U.S. building prototype laser for missile defense

Charles B. Stevens reviews the status of the Free Electron Laser, one of the top candidates for interception of nuclear missiles in the SDI program.

The Strategic Defense Initiative Organization and the U.S. Army Strategic Defense Command announced this summer that they are constructing a $600 million facility at the White Sands Missile Range in New Mexico, to test prototype ground-based lasers for defense against ballistic missiles. It has long been recognized that high-power lasers offer one possible means to efficiently and effectively intercept nuclear-tipped missiles at the speed of light, before they even leave the airspace of the attacker, and much of President Reagan's Strategic Defense Initiative program has been concerned with developing appropriate candidates.

According to government reports, the White Sands facility will primarily focus on one particular type of laser, the free electron laser. The free electron laser is among the newest types of lasers, and was only first demonstrated in principle within the last decade. Other potential SDI laser candidates are chemical, excimer, and x-ray lasers.

Published schedules indicate that the SDI office plans to complete construction and testing of two prototype free electron lasers at White Sands by the early 1990s. If this technology demonstration program, costing more than $3 billion, is successful, then ground-based free electron lasers could be deployed to provide one robust system for missile defense. One plan calls for deploying ground-based free electron lasers at six geographically dispersed locations with a half-dozen lasers at each site. Each free electron laser would have a laser light energy output approaching that of a 1,000-megawatt electric power plant.

Experts have already noted that a single such ground-based free electron laser, making use of large segmented relay mirrors in geosynchronous orbit (50,000 kilometers above the Earth) and 1,000-kilometer-high orbiting fighting mirrors, has the firepower to shoot down the world's current inventory of ICBMs within a few minutes, while they are being boosted into space. If anything escapes this boost phase, the same laser could destroy thousands of warheads during the 20 minutes they traverse space. Alternatively, the free electron laser output could be utilized to find and laser-designate warheads for other interception systems.

Thirty-six such lasers, each currently estimated to cost about $1 billion, would go a long way toward realizing President Reagan's goal of making offensive nuclear missiles impotent and obsolete. But beyond considerations of national defense, the free electron laser portends a revolution in science, industrial technology, and space transport. Important scientific advances were achieved prior to 1983, as will be detailed in a later article, but the free electron laser has only emerged as a practical technology since President Reagan first announced the SDI, and is one of the program's first major accomplishments.

What is the free electron laser?

The free electron laser is not actually a laser, but a relativistic electron beam (relativistic refers to near the speed of light). It could also be described as a relativistic radar, since the electromagnetic waves that constitute the radar's beam are also generated by electron beams. But in the free electron laser, the electrons are traveling near the speed of light, and it is therefore said to consist of relativistic electrons.

In both radar and the free electron laser, the coherent electromagnetic radiation output is simply the product of organized electron motion, as in the generation of radio waves. When electrons, in the form of an alternating electric current, are made to traverse back and forth on an antenna, they generate an electromagnetic wave. With a properly tuned current, the antenna will transmit electromagnetic radiation coherently at a wavelength that is a multiple of the length of the antenna. TV broadcasting operates in the wavelength range of meters, as can be easily determined by noting the dimensions of TV antennas.

Shorter wavelengths, like those of radar, are on the order of centimeters, and the required electric current power densities are too much for ordinary materials to withstand; that is, a metal antenna melts. The solution for this problem was achieved by abandoning material antennas for electromagnetic ones. The electric current is passed through an evacuated tube, and electric and magnetic fields (instead of a metal antenna) are utilized to make the current wiggle back and forth.

These large vacuum tubes or cavities were also developed to trap the continuous electromagnetic wave output and concentrate it into a short and powerful pulse. Such "resonating" cavities could also be used to transform radiation from one wavelength into another. Many electron-beam accelerators, in fact, make use of these cavities. Here, the cavity is tuned such that the broadcasting process is reversed; the electrons absorb the electromagnetic radiation and are thus accelerated to higher velocities.

In addition to overcoming the imposed power density limit, replacing a material antenna with a vacuum and electric/magnetic field configurations means that the electron oscillation length can be scaled to produce extremely short wavelengths. (In conventional lasers, this shortening of the oscillation wavelength is increased by making use of the collective output of electrons oscillating on a subatomic or molecular scale.)

The free electron laser represents a quantum leap in this electronic-tube-type technology for generating coherent radiation. This is primarily because radiation produced by electrons at the relativistic limit—that is traveling very close to the speed of light—benefits from a double Doppler shift to shorter wavelengths.

First, the Doppler effect becomes substantial for electromagnetic waves as the speed of light is approached. A more familiar case is the Doppler shift you hear as a train passes, because for sound waves the Doppler shift is substantial at the speed of trains. That is, the whistle of a train moving toward you has a higher pitch—shorter wavelength—than if it were stationary. When the train is receding, the whistle pitch is lower. This is the classic Doppler shift. The radiation generated by relativistic electrons is also Doppler-shifted to shorter wavelengths, as one would see if one were a passenger traveling along with the electron train at near the speed of light.

The second Doppler shift results from the relativistic Lorentz contraction. As an electron, or any object for that matter, approaches the limiting velocity of light, its mass increases, and would apparently become infinite at the speed of light. Similarly, the length of stationary objects, in a direction parallel to the speeding electron, becomes asymptotically smaller and smaller, tending toward zero, as would be seen from the vantage of the speeding electron, as it approaches the speed of light.

As a result of this double Doppler shift, if the relativistic electron velocity and the oscillation (wiggle) in its motion are properly tuned, the electron can be made to generate electromagnetic waves at wavelengths far shorter than would be expected from a simple classical model of an antenna. For example, while a centimeter-long antenna, or oscillation, would primarily broadcast centimeter-long waves, a properly tuned relativistic electron would generate micron-long waves—10,000 times shorter.

In this manner the free electron laser can extend the broadcasting capabilities of "electron tubes" from the classical region of radio and microwaves through the infrared, visible, etc. And in principle, the free electron laser could be extended down into the X-ray wavelength region and beyond.

At the same time, unlike ordinary lasers based on specific atomic transitions, the same free electron laser can in principle be tuned to different coherent wavelengths. This can be achieved by simply retuning the electron velocity and the wavelength of the electron oscillation. In practice, only segments of the electromagnetic spectrum can be covered by a single free electron laser. But this tunability is orders of magnitude greater than that achieved with more conventional atomic and molecular transition lasers.

Also, because the free electron laser dispenses with the need for atoms in the generating region, the power densities at the point where the coherent radiation is produced are far greater. For the same type of reasons, the free electron laser has a far greater potential for higher operating efficiencies, too. Conventional high-power glass lasers convert only a fraction of a percent of the energy put into them into laser light. Recent progress in high-power gas lasers, like the excimer type, has demonstrated that efficiencies in the range of 5%-7% can be attained. The free electron laser experiments at Lawrence Livermore National Laboratory, however, have already demonstrated efficiencies in the 40% range.

The free electron laser and conventional lasers

The free electron laser is a relative newcomer to the field of high-energy lasers. A series of major breakthroughs was achieved in the last few years, primarily by researchers at the California-based Lawrence Livermore National Laboratory working on the free electron laser amplifier-type system, and the free electron laser quickly became the frontrunner for ground-based laser defense systems. Other candidates included excimer-laser and chemical gas-laser-based systems. Although these latter systems may demonstrate anti-missile defense capabilities sooner than the free electron laser—because of both congressional funding cuts and the perceived, overall greater technological potential of the free electron laser—their R&D programs have been put in neutral. As SDI office Director Lt.-Gen. James Abrahamson has continually emphasized, Congress's single-track approach is neither the best, nor most efficient route for realizing laser-based missile defense. As will be shown later in this report, many of the system elements—the mirrors, optics, and atmospheric compensation—which are combined with the free electron laser to make a robust defense, are also compatible and effective with more conventional lasers.

More than one year ago, Dr. George Keyworth, then presidential science adviser, reported that free electron laser scientists at Livermore had already catapulted accelerator technology into the next century. They had demonstrated that linear-induction accelerators could be scaled to power levels a thousand times beyond what had been previously projected as technologically feasible before the year 2000. When combined with Livermore's free electron laser amplifier experiments, which showed that such powerful electron-beam energy could efficiently be transformed into laser light, this development led Keyworth to publicly state that a single such ground-based free electron laser would have the firepower to destroy the entire Soviet inventory of ballistic missiles within a few minutes.

This is a breathtaking rate of progress for a system which, in 1983, had at best a very tenuous scientific basis for being scaled to the high powers needed for missile defense: Going from milliwatts to terawatts (10^{-3} to 10^{12} watts), is like transforming a firecracker into a hydrogen bomb.

The two types of free electron lasers that will be developed at the White Sands facility each have two basic elements, an accelerator to generate a high-power electron beam, and a vacuum chamber (the "tube") in which a properly configured magnetic field is imposed. The vacuum chamber is referred to as a wiggler or undulator. It consists of magnets arranged in alternating north and south gradients that cause the beam to wiggle back and forth.

The path of the electron beam describes a large spiral or sinusoidal oscillation whose wavelength is determined by the speed of the electrons and the strength and geometry of the imposed magnetic fields. If these parameters are properly tuned, then the energy of the electron beam can be extracted and transformed into electromagnetic radiation at a wavelength equal to that of the oscillatory wavelength. When a relativistic electron beam is traveling near the speed of light, the radiation is shifted to a much shorter wavelength by the double Doppler effect discussed above.

More precisely:

$$L_e = L_o/2\gamma^2,$$

where L_e is the emitted wavelength, L_o is the oscillatory wavelength in the stationary frame, and γ is $1/\sqrt{1-(v/c)^2}$, where v is the electron velocity and c is the speed of light. γ is close to a value of 1 at non-relativistic velocities, but becomes quite large as the velocity of light is approached.

Two types of free electron lasers

Two different approaches to extracting radiation will be explored at White Sands. In the first, pioneered by Lawrence Livermore, a single, high-current pulse of electrons generated by a linear induction accelerator is passed through a wiggler system at the same time that it is hit by a conventionally produced laser pulse. The input laser pulse extracts a significant fraction of the electron-beam energy in this single pass, thereby greatly amplifying its total energy and power. The Livermore type is generally referred to as the induction-linac-driven free electron laser amplifier (linac is short for linear accelerator).

The second approach, the radio-frequency resonant-cavity free electron laser, has been more broadly pursued by researchers in industry, universities, and national laboratories. It is also being researched at the second major national weapons laboratory, the Los Alamos National Laboratory in New Mexico.

In this second free electron laser approach, a higher-energy, though lower-current, electron beam generated by a radio frequency accelerator is semi-continuously passed through a wiggler. The radio frequency accelerator uses resonant microwave cavities to accelerate electrons. The input electron beam consists of a continuous train of very short electron pulses, each a few millimeters long. As the beam electrons pass through the wiggler, their spiral motion generates a small electromagnetic output.

When appropriate mirrors are placed at either end of the wiggler, a resonating cavity is created that traps the small electromagnetic output as the electron beam passes through the wiggler. The emitted light reflects back and forth between the cavity mirrors. This optically trapped radiation then acts on the transiting electron beam and results in the extraction of more energy at a greater rate. The rate at which energy is extracted from the wiggling electron beam is a direct function of the intensity of the radiation field within the cavity. In the resonant-cavity free electron laser, the radiation field intensity is built up from the initially small electron radiation output. The cavity mirrors are designed to "leak," once the desired intensity and resulting rate of energy extraction is achieved, so that the trapped radiation field intensity as well as the electron laser output is kept constant. In this regard, the resonant-cavity free electron laser is said to operate in the "low-gain" continuous regime, compared to the single-pass free electron laser amplifier, which generally operates in a "high-gain" regime. (Gain refers to the rate at which energy is extracted from the electron beam and converted to radiation.)

In order to attain high gain, the free electron laser amplifier makes use of an intense laser pulse, whose high field intensity generates the high-gain, fast extraction. Since the extracted radiation becomes one with the initial seed laser pulse, the rate of extraction grows as the amplified pulse passes down the wiggler.

In the resonant-cavity free electron laser, the "leaking" radiation constitutes the output of the laser. The resonant-cavity free electron laser is distinguished from the single-pulse free electron laser amplifier in that its cavity radiation field intensity is kept constant, while that of the single-pass amplifier grows exponentially. (Actually, like the input electron beam, the resonant-cavity free electron laser output is semi-continuous and broken up into extremely short bursts lasting on the order of a few 100 billionths of a second.) The resonant-cavity free electron laser output is continuous and is a relatively small fraction of the power of the electron beam passing through it. The free electron laser amplifier, on the other hand, extracts a very large portion of the single-pass electron-beam energy and therefore, the power of its output laser pulse is a significant fraction of the input electron beam.

In broad terms, the Livermore free electron laser amplifier leads to a device which produces thousands of extremely powerful laser pulses per second, while the radio-frequency resonant cavity possibly leads to a more compact, efficient, and versatile, continuous output, but at lower energy density. Because the radio-frequency free electron laser extracts only a small portion of the electron beam's energy during a single pass, it is possible to recycle the beam, thereby increasing the operating efficiency. Furthermore, because the radio-frequency free electron laser operates at lower power densities, it is technologically easier to construct a variable wiggler design for tuning the free electron laser over a wide range of wavelengths.

The induction linac

The induction linac (linear accelerator) is currently among the most efficient methods of generating intense, high-current pulses of relativistic electrons. Livermore's experience with induction linacs dates back to the early 1960s' Astron program, in which induction linac relativistic electron beams were being developed for both fusion energy research and as a possible means of destroying ICBM warheads. In this case, the relativistic electron beams would be directly shot through the atmosphere to destroy warheads as they descended on the United States.

In fact, both the current Livermore accelerator facilities—the 45 gigawatt Experimental Test Accelerator (ETA) and the 500 gigawatt Advanced Test Accelerator (ATA), which have recently demonstrated high-power free electron laser amplifier lasing—are also being utilized to determine the feasibility of intercepting incoming warheads with their relativistic electron beams. Since the penetration of the atmosphere and target by a relativistic electron beam pulse is partially determined by the electron velocity, it is thought that properly "tuning" the relativistic electron beam velocity will result in efficient transmission through the atmosphere and deposition into the warhead's interior.

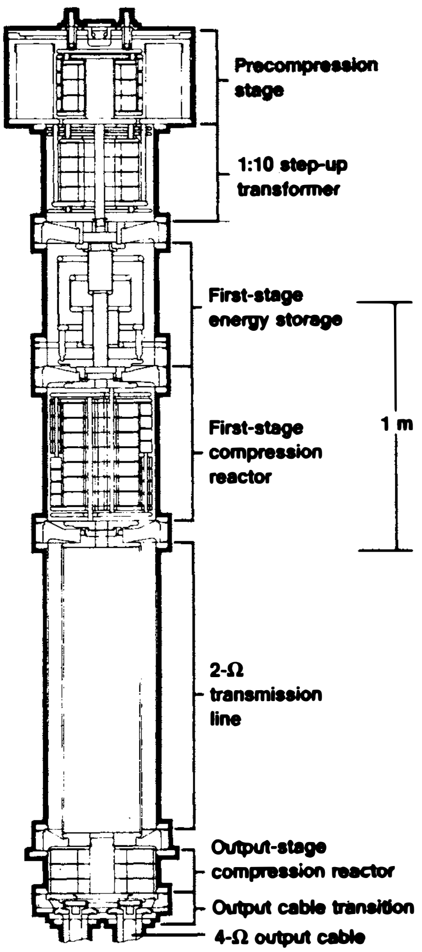
The induction linac utilizes a long series of transformers to accelerate electrons along a straight path. Transformers are among the most highly developed forms of electrical technology and offer the most efficient means of accelerating large currents of electrons to relativistic velocities and energies. There was one major technological barrier, however: The transformer action also slightly defocuses the relativistic electron beam. That is, the transformer not only accelerates the electrons in the desired path, but also slightly in transverse direction. This defocusing is non-linear, and makes it technologically impractical to continue acceleration of the beam when its divergence grows beyond a certain level. Furthermore, achieving efficient free electron laser action depends strongly on the brightness of the electron beam—that is, having a well-focused and well-collimated electron beam.

The initial method for dealing with beam defocusing, was to interpose magnetic lenses that refocused the beams. But this was only a limited remedy. The breakthrough came when Livermore researchers replaced their magnetic guide fields with a low-density plasma. A low-density gas was first placed in the accelerating chamber. Then a short pulse from a small laser was used to ionize the gas and transform it into a low-density plasma. As the electron beam passes through the plasma, the plasma collectively acts to focus the beam and remove transverse motions from the relativistic electron beams. The gas was essentially the vapor from a household cleaner, and the small laser cost less than a month's electric bill for running the magnets on the now-unneeded guide field. Plasma-electrostatic focusing improved the output of existing induction linacs with a concomitant reduction in operating costs.

This was the technological breakthrough that changed everything. Based on this new plasma-electrostatic focusing, induction linacs can now be confidently designed with existing technology to attain about a 1,000-fold increase in average operating power levels, characteristically going from existing megawatt levels to gigawatt levels. It is not often that one sees such startling progress in a field as old and well-developed as transformers.

Over the past two years, scientists working on the less powerful Livermore ETA have demonstrated the essential aspects of high-power free electron laser amplifier operation. Better than 40% efficiencies were attained in transforming relativistic electron beam energy into high-power microwaves. Most significantly, the ETA has demonstrated the operation of steeply tapered wigglers. In the free electron laser amplifier the relativistic electron beam energy is rapidly extracted. This means the electrons are drastically slowed down. And since the double Doppler shift depends strongly on electron velocity, the wavelength at which the relativistic electron beam is radiating within the free electron laser wiggler would rapidly increase unless there was a compensating decrease in the wiggler wavelength. In this sense, a steep conic spiral or wave is needed in place of a simple cylindrical spiral or wave.

FIGURE 1



Cross section of the MAG-I-D nonlinera magnetic-pulse compressor. This three-stage modulator provides a 100-fold compression of electric inputs with an output power level of 10 billion watts. Electrical energy compression—pulsed power—and rapid switching are the key technologies that give the FEL is potential for high levels of firepower as an SDI laser.

Radio-frequency free electron lasers also utilize tapered wigglers, but since they extract only a small fraction of the relativistic electron beam energy in each pass through the wiggler, the change in velocity and emitted wavelength is much smaller. Therefore, the wiggler need be tapered only slightly.

Free electron laser amplifier current status

The outstanding scientific question facing free electron laser amplifier design is that of scaling from microwave outputs to infrared wavelengths measured in microns. The Livermore ATA is currently being configured for experiments which will demonstrate lasing at 10.6 microns—the same wavelength as that of carbon dioxide lasers. These experiments, code-named Paladin, will resolve the major scientific issues for scaling to the visible and near-infrared wavelengths. Utilizing the 50-million-volt, 500-gigawatt-peak-power ATA, the tests will explore both high and low signal gain regimes. The small signal gain experiments, in which only a small level of amplification will be attained, will use a five-meter-long wiggler made with iron-core electromagnets.

The high signal gain tests will be carried out with a tapered wiggler 25 meters long, consisting of elements based on the 5-meter wiggler. These final tests will demonstrate laser amplification at 10.6 microns with a projected extraction efficiency of about 10%.

Other technology elements for free electron laser amplifier operation are being rapidly developed and demonstrated. For example, pulsed power systems and switches are key components for an SDI-practical free electron laser. The ATA normally operates with a couple of electron bursts per second. It is capable of attaining burst rates of 1,000 shots per second, but only for a very brief time. SDI free electron lasers will have to operate at high burst rates for many minutes. Therefore, long-lived and robust systems have to be developed to compress and switch electrical energy for powering free electron laser induction linacs.

Major progress in this area has been reported by the Livermore Accelerator Research Center. New accelerator prototype modules have been tested. These modules form the basic building blocks for SDI free electron lasers. The power for these modules is supplied by a non-linear magnetic pulse compressor (MAG-I-D) shown in cross section in **Figure 1.**

This completely passive device provides a reliable means of compressing input 100-megawatt pulses of electricity into 10,000-megawatt outputs utilized to power the accelerator transformers. The MAG-I-D has the inherent capability of producing these pulses at a repetition rate exceeding 5,000 times per second with an efficiency approaching 90%. One such device has already been operated for 100 million pulses—better than five hours. Continuing developments strongly indicate that near-term pulsed-power technology could easily support a laser-pulse rate of 1 million per second—a megahertz.

The SDIO's projected schedule is to construct a full-scale prototype free electron laser based on the Livermore approach by 1993. This project is officially called the Ground-Based Laser Technology Integration Experiment and is designed to completely test all of the components needed for a full-scale missile defense. As shown in **Figure 2,** the Livermore Paladin experiments will be followed by a further series of tests, code-named ALEX, at Livermore.

The full-scale prototype induction free electron laser, to be located at White Sands, will be about 1.1 miles long. This includes an 800-meter-long accelerator and a 200-meter-long wiggler. Because of its extremely high power at the point of generation, the induction free electron laser's laser-pulse outputs will be permitted to expand through a 2.6-mile-long vacuum chamber. The diffraction expansion of the beam is required so that its power density can be lowered to a point where even cryogenically cooled optical mirrors will withstand the pulse. (Even so, major advances in high-power optics are an assumed part of the White Sands program.) The pulse would then be further expanded via optics, and redirected to a beam director, which directs the beam on a path through the atmosphere to a mirror in space.

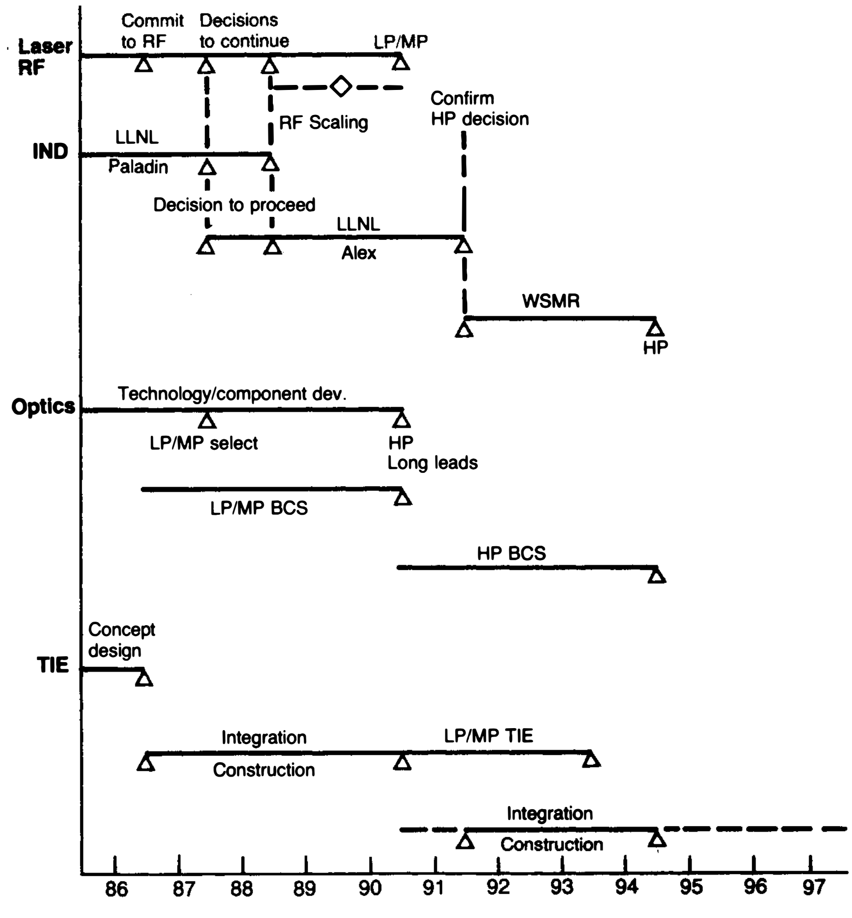
The potential of radio-frequency free electron lasers

Until very recently, the more widely researched radio-frequency-driven free electron laser resonant-cavity approach was considered a very poor second as a candidate for a ground-based anti-missile laser system. This was because the radio-frequency free electron laser produces an essentially continuous output, while the Livermore free electron laser amplifier inherently generates short, extremely high-power density pulses. These high-power density laser pulses are far more lethal per unit of laser energy than a continuous beam, because they produce shock waves that punch holes through warheads and missiles, as opposed to lower power continuous beams, which slowly burn their way through the outer skins.

The radio-frequency free electron laser is being widely pursued, because it is more readily operated at shorter wavelengths and tuned over a range of frequencies, and is potentially far more efficient and compact—characteristics that make it a good candidate for space-based laser defense. They also make it a tremendous candidate as a scientific and industrial tool. Major R&D programs along this line are being carried out by Boeing, TRW, and Stanford University.

The radio-frequency free electron laser was first demonstrated at Stanford University in 1976. By 1982, Los Alamos scientists had successfully built and demonstrated a radio-frequency free electron laser with a tapered wiggler, which greatly increased its efficiency. More recently, Stanford scientists report that they have succeeded in recycling the elec-

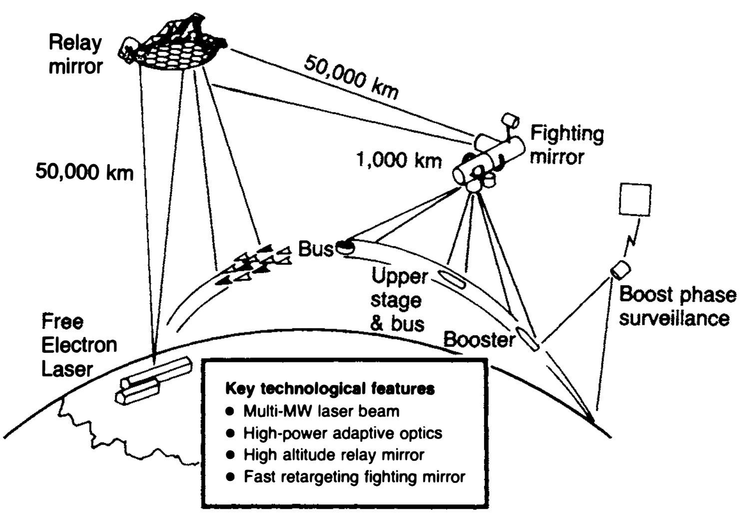
FIGURE 2
White Sands public schedule of experiments



Source: U.S. Army

This schedule has been taken from a recently released U.S. Army Strategic Defense Command slide. This public schedule shows the years for completion of the various components of the White Sands ground-based laser technology integration experiment (TIE) and decision points for alterative paths. The resonsant cavity FEL driven by a radio frequency (RF FEL) accelerator will be built first. It will carry out low-power (LP) and medium-power (MP) experiments on laser beam propagation through the atmosphere. The Livermore induction driven FEL amplifier (IND) will complete tests at Livermore with both the Paladin and Alex series. If successful, a high-power (HP) IND FEL will be constructed at White Sands Missile Range (WSMR) for full scale demonstrations beginning in 1993 or 1994. Besides the lasers themselves, the White Sands program consists of large elements such as optics, command and control, target acquisition, and tracking.

FIGURE 3



The chief components of a ground-based laser missile defense system are shown here. First, a large FEL laser based on the ground generates a laser beam output sufficient to destroy tens to hundreds of targets per second. This beam is sent through the atmosphere to a large relay mirror, which is in geosynchronous orbit 50,000 kilometers above the earth. Adaptive optics are used to compensate for atmospheric distortion of the laser beam. The relay mirror is made up of many smaller mirror modules which are phased arrayed to act like one large mirror. The beam is reflected from the relay mirror over 50,000 kilometers to a much smaller fighting mirror. The fighting mirror is part of a satellite orbiting 1000 kilometers above the earth. Boost phase surveillance and command, control, and communication (C^3) satellites provide overall battle management. Fighting mirrors could engage missiles throughout their trajectories: 1) boost phase; 2) upper stage and bus; 3) bus stage; 4) re-entry vehicles.

tron beam after it has passed through the wiggler. The experiments demonstrated that 99% of all of the energy in the relativistic electron beams exiting the wiggler could be recovered. This means that the operating power for the input accelerator can be reduced 100-fold; alternatively, given a larger accelerator, both the relativistic electron beam and therefore, the free electron laser output can be increased 100 times—a figure not far removed from that of the Livermore induction linac plasma-focusing advance.

Los Alamos is also pursuing the technology of beam recovery, and has made a major advance in the back-end of radio-frequency accelerators. Just as unwanted transverse oscillations of the relativistic electron beam are amplified in the induction linac, this is also the case for radio-frequency accelerators. The free electron laser resonant cavity is even more sensitive to poorly focused and collimated relativistic electron beams than the single-pass amplifier.

The unwanted transverse oscillations derive from the fact that the electrons are not at absolute zero temperature when they are injected into the accelerator; they have a thermal velocity that is not unidirectional. It is these thermal oscillations that get amplified in the accelerator and produce the beam defocusing.

Los Alamos has developed a new, super-cold, high-current electron injector, consisting of a laser and a cold cathode. The cathode is made up of a photoelectric material; and when irradiated by the laser, it emits very cold photoelectrons. This system is projected to be capable of producing current pulses of hundreds of amperes of cold electrons. This will greatly enhance both the potential power and brightness of radio-frequency accelerator technology.

Among the recent advances that have now transformed the radio-frequency resonant-cavity free electron laser from a poor second into a strong contender, has been the R&D carried out by Boeing Aerospace. Boeing has scored major advances in optics technology demonstrating recently that high-power free electron laser resonating cavities are feasible.

As noted above, the prototype single-pass Livermore induction free electron laser will utilize a 2.6-mile expansion tunnel to permit the laser pulse to expand so that mirrors will survive. With the radio-frequency resonant-cavity free electron laser, the laser output must be reflected back and forth through the cavity thousands of times. Although the continuous radio-frequency free electron laser output is more evenly distributed over time (compared to the short, extremely power-dense pulses of the Livermore system), the radio-frequency free electron laser for missile defense would still have extremely high-power densities within the resonating cavity. And the resonating cavity mirrors must not only survive, but must remain highly aligned to maintain the cavity as a resonating cavity.

Besides the problem of the inherently high power densities of free electron lasers, electron beams can also damage fragile optical components. For example, high energy electron beams can generate synchrotron radiation that will destroy fine optical finishes, and stray electrons are very efficient at destroying optical surfaces in general.

Boeing has developed innovative techniques to solve these problems. Instead of using only two mirrors to form the optical cavity, Boeing scientists have developed a system of four mirrors. Two mirrors at either end of the free electron laser cavity are aligned so that they do not reflect the laser pulse 180 degrees back on itself, but deflect it instead at a slight "grazing" angle. The beam then passes via two large transfer mirrors back around to the second grazing-angle cavity mirror, which refocuses the beam and directs it back into the cavity. Thus the laser beam travels a trapezoidal path between the four mirrors.

Even though the 4-degree grazing angle produces a significant expansion of the laser beam's footprint and thereby lowers its power density, the fine finish and alignment of the grazing-incidence mirror could not survive unless it was capable of rapidly dissipating heat. This is attained by making the grazing-incidence mirror out of many slabs of material, instead of a single surface. The mirror looks like a stepped deck of cards, with only a small portion of each slab exposed to the incident laser beam.

These recent advances have completely transformed the relative ground-based-laser fighting potential of the radio-frequency resonant-cavity free electron laser. Strategic defense plans call for actually completing a radio-frequency free electron laser facility at White Sands before 1988 both as a backup to the full-scale induction free electron laser and as a facility for atmospheric-propagation experiments.

The free electron laser defense potential

A missile defense using a ground-based free electron laser would consist of the components shown in **Figure 3**: 1) the laser itself, together with its accelerator, power supplies, and beam director; 2) satellites for boost-phase surveillance and command, control, and communication (C^3); 3) two or more large phased-array mirrors in geosynchronous orbit 50,000 kilometers above the Earth (these are utilized to relay the laser beam around the world); 4) fighting mirrors located in orbits 1,000 kilometers above the Earth.

As shown, the free electron laser would begin firing as soon as the launch of the offensive missiles had been detected. The relayed beam would then be directed to several fighting mirrors at the speed of light. In this manner, a single laser could destroy more than scores of missiles per second anywhere in the world. The system would be even more effective against the slower intermediate and short-range missiles.

If any weapons survive the boost phase, the free electron laser could then be used to destroy warheads during their 20-minute transit through space—the so-called midcourse. First, a diffuse free electron laser beam would be utilized to actively discriminate real warheads from decoys, and determine their precise trajectory. This would greatly enhance a wide variety of effective midcourse interception systems. The free electron laser beam could also be used to destroy warheads. Even though warheads are hundreds of times harder to disable than thin-skinned booster rockets, the free electron laser would minimally have 10 times longer to do it. Furthermore, pop-up fighting mirrors could be launched into space, once an attack was under way. Such pop-ups could be directed toward large warhead clusters, increasing the effective free electron laser firepower 100-fold against warheads.

Although the SDI is primarily directed against the threat of nuclear-tipped missiles, the free electron laser has a far greater potential against slower-moving targets, such as jet aircraft and cruise missiles. Theoretically, a single free electron laser, which is capable of destroying the entire Soviet ICBM arsenal within a couple of minutes, would easily have the firepower to do-in the entire world inventory of military aircraft and cruise missiles in a couple of hours.

Spinoffs

Many of the specific free electron laser programs, such as those at Boeing, Los Alamos, TRW, and Stanford University, were initially to explore the scientific and technological applications. Even the high-intensity Livermore amplifier system has been examined for its potential as a driver for laser-fusion electricity production. Because of its potential to remain tuned over a wide range of electromagnetic wavelengths, and to operate at high efficiencies, the free electron laser may develop into a tool whose uses range from delicate scientific and medical procedures to heavy-duty industrial applications.

The Los Alamos resonant-cavity free electron laser effort was initiated to explore the applications of free electron lasers to chemical processing. The idea is that the free electron laser could be tuned in to generate the specific chemical reaction desired. This could lead to the efficient, large-scale production of new and old chemicals, whose structure is engineered with the refinement of "genetic engineering." This could radically increase the efficiency of existing chemicals production and could directly lead to entirely new types of materials and families of chemicals. The SDI's development of high-energy free electron lasers will permit the exploration of heavy-duty industrial applications, such as metal-working and laser-machining. The free electron laser promises to revolutionize every aspect of existing technology.

The potential scientific applications of the free electron laser are vast. First, what is the shortest wavelength that the free electron laser can attain? In principle, the free electron laser offers the possibility of exploring the very frontiers of the electromagnetic spectrum. One probable predicate for such a goal will be bigger and brighter electron-beam accelerators. The free electron laser offers the means to achieve this. Since the free electron laser operates on the basis of extracting energy from an electron beam, by reversing the process it can be used to accelerate electrons. Because of its inherent high power and wavelength coherence of its output, the free electron laser offers the prospect of much more powerful and brighter electron beam accelerators. By stacking free electron lasers—alternating between electron acceleration and radiation generation—shorter and shorter wavelengths could be approached. TRW, Livermore, and Stanford University are exploring these possibilities for both development of new technologies for processing computer microchips and for fundamental scientific studies. The scientific applications include making atomic-scale holograms—three-dimensional pictures—of both living and dead materials.