Advances in the science of the free electron laser

In the second part of our three-part series, Robert Gallagher discusses recent milestones and the physical principles that lie at the basis of its operation.

In 1985, Lt.-Gen. James Abrahamson, director of the Strategic Defense Initiative Organization (SDIO), announced a decision to accelerate the program for development of a free electron laser (FEL) toward the construction of a prototype, ground-based ballistic-missile interceptor by the early 1990s. Abrahamson explained that the decision was prompted by advances made in the development of free electron lasers over the previous year. Indeed, the free electron laser program had produced significant advances in beam output power, optics, and advances toward ultraviolet (UV) and x-ray free electron lasers.

This article reviews recent work at major national laboratories in the United States and Europe in the development of the free electron laser, and discusses the basic physical geometry of its operation.

The free electron laser offers numerous advantages for military and industrial applications.

1) **High power.** Because the free electron laser is driven by relativistic electron beams, one intrinsic characteristic is that it produces a high-power laser beam. **Table 1** (column 9) shows that experimental free electron laser devices at several national labs, have produced hundreds of megawatts in peak power.

2) **Tunable output.** In principle, it is possible to develop a free electron laser whose wavelength (or frequency) of output radiation is as tunable as a radio tunes onto a signal; for example, an free electron laser whose laser light output could be tuned from red to orange to green to blue, by varying electron beam energy. The physical principles underlying this property are discussed below. It is important for several

All interactions between light and matter depend in a complementary way on the wavelength of light and the properties of the gas, solid, or liquid it interacts with. For example, specific chemical reactions correspond to wavelengths of electromagnetic radiation; specific wavelengths of electromagnetic radiation reduce specific chemical bonds. As a result, the widespread availability of tunable sources of coherent radiation, will revolutionize chemical processing and basic industry.

Tunable devices will find military applications in advanced laser radar, by which the composition of the atmosphere, or of the surface of a target, can be determined from the wavelengths of light emitted by them after being irradiated by an free electron laser over a range of wavelengths. With such information on a target's surface characteristics, an free electron laser interceptor can select the optimum wavelengths with which to destroy the target. Once atmospheric conditions between the interceptor and the target are so determined, the interceptor can choose the specific wavelength of attack, to minimize energy-dissipating interaction with the atmosphere.

The property of tunability will permit the same free electron laser to play roles in both boost-phase ICBM interception and terminal defense against warheads. free electron lasers that are tunable in the ultraviolet and x-ray portions of the spectrum, may generate ultraviolet beams for relay to space-based mirrors for destruction of ICBMs in the boost phase of their trajectory (the first five minutes after launch), or may generate x-rays to attack and disarm nuclear warheads descending over the United States.

As indicated in Table 1, the first (and easiest) free electron lasers to operate, were not tunable, but only amplified a signal guided into them. The development of tunable free electron laser oscillators, devices whose inherent oscillations generate laser light, has only occurred since President Reagan's March 23, 1983, speech announcing the Strategic Defense Initiative.

Free electron lasers based on radio frequency linear ac-

TABLE 1

Milestones in the development of the free electron laser

	Free electron laser characteristics										Accelerator characteristics	
	(1) Date	(2) Wave-length achieved (microns)	(3) Undulator type	(4) Efficiency of beam energy extraction (%)	(5) Oscillator?	(6) Undulator length (meters)	(7) Pulse length (p sec)	(8) Laser input power (kW)	(9) Peak laser intracavity power[1] (MW)	(10) Accel type	(11) Beam peak current (amp)	(12) Electron kinetic energy (Mev)
Motz	1959	1000s	Linear	NA	No							
Phillips	1960	1000s	Linear	13	No							
Stanford	1975	10.6	Helical	0.2	No	5.2	3	0.015	NA	SL	0.07	24
SLA	1977	3.147	Helical	0.25	Yes	5.2	4	0	0.5	SL	2.6	43.5
	1984	1.57&0.5	T-linear	1.2	Yes	5.4	4.3	0	460	SL	2.6	66
Lure	1981	0.488	Linear	NA	No	NA	NA		NA	SR	NA	240
	1983	0.650	Klystron	low	Yes	1.3	500-1000	0	NA	SR	0.05	160
LASL	1983	10.6	T-linear	3.7	No	1.0	5000	MWs	900	L	NA	19-22
	1984	9-35	Linear	1.0	Yes	1.0	30	0	800	L	27-40	10-21
LLNL	1984	8671	Linear	5	No	3	15,000	30	80	IND	500[2]	4.5
	1986	8671	Linear	6	No	1.3	15,000	50	180	IND	850[3]	4.5
	1986	8671	T-linear	34	No	2.4	15,000	50	1,000	IND	850[3]	4.5

Notes:
1. This measure factors out any optics technology and accelerator duty cycle limitations.
2. Generated beam of 6,000 amps reduce-filtered to 500, or 8% of original current.
3. Generated beam of 4,000 amps reduce-filtered to 840, or 21% of original current.

Legend for Symbols. Undulator types: T-linear = Tapered linear; Klystron = optical klystron. NA = Data not available. p sec, (picosecond) = 1 trillionth of a second. kW = kilowatts. 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 = millon electron volts.

celerators have operated from 1.6 microns to 40 microns in wavelengths in the infrared portion of the electromagnetic spectrum. The free electron laser at the Los Alamos, New Mexico, scientific laboratory has been tuned continuously from 9 to 35 microns by varying the electron beam energy from 20 to 10 million volts.

Lawrence Livermore National Laboratory has amplified millimeter radar wave radiation of 50 kilowatts to as high as 1 gigawatt in power, with the electron beam from its linear induction Experimental Test Accelerator. However, the Livermore device is not an oscillator, and thus is only as tunable as the source it amplifies.

The present challenge facing the free electron laser programs around the United States and Europe, is the development of tunable machines that can produce coherent radiation at shorter and shorter wavelengths in the infrared, visible, ultraviolet, and x-ray portions of the electromagnetic spectrum, and produce this radiation at sufficient power to destroy ballistic missiles in the boost phase of their trajectories, or, in the case of x-ray producing free electron lasers, disarm nuclear warheads as part of a terminal defense system.

As noted, the same free electron laser technology promises tremendous applications in basic industry, especially the chemicals industry. Free electron lasers, driven by the radio frequency linear accelerators, have demonstrated the capability of producing coherent radiation in pulses of a few to a few tens of picoseconds (one picosecond is one trillionth of a second). Radiation of such pulse lengths exhibits "self-induced transparency," that is, its electrodynamic properties permit it to propagate without loss through the entirety of a chemical solution except at those specific chemical bonds with which it resonates in wavelength, and performs work.

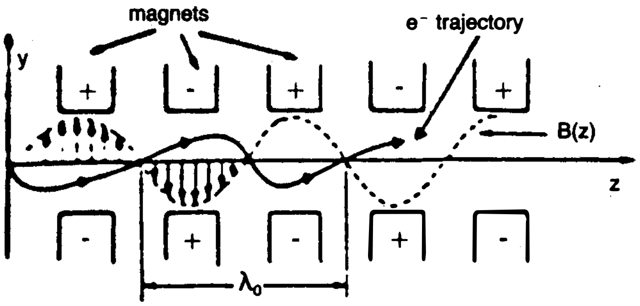
The basic principles of free electron lasing

The free electron laser is based on the phenomenon that electrons traveling close to the speed of light emit electromagnetic radiation when they are accelerated or decelerated by the action of electric or magnetic fields. The specific wavelength of the radiation emitted, is determined by the speed of the electron beam and by the radius of curvature in which the electron beam is forced to turn.

The concept of the free electron laser was first presented in 1950 by Prof. Hans Motz of the Microwave Laboratory at Stanford University. **Figure 1,** from a recent report by the group working on the free electron laser at the Laboratory for the Utilization of Electromagnetic Radiation (LURE) in Orsay, France, is a diagram of a free electron laser undulator or "wiggler," composed of magnets of alternating polarity. An electron accelerator directs a beam of electrons down the center of the undulator, which alternately turns the electrons

FIGURE 1

Sketch of a linearly polarized undulator and electron trajectory



Dotted curve indicates shape of magnetic field, B(z); solid curve is electron trajectory.

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

in one direction or the other, and thus undulates or oscillates their trajectory. Along a linear wiggler, as shown in Figure 1, magnetic field strength varies as a sinusoidal wave. The electron trajectory appears as a sinusoid in the plane of the figure, but is actually a helix. The electron can be considered as an oscillator. As the electrons turn, they emit electromagnetic radiation.

Motz presented nearly the entire theory of the free electron laser in his 1950 paper "Applications of the Radiation From Fast Electron Beams," in the *Journal of Applied Physics*. He declared: "The entire spectrum of electromagnetic radiation starting with microwaves and extending to x-rays may be easily obtained from electrons with speeds ranging from a megavolt, say, to 1,000 megavolts." He described the arrangement of the undulator as "a succession of electric or magnetic fields of alternating polarity, regularly spaced," as in Figure 1.

Motz showed that:

1) By varying the energy, that is, the speed of the electrons, the spacing of the magnets, or the strength of the magnetic field, the radiation of the undulator could be tuned to a desired wavelength.

2) The spectral distribution of the radiation is a series of harmonics of the radiation's fundamental frequency, and that the intensity of these harmonics could be high if magnetic field strength in the undulator was large enough.

3) The electrons emit radiation in a narrow cone, whose narrowness and brightness increases with the electron beam energy.

4) In the undulator, the stream of electrons forms into bunches, spaced by the optical wavelength. An free electron laser undulator, driven by a radio frequency linear accelerator, upshifts microwave power oscillating at a radio frequency, used to accelerate the electrons, into higher-frequency coherent radiation, by transforming the beam into a discontinuous train of dense bunches of electrons spaced at the desired (shorter) wavelength (explained below).

5) Either magnetic or electric fields can be used to undulate the beam.

6) The undulator can be indefinitely long.

7) Motz derives his radiation-emission analysis from the relativistic Doppler effect, as is still done.

Confirming Motz's theory of free electron laser harmonics, the LURE group reported in 1985 in the IEEE *Journal of Quantum Electronics*, that with a magnet spacing of 8 centimeters, a magnetic flux of 3,000 gauss, and an electron beam of about 200 megavolts (MeV) in energy, they were able to produce "an intense emission" of coherent laser radiation in the first 20 harmonics of 0.65-micron wavelength radiation from the LURE free electron laser. They thus produced the first coherent free electron laser emissions in the ultraviolet and x-ray portions of the electromagnetic spectrum. As they report, "a measurement of the spectral brilliance has been made at Orsay around 300 angstroms [x-rays]. This source is about 300 times brighter than the classical synchrotron radiation obtained in a bending magnet of the same [storage] ring." (One angstrom equals one ten-billionth of a meter.)

Although an entire spectrum of harmonics is always emitted from a free electron laser, one can selectively maximize intensity at the fundamental, or particular, harmonics, by varying magnetic field strength. In 1984, a joint program of Stanford University and TRW, Inc., became the second project (after LURE) to produce coherent visible light from a free electron laser at 0.5 microns by apparently producing laser oscillation on the third harmonic of 1.6 micron infrared radiation.

Motz's other ideas have also been confirmed by experiment. As early as 1952, Motz himself produced visible light from an undulator pumped by the Stanford linear accelerator electron beam, and with a low-energy, electron gun, produced millimeter-wave radiation from the same device. In 1959, he and a collaborator announced the coherent amplification of microwaves in an undulator. Further advances were made by R. M. Phillips the following year.

Although work on development of a free electron laser was temporarily suspended following the discovery of lasers in 1960, since the early to mid-1970s, a vigorous program in the free electron laser has emerged in the United States out of the work at Stanford University led by Professors Alan Schwettman and John Madey.

The free electron laser and electron tubes

Motz's work on the free electron laser evolved out of the development of electron tubes that generated or amplified microwaves for radar in the World War II mobilization. Like electron tubes, the free electron laser is intrinsically a high-power device. An example of an electron tube is the traveling wave tube, a microwave-amplifier invented in 1943. In the traveling wave tube, an electron beam, confined by external magnetic fields, amplifies a microwave signal, as it propagates with that signal. In the interaction of the electromagnetic wave with the electron beam, energy is transferred from the beam to the microwave, producing amplification.

Engineers and physicists presently understand the amplification of radiation by electrons as follows:

Electromagnetic radiation, such as microwaves, is composed of oscillating electric and magnetic fields. An electron subjected to a positive field is accelerated and extracts energy from the microwave. An electron subjected to a negative field is decelerated and gives up energy to the microwaves and thereby amplifies them. This action produces a velocity modulation in the beam with the result that the stream of electrons is concentrated into bunches, spaced by the wavelength of the output electromagnetic waves themselves. This bunching is critical to the coherence of the output radiation.

In the traveling wave tube, a helical waveguide that spirals around the path of the electron tube, guides the microwave signal to be amplified (see **Figure 2**). Since the microwave is slowed down by the helical waveguide, the electron beam is initially moving faster. As a result, more electrons are decelerated than are accelerated, and more energy is transferred to the microwave than it loses to the beam. Since this interaction is cumulative, the microwave grows in power exponentially, as it travels down the tube. The wavelength of amplification may be tuned, as in the free electron laser, by varying the initial velocity of the electron beam.

The basic operative principle is resonance between the microwave signal input to the traveling wave tube, and the electron beam itself. In order for the electron beam to give up energy to the microwaves or vice versa, there must be a relationship of resonance between the electron beam and the wavelength of the microwave.

The same principle of operation is at work in the free electron laser. In the free electron laser, the resonance condition is established between the energy (i.e., the speed) of the electron beam, the spacing of the magnets in the undulator-wiggler (which determines the radius of curvature of the beam there), and the strength of the magnetic field.

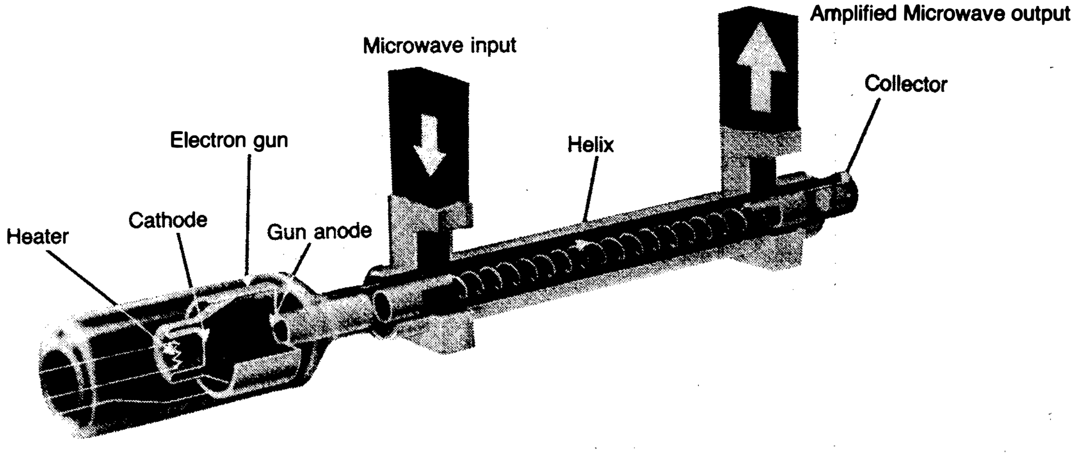
If the electrons were not traveling at a speed close to the speed of light, the result of their undulation would be the emission of radiation at wavelengths close to that of the spacing of the undulator magnets, that is, in the range of millimeter or centimeter radiation. However, a relativistic electron traveling close to the speed of light, upshifts the emitted radiation to higher and higher frequencies (shorter and shorter wavelengths) as the energy of the electron beam is increased. As a result, a constant-period magnet spacing of 2 centimeters and a 100 MeV electron beam, may produce visible light of a wavelength of one-half of one-millionth of a meter (0.5 micron).

This upshift in frequency 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, regardless of the speed of the source. 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 called the "Doppler effect." (See **Figure 3a and b** for the case of water waves.)

In the free electron laser, a relativistic electron-emitting radiation, following close on the heels of its emitted output, upshifts the radiation frequency by a factor of the ratio of the energy to which the electron had been accelerated, to the energy of the electron at rest (0.511 MeV), a factor of about 200 in the above example. The greater the energy of the

FIGURE 2

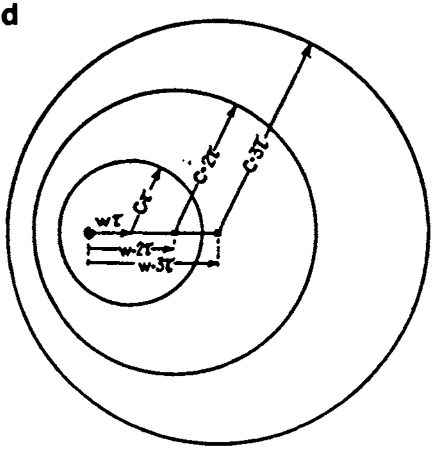
Construction of a typical traveling wave tube, showing the electron gun, the helix, and the electron collector



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

FIGURE 3a.

The propagation of a disturbance from a point source whose velocity is less than that of sound

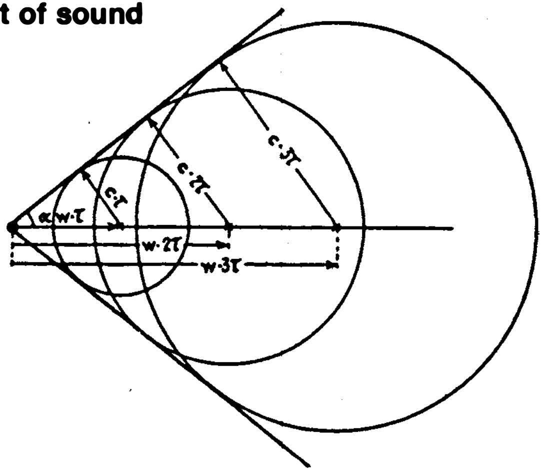


This illustrates the "Doppler" upshift in the frequency of the water waves provided by a moving source

Source: L. Prandl and O. Tietjens, Fundamentals of Hydro- and Aeromechanics, Dover, New York, 1957.

FIGURE 3b.

The propagation of a disturbance from a point source whose velocity is greater than that of sound



This shows graphically the spherical-conical action underlying the "Doppler shift."

Source: same as Fig. 3a.

electron, the greater the compression, and frequency, of radiation output.

This contraction of the wavelength of the emitted radiation by the action of the electron beam, provides a unique geometrical definition of the resonance condition that must be fulfilled by the relationships among the electron beam, the undulator magnet spacing, and the emitted laser beam in a free electron laser. As Phillips stated in 1960:

> A synchronism between the [electrons and the radiation] must be established. . . . A synchronous condition is obtained when the [electron] beam velocity is adjusted such that an electron travels one period along its trajectory in the time that the [electromagnetic] wave travels one period plus one wavelength.

This is the condition that must be met to produce the Doppler shift required to generate a particular wavelength of light in the free electron laser.

From the standpoint of the above discussion, the helical model of electron and light beam propagation is inadequate. The net work carried out by the electron accelerator on the beam, makes the energy transfer possible. As illustrated by Figures 3a and 3b, the form of action of the compression is spherical-conical, not helical.

As the electron beam passes through the undulator, it is transformed from a stream into a discontinuous train of bunches of electrons spaced at the period of the wavelength of the emitted radiation. Once an oscillating laser beam has been established, the laser light itself contributes to the acceleration or deceleration of the electrons, intensifying the bunching of the electron beam as it passes through the undulator. Charles Brau of Los Alamos Scientific Laboratory recently explained in the IEEE *Journal of Quantum Electronics*:

> At resonance . . . the interaction becomes strong and the electrons are accelerated or decelerated slightly by the optical field, depending on whether the electrons are oscillating, in phase or out of phase, with the local electric field. As a result, the faster electrons catch up to the slower ones and form bunches spaced at the optical wavelength. The electrons then radiate coherently with respect to each other and with respect to the incident optical field.

Figure 4 dramatically illustrates this bunching process generic to all electron-based oscillators and amplifiers, with a diagram of the electron trajectories in a klystron. As the electrons travel the length of the device (vertical axis), the input microwave signal modulates their velocities; bunches form as the faster electrons catch up with the decelerated ones, and their trajectories cross, forming discontinuities in electron density spaced at the microwave wavelength. Without this bunching on the optical wavelength, the emitted radiation would not be spatially coherent; the radiation might be of the same frequency, but not in phase. *The ordered generation of discontinuities is the fundamental principle of free electron lasing.*

The close relationship between electron tube microwave technology and the free electron laser is illustrated by the fact that existing radio frequency linear accelerators in use in free electron laser laboratories at Los Alamos and elsewhere, are presently being modified to extract microwave power out of the electron beam after it has passed through the undulator, so that its remaining energy may be used in the accelerator, and increase the overall efficiency of the system. Stanford and TRW have just announced successful recovery of over 90% of the beam energy in one technique.

Keeping the free electron laser in resonance

The very generation of coherent light, however, de-tunes the electrons and undulator, whether it be linear or helical. As the electrons give up their energy to produce or amplify the laser beam, they decelerate, their electron velocity (and energy) decreases and, in accordance with the relationship we have discussed, they fall out of resonance with the undulator. For this reason in the first free electron lasers developed in the 1970s and early 1980s, coherent amplification and emission saturated after the electron beam passed about 1 to 1.5 meters into an undulator, the distance by which electrons giving up their energy to the laser field had been decelerated below resonance. If longer undulators were used in such machines, the coherence of the beam produced, would be degraded by the emission of lower-frequency radiation from the decelerated electrons radiating at a different energy level with the undulating magnetic field, and at a longer wavelength. It appeared that there was a maximum amount of energy that could be extracted from relativistic electrons in amplifying or generating a laser pulse.

In 1960, R. M. Phillips had already foreseen this problem, and in the *IRE Transactions on Electron Devices,* proposed a solution in the form of varying the spacing or strength of the undulator or wiggler magnets. If the power of the magnet is gradually decreased, or "tapered," along the path that the electrons must travel down the undulator, then the amplitude of their oscillations is decreased, resulting in a shortening of the distance they must travel to get through the undulator. In this way, their average speed down the undulator may be kept constant, so that they are kept in resonance, despite their loss in instantaneous speed; thus they can give up a greater proportion of their energy to the laser pulse. As Phillips wrote, "The use of a tapered phase velocity for increased efficiency is attractive."

The same principle is in use in particle accelerators developed over the past 40 years. Particle beams accelerated in the cyclotron of the 1930s, fell out of resonance with the cyclotron's microwave voltage accelerator system as soon as the beam approached relativistic velocities. In the synchrocyclotron and the synchrotron, variation was introduced in the magnetic fields and in the rate of acceleration by the microwave cavities in order to keep the machine in resonance with the accelerating particle beam.

In 1981, Los Alamos operated the first free electron laser amplifier with a tapered undulator and achieved an approximate tenfold improvement in the extraction of energy from the electron beam. In 1983, a joint TRW-Stanford group headed by Schwettman, operated the first free electron laser oscillator with a tapered undulator. Earlier this year, Livermore used a 45% taper to achieve 34% efficiency of energy extraction in amplifying a 50 kW microwave pulse to one gigawatt. The TRW-Stanford group explains tapering in a 1984 report "Tapered Wiggler FEL Oscillator":

> In an untapered wiggler, electrons are injected with a velocity slightly greater than the resonance velocity so that the electrons spend more of their time . . . decelerating, than accelerating. . . . In a tapered wiggler we adjust the wiggler so that the resonant velocity itself of the wiggler, decreases so that the electrons remain trapped in resonance even as they decelerate.

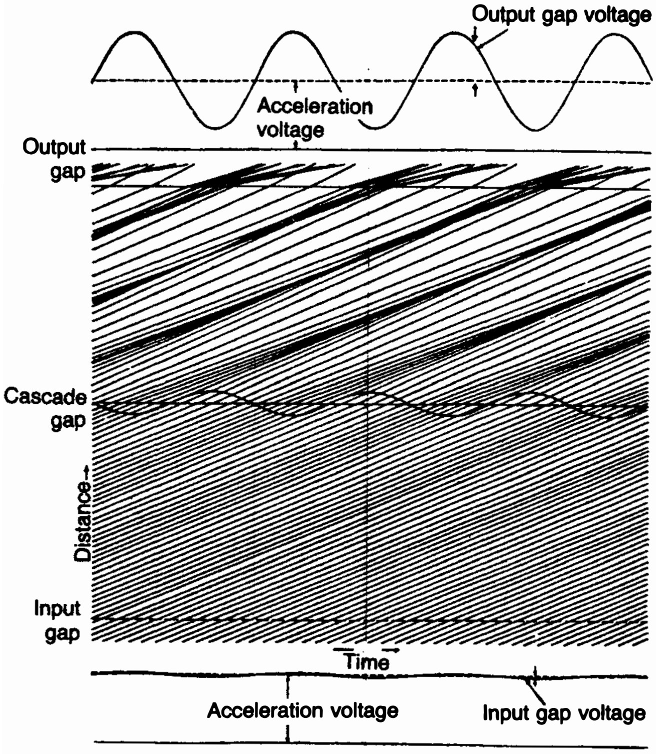
The TRW-Stanford group relies for much of their approach on the work of Phillips.

Electron beam 'shape'

In addition to the need to use tapered wigglers to keep the electron beam in resonance with the coherent energy being produced, there are other conditions on the length of the undulator portion of a free electron laser, that portion of the

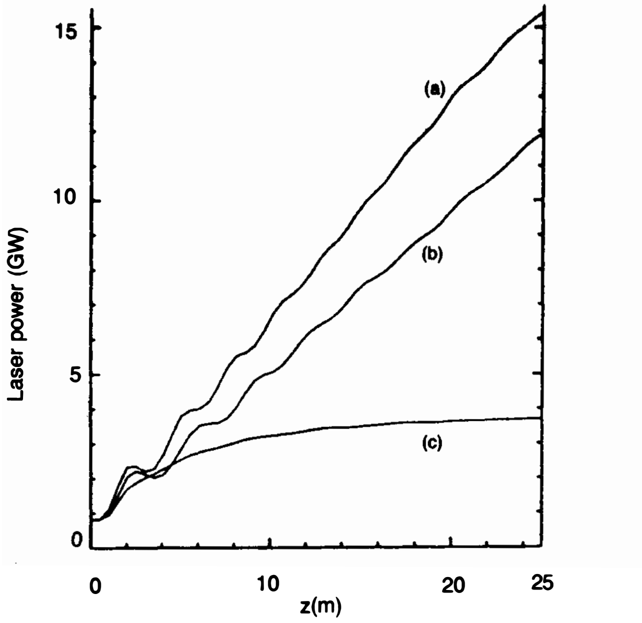
FIGURE 4.

Diagram of electron trajectories in klystron microwave amplifier



Source: D.R. Hamilton et al., Klystrons and Microwave Triodes, Dover Publications, New York, 1966.

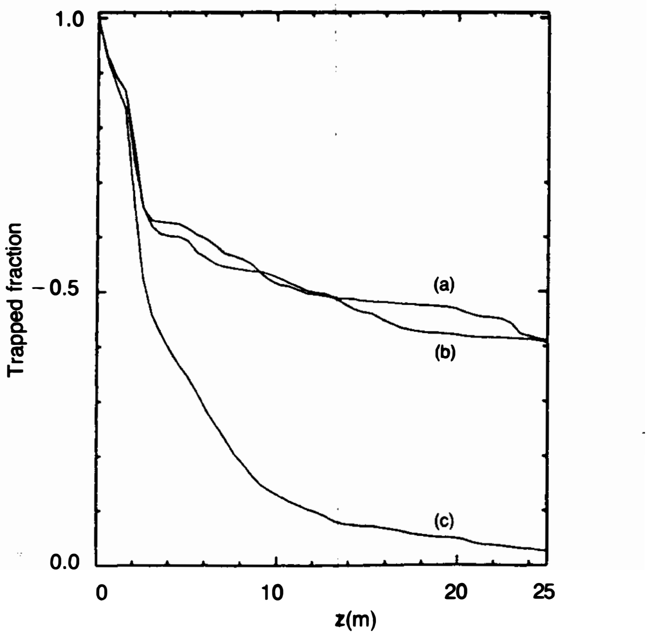
FIGURE 5



Laser power as a function of distance z in the wigglers for the three cases discussed in the text: (a) a helical wiggler, (b) a linear wiggler with parabolically curved pole faces, and (c) a linear wiggler with quadrupole focusing strong enough to keep the electron beam circular. The stimulation parameters are listed in Table 1.

Source: E.T. Scharlemann, "Wiggle Plane Focusing in Linear Wigglers," Journal of Applied Physics, Vol. 58, 1985, page 2154.

FIGURE 6



Fraction of electrons trapped in the bunches spaced at the wavelength of radiation, as a function of distance z along the wiggler, for the three cases of Fig. 5.

Source: E.T. Scharlemann, "Wiggle Plane Focusing in Linear Wigglers," Journal of Applied Physics, Vol. 58, 1985, page 2154.

machine in which the coherent radiation is generated. Here we begin to address some recent developments at the national labs.

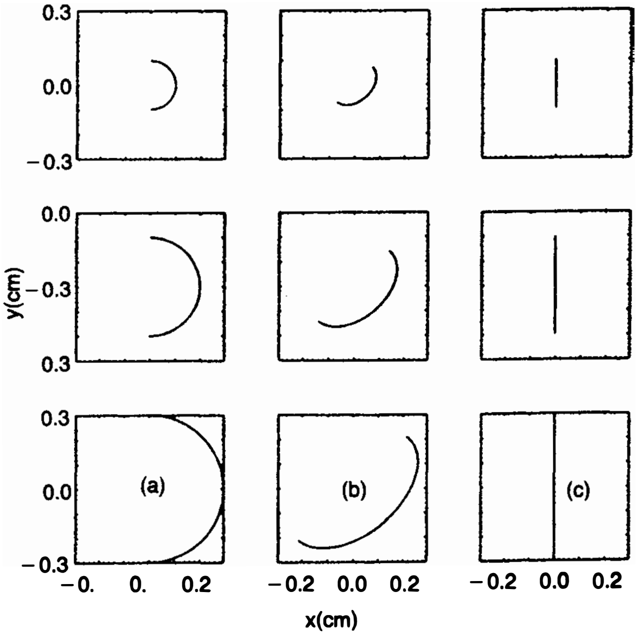
It is necessary to focus the electron beam as it travels through a long linear undulator. Focusing carried out with quadrupole magnets, and other forms of external focusing, however, produces an oscillation in the longitudinal velocity of the electrons. These so-called synchrotron oscillations in the longitudinal velocity of the beam, produce slight frequency variations (or combination tones) in the laser output, that broaden the spectrum of the laser beam and reduce its coherence.

In 1984, Los Alamos researchers found that the spectrum of the laser light out of their free electron laser, broadened tenfold from 0.3% at low power, to 3% at high power, due to "synchrotron instabilities," reported Brau. The LURE group was able to resolve the sidebands produced in their 1983 free electron laser oscillator experiments, into narrow lines or spikes of coherent radiation on either side of the main 6,476 angstrom line. These two lines (at 6,405Å and 6,538Å) contained 11% of the output radiation.

E. T. Scharlemann, of Lawrence Livermore National Laboratory, discussed the nature of this problem in a recent paper in the *Journal of Applied Physics*:

> The gain [that is, the laser beam amplification per pass through the undulator] of a free electron laser depends critically on maintaining a precise phase relationship between the wiggle motion of the electrons and the electric field of the light. The electrons in a focused electron beam undergo transverse oscillation (betatron oscillations). . . . The oscillating transverse velocity can produce an oscillating longitudinal velocity [synchrotron oscillations], and thereby affect the gain [at the desired wavelength]. In a long wiggler, some focusing is required; all electron beams . . . will eventually disperse in the absence of focusing.
>
> In a helical wiggler, focusing in both transverse directions is provided by the wiggler itself. . . . Helical wigglers [however,] are unfortunately more difficult to build than linear wigglers. A helical wiggler with an adjustable taper is extremely difficult to build. . . .
>
> In a linear wiggler of conventional design, focusing is provided by the wiggler itself in only one of the transverse directions, the direction of the wiggler magnetic field. External focusing, usually provided by adding a quadrupole component to the field, is required in the other transverse direction.

FIGURE 7



Exact transverse x-y electron orbits for nine electrons in linear, untapered wiggler with curved pole faces. The electron orbits were followed for half a betatron period in the z direction along the wiggler; plotted here are the projections of the trajectories onto the x-y plane. The orbit types are circular (left column), elliptical (center column), and linear in y (right column); the maximum betatron radii are 0.1 cm (top row), 0.2 cm (center row), and 0.3 cm (bottom row).

Source: E.T. Scharlemann. See Fig. 5.

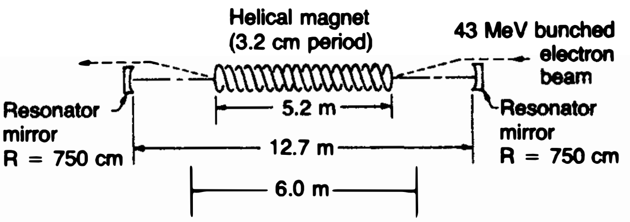
However, Scharlemann writes, "Quadrupole focusing and most other forms of external focusing, introduce an additional problem": namely, longitudinal "synchrotron" oscillations of the beam.

> The end result is that the difference in performance between a conventional linear wiggler with quadrupole focusing and the equivalent helical wiggler with the same electron beam parameters is much greater than would be expected.

To solve the problem of longitudinal beam oscillations produced by quadrupole focusing in linear wigglers, Scharlemann proposes to return to the magnetic focusing design used by Phillips in 1960, where he used magnets of parabolic curvature to focus the electron beam in the transverse direction not focused by the wiggler itself. Scharlemann conducted simulation studies using the computer code for the free electron laser developed at Lawrence Livermore, to study whether parabolic focusing would solve the problem of the fall-off in gain, with an increase in the length of the undulator, as the result of the need to focus the electron beam.

FIGURE 8

Diagram of Stanford helical undulator.



The first free electron laser oscillator had a helical magnet organizations.

Source: L.R. Elias et al., "The Free Electron Transverse B Laser: 10.6 Micron Gain Measurements," presented at the International Conference on Quantum Electronics, Amsterdam, June 14, 1976.

Figure 5 from his simulation studies shows how laser power as a function of distance falls off rapidly in a linear wiggler with quadrupole focusing. The figure shows the tremendous advantages of helical wigglers, and linear wigglers with parabolically curved pole faces. **Figure 6** shows how the number of electrons trapped into bunches on the laser wavelength, falls rapidly with the length of the undulator, in the usual case of a linear wiggler with quadrupole focusing, but does not so fall in the cases of helical or parabolic focusing. **Figure 7** from his simulation shows that the electron orbits in a linear wiggler with quadrupole focusing are open in one transverse direction, whereas in the case of the helical wiggler or the linear wiggler with parabolic focusing, the orbits are closed, being circular (cylindrical) in the case of a helical wiggler and elliptical (ellipsoidal cylindrical) in the case of a linear wiggler with parabolic focusing.

These results strongly argue that:

1) A solution must be found for the problem in construction and operation of helical wigglers. The first free electron laser amplifier and the first free electron laser oscillator were not linear undulators but had a helical undulator magnet structure developed at Stanford for use with their Superconducting Linear Accelerator (SLA) (see **Figure 8**).

2) With either helical wigglers, or linear wigglers with parabolic focusing, the undulator length can be 25 meters or longer.

John Madey at Stanford University is completing construction of an undulator 27 meters in length, and according to *Aviation Week and Space Technology* magazine, Livermore is planning to build a 25-meter-long undulator for the Advanced Test Accelerator. Both of these projects rely upon an additional property of the coherent interaction of light and electron beams, for the effective use of long wigglers, a matter that has also been investigated by Scharlemann and his associates at Livermore.

To be continued.