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# FEL beam weapon ready

*Charles B. Stevens of the Fusion Energy Foundation reports on breakthroughs making near-term deployment possible.*

According to informed sources and recent public statements by Lt.-Gen. James A. Abrahamson, director of President Reagan's anti-missile Strategic Defense Initiative (SDI), breakthroughs at Lawrence Livermore National Laboratory in California have made rapid deployment of the free-electron laser feasible. The first generation free-electron laser (FEL) weapon would be based on the ground and utilize battle mirrors popped up into low Earth orbit to direct the laser beams onto missiles as they rise into space over the Soviet Union. One such laser could destroy hundreds of missiles per second before they leave Russian air space. At the same time, the electron beam accelerator, which powers the FEL, can be used to directly destroy nuclear warheads as they descend on the United States. The FEL also promises to be the most powerful tool yet realized for industrial applications.

Speaking before a delegation of foreign journalists on Sept. 6, General Abrahamson reported that there had been "extraordinary progress" in research on the FEL. "Two years ago there were a very, very few, small laboratory versions of these, and mostly there were ideas on paper," he said. "Now, we have already demonstrated the most efficient laser in the world, operating at 42% [efficiency], at the Lawrence Livermore Laboratory. And as a result of that, we're ready to skip steps. We're ready to skip the intermediate steps and move directly to much larger versions."

The FEL has generally been regarded as the most advanced and versatile laser concept developed since the first laser was fired in 1960. Before the FEL was realized in the early 1970s, lasers were all based on utilizing energy transformations within atoms and molecules, where only a small fraction of the energy used to pump up these atoms and molecules could be extracted as the laser beam. The FEL utilizes "free electrons," like those seen in the electron beam which generates the picture in ordinary TV sets. As a direct result, the FEL has the potential of achieving greater than 50% efficiencies in operation and the ability to be "tuned" to virtually any wavelength of light output. Furthermore, since the FEL is powered by an electron beam, the FEL power output is determined by the power level of the electron beam (e-beam) input. And e-beam accelerators are a well-known technology with which the highest efficiencies and power levels have been reached.

In the most general terms, the FEL consists of an electron beam and a configuration of magnets. A linear electron beam consisting of electrons traveling at near the speed of light are directed through a chamber surrounded by the magnets. The magnetic field causes the electrons to follow a spiral trajectory. This spiraling, or "wiggling," of the electrons causes them to emit electromagnetic radiation—light. The magnet configuration for the FEL is therefore often called the "wiggler."

The spacing of the magnets and the strength of the magnetic field, together with the velocity of the electrons in the beam, determine the physical dimensions of the wiggler spiral. It can be shown that, just as the size of an antenna will determine the wavelength of electromagnetic radiation emitted, the "wavelength" of the e-beam spiral—that is, the physical dimension of the wiggler spiral—will determine the wavelength of the light emitted by an electron beam passing through a wiggler.

But in order for the FEL to achieve actual lasing—all of the electrons emitting the same wavelength in unison such that the net result is a coherent beam of light—at short wavelengths, two other relativistic phenomena must occur.

First, conventional magnet technology would appear to limit wiggler spacings to, at least, a few centimeters. Thus, electromagnetic wavelengths would be limited to centimeters when those desired are tens of thousands of times shorter, in the micron and submicron range. But because the electrons are traveling very close to the speed of light, their radiation output undergoes a double "Doppler" shift to shorter wavelengths. In ordinary phenomena, a Doppler shift is seen, for example, when the whistle of a train moving toward a stationary observer appears to have a higher frequency (shorter wavelength) than when the train were moving away. In the relativistic case, where objects moving near the speed of light are involved, the radiation output of the electrons will be shifted to shorter wavelengths also. A second Doppler shift also occurs with regard to the wiggler spacing. For the electron moving at near the speed of light, the spacing between the wiggler magnets appears to be shortened. As a direct result, the radiation output of the electron undergoes a second Doppler shift to shorter wavelengths.

Secondly, if the electrons within the beam were to remain evenly spaced, no net radiation would be emitted within the wiggler. This is because some electrons would be absorbing radiation at the same time that others were emitting. What actually happens is that the electrons undergo a self-focusing process within the wiggler magnetic field, and form into discrete bunches. This bunching of the electrons involves highly non-linear hydroelectrodynamic processes. The direct result is that the bunched electrons radiate in unison so that a net radiation output is achieved.

From this point on, there are two general paths that can be followed in the development of the FEL. In the first case, semi-transparent mirrors can be placed at either end of the wiggler chamber so that the laser radiation is reflected back and forth (an oscilating cavity), and energy is slowly extracted from the continuously recycled electron beam. As in a conventional laser, the pulse escapes the oscilating cavity through the semi-transparent mirrors when it reaches a preset energy level. The second approach is to simply use the wiggler chamber as a single-pass laser amplifier. In this case, a light pulse from an ordinary laser, tuned to the correct wavelength, is passed through the wiggler simultaneously with the electron beam. The laser pulse grows through extracting the energy of the electron beam via its radiation. The first approach is being pursued with significant success at Los Alamos National Lab in New Mexico. The FEL laser-amplifier approach is that being developed by Lawrence Livermore National Lab.

## Two breakthroughs

According to informed sources, two recent experimental breakthroughs have catapulted the Livermore FEL laser amplifier approach decades ahead of previous schedules: 1) demonstration of efficient FEL extraction (42%) with a tapered wiggler magnet on the Livermore Experimental Test Accelerator (ETA); 2) laser-produced electrostatic plasma channel guiding and focusing both within the electron beam accelerator and through gases external to it. These breakthroughs, combined with successful experiments on the larger Advanced Test Accelerator (ATA) Livermore scheduled for early next year, mean that construction of a full-scale, ground-based, FEL anti-missile beam weapon could begin immediately, as indicated by General Abrahamson.

## Tapered wigglers

As noted above, the pure FEL laser approach is based on the slow extraction of e-beam energy within an oscillating cavity. The FEL laser amplifier approach being pursued at Lawrence Livermore involves extraction in a single pass. Therefore, in this case, extraction efficiency must be very high. Because of this requirement, the FEL laser amplifier must utilize a tapered wiggler as explained below.

The wavelength of FEL output is doubly determined, through the double Doppler shift, by the energy of the e-beam. The energy of the electrons is proportional to the electron's velocity squared. The wavelength output is also directly determined by the wiggler magnetic spacing. As the energy of the e-beam is decreased, its wavelength output would increase. This is a major problem in the FEL amplifier mode since a significant fraction of the e-beam's energy must be extracted during a single pass.

The solution is to compensate for the energy-dependent shift to longer wavelengths by progressively shortening the spacing of the magnetic wiggler within the FEL chamber. Thus, the magnetic wiggler for an FEL single-pass amplifier must be tapered such that the wiggler spacing decreases throughout the length of the FEL chamber.

Experimental demonstration of an FEL tapered wiggler has long been identified as the most important step needed for making weapon-scale FEL technology feasible. According to General Abrahamson's remarks and informed sources, the ETA facility at Livermore has accomplished this with a 42% efficiency: that is, 42% of the input e-beam energy was extracted with a tapered wiggler and output as laser light. Given that the e-beam is generated with over a 50% efficiency from input electricity, the overall FEL system efficiency demonstrated on ETA is on the order of 21%. This is in the upper range of efficiencies projected by FEL laser-amplifier designers as needed for feasible weapon systems.

## Electrostatic channeling

Earlier this year, scientists working the Livermore ATA achieved the most significant e-beam technology breakthrough in the laser five decades. Using a small excimer laser, they were able to generate a cylindrical plasma-channel within the ATA. This plasma channel produced better beam focusing than that normally produced by the ATA's guiding magnetic fields, which were turned off during the experiments. (The actual cost of the excimer laser was less than the monthly electric bill incurred for the guide magnets.)

Most significantly, the laser-produced plasma channel method of beam focusing and guiding demonstrated that beam currents hundreds of times greater than those based on magnetic guiding could usefully be accelerated with linear induction accelerator (linac) technology. In terms of FEL operation, the electrostatic guiding method produced higher quality electron beams. That is, the e-beam output was better focused with less overall divergence and beam oscillations. Such high quality, bright e-beams are essential to achieving efficient FEL operation.

In experiments at both Lawrence Livermore and Los Alamos, it has been shown that these same laser-generated electrostatic plasma-channels can be utilized to guide and focus e-beams through gases outside the accelerator. The plasma channel will even focus misguided beams onto the path determined by the plasma channel, and will simultaneously exclude any effects of external magnetic fields, such as that of the Earth.

## Stand alone e-beams

While electrostatic channeling has revolutionized e-beam technology for FEL applications, the same breakthrough has also made stand-alone e-beams more feasible as anti-missile beam weapons. The breakthrough has applications over a wide range of possible beam-weapon missions and technologies.

First of all, the same e-beam which would power an FEL could alternatively be utilized to destroy nuclear warheads as they descend over the United States at a rate of 1,000 per second. Unlike the intercontinental range of the FEL, this alternative application of the e-beam would only function within a radius of several hundred miles. Therefore, the e-beam would constitute a point-defense system. But it would be quite effective in such a mode of operation, since high-energy electron beams can be tuned to penetrate the interior of nuclear warheads. The result is that the warhead can be incapacitated through destruction of its electronic nervous system with orders of magnitude less energy deposited than is otherwise needed for assured kills with laser energy deposition on the surface of the warhead.

Second, combining electrostatic channeling with compact e-beam technology, such as that being demonstrated with the advanced betatron, the system could be popped up into near space for intercepting warheads over the Artic. Given the much lower energy kill requirements for e-beams, such space-based systems could operate at much lower power levels than that of ground-based FEL e-beams. But they would have upwards of 20 minutes to achieve warhead intercept, since that is the average transit time for the missile accross the Artic.

Third, compact e-beams can also be deployed on ships and tanks for intercepting tactical missiles. The extremely high firing rates—thousands of shots per second—and high lethality of penetrating electron beams, combined with the ease by which they can be retargeted, mean that hundreds of tactical missiles could be destroyed within less than a second at extremely short ranges.

The linear induction ETA produces an e-beam with 4.5 million volts energy and a 40-nanosecond (nanosecond = one-billionth of a second) pulsed current level of 10 kiloamps. Its maximum pulse rate is 1,000 bursts per second, which can be achieved every 200 seconds, or in other words, at an average rate of 5 per second. Previous to the electrostatic channeling breakthrough, ATA represented the technological frontier for high-power linacs. It produces a 50 million volt, 10-kiloamp electron beam with a 70-nanosecond pulse length with the same burst rate as ETA.

Based on public scientific reports, the technology now exists for construction of linacs with beam currents ranging from 100 to 1,000 kiloamps and voltages ranging from 10 million to 100 million volts. Such an accelerator would produce 1,000 e-beam pulses within one second. Each of the thousand e-beam bursts would have a pulse length of less than 70 nanoseconds and a total energy level of 3.5 million joules. The pulse power level would then be 50 trillion watts. The average total kilohertz second-burst power level would be 3.5 billion watts and the average operating power level would be 70 megawatts. Maximum kiloburst outputs could be generated every 50 seconds. Therefore, with a 42% FEL extraction efficiency, the system could deliver 1,000 multimegajoule laser pulses within one second and could repeat this output every 50 seconds.

The ground-based FEL beam weapon system would utilize orbiting transfer and battle mirrors several meters in diameter to direct the multi-megajoule laser pulses onto missiles as they are launched, from anywhere on Earth. Some of these mirrors could be pre-deployed in orbit or popped up after initial detection of the launch.

Because the FEL amplifier can be tuned to any input laser wavelength, those wavelengths which would achieve most efficient propagation through the Earth's atmosphere on a given day could be chosen. The low energy laser input could be generated by existing types of excimer lasers and shifted to most efficient wavelength with Raman phase conjugation cells currently in operation. High efficiency for transiting the atmosphere has already been demonstrated in this manner. Sending a series of shortly spaced pulses will further increase propagation efficiency.

## Versatile operation

Given the high-energy and short-wavelength output of the FEL, combined with the capability of the e-beam to intercept descending missiles in a point defense mode, the ground-based FEL would be quite versatile and robust as a missile defense system. A single FEL beam weapon would be capable of intercepting 24,000 missiles and warheads at all phases of their trajectories within a 20-minute time span. For example, working with small, orbital mirrors three-meters in diameter operating at ranges greater than 5,000 miles, a single FEL could deliver within a few minutes 3,000 lethal pulses at energy deposition levels greater than 10,000 joules per square centimeter—far greater than that needed to destroy any currently conceivable type of missile booster.

During the following 15 minutes, the same FEL/mirror configuration could generate, at 500-mile mirror fighting ranges, 20,000 lethal pulses with energy deposition levels greater than several hundred thousand joules per square centimeter—in the range needed for punching through warhead re-entry vehicles. Finally, within a radius of several hundred miles of the FEL itself, the e-beam could disable up to 1,000 descending warheads within as little as one second. In other words, a single FEL prototype could be capable of intercepting the entire Soviet ballistic missile inventory, even if all were launched simultaneously in a single salvo.

The ground-based FEL would cost in the range of several billion dollars and the orbiting and pop-up mirrors on the order of $10 billion. But the mirror configuration would be capable of efficiently servicing upwards of 50 ground-based FELs with a resulting 50-fold increase in fire power.

## Industrial applications

Besides the wide range of alternative military applications of FELs—communications, radar, and beam weapons—they have the potential of revolutionizing all phases of industrial economy. FELs offer several potential advantages over conventional lasers. These include continuous tunability, high efficiency, high power, high beam quality, and low cost. Wavelength tuning is achieved through varying the e-beam energy and/or the wiggler spacing and magnetic-field strength. Wavelengths from the millimeter through to the ultraviolet have been experimentally demonstrated. High overall efficiency, up to 50% or more, can be achieved utilzing tapered wigglers' collective effects and by recovering the energy of the electrons emerging from the FEL. High power is possible because high-power e-beam accelerator technology has been demonstrated and in use for decades. By avoiding a gaseous or solid medium with its associated inhomogeneities and self-focusing properties, good optical-beam quality can be attained. Also, the flow system and pump power are avoided. Finally, low capital and operating costs should be possible. Because the capital cost of large lasers is driven by the power supply and cooling costs, which vary in proportion to the input power, high efficiency should make possible substantial reductions in capital costs per output watt. For example, studies at Los Alamos have projected FEL capital costs on the order of $50 per watt of output.

Given the high efficiency of the FEL and the demonstrated high reliability of electron beam accelerator technology upon which it is based, low operating costs are projected. When the projected costs of amortization and operation are added together, the result is a cost of a few cents per mole of photons at visible wavelengths. (One mole of visible photons should be able to initiate one mole of chemical reactions. One mole of water weighs 18 grams, for example.)

FEL applications already being considered range from industrial processing, such as welding, metalworking, and chemical processing. Especially for the case of the chemical industry, the tunability and high efficiency and power level of the FEL shows great promise.

The accompanying charts shows the cost versus consumption of various chemicals. The projected cost of photons for rare gas halide (RGH) and free-electron shown. It is presumed that only one product molecule of molecular weight 100 is generated per input laser photon.

The cost per pound for photons is projected on the basis of one near ultraviolet photon for each product molecule, presumed to have a molecular weight of 100. From this chart it is apparent that all but the cheapest chemicals would be economically accessible to FEL laser photochemical processing. But this is an underestimate, since properly tuned, single laser photons should be capable of initiating chain reactions producing many product molecules. This leveraging will reduce projected costs many-fold, well below those shown in Figure 1.

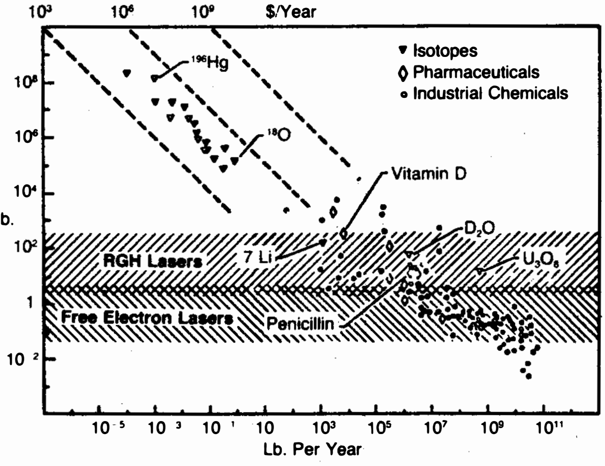

*Chart showing cost vs, consumption of chemicals together with projected cost of photons from rare gas halide (RGH) and free electron lasers. One photon is presumed to be required for each product molecule of molecular weight 100.*

Existing examples of such leveraging processes are: 1) laser purification of feedstocks in which removal of a few impurities from many product molecules greatly reduces overall costs; 2) laser cross-linking of polymers.

Probably the most revolutionary implication of the FEL for photochemistry will be the possibility of molecular engineering. Given the tunability and high selectivity of the FEL, it will now become practical to efficiently engineer the production of molecules that otherwise would be impossible to generate on a large scale. This capability promises to completely transform the pharmaceutical industry, in particular.