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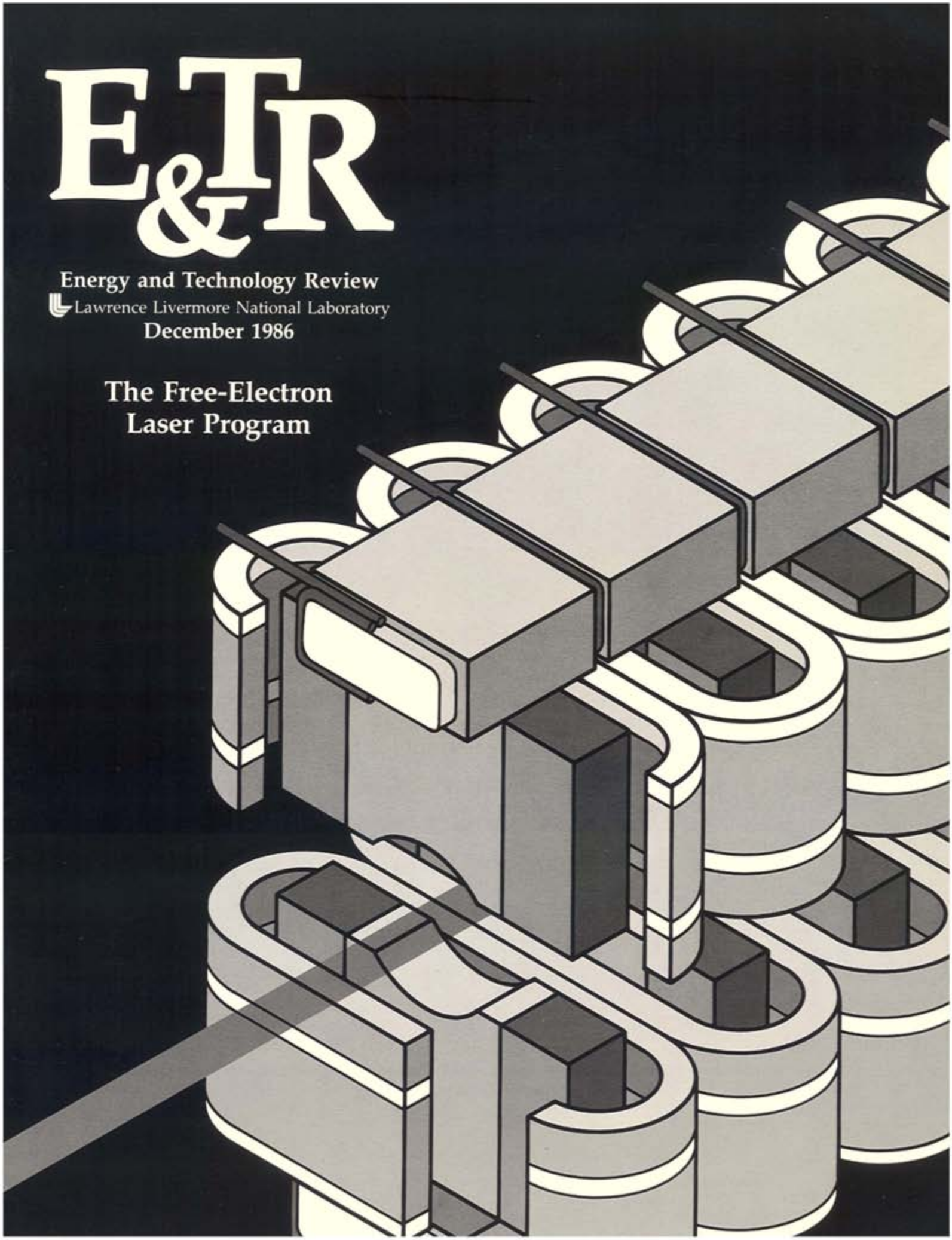
Lawrence Livermore National Laboratory
December 1986

The Free-Electron Laser Program



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About the Journal

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. Since then, we have added other major programs, including laser fusion and laser isotope separation, biomedical and environmental sciences and applied energy technology. Our most recent major project, for the Strategic Defense Initiative Organization, is research on the free-electron laser. These programs, in turn, require research in basic scientific disciplines, including chemistry and materials science, computer science and technology, engineering, and physics. The Laboratory also carries out a variety of projects for other Federal agencies. *Energy and Technology Review* is published monthly to report on unclassified work in all our programs. A companion journal, *Research Monthly*, reports on weapons research and other classified programs. Titles of recent articles published in *Energy and Technology Review* are listed at the back of the journal. Please address any correspondence concerning *Energy and Technology Review* to Mail Stop L-28, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550.

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About the Cover

The heart of the free-electron laser (FEL) is a linear array of magnets called the wiggler. In the wiggler, electron beam energy is converted to coherent radiation. The wiggler designed for our current set of FEL experiments (Paladin) is shown schematically on our cover. The electromagnets for Paladin, designed to provide a magnetic field of 0.27 T, have curved pole faces to provide a field gradient for horizontal focusing of the electron beam. The combined electron and coherent radiation (laser) beams are shown propagating down the axis of the wiggler in the drawing. This special issue on the Laboratory's FEL Program contains detailed information about our theoretical and experimental work with the free-electron laser concept and applications.

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The Laboratory's Free-Electron Laser Program: An Interview

In the past year, the free-electron laser (FEL) has become a leading candidate for an effective ballistic-missile-defense technology. Although many technical challenges lie ahead, the inherent flexibility of the FEL makes it uniquely adaptable to evolving concepts of strategic defense. In the following interview, Richard J. Briggs (Director of the Beam Research Program), Gregory D. Poe, Donald Prosnitz, and James C. Swingle discuss technical and programmatic issues associated with the FEL.

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May we begin with a historical review? How did the free-electron laser program start, and when and where?

Briggs: The FEL program was an outgrowth of the linear induction accelerator work which has been going on at the Laboratory for over 25 years. It was the result of a proposal to the Department of Energy by Andy Sessler of Lawrence Berkeley Laboratory and Don Prosnitz. Right, Don?

Prosnitz: Yes, the Laboratory became interested in it shortly after the JASONs, a panel of scientific advisors to the Department of Defense, studied the subject in the summer in 1978. They suggested that a free-electron laser could, with high efficiency, take the energy from an electron beam and turn it into light—coherent light—to produce a high-intensity laser. Their idea built on earlier work John Madey had done at Stanford. But it was the JASON people who predicted that such a device might be very efficient. They had recognized the connection between the FEL and our linear induction work and had come to tell us about it immediately. They were very excited about that. Needless to say, it attracted the interest of our own people.

At that point, the people at the Laboratory most interested in high-intensity lasers were in the Inertial Confinement Fusion (ICF) Program. So a collaboration began almost immediately between ICF and the Beam Research Program to pursue the idea. Beam research had the accelerator to develop the power, and ICF needed such a device. The two programs worked together for about a year trying to scope out the concept.

Briggs: Meanwhile, the Department of Defense—in particular, DARPA [Defense Advanced Research Projects Agency], which was funding the Laboratory's Advanced Test Accelerator [ATA]—was becoming interested in the FEL for the DOD's high-energy-laser weapon applications. Following the JASONs' recommendation, DARPA recognized that the ATA would be a very valuable instrument for developing FEL technology. By 1979, construction had started on the ATA, which DARPA funded originally for propagation studies of high-energy electron beams. When its utility for FEL experiments was recognized, we were asked to modify it midway through construction to make sure we could accommodate FEL experiments in the future. In about 1983, Congress appropriated $2 million to reconfigure the ATA for FEL experiments. After that, DOD began to fund the program to develop what is now known as the Paladin experiment on the ATA. This was before the Strategic Defense Initiative [SDI] started.

After the SDI began, consideration was given to ongoing directed-energy programs that could play a role in strategic defense. As a result, the FEL program has moved quickly to a position of prominence in SDI during the past two years.

What's the current funding level of the program?

Briggs: As I've just indicated, the program has grown very rapidly in the past couple of years. We've come from a funding level of about $15 million in 1985 to $72 million in fiscal year 1986. Laboratory involvement has also broadened to draw more on the optics expertise in the ICF and LIS

[Laser Isotope Separation] programs. Their participation began with the master-oscillator program about a year ago, and that's been augmented to include more of the FEL's optical components.

Prosnitz: The first year's funding for FEL experiments actually came from the Office of Basic Energy Sciences in DOE. They provided $300,000 to support microwave experiments aimed at establishing heating requirements for magnetic fusion energy. So funding has really gone from there to $72 million.

Will somebody explain the FEL technology?

Briggs: The traditional processes that produce coherent optical radiation—that is, radiation in the visible region of the spectrum—use atomic transitions in a solid or gaseous medium. Those processes are inherently inefficient. The basic problem in scaling a conventional laser up to high average power is that, to extract a lot of energy from the medium, you have to put a lot of energy into it. But the heated medium interacts with the laser light, distorting the phase fronts and destroying the quality of the beam, among other undesirable things. Power input into the lasing medium in conventional lasers places very severe limits on scaling to high average power.

The free-electron laser is fundamentally different. The lasing medium is a bunch of electrons in a vacuum, which means that there are no power-density limitations associated with going to high average power. So, to first order at least, you can scale the FEL to very high average power while avoiding the problems of conventional lasers.

Prosnitz: As a technology, the FEL is basically an extrapolation of the microwave tube. That means it can exploit a very mature technology, the kind of thing that people have been developing for a long time. What the FEL does is to use relativistic effects to make the microwave tube work at optical wavelengths. There was a catch, however. FEL technology couldn't be developed until very good electron-beam sources were available. And that's what made the idea so intriguing. Some of the earliest references to the basic concept date to the 1950s and even before.

Briggs: About 1960, when I was a graduate student in a group doing microwave-tube research, I learned about the work of Robert M. Phillips at General Electric. He had built a tube based on essentially the same technology as the FEL: an electron beam and a wiggler magnet. It was called the Ubitron. The beam was about 100 kV, I think, a much lower voltage than the current FEL and nonrelativistic. He did experiments at 3 and 10 GHz—typical radar frequencies. It was an interesting device, but it didn't appear to offer significant advantages over traveling-wave tubes and magnetrons. It was clearly recognized at the time, however, that it was a natural approach to scaling to millimetre wavelengths—which has turned out to be the case. So, as Don has pointed out, the roots of FEL technology were there in microwave tubes.

What happened to Phillips's work? Why wasn't it exploited at the time?

Prosnitz: That's an interesting irony in the history of technology. Phillips stopped his work around 1960, just at the time when optical lasers were beginning to appear. I suspect that because the laser offered a reduction in wavelength of many orders of magnitude, people just stopped cold on the Ubitron. It wasn't until John Madey's work at Stanford in 1977 that the field came alive again. But he called it a laser rather than a microwave tube.

Madey's device looked more like a conventional laser, with mirrors and all. The next operational system wasn't built until three or four years later; it took that long for others to catch up to John.

Briggs: I think it's important to give full credit to Madey, because when people with a background in microwave tubes first heard about the idea, they dismissed it as crazy. The idea of making such a good electron beam that it could radiate at those frequencies just seemed intuitively wrong. Their intuition tells them otherwise now, of course.

How do the technologies of microwave tubes and electron beams intersect?

Briggs: High-energy physicists have known for a long time that individual electrons moving through periodic magnetic fields at relativistic speeds emit radiation at very short wavelengths. Devices with wiggler magnets are now used in synchrotron light sources all over the country to produce short-wavelength radiation, ultraviolet and so on, but very inefficiently.

FEL technology, then, is a marriage of the interaction modes, as understood for microwave tubes, with synchrotron radiation principles of relativistic electrons. What it does is to bring those two technologies together to produce a coherent synchrotron radiation process. Instead of individual electrons radiating, each in its own fashion, you have a bunch of electrons packed together so that they radiate cooperatively, so to speak. The result is coherent radiation at much higher frequencies.

What makes a linear induction accelerator an especially good driver for a free-electron laser?

Prosnitz: To decide on the best accelerator to use, you have to consider what you're going to use it for. If you want a low-power system, for example, for medical applications or basic research, there is an accelerator called a microtron. It's so small it would fit on a table. A

microtron gives you a laser pulse that is very, very short in time—tens of picoseconds. You can use it to probe chemical systems, solid surfaces, all sorts of things where you want to see what happens on a very fast time scale. You hit them very quickly and observe what happens. If you need very short wavelengths, x rays, for example, then you go to a storage-ring accelerator, which operates at billions of electron volts. Again, it doesn't give you high average power, but you don't want high average power or even high efficiency. You want a scientific probe to tickle something. If you want high average or peak power for inertial confinement fusion or magnetic fusion experiments, for example, then you need a linear induction accelerator.

Briggs: Linear induction machines were invented to produce very high peak currents—in the multikilo-ampere range—much higher than can be achieved by radiofrequency [rf] accelerators. It turns out that the FEL improves in efficiency and other parameters as you go to a higher current. That means you can use an amplifier configuration with high gain on a single pass of the electron beam, and that's a distinct advantage. When gain is low, say a factor of two, you have to configure the system as an oscillator and bounce the optical beam back and forth to build up to an intensity that extracts a significant quantity of energy from the electron beam.

It's generally recognized now that for DOD applications, for the very high average powers that are needed for SDI technologies, the linear induction accelerator is the most promising approach to achieving the required power. It's farther ahead. The advantages of induction machines for driving high-average-power FELs are fundamental and not just because our high-average-power accelerators are in an advanced state. On the other hand, proponents of rf accelerators for driving FELs continue to search for improvements in their approach to compete with us in the medium- to high-power regime at optical wavelengths.

Where are we now with respect to our theoretical understanding of the FEL?

Prosnitz: I have a friend at MIT, a professor there. He has a wonderful photo that I think pretty well summarizes the current state of our theoretical understanding. He's standing next to two piles of journals; one pile is over his head; the other is about two inches thick. The one above his head is the theoretical papers; the other, the little one, is all the experimental results. The point is that there's been a lot of theoretical work done, but we can't be sure how much we understand until more experiments are done to test the theory. You see, it's an interesting problem, but the experiments are very expensive and take a long time to field, so a lot of people are working on theory. You might say we have more theory than we can usefully apply right now.

Briggs: Don and his people have already demonstrated a very good understanding of how to operate the FEL in the microwave regime with high efficiency. To scale those experiments to short wavelengths, the dominant issue is the brightness of the electron beam. "Brightness" describes how much dispersion of the beam there is, how much individual electrons in the beam spread out if there is no focusing mechanism. A very bright beam—a very high-intensity beam—diverges very slowly. Short wavelengths also require high accelerator voltages. High voltages are attained by adding more modules, so you have to pay more.

What are the physics problems associated with scaling to high-brightness electron beams?

Briggs: First of all, you need a good electron source. Then, as I've indicated, you want to keep the electron beam from spreading. The optics of the electron beam in that first acceleration region are absolutely critical because space-charge fields will tend to disperse the electrons, reducing their brightness. Then you have to transport the beam through a long accelerator, as we do with the ATA. The problem there is beam interactions that cause the beam to wiggle back and forth too much, which also tends to disperse it. This is the sort of physics we've been dealing with here at the Laboratory in developing linear induction accelerators over the years, so we know what we need to worry about. We believe it can be done, but a very important part of our program over the next several years is to demonstrate it.

Can you distinguish between the physics problems and the technology challenges?

Briggs: The fundamental physics of producing a bright beam depends on transporting a beam with very intense self fields. The charge and current in a beam of many kiloamperes generate intense electric and magnetic fields. Those fields act on the particles, and the particles interact with one another. Remember, it's a very dense beam of electrons that we're trying to accelerate. To understand these interactions, we use sophisticated computer codes to model the physics. That's where a lot of effort is going from a physics standpoint. Cathodes aren't considered physics, but they're a key technology somewhat akin to witchcraft. The thrust to make millimetre-wave tubes, for example, has stimulated the development of cathode technologies that are extending the state of the art very dramatically. The industrial sector has an impressive capability in this area, and we're getting a great deal of help from it, in a sort of reverse technology transfer. The technologies for producing electron beams at very high repetition rates and the handling of

these high-average-power beams are good examples of the technology challenges we face.

What are the near-term plans for developing FEL technology?

Prosnitz: Well, we've built and operated a microwave free-electron laser. We feel we've demonstrated that technology. We can model it in many areas; there are still some things we don't understand, but that makes it fun. Now we have the confidence to move on to the next stage.

And what is that?

Prosnitz: A microwave FEL operates in what's called a waveguide, which is essentially a metal pipe. The microwaves interact with the pipe as they travel along it, reflecting off the walls. Now, when the FEL operates at optical frequencies—in the visible region—you can't use a waveguide any more. The physics changes, because the pipe is no longer there. So the next step is to build an FEL that operates at shorter wavelengths, and that removes the difficulties of having to use a waveguide. The first phases of that experiment, Paladin, are now underway at our 50-MeV ATA at Site 300.

The Paladin is a ten-micron, free-electron-laser experiment. Ten microns is the same wavelength as the carbon-dioxide laser that's used all over the world for welding and many other applications. Our goal, as I've indicated, is to show that what has been done in the microwave regime can also be done at optical wavelengths, with a slight difference in the physics. The experiment will be running for the next two years or so. We'll be able to see whether our theoretical predictions are even close, and then we'll take it from there.

What are the criteria for a driver laser for the FEL?

Prosnitz: The free-electron laser as we've described it is basically an amplifier system. That means you need to start with something to amplify. We've chosen to start with light from a conventional laser. In this case, we would like to build a solid-state laser with a wavelength of one micron, which seems a good wavelength for our application. In that respect, we're fortunate that the Laboratory's Laser Program knows more about building solid-state lasers than anybody else in the world. However, we haven't made the job easy for them. We need a laser that runs at a very high repetition rate and that produces a very high-quality beam. A laser beam can look like a flashlight or it can look like the famous and elusive pencil point. To get the pencil point, you have to work very hard.

So we're talking about a driver laser that produces from a fraction of a joule to a few joules of coherent energy, which would be many kilowatts of average power by the time it's fully amplified. We'd like the power of the driver laser to be very low, which would make it less expensive and easier to build. There's enough uncertainty in the physics, however, so that we don't know exactly how much power we will need. What we've asked the laser people for is a single laser that will allow us to run the whole range of input power so that we can test the physics.

Poe: I think you've summarized it pretty well. Given the requirements for high beam quality, pulse format, pulse repetition frequency, and various stability issues such as jitter, pointing, and so forth, it appears that with some development a solid-state laser will do the job. We can scale what we currently know to the levels required for driving the FEL.

Why do you need a high repetition rate?

Poe: To attain the high average power. Each pulse contains a certain amount of energy that must be repeated at a high rate to produce a lot of average power. A target is destroyed by the average power deposited on it—generally speaking, the more the better.

May we consider applications of the FEL? Where does all this fit into the goals of the SDI? What does high average power in a laser buy us?

Swingle: The original goal of the SDI, as stated by President Reagan, was to study the feasibility of a wide-area defense against ballistic missiles; that means protecting continents from incoming warheads. To do that, you find you must place at risk ICBMs and submarine-launched missiles during their boost phase, and you must be able to discriminate warheads from other objects, such as decoys, that make it through the boost phase. Lasers may be able to perform both of these missions because they're potentially able to reach out over intercontinental distances. The requirement for high power comes from the necessity of destroying a sufficient number of missiles during their boost phase, the powered portion of their flight. If the missiles are launched in a salvo, the kill rate has to be high, and that implies high average power.

There's another reason you want high average power: the beam has to propagate over long distances. Especially with ground-based lasers, the laser light has to penetrate the atmosphere to relay mirrors, where it's reflected to targets. There's a significant optical loss associated with that process, and you need a lot of average power to begin with if you're going to overcome this loss.

What is the current status of the FEL in that role? Where does it stand in the development cycle?

Swingle: To answer that, you have to consider the basing mode—whether it's ground based or space based. Since the optical losses are less for space-based lasers, lower average

power is required. Some people have advocated the use of rf linear-driven FELs in this regime. Induction FELs are best suited for high-average-power operation and may be the best choice for ground-based concepts. Their size and weight probably precludes their use in space. There are a lot of complex issues wrapped up in the choice of where to base the laser. If you decide to put a lot of heavy hardware in space, you first face some substantial lift requirements. Then you have to deal with the problems of operating and maintaining all these high-tech gadgets over a significant period of time—at least a decade. Finally, we have no experience in operating a big accelerator in space. A major issue to be resolved, then, is whether you can make the hardware reliable enough to function in that environment.

Another aspect of basing is survivability. A laser system that holds hundreds of valuable ICBMs at risk becomes an attractive target for various counterdefensive weapons. Direct-ascent interceptors or ground-based lasers may be able to shoot up at such weapons. I think no matter what kind of laser architecture we consider, we're going to have to face that question. Even a ground-based laser requires mirrors in orbit, which are potentially vulnerable to a variety of weapons.

Finally, there's the cost issue. We must be able to demonstrate that any strategic-defense concept has a cost that's at least comparable to that of the offensive threat it's holding at risk. Otherwise, the other side can simply turn on production lines for more boosters to overcome the defense. If there's a cost advantage in doing that, the balance swings to the offense, and maybe it's not worth deploying a strategic defense.

Briggs: I think Buddy has outlined the issues very well. Of course, there's always competition among weapons technologies, and choices made very early in the development of the technology tend to be controversial. Since the Fletcher study [by the panel convened in 1983 to develop a plan for SDI] and the President's SDI speech, there's been an emphasis on the more robust weapons technologies, those that appear to be cost-effective in comparison to countermeasures over the long haul.

Poe: If your goal is to damage or destroy a ballistic missile, it's hard to do much better than throw a high-velocity chunk of metal at it. If you're trying to apply a laser to that task, you need extremely high average power. The major advantage of a laser is that photons, its "projectiles," travel at a million rather than ten or a hundred times the speed of sound, so you can access many targets very rapidly. People began to think about the laser as a weapon system in the 1960s, but we still don't have one. No conventional laser is powerful enough, in terms of delivered power on target, to compete with high-velocity metal. I think the FEL offers that possibility for the first time.

What are the optical problems presented by these highly energetic beams?

Poe: Optical damage is probably the most critical issue. A laser beam with very high energy and a small diameter can't be allowed to touch any optical component, such as a reflecting mirror, which would be destroyed. So the first thing you do is expand the beam to a diameter that will not damage your optics. An approach that seems technically feasible at this point, for a ground-based laser, is to allow the beam to expand as it normally would in space. It must be isolated from the atmosphere while it expands. To do this, all we need is a long vacuum pipe—maybe a few kilometres in length. That's what you might call an Edisonian solution to the problem: simple but effective. It's been criticized for being too simple. We're looking at other techniques for expanding the beam that do not require so much real estate, although I don't expect that will be a critical issue for SDI applications.

The approach taken with the Laboratory's Nova laser is to make the beam diameter larger as it gains energy. In the FEL we have an additional problem; we have high average power as well as high energy per pulse. Furthermore, the FEL generates not only the fundamental wavelength but frequency harmonics at shorter wavelengths. Although the harmonics have less power, they contain more energetic photons and therefore have an even greater potential for damaging optics. We're looking at ways to remove or attenuate the harmonics to prevent optical damage.

And then you need to focus the beam on the target. Are there any interesting problems associated with that requirement?

Poe: Yes, interesting and enormously difficult. You should view the optical system as starting at the exit of the wiggler and ending at the target. It must efficiently transport the photons from the wiggler to a target located on the other side of the earth and moving at several kilometres per second. For a ground-based laser, one of the critical issues is the atmosphere. The beam has to traverse the atmosphere at least once, and perhaps twice, depending on where the target is. That creates a lot of problems.

Beam propagation from the ground to the target encounters essentially three phenomena. First, the natural turbulence of the atmosphere, which causes the stars to twinkle, also causes the laser light to twinkle. Next is thermal blooming, which is essentially a self-induced twinkling of the laser light that causes the atmosphere to defocus the beam. Finally, there's Raman scattering, which converts the photons to a different wavelength and allows them to escape the beam. Turbulence has been recognized and understood for some time; we can design systems to compensate for it.

In the cases of thermal blooming and Raman scattering, we don't understand the physics as well as we need too, much less how to design a system with engineering feasibility.

Briggs: Our basic understanding of thermal blooming and Raman scattering isn't adequate yet to be able to say with certainty whether it is feasible to propagate a high-power, high-quality laser beam through the atmosphere. The issues are every bit as fundamental as those for the FEL.

Poe: In a ground-based FEL weapon system, the photons start at the master oscillator, propagate through the wiggler, get amplified, and are relayed around in space to the target. One way to look at the mission requirements for a ground-based FEL weapon is to start with the damage mechanism, which must destroy a ballistic missile in flight, and then work back to the source. We find that even at the target, we don't understand everything we need to know.

Prosnitz: One of the principal advantages of the FEL is that it's a good device in the presence of uncertainty. We don't know all the answers, but the FEL isn't a single-point design. You can vary the wavelength, vary the pulse format, do a lot of different things. So if somebody five or ten years from now says, "We really want to change this piece a little bit," that's fine. We often talk about efficiency, but for this application flexibility is equally important.

What are the DOD plans for the next generation of FEL devices?

Briggs: Current plans are to field an experiment at White Sands, New Mexico, that will couple an FEL device with a projection telescope to study the issues of propagating a high-power laser beam at subscale through the atmosphere. This will help us develop the basic understanding that Greg spoke about earlier. The emphasis won't be on the device, which won't have the power level of a weapon system, but on the propagation process. Plans are to have such an experiment in place by the 1990 to 1991 time frame. The Laboratory's main role during this period is to develop the linear-induction-accelerator technology for an FEL with the power for ballistic-missile defense at short wavelengths.

May we turn now to another kind of issue? It's been claimed that the construction of a very large, ground-based FEL will be inconsistent with the existing Antiballistic Missile [ABM] Treaty.

Briggs: The ABM treaty has been a very important consideration in planning the FEL experiments. Any experiment involving propagation of a high-power beam through the air will be done at the White Sands Missile Range, which is one of two sites for ABM testing and development named in the treaty. We believe the propagation experiments are fully consistent with the treaty.

Swingle: What the treaty actually controls is the ground-based interceptor, which is the technology that was well enough developed at the time so that both sides—we and the Russians—were ready for some sort of deployment. The treaty controls the number of sites that can be defended and the numbers of interceptors that can be used. It also identifies two ranges for each side that can be used to test ABM components. It was anticipated that new technologies would come along, and the treaty specifies a mechanism for bilateral consultation to determine the ground rules for developing and testing advanced technologies. I think that process is starting now; we're beginning to discuss the new SDI technologies. I think it's very likely there will be some kind of constraint on which components of the new technologies can be tested beyond the laboratory stage. Some laboratory-scale experiments would be hard to control; it would be very difficult to verify what's going on at such facilities. But when you're ready to take a high-average-power beam and begin propagating it through the atmosphere and making it interact with targets of various kinds, then I think the constraints of the treaty will be spelled out. They will probably involve some approved test ranges. For the United States that will likely include White Sands, which is the reason for doing the propagation experiments there.

What is known about the Soviet Union's SDI technology? Are they doing similar experiments?

Prosnitz: Yes, there is some FEL work going on in the Soviet Union. There's an interesting device called an optical klystron, which can be used to enhance the gain of an FEL, particularly in a storage ring. It was first proposed by some accelerator people at Novosibirsk. There's an infrared FEL experiment actually running at Yerevan, in Armenia.

Do you think the capabilities of the Soviet Union are such that they would have no difficulty in developing a similar technology?

Prosnitz: They will have the same difficulties we have.

Briggs: I think that with respect to the state of FEL technology in the Soviet Union, ignorance abounds. It's probably fair to say that there isn't much evidence of a large, concerted Soviet effort on free-electron laser devices. However, the Soviets seem to be quite interested in large, ground-based laser systems.

Are there defense applications of the free-electron laser besides ballistic missile defense?

Briggs: The ability to project a high-power laser beam through the

atmosphere, a beam of such high quality that it can be focused on an object in space even without a relay mirror, would be of interest to anybody who wants to destroy satellites, for example. Adding relay mirrors would let you reflect the beam toward a variety of targets of military interest besides boosters. I think the first application of a ground-based laser system, both for us and for the Soviets, might be as an antisatellite weapon.

What about nonmilitary applications of the FEL?

Prosnitz: At this point, it's possible to envision several. One is as a laser driver for inertial confinement fusion. There aren't many things we would be doing differently if we were developing it for that application. However, an ICF driver may be even further down the road than a defensive weapon. When the FEL Program was initially funded by the DOE's Office of Basic Energy Science, we were looking at a microwave FEL as an alternative to the gyrotron for heating a plasma in a tandem-mirror magnetic fusion machine. Right now, there's a lot of interest in using microwave FELs to bring up the temperature and drive current in a tokamak fusion device [this application is discussed in the article on p. 33].

Medical applications are another prospect. In some kinds of surgery, for example, you may want to burn off the top layer of a patient's skin. You would need to control the depth of the burn very precisely, and with the FEL you could adjust the wavelength of the laser light and thereby change the absorption depth of the energy in the skin. There are several research efforts on that problem in the form of joint programs involving medical facilities and laboratories.

Another application, which the Laboratory is involved in, is something called a two-beam accelerator. It's a device used to study the interactions of nuclear and subnuclear particles. The high-energy physics community wants an extremely energetic accelerator, in the tera-electron-volt range; that's a thousand billion electron volts. In comparison, the SLAC accelerator, the two-mile-long machine at Stanford, produces about 50 billion electron volts. So the proposed accelerator would represent a twentyfold increase in energy over SLAC. We don't know what kinds of nuclear reactions would occur at such energies, but many physicists would give a great deal to find out. Without the FEL, the problem is that you'd have to scale up SLAC from two miles to 40 miles. What the FEL provides is a new kind of microwave source that can put much more power into accelerating, so you don't need an impractically long structure (see the article on p. 33).

In conclusion, what are LLNL's future goals for FELs?

Briggs: The Laboratory's plans for FELs over the next few years are to fully exploit the Paladin experiment to understand the physics of a high-efficiency optical wiggler, including optical guiding in the 25-m device. This will allow us to validate models for scaling to one-micron wavelength. We will also be studying advanced wiggler designs for the one-micron regime.

Two other major goals of our program are to develop high-brightness electron beams and high-power electron beams. All of this work is vitally important for the development of high-average-power FELs operating at militarily useful wavelengths to support the Strategic Defense Initiative.