of P elements make them unusually useful for controlled genetic manipulation. Transposition of both full-length (complete) and internally deleted (defective) P elements is dependent on an element-encoded transposase whose production is limited to germline cells by tissue-specific splicing (*4*). In P strains, which contain 30 to 50 complete and defective P elements, transposition is repressed by a cytoplasmic state known as P cytotype. The molecular basis of cytotype is unknown; repressor molecules may be produced by certain defective elements or from incompletely spliced transposase messenger RNA (*4*). Most laboratory strains lack P elements; the absence of repressor activity in such a strain constitutes the M cytotype. P elements are released from repression in the progeny of crosses between females of the M cytotype and P strain males. Activation of P elements in the germline cells of such flies leads to a syndrome of traits (including new insertion mutations) known as "hybrid dysgenesis" (*5*). P element transposition can therefore be experimentally regulated by controlling either the supply of transposase or the P cytotype.

P elements have been used extensively as insertional mutagens activated by "hybrid-dysgenic" crosses between wild P strains and laboratory strains (*5*). However, the heterogeneous collection of elements present in wild P strains greatly limits the utility of this approach. Newly induced insertion mutations are highly unstable; they are frequently lost unless stabilized in the P cytotype by crossing to a P strain. Stabilized strains retain dozens of P elements,

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