Status of the experimental free electron laser

In this article concluding a three-part series on the free electron laser, Robert Gallagher reviews the status of the leading experimental programs.

The Strategic Defense Initiative Organization (SDIO) has chosen to develop and construct a ground-based free electron laser as a prototype interceptor for destruction of ballastic missiles in the early, boost phase of their trajectories. For strategic defense, the free electron laser would direct its beam towards mirrors in space which would focus it on enemy missiles to destroy them.

In a free electron laser, an electron beam traveling close to the speed of light, is directed between a series of alternating polarity magnets which oscillate the trajectory of the electrons (see **Figure 1**). Whenever the path of electrons traveling at such speeds is oscillated, the electrons emit electromagnetic radiation whose frequency varies with the speed of the electrons and the spacing of the magnets. The electrons are not bound to any atomic nucleus while emitting radiation, and for that reason are called "free electrons."

There are several types of free electron lasers, differing by the type of electron accelerator or other source for the electron beam, and by whether or not the device generates, or only amplifies laser radiation.

Free electron laser amplifiers are being developed at Lawrence Livermore National Laboratory driven by the linear induction accelerators developed there, in an application of the principles of the transformer, and originally intended for use as electron beam missile interceptors for terminal defense. Last spring, a Livermore free electron laser amplified a 50-kilowatt millimeter-wave pulse to 1,000 megawatts.

Second, there are the free electron laser oscillators driven by radio-frequency linear accelerators which were developed out of World War II A radio-frequency linear accelerator accelerates an electron beam with pulses of current alternating at microwave frequencies produced from electric tubes, such as the klystron. Work on these devices is being conducted at Los Alamos Scientific Laboratory, Stanford, TRW, and also at Boeing Company. Los Alamos researchers achieved 800 megawatts peak power of 10-micron wavelength infrared radiation inside the optical cavity of their free electron laser oscillator in 1984.

In addition, a joint project of TRW, Inc. and Stanford University is developing radio-frequency linear accelerator-based free electron lasers with supercooled accelerator cavities using superconducting materials. The Stanford-TRW team achieved 460 megawatts peak power of 1.6-micron infrared radiation inside the optical cavity of their free electron laser oscillator in experiments in 1984.

Third, there are the free electron lasers under development at the Laboratory for the Utilization of Electromagnetic Radiation (LURE) in Orsay, France, and at Stanford by John Madey's group, based on electron-beam storage rings. The LURE group generated low-power 0.65-micron wavelength visible laser light in 1983. Madey forecasts a peak power of 130 megawatts in a "slow pulsed mode" for his device.

Table 1 presents the parameters of and the results achieved to date with these free electron lasers. These programs must meet the following requirements and solve the following problems to be relevant to the SDI:

1) Electron beam energy must be hundreds of million-electron-volts (MeV), to produce radiation at those wavelengths necessary for interception of ballistic missiles in their boost phase, with radiation ranging from the near infrared (1 micrometer) to the ultraviolet.

Radio-frequency linear accelerators and storage rings met this requirement many years ago. In a recent development, Livermore researchers attained 50 MeV with the induction linear Advanced Test Accelerator.

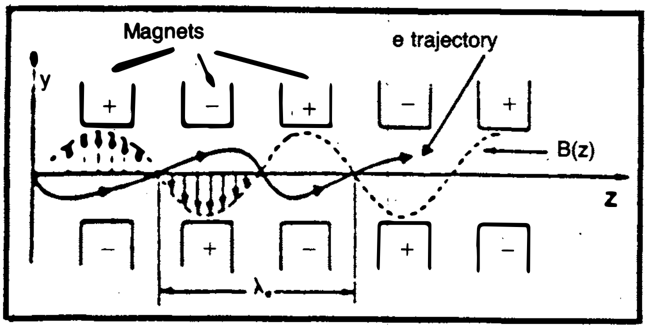
2) The free electron laser must produce a high power output of gigawatts of coherent light. A Livermore induction linear accelerator free electron laser device has shown the capability to amplify long-wavelength microwaves to one gigawatt power level. Los Alamos plans to combine a tunable radio-frequency linear accelerator-based free electron laser oscillator with a radio-frequency linear accelerator free electron laser amplifier, to attain required power levels.

3) Electron beam "brightness" must be high for free electron lasers. "Brightness" measures the extent to which a beam is intensely focused. It increases with beam current and decreases with the square of "emittance," a measure of transverse beam motion. Bright beams are required in order to generate short wavelength light in the visible or ultraviolet regions of the electromagnetic spectrum, and to produce high laser gain.

Beam control in radio-frequency linear accelerators is considerably better than in induction linear accelerators. Radio-frequency-linear accelerators at Los Alamos and Stanford have produced beams with an emittance thousands of times better than that of the Livermore induction linear Experimental Test Accelerator (see Table 1, column 10). This is one reason why radio-frequency linear accelerator free electron lasers have produced such high powers inside their optical cavities with electron beams that have only a tiny

FIGURE 1

Sketch of a linearly polarized undulator and electron trajectory



The undulator or wiggler for a free electron laser is composed of magnets of alternating polarity in a linear arrangement. An electron beam is directed down the center of the device, which turns the electrons alternately from north to south, thus oscillating their trajectory as shown. As the electrons turn, they emit electromagnetic radiation. The dotted line shows the shape of the periodic magnetic field that oscillates the electrons; the solid line shows the electron trajectory produced by the oscillation, as currently understood.

Source: M. Billardon, et al., "Free Electron Laser Experiment at Orsay: A Review," IEEE Journal of Quantum Electronics, Vol. QE-21, 1985, page 805.

TABLE 1

Status of free electron laser experimental programs

		Free electron laser characteristics					Electron accelerator characteristics			
	(1) Date	(2) Wavelength achieved (microns)	(3) Efficiency of beam energy extraction (%)	(4) Oscillator?	(5) Pulse length (p sec)	(6) Peak lasing power[1] (MW)	(7) Accelerator type	(8) Beam peak current (amp)	(9) Electron kinetic energy (MeV)	(10) Beam emittance (π mm mrad)
Stanford	1984	1.57 & 0.5	1.2	Yes	4.3	460	SL	2.6	66	0.15
LURE	1983	0.650	low	Yes	500-1000	NA	SR	0.05	160	NA
LASL	1983	10.6	3.7	No	5000	900	L	NA	19-22	0.5-6.0
	1984	9-35	1.0	Yes	36	800	L	27-40	10-21	2.5-5.0
LLNL	1986	8671	6	No	15,000	180	IND	850[2]	3.5	4700
	1986	8671	34	No	15,000	1000	IND	850[2]	3.5	4700

Notes:
1. This measure (the same as peak intracavity power for oscillators) factors out accelerator duty cycle limitations.
2. Generated beam of 4000 amps reduce-filtered to 840 amps, or 21% of original current.

Legend for Symbols. LURE = Laboratory for the Utilization of Electromagnetic Radiation; LASL = Los Alamos Scientific Laboratory; LLNL = Lawrence Livermore National Laboratory. NA = Data not available. p sec, (picosecond) = 1 trillionth of a second. MW = megawatts. Accelerator types: SL = superconducting radio frequency linear accelerator; SR = storage ring; L = radio frequency linear accelerator; IND = linear induction accelerator. amp = amperes. MeV = million electron volts.

fraction of the current of beams produced by induction linear accelerators.

Linear induction accelerators introduce transverse oscillations into the beam, which increase emittance and degrade brightness as an inherent characteristic of the accelerator action. These oscillations are amplified as the beam is accelerated.

Even in radio-frequency linear accelerators, the geometry of the resonant microwave cavities which accelerate the beam, can generate higher harmonics of microwave power which can introduce oscillations in the beam and degrade emittance and brightness.

Storage rings produce high brightness beams, but presently are considered inefficient for free electron lasers for strategic defense, because most of the beam energy is dissipated in synchrotron radiation emitted in the beam's circuit around the ring.

4) Interactions between the electron beam and the undulator at high beam currents, can significantly reduce the coherence of the free electron laser output. The interaction can produce longitudinal "synchrotron" oscillations of the beam within the undulator, resulting in the generation and growth of significant sidebands about the fundamental lasing frequency, from the production of "combination tones" by the addition (or subtraction) of the low-frequency longitudinal oscillations to or from the fundamental frequency of laser output.

Los Alamos reported 3%-wide sidebands in their free electron laser in 1984. LASL researchers propose use of gratings inside the optical cavity that would diffract (and thus not oscillate) the frequencies of sideband radiation, in order to eliminate them from the output. This technique would preserve the tunability of the device since the frequencies passed through the gratings can be tuned with the free electron laser by rotating them relative to the axis of the optical cavity.

5) In experiments conducted to date, laser power extracted from an electron beam in a free electron laser is limited by a phenomenon which limits the length of the free electron laser undulator, the region where radiation is extracted from the beam, and thus the maximum laser power obtainable.

All forms of directed energy, whether electrons or laser light, diffract spherically.

> **a)** Therefore, in a long undulator, it is necessary to focus the electron beam to maintain beam brightness since otherwise, like any form of radiation, the electron beam would spherically diffract. However, most focusing schemes induce synchrotron oscillations.
>
> **b)** Second, in long undulators, it is necessary for the laser light produced from the electron beam, to be actively focused about the beam. Otherwise, it will diffract away from the electrons, with the result that radiation already produced will not be able to stimulate lasing and produce an exponential growth in laser gain along the length of the undulator. This is more of a problem for long-wavelength free electron laser operations, since the longer the wavelength, the greater the angle of diffraction.

6) Existing accelerators used in free electron lasers, such as those at Livermore or Los Alamos, have a low duty cycle; they generate only one pulse or train of pulses per second. Pulse rates of thousands per second will be required by both SDI and any serious industrial application of free electron lasers.

The Livermore Advanced Test Accelerator (ATA) can at present produce only a single pulse of electrons per second, 15 billionths of a second (15 nanoseconds) long, because of the electric power switching technology it uses. The Los Alamos radio-frequency linear accelerator produces a single pulse train per second, 150 microseconds long. In either case, the duty cycle of the accelerators, the proportion of operating time in which accelerator power is on, is very low, a ratio of about one in 66 million for the ATA, and about one in 13 thousand for the Los Alamos machine.

Low duty cycles usually reflect a physical limitation of a technology used in the accelerator. For example, in radio-frequency linear accelerators, the accelerating microwave power heats the copper of the resonant cavities to such high temperatures that it is necessary to cool them to prevent damage, prior to the next pulse of the electron beam. This cooling requirement places a limit on the duty cycle attainable in radio-frequency linear accelerators. In one reported case, fully a megawatt of power is being used per meter of accelerator length to pump coolant water around the cavities.

Livermore has announced that it is working on a system to raise the pulse rate to 2,000 per second for a duty cycle of about 0.004 percent. Los Alamos researchers report that they will be able to achieve a thousand pulses per second, each 100 microseconds long, for a duty cycle of 10%.

7) Free electron laser oscillators are at present limited to low output powers (i.e., tens of megawatts) because optical components cannot withstand high output powers required by SDI. Although the Los Alamos free electron laser achieved 800 megawatts in peak intracavity power in 1984, its peak output power was only 10 megawatts. However, by feeding the megawatt output of an oscillator into a radio-frequency linear accelerator-based free electron laser amplifier, Los Alamos hopes to produce gigawatt output in a dual-laser system.

8) Free electron laser output radiation wavelength and pulse shape, must be optimal for transmission through the atmosphere from ground-based systems to relay mirrors in space.

9) For high-power operation for the SDI, it is desirable for free electron lasers to have high efficiencies in conversion of electron beam power into laser power so that the size and complexity of power sources for the accelerator can be minimized. Free electron lasers based on radio-frequency linear accelerators promise to achieve efficiencies in use of the electron beam of 95% or greater.

Classical hyperbolic saturation

In order to meet these requirements in electron beam energy, brightness, and focusing, and solve remaining problems in laser output power, coherence, transmission, and efficiency, and in accelerator duty cycle, physicists must develop and engineer superior physical principles on which to base the operation of both the accelerators that power their free electron lasers and the lasers themselves, especially for induction linear accelerator-based devices.

A physical principle of a machine's operation is a past or current discovery in experimental or applied physics, that can be translated into a new engineering design for a superior machine. The replacement of waterwheels by steam engines, to power blast furnaces in the 1840s, is an example of the application of a superior physical engineering principle, new to iron making. The practice of distinguishing machines by the physical principles of their operation, was elaborated by Leonardo da Vinci, Leibniz, and Lazare Carnot.

The contrary approach involves making incremental changes in existing machines. This will produce only "diminishing returns," minor improvements in the brightness of beams, or higher frequency operation, at the sacrifice of efficiency, tunability, and other features. Historical precedent in the development of electron tube devices, shows this to be the case.

Our past experience in the development of electron tubes is entirely relevant to the free electron laser. In fact, the free electron laser is not a laser in the ordinary sense, but rather, a more advanced electron tube, falling into the same general class of technology as the magnetron microwave tube that is used in everyday microwave ovens, or the klystron that provides microwave power to accelerate electron beams in radio-frequency linear accelerators.

The Los Alamos free electron laser experimental device is a case in point. It is nothing but an assemblage of electron tubes. It uses an electron gun from a traveling wave tube to produce a beam, which is then accelerated by microwave power, provided by a series of klystrons.

Because different electron devices are based on different physical principles, they cover different, bounded regions of the electromagnetic spectrum. This will prove to be just as characteristic of free electron lasers as it has been of previous electron tube technology; each electron tube developed before the free electron laser, has a definite frequency range of efficient operation.

The magnetron, an electron tube microwave oscillator developed during World War II, can step up the frequency of electric power to tens of millions of cycles per second with 65 to 75% efficiency. As you push the device-type to its limits, to produce higher frequency electromagnetic action, such as microwaves for radar (1-40 billion cps), the technology begins to display a classic hyperbolic saturation, and the efficiency begins to drop off. Magnetron microwave radar efficiency is as low as 40 to 50%. Like the magnetron, each electron tube device leading up to the free electron laser, has inherent limitations. Each has its optimal range of operating frequencies after which its efficiency degrades and its operation ultimately collapses.

The need for the development of each of these devices, derives from the fact that as we raise the frequency of electric power—that is, its frequency of action—its behavior begins to change; it escapes the boundary conditions that we have imposed on it through technology: For example, as the wavelength being transmitted by a wire approaches the size of the wire, the wire's properties as a waveguide break down, and it broadcasts radiation like an antenna.

The traveling wave tube (described in a previous article of this series), displays a nonlinear hyperbolic fall-off in amplification as it is driven to operate at higher frequencies (see **Figure 2**) and for any particular frequency, a hyperbolic saturation and fall-off in amplifier gain (and efficiency) as the power of the input microwave beam to be amplified, is increased (see **Figure 3**). This hyperbolic saturation of the efficiency and output of a device as more energy, of the same type, is pumped through it, is characteristic of the history of technological development, and has been documented in *Executive Intelligence Review* for the cases of iron and steel making technology, and electric power production.

There thus appears to be considerable basis, for assuming that free electron lasers will be organized into regions or "octaves" along the electromagnetic spectrum, in accordance with differences in the physical principles of their operation. One machine dealing perhaps with x-ray and ultraviolet light, another machine dealing with visible and the near infrared, and perhaps another dealing with the far infrared, or some arrangement of that sort.

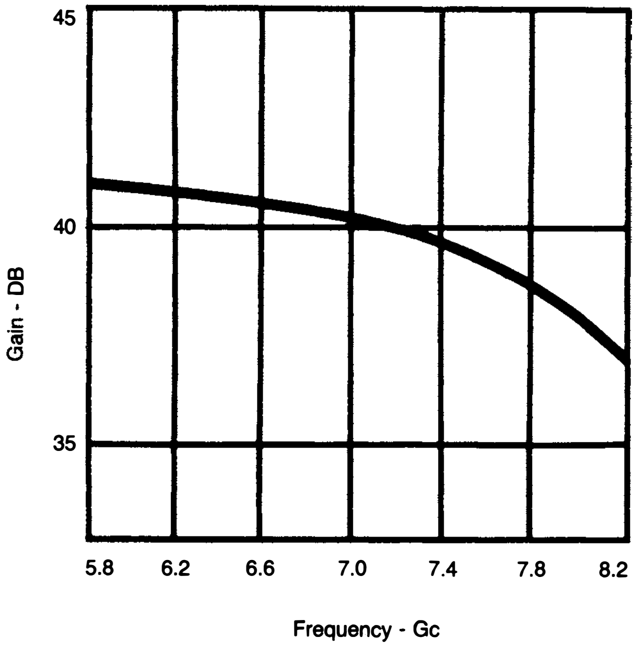
Charles Brau of Los Alamos made one attempt to convey a similar concept in **Figure 4** from a recent paper. Although his projection of the relative performance of the various free electron laser types, in terms of operational wavelengths and peak power, is probably wrong in detail, the notion that machines differ by their physical principles of operation is correct.

By contrast, quantum electrodynamics (QED) based on its statistics of "random uncertainties," does not provide a methodological guide for comparing or transforming existing machines, and thus appears somewhat irrelevant.

The proper concern of researchers in free electron lasers, is not only the linear scaling of their machines to longer,

FIGURE 2

Typical hyperbolic gain vs frequency relationship for a traveling wave tube



Source: "Introduction to the Traveling Wave Tube," Selected Articles from the Lenkurt Demodulator, Lenkurt Electric Company, subsidiary of GT&E, 1966.

more powerful, highly computerized versions based on the same physical principles, but the application of more advanced principles to their design and operation. This need is acute at Lawrence Livermore National Laboratory. With its previous work, Livermore has shown promising results in amplifying millimeter radiation, but now must upshift to frequencies 10,000 times greater (1 micron or less in wavelength) to attain laser radiation effective for SDI boost-phase intercept. As discussed above, efforts to accomplish lesser tasks in the development of electron tubes, have led to dramatic fall-off in amplifier gain and efficiency, or simply failure.

Livermore's challenge

Earlier this year, Livermore achieved a 34% efficiency of energy extraction in amplifying a 50-kilowatt beam of 8.7-mm wave radiation, to 1 gigawatt power with a tailored, 850 ampere, 3.5 MeV electron beam, produced by the Experimental Test Accelerator, as reported in *Physical Review Letters* in October. In order to achieve this result, Livermore used a 3-meter undulator with a magnetic field tapered 45% along the undulator. Although this extraction efficiency is high for a free electron laser, it is low for electron devices that produce or amplify radiation of the same wavelength, such as the magnetron.

Furthermore, to produce the stated results in power and efficiency, Livermore first generated a 4,000 ampere electron beam and then used a filter to produce a beam 80% smaller in current but geometrically superior.

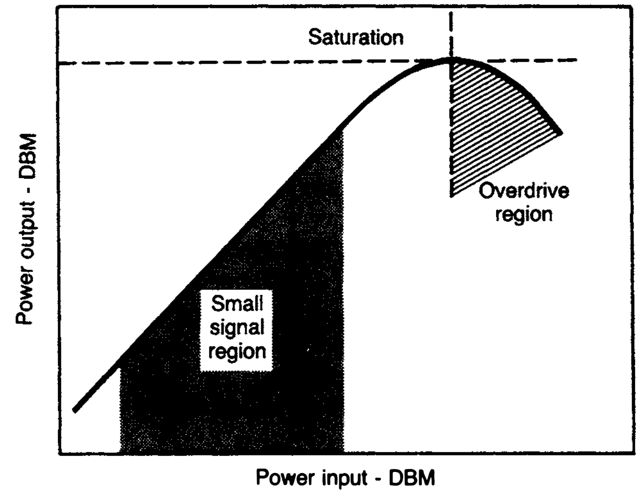
In the next year, Livermore will attempt to go to a frequency 1,000 times greater than previous experiments, in an experiment to amplify a 10.6-micrometer infrared laser beam, by driving a 5-meter undulator with a 50-MeV beam from the Advanced Test Accelerator. If successful, the lab will attempt to use the same accelerator to drive a 25-meter undulator, to maximize energy extraction from the electrons.

Many researchers both inside and outside Livermore have their fingers crossed over the lab's 10.6-micron "Paladin" experiment. Given that the lion's share of free electron laser funding, is invested in the Livermore program, and that the free electron laser is the only SDI program oriented toward development of a prototype weapon system, a failure for Paladin would be a serious setback for the SDI program as a whole.

Livermore did not want to carry out a free electron laser experiment with the ATA, in part because the machine could not produce a 10,000 amp, 50-MeV beam with magnetic focusing of the beam within the accelerator. The energy (or speed) to which the machine could accelerate a beam, appeared limited by the growth of a beam-accelerator interaction instability known as "beam breakup," which grows as

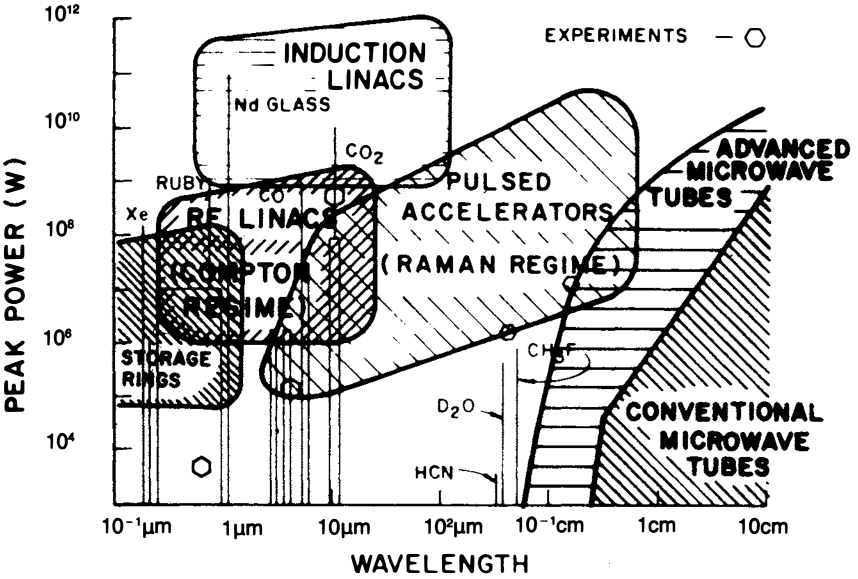
FIGURE 3

A hyperbolic power output vs. power input relationship in traveling wave tube.



Source: same as Fig 2.

FIGURE 4
Power and wavelength



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.

the beam is accelerated to higher and higher energies. Beam breakup instabilities are symptomatic of accelerators that produce long, continuous-pulse beams, report SDI scientists. Radio-frequency linear accelerators avoid them, by producing trains of short "micropulses."

Beam focusing with the ATA's external magnets was insufficient to prevent the beam from literally thrashing against the walls of the accelerator, unless monstrously large solenoid magnets whose engineering feasibility is questionable, were applied. Experiments in beam propagation conducted in the ATA, indicated that the machine could not achieve its design specifications of producing a 10,000-ampere current, 50-million-electron-volt (50 MeV) electron beam. Beam breakup destroyed the beam before it ever reached those power levels.

For this reason, Livermore proposed building another accelerator, designed specifically for use in a free electron laser, to amplify shorter-wavelength near-infrared radiation, 1-micron in wavelength. The proposal for this machine (known as "Alex") was turned down by the SDIO, pending the results of the Paladin experiments.

In order to get the ATA to work, Livermore scientists have developed a technique they call "laser guiding" of electron beams within the ATA. Laser guiding (also called "electrostatic channel guiding" by Livermore) has been successful in reducing beam instabilities by a factor of 1,000 (see *EIR*, Nov. 14, 1986); it suppresses beam transverse oscillations and focuses the beam about a line of benzene ions introduced into the accelerator. As a result, the ATA can now produce the high current, 50-MeV beam required for Paladin.

While laser guiding was under development, Livermore's E.T. Scharlemann led theoretical studies to investigate ways to focus electron beams in undulators and extend the possible length of undulators to the high values required by Paladin (25 meters) and SDI prototypes. This work identified two possibly feasible physical engineering principles to bring to bear in Paladin, that were not used in the previous Livermore free electron laser experiments:

a) the use of parabolic magnets to focus the beam inside the undulator without exciting the synchrotron oscillations that generate sidebands; and

b) the use of the optically refractive properties of the electron beam to focus the emitted radiation around the beam itself, a phenomenon known as "optical guiding."

The use of parabolic focusing of the electron beam in the undulator was discussed in the previous article in this series (see *EIR*, Nov. 7, 1986). Parabolic focusing may permit propagation of focused electron beams down long undulators, eliminating synchrotron oscillations and removing limitations listed above 4) on free electron laser coherence, and 5a) on free electron laser power. Optical guiding is hoped to eliminate limitation 5b) on laser power. Both parabolic focusing and optical guiding remain to be demonstrated experimentally.

Electron beams as fiber optics

It has been known for some time that the coherent interaction between light and electrons in a free electron laser, produces a phase shift of the light, such that light is refracted toward the electron beam. Lawrence Livermore National Laboratory and Lawrence Berkeley Laboratory conducted an extensive computer simulation of beam-laser interaction to study this property. Last year they announced that the electron beam in a free electron laser has properties of an optical fiber, and could itself focus the laser beam. E.T. Scharlemann of Livermore and his associates at Lawrence Berkeley Laboratory wrote in *Nuclear Instruments and Methods in Physics Research:* "The electron beam in a high gain free electron laser physically bunches on the optical wavelength; because of the bunching, the beam has an effective index of refraction greater than 1," that is, it focuses the laser light. They write that there are two fiber-optic effects, "refractive guiding" and "gain focusing."

"The first refers to the familiar guiding of an optical beam by a fiber with a real index of refraction. The power in the optical beam propagates exactly parallel to the fiber. The second, gain focusing, refers to self-similar propagation of an optical beam profile around a fiber with gain: Power diffracts away from the fiber, but the gain in the fiber more than balances diffraction. The result is an optical profile that grows in amplitude but does not change shape (hence the description as self-similar propagation)."

The research team writes:

"The importance of optical guiding . . . to free electron laser performance [is that] one can contemplate free electron lasers of exceedingly long length. In this way it appears possible to have a small electron beam radius and a very long wiggler (hence a very high gain free electron laser) even in the vacuum ultraviolet range.

The success of the 25-meter-undulator Paladin experiment hinges on whether the ATA electron beam's optical guiding of the long wavelength, 10.6-micron infrared radiation, is intense enough to prevent significant diffraction, and diffraction is greater at long wavelengths. The severity of the problem for Paladin is illustrated by the fact that the minimum divergence angle for 10.6-micron infrared radiation is over 10 times greater than that of all wavelengths of radiation of interest for the SDI (1 micron and lower), assuming the focusing element, the electron beam, has the same diameter.

On the other hand, if optical guiding is as intense as Scharlemann and his associates project, it may find widespread application. They note: "Because of the effect of optical guiding, it is possible to direct and focus the free electron laser-generated optical beam. This is of interest for very intense beams, such as are contemplated for laser inertial fusion, where lenses and mirrors of conventional materials would be destroyed by the light. . . . Optical guiding applies, also, to very short wavelength light, which does not interact coherently with normal material. Application of this to the vacuum ultraviolet and to soft x-rays would appear to make possible some interesting devices. . . ."

Radio-frequency linear accelerator-based free electron lasers also show tremendous promise for the SDI. They have already demonstrated the ability to produce short wavelength radiation. It is known that they meet, or can be easily modified to meet, all the requirements listed above.

A tunable gigawatt source

Research in laser chemistry has shown that the picosecond laser "micropulses" produced by radio-frequency linear accelerator free electron lasers, are optimal for transmission through the atmosphere. The primary problem in these devices, is increasing their output power.

As noted above, output power of radio-frequency linear accelerator-based free electron laser oscillators, is limited by the tolerance of mirrors and other optical components that direct the laser radiation to bounce back and forth through the undulator, forming a resonating optical cavity that extracts energy from the electron beam. Existing optical components cannot withstand the gigawatt power levels required by the SDI, scientists report.

However, there is a simple solution to this problem of relatively low peak powers: Use a high current radio-frequency linear accelerator electron beam, to amplify the output of a free electron laser oscillator, in a single pass through another free electron laser undulator. By combining an oscillator and a high current amplifier in series in this way, gigawatt power levels may be achieved while retaining the tunability of the system, since the signal originates from a tunable free electron laser oscillator. Reportedly, Los Alamos has submitted a proposal to develop such a system.

Recent experiments have confirmed that radio-frequency accelerators are also capable of extremely high efficiencies. Scientists at Stanford University and TRW, Inc. have demonstrated over 90% efficiency in recovery of the energy from the electron beam produced by the Stanford superconducting radio-frequency linear accelerator that drives the free electron laser under joint development by the two organizations.

The announcement of the success at an international conference on free electron lasers held in Glasgow, Scotland in early September, was no surprise to scientists familiar with the evolution of the free electron laser from electron tubes that produce microwaves.

A radio-frequency linear accelerator accelerates an electron beam with pulses of current alternating at microwave frequencies produced from electric tubes. Stanford and TRW have simply established a system for converting the energy of the accelerated beam of electrons back into microwave power for the accelerator, after the beam has passed through the interaction, or "undulator" region of their free electron laser, where radiation is generated. In this machine, microwave power and electron beams are simple transformations of each other.

Los Alamos Scientific Laboratory had already demonstrated in 1983 a 4% efficiency of extraction in transforming the power of a radio-frequency linear accelerator beam, into coherent laser radiation. Boeing Aerospace projects a 5% peak extraction efficiency for a free electron laser under development there. Together, these results and projections indicate that a free electron laser driven by a radio-frequency linear accelerator equipped with a system for beam energy recovery, can achieve an efficiency in use of the energy of the electron beam of 95% or greater.

The promise of superconducting accelerators

Although radio-frequency linear accelerators already produce extremely low-emittance, high-brightness beams, efforts are under way to make further improvements in accelerator design. In a radio-frequency linear accelerator, the electron beam is accelerated by microwave power fed into resonant cavities along the course of the accelerator. Degradation in beam quality is produced by the interaction of the longitudinal (that is, along the accelerator) and transverse action of the microwave power. The geometry of the resonant cavities can also generate higher harmonics of microwave power, which can introduce oscillations into the beam. Increasing the size of the cavities minimizes such effects, but increases power losses to their walls. Considerable effort is now being devoted to making improvements in the design of resonant cavities for radio-frequency linear accelerators.

At the same time, the high microwave power fed into the cavities, heats them to temperatures they cannot withstand for longer than a fraction of a second, limiting accelerator duty cycle. Various schemes are being applied to cool microwave cavities in radio-frequency linear accelerators around the country.

These problems with power loss and accelerator duty cycle, are resolved with use of superconducting accelerator cavities, according to scientists on the Stanford-TRW project. The use of superconducting materials, reduces losses to the cavity walls by 99%, according to one researcher. As a result, the accelerating gradient may be increased, to produce a beam of many times more current.

In supercooled, superconducting accelerators such as in the TRW-Stanford project, the cavities are kept cool by a liquid helium bath, eliminating the requirement to cool them between pulses, and thereby permitting a higher duty cycle. Stanford and TRW, Inc. are collaborating in the only project on superconducting radio-frequency linear accelerators. Project spokesmen emphasize that their free electron laser design can achieve the wavelength and power requirements of the SDI program. Unfortunately, the project has long been underfunded. In fact, for two years between 1984 and 1986, the Stanford Superconducting Accelerator-based free electron laser, which produced the world's first free electron laser oscillations, was shut down due to underfunding.

The free electron laser is best understood by analogy with hydrodynamic phenomena such as the "Doppler shift."

If the electrons in the free electron laser were not traveling at a speed close to the speed of light, the result of their undulation, would be the emission of radiation at wavelengths close to that of the spacing of the undulator magnets, that is, in the range of centimeter radar waves. However, an electron traveling close to the speed of light, upshifts the emitted radiation into the infrared, visible, and ultraviolet, as the energy of the electron beam is increased. This upshift in frequency (or compression in wavelength) is produced by the movement of the source (the oscillating electron), with respect to the emitted electromagnetic waves, which travel at the speed of light. Any moving source of radiation, will upshift or downshift the frequency of its output, depending on whether its motion relative to the direction of the waves it emits, results in their compression or rarefaction. This is the so-called Doppler effect.

The action of the electron beam in "compressing" the emitted electromagnetic wave in this fashion is thought to involve a clean transfer of energy from the electron beam to the electromagnetic wave; there is no "waste heat." By definition, such a process is termed "isentropic." Free electron lasers thus appear to vindicate Bernhard Riemann's 1859 paper on the creation of new wave forms out of the isentropic compression of propagating waves. Electrons traveling close to the speed of light and oscillating spatially at a wavelength equal to the period of the magnets in the undulator of a free electron laser, isentropically emit electromagnetic waves of a wavelength that is compressed, or "contracted," relative to that of their own oscillations. This is a classical example of a "relativistic effect."

Unlike conventional lasers, there appears to be no need for modern "quantum theory" to explain the free electron laser. Charles Brau of Los Alamos Scientific Laboratory wrote in *Laser Focus* in May 1981: "There is nothing inherently quantum mechanical about a free electron laser. In fact, Planck's constant appears nowhere in the final formulas, at least for photon energy small compared with the electron energy (many million electron volts)." Brau's condition holds all the way down into the x-ray region of the electromagnetic spectrum.

The free electron laser does, of course, involve quantized phenomena. An electron beam itself is quantized. The mastery of quantized phenomena, however, will not come about through the statistics of "random uncertainties," but only through the study of, for example, beam-laser physical geometry. In this way, the free electron laser was conceptualized based on the classical hydrodynamic relativistic Doppler effect—not with quantum electrodynamics' uncertain theory.

Robert McLaughlin carried out some of the research that went into this series. The first two parts appeared in the Oct. 24 and Nov. 7 issues.