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U.S. laboratories achieve free electron laser progress

Robert Gallagher reports on developments in work at Stanford, TRW, Inc., and Los Alamos National Laboratory in this most promising technology for destroying Soviet missiles in flight.

Scientists at Stanford University High Energy Physics Lab and TRW, Inc. produced coherent blue-green laser light, the shortest wavelength of radiation ever generated from a free electron laser powered by a high-power linear electron accelerator, in late February. Blue-green light of a slightly shorter wavelength was also produced recently from a free electron laser powered by a low-power electron beam storage ring at the Laboratory for the Utilization of Electromagnetic Radiation (LURE) in Orsay, France.

At Stanford the peak power achieved inside the laser resonant cavity was 260 megawatts at the blue-green wavelength of one-half of one-millionth of a meter (0.5 microns). The team achieved this with a 115 million volt electron beam. The Stanford work demonstrates that the same high powers achieved by free electron lasers in producing longer wavelength infrared radiation, can also be achieved in producing more lethal, shorter wavelength laser light. Radiation of shorter wavelengths is more lethal because the intensity of action of electromagnetic radiation increases as it becomes more concentrated with decreasing wavelength. After more work in generating blue-green laser light, the Stanford-TRW team plans to produce lasing in the ultraviolet region of the electromagnetic spectrum.

The new results at Stanford are only a few of a series of promising developments in free electron lasers powered by radio-frequency linear electron accelerators. The free electron laser under development at Los Alamos National Laboratory is undergoing extensive modifications that are predicted to enable the device to produce 160 to 200 million watts (megawatts) in peak *output* power of infrared laser radiation. Already in September 1986, Los Alamos scientists announced at a conference in Glasgow, Scotland that they had produced 40 megawatts in peak output power from the device while operating it at an efficiency of 2% in extracting energy from the electron beam, and with a peak laser intracavity power of 2 billion watts (2 gigawatts). Now scientists estimate that modifications on the device will boost efficiency (and output power) by a factor of 4 to 5, resulting in efficiencies of 8-10%.

With these and other advances, free electron lasers driven by radio-frequency linear electron accelerators, have become the leading candidate for deployment of space-based or ground-based free electron lasers that will be able to direct powerful laser beams via mirrors, to destroy Soviet ballistic missiles in their initial boost-phase of flight.

One plan for ground-basing, known as the "Rimfire" concept, calls for placing these relay mirrors in equatorial orbits, low enough so that Soviet ground-based laser systems could not sight and destroy these mirrors. These 10-meter mirrors would focus and relay the beam to so-called fighting mirrors of smaller diameters, that would pass within range of Soviet missile sites.

The box (page 34) describes how free electron lasers work.

Are atmospheric propagation problems exaggerated?

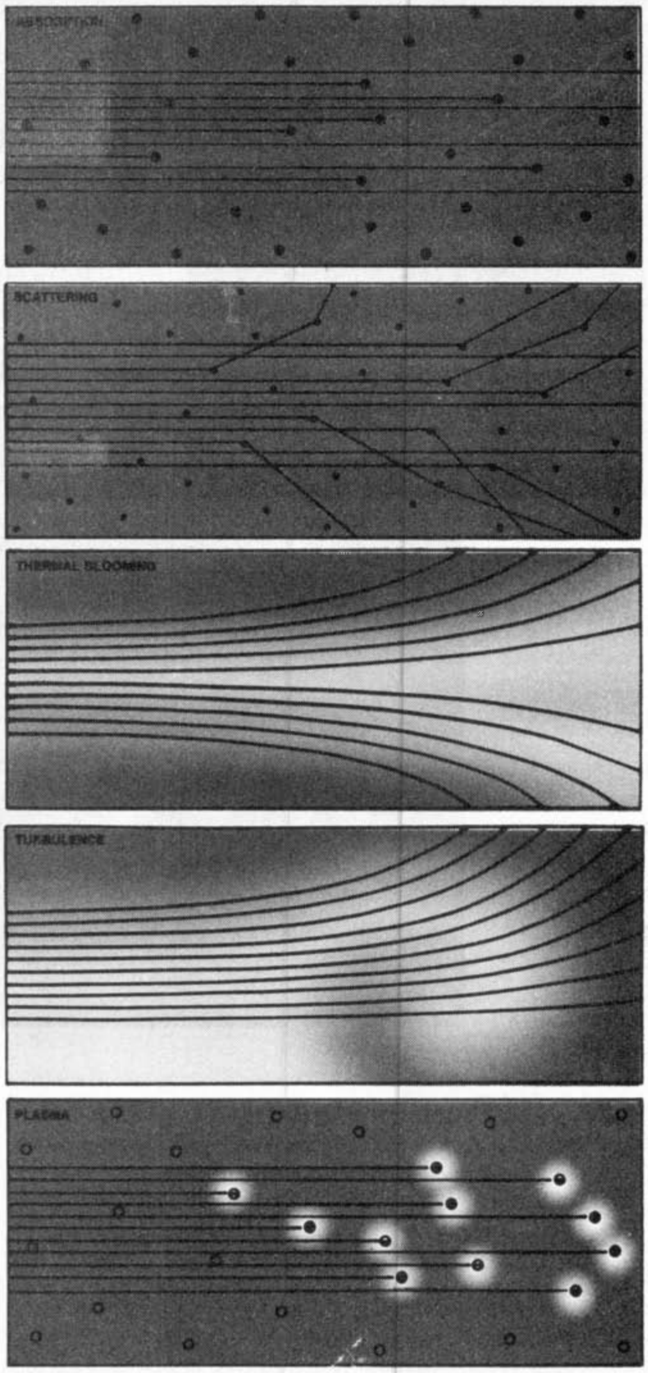
One remaining problem that scientists assume exists for ground-based free electron laser interceptors, is propagation of the laser beam through the atmosphere to the relay mirrors in space. SDI scientists have been convinced that at best *only 10%* of the beam power emitted by the laser will reach an orbiting mirror due to atmospheric turbulence, or absorption or scattering of the radiation by the molecular constituents of the atmosphere, and other atmospheric effects (see **Figure 1**). This conclusion is based on computer models of laser beam interaction with the atmosphere.

Thus since tens to hundreds of megawatts of laser power must be available in space for destruction of Soviet missiles, SDI scientists conclude that ground-based lasers must be designed to produce *gigawatts* of power. Because of the power loss expected from ground-based systems, the pendulum is swinging back toward space-basing of lasers as the preferred mode of deployment, according to some SDI scientists. Space-based systems do not require power levels as high as ground-based ones, although, since they must still be able to shoot down through the atmosphere at missiles rising from their silos, as well as at aircraft, their output must be considerably higher than that required to simply destroy a booster in space, according to the accepted models of laser beam propagation.

Kosta Tsipis summarized the accepted theory of beam propagation in his December 1981 anti-laser weapon article in *Scientific American*.

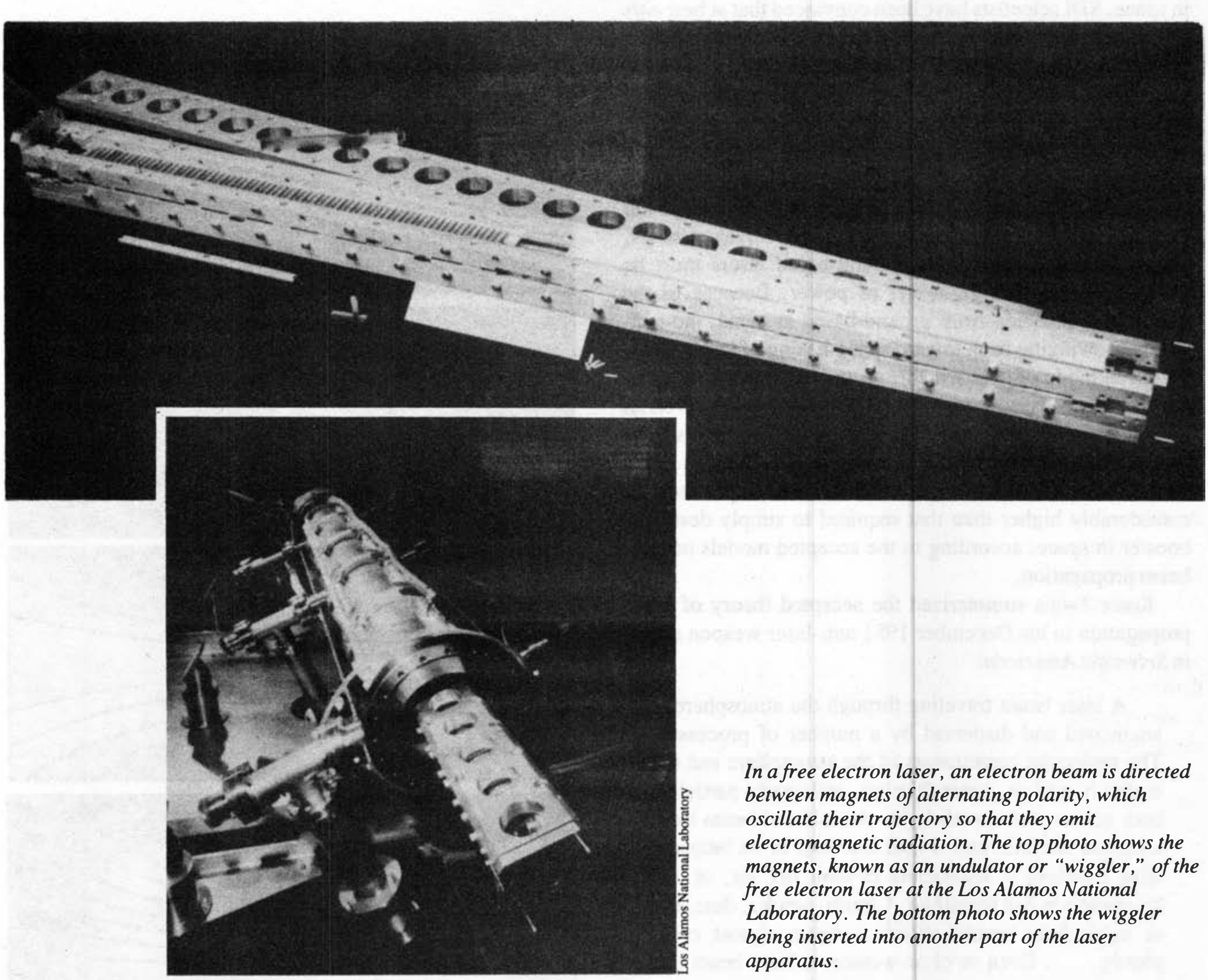
> A laser beam traveling through the atmosphere is attenuated and dispersed by a number of processes. The molecular constituents of the atmosphere and the matter in it (dust, water droplets, and smoke particles) both scatter and absorb light. An infrared beam from a carbon dioxide laser would lose half of its intensity after traveling 4 kilometers in cool dry air, or 1.5 kilometers in hot humid air. Clouds, smoke, dust, fog or thick haze would absorb a beam almost completely. . . . Even in clear weather a laser beam can be deflected, dispersed or completely interrupted by atmospheric phenomena. Turbulence causes rapid local changes in the density of the air, which can deflect a beam of light or make it diverge. The twinkling of stars and distant lights is a manifestation of this effect.
>
> A considerable fraction of the energy in a laser beam is absorbed by the atmosphere. As a result, the air in the path of the beam is heated; the heated air expands, creating a channel of low-density air. Light waves bend away from the hotter, less dense regions of a medium, and so the beam diverges. The phenomenon is called thermal blooming; it is a common reason for the defocusing and divergence of a laser beam in air.
>
> A final difficulty in propagating a laser beam through the atmosphere is the risk of creating a plasma. Since light waves are a form of electromagnetic radiation, an intense light beam is accompanied by a strong electric field. At an intensity of about 10 million watts per square centimeter (the exact value depends

FIGURE 1



Only 10% of a ground-based laser's power can reach space, according to models of atmospheric propagation of laser beams, due to (a) absorption of laser light by the molecular constituents of the atmosphere, (b) scattering of the light, (c) "thermal blooming" of the beam, (d) atmospheric turbulence, and (e) ionization of the atmosphere at high beam power densities.

Source: Adapted from *Scientific American*, December 1981.



Los Alamos National Laboratory

In a free electron laser, an electron beam is directed between magnets of alternating polarity, which oscillate their trajectory so that they emit electromagnetic radiation. The top photo shows the magnets, known as an undulator or "wiggler," of the free electron laser at the Los Alamos National Laboratory. The bottom photo shows the wiggler being inserted into another part of the laser apparatus.

on the frequency of the radiation) the field is so strong that it removes electrons from atoms in the air, thus ionizing the air and creating a plasma. The plasma absorbs the beam and interrupts its transmission. The effect sets an upper limit on the intensity of a beam of laser light that can propagate through the atmosphere.

The purely theoretical result that 90% of ground-based laser power must be lost in the atmosphere, should not determine the direction of the program. Experiments must be conducted to investigate what the conditions for laser propagation actually are. They may show that we are closer to the requirements for a free electron laser boost-phase interception system than is generally assumed at the national labs. Experiments on atmospheric propagation are scheduled to be conducted at White Sands Missile Test Range in New Mexico in the early 1990s, with a free electron laser operating in the near infrared at a wavelength of 1.5 microns and generating tens of megawatts of power. Certainly the advocacy of the propagation model by Tsipis, an official of the Soviet-controlled Pugwash Conference, should be enough to render it suspect.

Because of this believed "power density barrier" for propagation of a laser beam, it is expected that gigawatt-power free electron laser beams must be expanded in cross-section before directing them through the atmosphere, in order to spread beam power over a larger cross-sectional area and thus decrease power density. *EIR* discussed the inherent weaknesses of statistical models of beam propagation, and how they have led scientists toward exaggerating the problems of atmospheric propagation, especially in regard to propagation through turbulence, in its Dec. 13, 1985 issue.

To attain the power levels assumed to be required for ground-basing, Los Alamos plans to combine a radio-frequency linear accelerator-driven free electron laser oscillator with a radio-frequency linear accelerator-driven free electron laser amplifier. An oscillator producing tens to hundreds of megawatts of power could also be deployed in space. A space-based system need only be one-tenth the size of a ground-based one.

Livermore hopes to produce gigawatt-power-level infrared laser radiation with its system, by using an undulator as long as hundreds of meters. The Livermore type of system is too large for space basing.

Advances in beam brightness

Los Alamos has recently produced an electron beam with a brightness 10 times greater than that produced by any electron accelerator used in the SDI program. Last September at the Glasgow conference, both Los Alamos and Stanford reported electron beam brightness in their accelerators that was 10 times better than that of Livermore's Advanced Test Accelerator. Now Los Alamos has progressed yet another order of magnitude.

Free electron lasers require higher quality electron beams than those produced in accelerators prior to the SDI program. Electron beam "brightness" must be high. "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, low emittance beams are required in order to generate short wavelength light in the near infrared, visible, or ultraviolet regions of the electromagnetic spectrum, and to produce high laser gain.

Geometrically, emittance is the product of the size of the waist of the electron beam and its angle of divergence. In a properly designed accelerator it should decrease as the beam is accelerated to higher energies. (By analogy with optics, a higher energy beam can be more tightly focused, in the same way that light of higher frequencies, and shorter wavelengths, can be focused more sharply than that of longer wavelengths.) In order to compare electron accelerators, geometric emittance is normalized to the energy of relativistic beams by multiplying it by the ratio of the energy to which the electrons are accelerated, to the electron rest energy (0.511 MeV). For maximum extraction of energy from the electron beam, it must overlap the optical beam as much as possible. Geometrically, this means that the product of the waist of the optical beam and its divergence angle must equal the emittance of the electron beam.

Livermore and Los Alamos have, to date, produced the highest peak electron beam currents in their free electron lasers (850 and 300 amperes, respectively). But beam brightness is also dependent on emittance.

Radio-frequency linear accelerators at Los Alamos and Stanford have produced beams with an emittance a hundred to a thousand of times better than that of the Livermore linear induction Experimental Test Accelerator.

Los Alamos scientists have also developed a photoelectric cathode for producing 2,000 amp current electron beams. With this they recently produced a 150 amp peak beam current with a normalized emittance of 24 π mm mrad.

Toward improving beam brightness, Livermore scientists have engineered the Advanced Test Accelerator so that the emittance of the electron beam produced will be 1,400 π mm mrad, over 10 times better than the ETA's emittance, but still a far cry from the 15 π mm mrad achieved at Stanford, or the 100 achieved at Los Alamos.

Continuous action via discontinuities

Los Alamos is now rebuilding the undulator of their free electron laser to intensify its action in concentrating electrons into bunches, in order to increase the coherent extraction of energy from the electrons threefold. A brief discussion of how electrons amplify radiation will illustrate the basics of Los Alamos's redesign.

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

Electromagnetic radiation is composed of oscillating electric and magnetic fields. An electron subjected to a positive field is accelerated and extracts energy from the radiation. An electron subjected to a negative field is decelerated and gives up energy to the radiation and thereby amplifies it. This action produces a velocity modulation in the electron beam with the result that the stream of electrons is concentrated into bunches, spaced by the wavelength of the output electromagnetic waves themselves. In this way, the free electron laser generates radiation by the continuous generation of discontinuities.

Figure 2 dramatically illustrates this bunching process generic to all electron-based oscillators and amplifiers, with a diagram of the electron trajectories in a klystron microwave amplifier. As the electrons travel through the device (vertical axis), the input microwave signal modulates their velocities. In a drift section, where there is no microwave power, the velocity modulation is transformed into a density modulation: Electron 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.

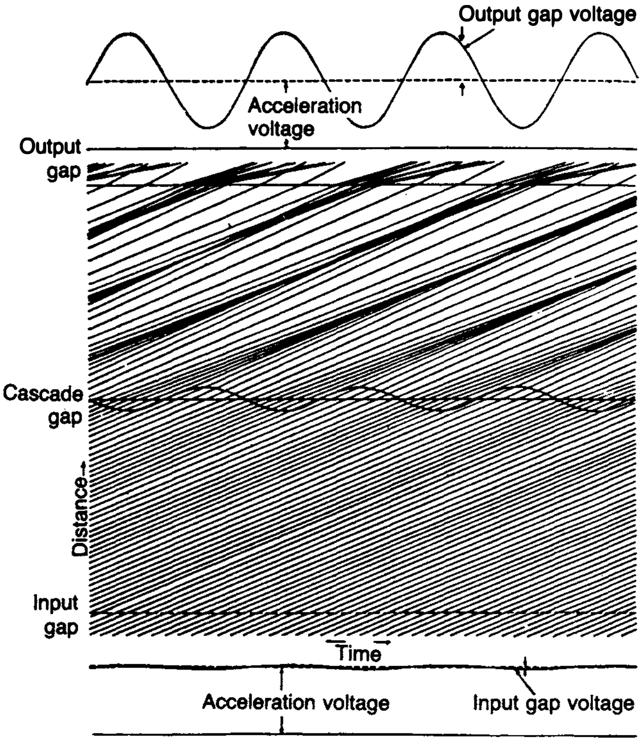
Los Alamos National Laboratory is now transforming its free electron laser into an "optical klystron" to take advantage of this intense bunching effect produced by a klystron electron tube geometry. The lab is adding an additional 55 centimeter section in front of its 1 meter undulator. The new section will be composed of 10 cells of magnets, to undulate the electron beam and introduce a velocity modulation into it, followed by a 30 centimeter drift section where the electrons traveling at varying speeds, due to the velocity modulation induced by the magnets, will bunch: The faster ones will catch up with the slower ones. With this design change, Los Alamos expects to increase the percentage of electrons "trapped" in bunches on the lasing wavelength from 50% of all the electrons in the beam to 70-80%, and together with the addition of copper mirrors to prevent losses in the optical cavity, they expect this will increase the efficiency at which the device extracts energy from the beam from its present 2% to 8-10%.

When the Los Alamos free electron laser achieved 2 gigawatts in peak intracavity power and an output power of 40 megawatts in the experiments reported at Glasgow, it began to destroy its dielectric-coated resonator mirrors. Los Alamos is installing copper mirrors in the device which they believe will enable them to boost the efficiency of tapered undulator operation to 3% or 4%.

The ability to transform the Los Alamos free electron laser into an "optical klystron" is characteristic of the close relationship between electron tube and free electron laser technology, at least that based on radio-frequency linear accelerators.

FIGURE 2

Diagram of electron trajectories in klystron cascade amplifier



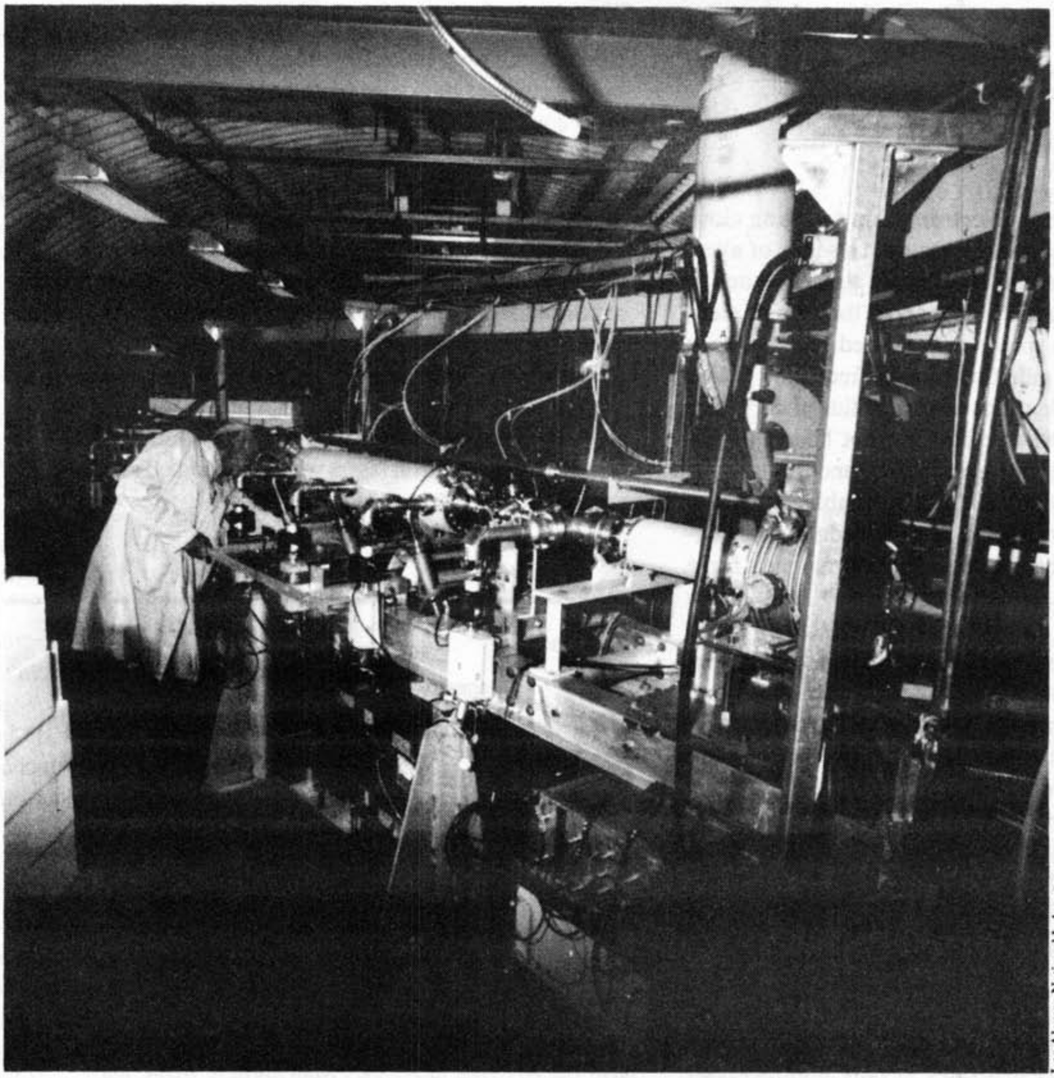
Source: D.R. Hamilton et al., *Klystrons and Microwave Triodes*, Dover Publications, New York, 1966.

There are designs already published for running free electron lasers *as electron tubes* to generate intense radiation with which to accelerate particle beams to higher energies than those yet attained. It thus was an obvious idea to run the electron beam of free electron lasers "in reverse," that is, once the electron beam has passed through the undulator generating coherent radiation, to recirculate it back through accelerating cavities in such a way as to give its energy back up to them, so as to reduce the microwave power that must be fed in from the klystrons. At the Glasgow conference, the TRW-Stanford group reported on experiments in which they recovered 90% of the electron beam energy after recirculating it back through the accelerator cavities, 180° out of phase. The group estimates that energy recovery will boost free electron laser *system* efficiency by a factor of 10, from 2-20%.

In these experiments, the laser undulator was powered down so as not to affect the energy coherence of the recirculating beam. Energy recovery with the laser on, is more complicated. The interaction of the electron beam with the undulator slows down electrons that are "trapped" in bunches and that give up their energy in laser light. Not all electrons in the beam are trapped, and slowed down; thus some electrons leave the undulator faster than others, introducing an energy spread into the beam. Unless something were done to restore the beam's coherence, this energy spread would make it difficult to recover all the remaining beam energy. Stanford and TRW scientists plan to add an "energy compressor" to their beam recirculation system to remove this energy spread.

At the same Glasgow conference, Los Alamos scientists also reported on experiments in energy recovery of which they report they were able to recover 68% of the electron beam energy with the laser on and operating at 0.7% beam energy extraction efficiency.

Free electron lasers based on radio-frequency linear accelerators promise a very high efficiency in extraction of the energy of electron beams for lasing and in energy recovery, total extraction efficiencies as high as 95%. This is very important for the SDI. Free electron lasers must 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, especially important for space basing. Unfortunately, due to the nature of induction linear accelerator technology, there appears to be no straightforward way to recirculate or recover the energy from the electron beams they produce. Furthermore, their energy extraction efficiency at even infrared wavelengths has been predicted to be low. The Livermore Beam Research group reported at a conference in Vancouver, British Columbia in 1985 that they hope to extract 1-2% of the energy in the



Los Alamos National Laboratory

The Los Alamos free electron laser device, like Stanford and TRW's, generates it own beam and for that reason, is called an oscillator. It builds up beam power by bouncing the light back and forth between two mirrors that form the ends of a resonating optical cavity. The photo shows the exterior of the apparatus that makes up this resonating cavity. The free electron laser undulator is inside the cylindrical object (to the right of the scientist's head).

electron beam in amplifying carbon dioxide laser radiation.

Problems at Livermore

In 1985 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 an 850 ampere, 3.5 MeV electron beam, produced by the Experimental Test Accelerator. However, this radiation is not suitable for intercepting missiles in their boost phase.

This year Livermore is attempting to go to a frequency 1,000 times greater than previous experiments, 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.

As originally designed the ATA could not produce a beam with magnetic focusing within the accelerator. The energy to which the machine could accelerate the beam, appeared limited by the growth of a beam-accelerator interaction instability known as "beam breakup," which grows as the beam is accelerated to higher and higher energies. Beam focusing with the ATA's external magnets was insufficient to prevent the beam from literally thrashing against the walls of the accelerator. 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."

In order to get the ATA to work, Livermore scientists developed a technique they call "laser guiding" of electron beams within the ATA. Laser guiding (also called "electrostatic channel guiding" by Livermore) focuses the beam about a line of benzene ions introduced into the accelerator. The ATA can now produce a high current, 50 MeV beam. How-

How does a free electron laser work?

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 3**). 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 radius of curvature of the oscillations. The electrons are not bound to any atomic nucleus while emitting radiation, and for that reason are called "free electrons." The assemblage of alternating-polarity magnets is known as the undulator or wiggler section of a free electron laser, since its magnets force the electron beam to undulate or "wiggle" as it passes between them.

Free electron lasers require tapering of the magnet strength along the undulator because the very generation of coherent light detunes the electrons and undulator. As the electrons give up their energy to produce or amplify the laser beam, they decelerate, their electron velocity (and energy) decreases, and they fall out of resonance with the undulator. However, if the power of the magnets is gradually decreased, or "tapered" along the path that the electrons must travel, their average speed down the undulator may be kept constant, so that they are kept in resonance.

Free electron lasers differ 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.

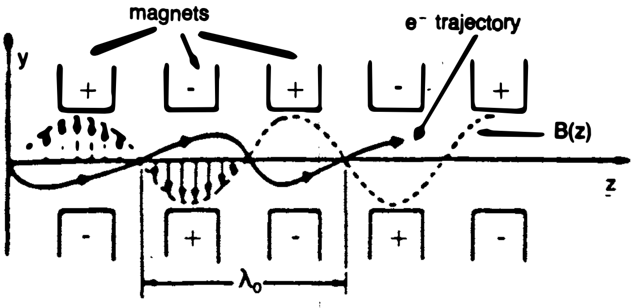
Lawrence Livermore National Laboratory is developing a free electron laser amplifier driven by the linear induction accelerators developed there, based on the principles of the transformer.

The Los Alamos free electron laser device, like Stanford-TRW's, generates it own beam and is called an oscillator because it builds up beam power by bouncing the light generated back and forth between two mirrors that form a resonating optical cavity. At the present, the Los Alamos and Livermore experiments are devoted to producing laser beams of the same wavelength—about 10 millionths of a meter (10 microns) long.

Radio-frequency linear accelerators such as the one in use at Los Alamos, accelerate an electron beam with pulses of current alternating at microwave frequencies produced from electron tubes, such as the klystron. Work on these devices is also being conducted at the Boeing Company.

The joint project of TRW, Inc. and Stanford University has been developing radio frequency linear accelerator-based free electron lasers with supercooled accelerator cavities using superconducting materials.

FIGURE 3

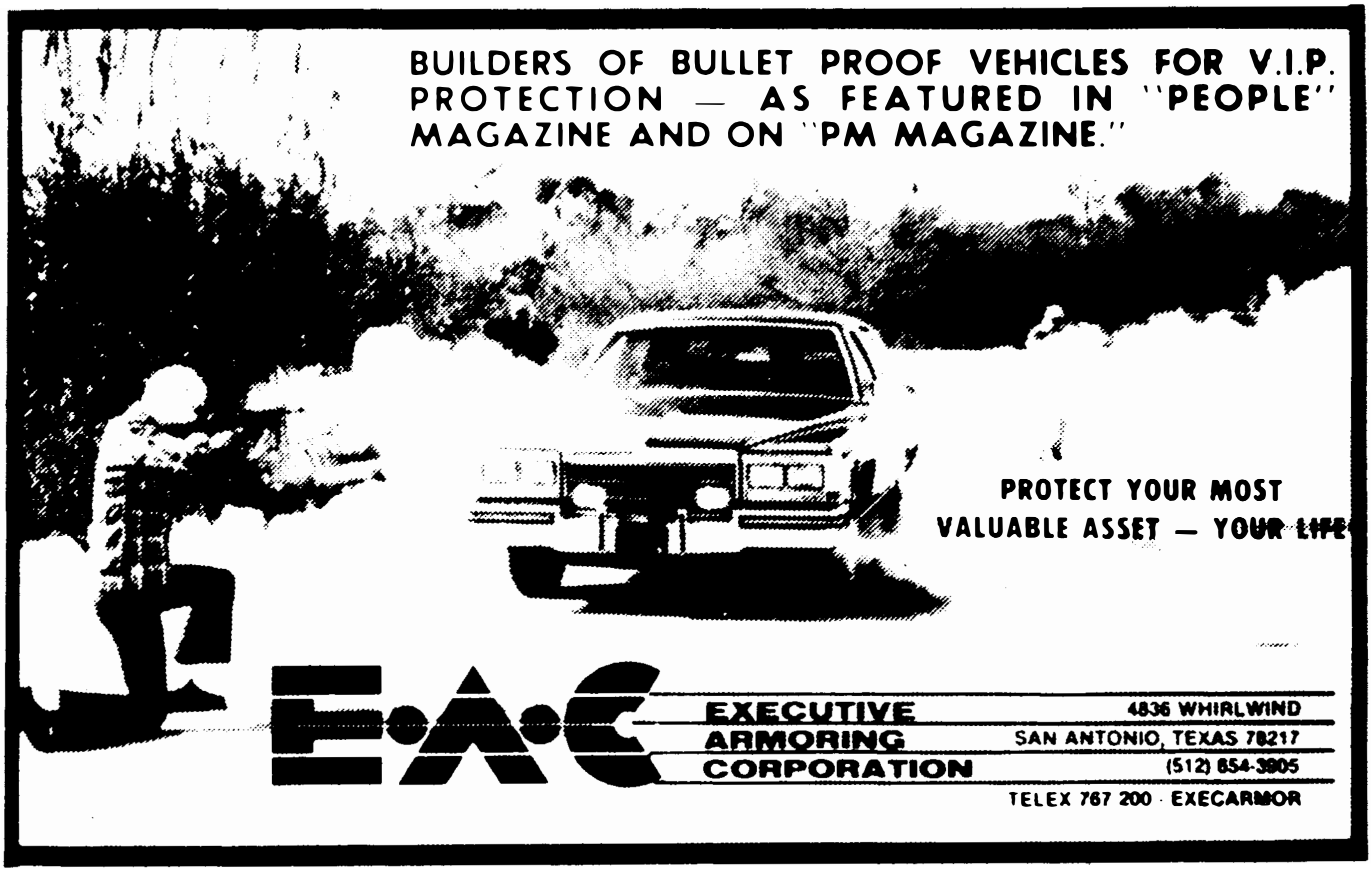


The undulator or wiggler for a free electron laser is composed of magnets of alternating polarity in a linear arrangement. An electron beam is directed down the center of the device, which turns the electrons alternately from north to south, thus oscillating their trajectory as shown. As the electrons 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.

ever, the system encounters a serious impedance mismatch in transporting the beam from the plasma regime of the accelerator beam line to the wiggler where magnetic focusing is required. As we go to press, SDI scientists report that the ATA beam is undergoing "beam breakup" inside the undulator to the point that there is little overlap between the electron and optical beams.

Once the ATA's beam breakup problem is solved, the lab plans to test free electron lasing in the high efficiency "saturated" regime where tapering of the undulator magnetic field is required to continue to extract energy from the decelerating electrons. To maximize this test, they plan to use, for experimental purposes only, an input laser power of 800 megawatts, to force saturation to occur earlier along the length of the 5 meter undulator than otherwise would occur. They estimate that they may be able to extract as much as 1 gigawatt in power from the electron beam in amplifying the 800 MW input carbon dioxide laser beam.



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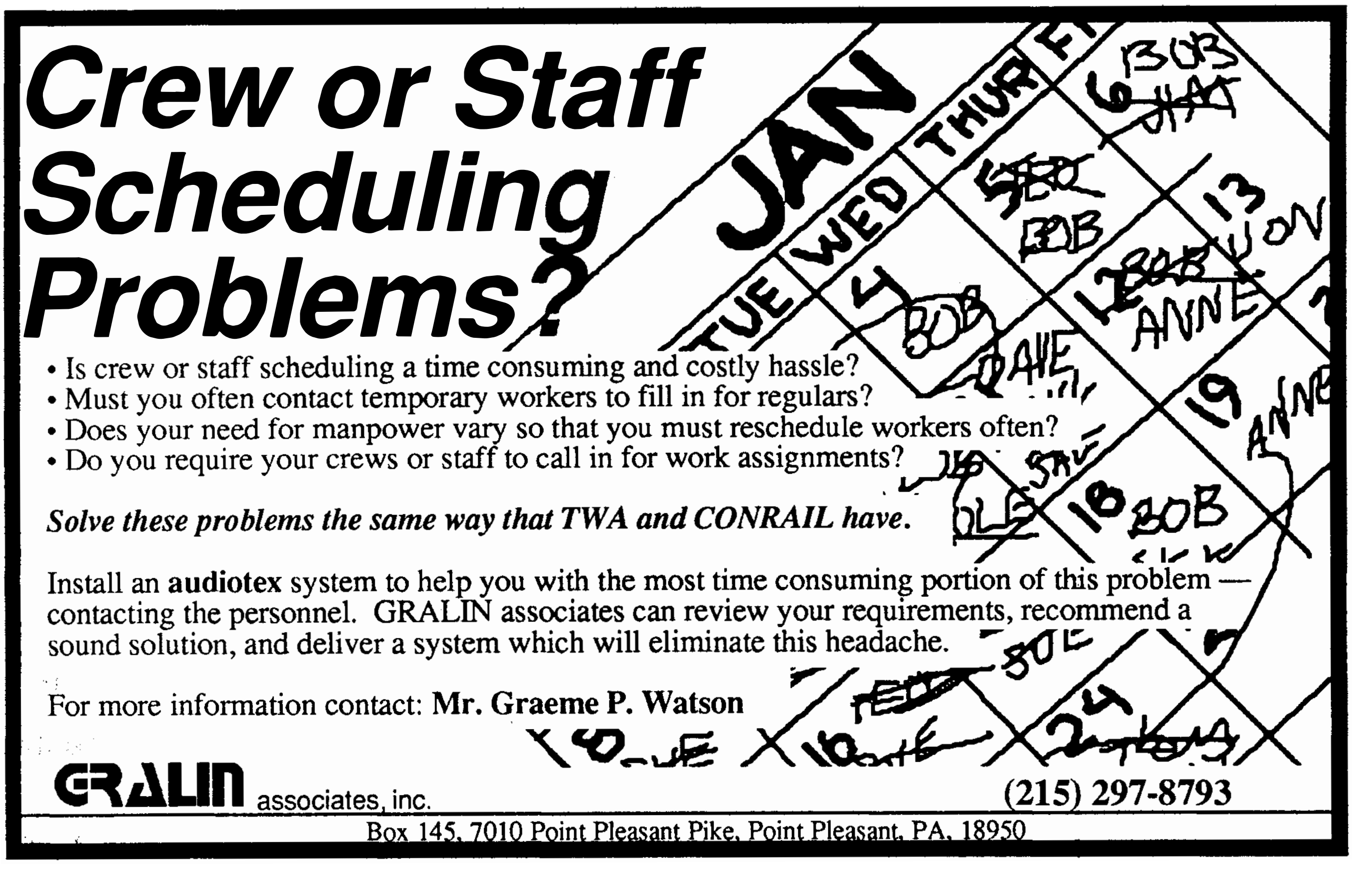

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