CONF-8411171--14

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--84-3149

DEES 02200

TITLE: PROGRESS TOWARD FREE-ELECTRON LASERS FOR APPLICATIONS

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SUBMITTED TO:

Conference on Applications of Accelerators,
November 12-14, 1984, North Texas State Univ.
Denton, TX; proceedings to be published in
Nuclear Inst. and Methods.

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PROGRESS TOWARD FREE-ELECTRON LASERS FOR APPLICATIONS

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Abstract

Using an electron beam in a magnetic field as the gain medium, free-electron lasers offer a powerful new source of tunable, coherent radiation. Results are just becoming available from several new experiments, but they are confirming the theoretical promise of these devices. Backed up by a strong base of accelerator technology, free-electron lasers are expected to become important in applications requiring wavelengths from the far infrared part of the spectrum to the vacuum ultraviolet.

I. PRINCIPLES

Free-electron lasers represent a totally new concept for producing coherent radiation, and offer a variety of advantages over conventional lasers. In place of a solid, liquid or gas as the gain medium, free-electron lasers use a high-energy electron beam in a magnetic field. First invented by Robert Phillips in 1960 as a microwave tube called the ubitron, the free-electron laser was independently rediscovered as an optical device by John Madey in 1970 as an outgrowth of research in synchrotron-radiation sources.

Reduced to its essentials, a free-electron laser consists of an accelerator to produce the electron beam, a "wiggler" magnet to force the electrons to oscillate and radiate, and an optical system to form the laser beam. These are shown schematically in figure 1. As shown there, the wiggler magnet consists of a series of alternating magnetic poles which form a magnetic field directed up and down along the length of the wiggler. As the electrons pass through this magnetic field, they are deflected alternately left and right. Because of this wiggle motion, the electrons emit radiation at the wiggle frequency. Due to relativistic effects, the radiation is strongly forward directed, and appears at a frequency which is doppler shifted to much shorter wavelengths. In fact, to a good approximation the wavelength λ_L of the light is related to the wiggler period λ_W by the expression

$$\lambda_L = \lambda_W / \gamma^2 \quad , \quad (1)$$

where γ is the energy of the electrons in units of their rest energy, which is 0.511 million electron volts. Thus, for 100-million-volt electrons ($\gamma=200$), travelling through a wiggler with a period of 2 centimeters, the wavelength is about 0.5 micrometers. This corresponds to green light, in the middle of the visible part of the spectrum. Since 100-million-volt electrons are conveniently obtained from

conventional radio-frequency (rf) linear accelerators, free-electron lasers promise to be a source of radiation at important wavelengths. In fact, by using different types of accelerators to produce electrons of different energies, it is possible to obtain wavelengths from the microwave region to the ultraviolet, as shown in figure 2. Free-electron lasers have already been operated at wavelengths from the microwave region to the visible portion of the spectrum, and experiments are underway to extend this to even shorter wavelengths. Of course, the electron radiation described above is just incoherent emission, similar to the spontaneous radiation from conventional lasers. However, when a coherent optical field from a laser (even the free-electron laser itself, as shown in figure 1) is superimposed on the electrons, the electric field of the optical beam acts on the electrons. At resonance, that is, when the laser satisfies equation (1), the interaction becomes strong and the electrons are forced to oscillate in phase with the optical field. The electron emission then adds coherently to the incident beam and amplifies it as in a conventional laser. When mirrors are used, as in figure 1, the light reflects back and forth between the mirrors, gaining strength on each pass through the wiggler. The laser beam is extracted through the output mirror, as in conventional laser oscillators. Thus, in most respects, free-electron lasers behave like other types of lasers, and share their properties.

STATUS

The first free-electron laser was built and operated by Madey and his co-workers at Stanford University in 1976. Using 23-million-volt electrons from an existing rf accelerator, they were able to amplify 10-micrometer (infrared) radiation from a CO₂ laser, and demonstrate stimulated emission (laser action). Shortly afterward, they increased the electron energy to 43 million volts and added mirrors as shown in figure 1, and were able to make the free-electron laser oscillate at 3.3 micrometers without the support of a conventional laser. The laser produced about 5 watts of power averaged over the millisecond pulses; the efficiency was about 0.2 percent for converting electron-beam power to laser power. Later experiments demonstrated that the optical beam quality was nearly perfect (diffraction limited). Although the laser power was small, considering the size and cost of the accelerator, the potential was obvious, and the results stimulated considerable interest.

The principal shortcoming of these experiments was their low efficiency. This was predicted theoretically, and was due to the fact that as the electrons lost energy to the optical beam, they slowed down and no longer satisfied the resonance condition, equation (1). To compensate for this, Phillip Morton of SLAC proposed that the change of electron energy, γ in equation (1), could be compensated by a corresponding change in λ_w . In fact, he showed that the process should be stable, with the electrons losing just enough energy to satisfy the resonance condition as the wiggler period is "tapered" to a smaller value. To prove this, an experiment was conducted at Los Alamos in 1981. An existing accelerator was modified to provide a beam of 21-million-volt electrons, and a wiggler was constructed to be resonant with 10-micrometer (infrared) radiation. The experiment was configured in the form of an amplifier: instead of mirrors, a CO₂ laser was used to provide the optical input. Photographs of the accelerator and the

wiggler are shown in figures 3 and 4, respectively. Both the energy removed from the electrons and that given to the laser beam were measured, although the optical measurements were much more difficult. Both measurements gave the same result, and confirmed the theoretical predictions. Some of the results are summarized in figure 5, where we see that an efficiency approaching four percent was achieved. These results represent the best confirmation yet obtained of the theory of free-electron lasers, and support the largely theoretical promise of these devices. In addition to the 10-micrometer radiation, harmonic radiation was observed at 5, 2.5, and 1.25 micrometers. This radiation derives from nonlinearities of the interaction between the electrons and the incident optical beam, and has the coherence properties of the incident beam. Although it was very weak, a million times less powerful than the 10-micrometer radiation, such coherent harmonic radiation may someday be useful for very short wavelengths, not achievable by any other techniques.

These results stimulated considerable interest because they pointed the way toward useful, high-efficiency lasers. However, for most applications, it will be necessary to operate the freeelectron laser as an oscillator, as shown in figure 1, rather than as an amplifier. For this reason, the experimental results obtained by a number of groups in 1983 are of particular interest. The first results were obtained by a team of French scientists using the electron storage ring at LURE, near Paris. The ring was originally designed as a synchrotron-radiation source, and operates at a rather low current. Measurements in 1981 showed a free-electron laser amplification of only four parts in ten thousand per pass. Thus, it was a considerable triumph when a specially designed wiggler, called an "optical klystron", achieved oscillation in the summer of 1983. With the storage ring operating at an energy of about 150 million volts, the free-electron laser produced about 100 microwatts of output power at a wavelength of 0.6 micrometers, in the red part of the spectrum. Although Soviet scientists at Novosibirsk had previously observed gain in the same wavelength region, using a similar wiggler (which they invented), the results obtained at LURE represented the first real freeelectron laser operating at a visible wavelength, and the first operating with the electron beam from a storage ring. While the laser power was small, it lasted for more than an hour, limited only by the storage time of the ring.

The next results were obtained by a team of scientists from TRW, working with the Stanford accelerator. Using a tapered-wiggler design incorporating ideas from the optical klystron, they obtained laser oscillation at a wavelength of 1.6 micrometers, with a maximum efficiency of 1.2 percent. These results show clearly that tapered wigglers can be used to enhance the efficiency of free-electron laser oscillators as well as amplifiers. The output power averaged over the millisecond pulses was as high as 10 watts. Unexpectedly strong third-harmonic radiation was observed at 0.5 micrometers (green).

Most recently, the Los Alamos amplifier experiment, described above, has been reconfigured as shown in figure 1, and operated as a free-electron laser oscillator, in the infrared. Because of the high current (100 amperes peak) produced by the Los Alamos accelerator, the laser produced 6000 watts average power during the 100-microsecond

pulses; even higher powers are expected in the near future. By varying the electron energy, it was possible to tune the wavelength from nine to eleven micrometers. The tuning range was restricted only by the reflective coatings of the mirrors. Measurements showed that the optical quality of the output beam was essentially perfect, even when the mirrors were deliberately misaligned.

Although most of the recent emphasis has been on free-electron laser oscillators, work at Livermore has focussed on high-gain amplifiers. Using a linear induction accelerator, rather than an rf accelerator, much higher peak current (as high as 10,000 amperes) can be obtained. This makes it possible to obtain sufficient laser amplification to make a useful free-electron laser amplifier. Besides the wavelength restrictions imposed by the need for a conventional input laser, this approach is limited by the fact that high-current electron beams are difficult to focus, making it difficult to operate the free-electron laser at short wavelengths. Nevertheless, induction linacs have advantages for applications which require high peak power. Recently, an efficiency of five percent was demonstrated at a wavelength of 9 millimeters. Although this is a rather long wavelength, the physics and technology should scale to much shorter wavelengths, as indicated in figure 2. The peak power in these experiments was about 100 million watts, in pulses lasting about 10 billionths of a second.

Quite recently at the University of California, Santa Barbara, an interesting experiment using a five-million-volt Van de Graaff accelerator began operation at wavelengths in the far infrared, near 400 micrometers. The experiment is particularly interesting because it is designed to operate with improved efficiency by recovering the energy remaining in the electrons after they have passed through the free-electron laser. Only preliminary results have been obtained, and the laser has not yet reached saturation. Nevertheless, a peak power of 3000 watts has been obtained. When it becomes fully operational in the near future, this facility will be used for solid-state physics research.

In the near future, several more experiments are expected to come on line. At the National Synchrotron Light Source at Brookhaven, a free-electron laser is being developed for the ultraviolet part of the spectrum, around 0.3 micrometers, using the uv storage ring. Meanwhile, at AT&T Bell Laboratories a compact type of accelerator called a microtron is being used to develop a free-electron laser for the far infrared part of the spectrum from about 100 to 400 micrometers. All these experiments illustrate the interest in free-electron lasers for wavelength regions not easily accessible to conventional lasers. Finally, a free-electron laser oscillator for the mid-infrared region, from perhaps 5 to 50 micrometers, is being developed at the Kelvin laboratory in Glasgow. This experiment which is intended mostly for research in free-electron lasers themselves, is undergoing preliminary tests.

In the future, the emphasis will be on free-electron lasers for very short wavelengths, reaching down into the extreme ultraviolet and soft X-ray regions. The problems in these regions are formidable: laser gain decreases at short wavelengths, mirrors are poor, and it is difficult to

collimate electron beams well enough to operate at such short wavelengths. But the difficulty of obtaining coherent radiation at these wavelengths by any other techniques makes free-electron lasers interesting despite the difficulties, and it may even be possible to make use of shortwavelength harmonics, as discussed above.

ISSUES

The further development of free-electron lasers must address a variety of problems involving the basic operation of the free-electron lasers themselves, as well as the technology of optics and accelerators. For free-electron lasers operating from linear accelerators, the most important fundamental issue is that of so-called "synchrotron" instabilities. As the electrons proceed down the length of the wiggler, they tend to oscillate about the resonant energy, which satisfies equation (1). These motions, which are called synchrotron oscillations, are predicted to cause radiation at wavelengths shifted from the laser wavelength by the frequency of the synchrotron oscillations. This radiation may rob power from the laser radiation, and degrade the performance of the device. This effect has recently been observed for the first time in the experiments at Los Alamos. If the instability proves to be detrimental, it should be possible to suppress it by various techniques. For free-electron lasers operating in storage rings, the principle problem is the tendency of the free-electron laser to disrupt the electron beam, stretch out the electron-beam pulses, and make the beam unsuitable for the free-electron laser on the next pass. Although the natural properties of the ring tend to damp out the effects of the free-electron laser, the interaction is not well understood at the present time. In fact, under some conditions the storage ring free-electron laser at LURE works better than expected due to anomalous shortening of the electron pulses in the storage ring.

Optics technology must also see some development for free-electron laser applications. In particular, optical damage to the mirror coatings by the high-intensity laser beam is expected to be a problem. The problem is complicated by degradation of the coatings by radiation other than the laser beam itself. This radiation includes harmonics of the laser radiation, as discussed above, as well as X-rays, gamma rays, neutrons, and stray electrons from the accelerator. Such degradation has already proved to be a problem in the storage-ring free-electron laser experiments at LURE.

Accelerator technology must also be advanced for free-electron laser applications. Both the peak and average current capability of rf accelerators and storage rings must be increased. As the current increases in rf accelerators, two problems arise. First, the ability of the electron beam to be collimated declines as the peak current increases. Second, instabilities caused by the interaction between the electrons and the accelerator structure develop at high average current. Interesting programs are underway at Los Alamos to address both of these problems, using photocathode guns to provide high peak current and advanced accelerator structures to avoid instabilities. The

most stressing problem for induction linacs is collimation of the high-current beams which these machines produce, but progress is being made at Lawrence Livermore Laboratory. Storage rings available for free-electron laser research in the past have all suffered from insufficient peak current to provide adequate optical gain. When it is fully operational, the uv ring at Brookhaven should have significantly higher current than older rings, and at Stanford, Madey and his co-workers are about to begin construction of a new ring designed specifically for free-electron laser applications. This will provide sufficient current for operation at very short wavelengths, down into the far ultraviolet.

APPLICATIONS

Due to their unique technology, free-electron lasers offer several advantages relative to conventional lasers. These include wavelength tunability, high power, good optical-beam quality, and high efficiency. Wavelength tunability follows, of course, from the relationship (equation (1)) between the wavelength and the electron energy. Since the electron energy can typically be varied over a factor of two in a given accelerator, it is possible to vary the wavelength over an even wider range. Generally it will be necessary to change the mirrors, which have a narrow range over which they are reflective, but this is not difficult. Free-electron lasers have two advantages for achieving high power. In the first place, conventional lasers are limited by the difficulty of removing the waste heat. The most powerful lasers, gas lasers, depend on high-speed (even supersonic) flow to remove the hot laser medium. In free-electron lasers the waste heat resides in the electron beam, which is moving at nearly the speed of light and exits the optical cavity in a few billionths of a second. Moreover, high-power accelerators already exist. SLAC, at Stanford, accelerates an average electron-beam power of hundreds of kilowatts, twenty four hours each day. Good optical-beam quality is another advantage of free-electron lasers. This follows from the nature of the optical resonators used in free-electron lasers: they are long, slender devices, and do not support undesirable optical modes. In addition, the optical-beam distortion due to the electron beam is very small. In the Los Alamos experiments, the electron beam is equivalent to a lens with a focal length of more than a kilometer. Finally, free-electron lasers may someday offer high efficiency. When used to accelerate high-current electron beams, accelerators can be made as much as 50 percent efficient. Combined with the demonstrated four percent conversion to laser radiation, this corresponds to two percent overall efficiency. In fact, it should be possible to improve on this by recovering a substantial fraction of the energy remaining in the electron beam after it passes through the wiggler. Experiments of this type are already being conducted at Santa Barbara, as discussed above, using a Van de Graaff accelerator. At Los Alamos it is proposed to use an rf linac to both accelerate the electrons and then to convert their energy back into rf power after they have passed through the free-electron laser. Experiments have demonstrated that this process is indeed possible, and application of this idea to free-electron lasers is planned for the near future.

These advantages suggest a number of applications. The easiest advantage to achieve, and the one which will be the first to be exploited, is the wavelength tunability. Long wavelengths, in the far

infrared from about 100 to 400 micrometers, are of interest for solid-state materials research. For this reason, AT&T Bell Laboratories is building a free-electron laser for this wavelength region. Shorter wavelengths, particularly in the ultraviolet, are of interest for chemistry, and high power may someday make photochemical processes of interest for industrial applications. For infrared photochemistry, where molecular spectra are strongly structured, the tunability of free-electron lasers is particularly important. Likewise, the ability of free-electron lasers to tune into spectral regions inaccessible to conventional lasers makes them of interest for medical applications. This is one of the principle motivations for the short-wavelength storage-ring free-electron laser program which is now beginning at Stanford. Finally, the advantages which free-electron lasers offer for the production of high-power laser beams of good optical quality has made them interesting for strategic defense, also known as "star wars". While such applications are only distant possibilities at the present time, and face a variety of problems of which the laser may be the simplest part, the possibility of enormously powerful laser beams still excites the imagination, and work in that direction is providing spin-offs for a variety of less ambitious applications.

Fig. 1. In free-electron lasers, the radiation is generated by passing the electrons through a so-called wiggler magnet which causes them to oscillate from side to side.

Fig. 2. To change the wavelength, or color of the beam from a free-electron laser, it is necessary to change the electron velocity, or energy; short wavelengths require higher energy. Different types of accelerators are used for low- and high-energy electrons. To operate in the visible portion of the spectrum, storage rings, rf linacs, and possibly induction linacs can be used.

Fig. 3. This photograph shows the 21-million-volt rf linac used in the Los Alamos free-electron laser experiments. The accelerator itself is the 10-foot long copper structure shown in the center of the photograph. To accelerate electrons to higher energies, proportionately longer accelerator structures are used.

Fig. 4. This photograph shows the wiggler magnet used in the Los Alamos free-electron laser experiments. The wiggler is one meter long, and contains about 340 small permanent magnets which form the magnetic field.

Fig. 5. This figure shows some of the results of the Los Alamos free-electron laser experiment. As the power of the input laser beam is increased, more of the electron energy is converted to light, increasing the efficiency. The results agree quite well with the theoretical predictions, and show an efficiency for extracting light from the electrons which approaches four percent.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5