Two Applications for the Free-Electron Laser

The high-power, high-frequency capabilities of the free-electron laser have found promising applications in fusion-energy research and high-energy physics: the auxiliary heating of plasmas at cyclotron frequencies, and the high-power drive for a two-beam, high-energy-gradient linear accelerator.

The free-electron laser (FEL) is being investigated at the Laboratory both for its potential use in strategic defense and for other possible applications. Among the latter are the use of the FEL as an auxiliary heater for fusion plasmas at cyclotron frequencies (discussed in section 1 below), and the application of the FEL as a high-frequency, high-power driver for a two-beam, high-energy-gradient linear accelerator (discussed in section 2).

1 FEL Technology and Fusion Power

The desire to heat plasmas with high-power microwaves at millimetre and submillimetre wavelengths may be fulfilled by the recently developed free-electron laser. The FEL appears ideally suited for this application because it is capable of producing extremely high power and because it has a virtually limitless frequency range. Plasma heating is accomplished by tuning the FEL output frequency to the resonant, or cyclotron, frequency of the plasma electrons. In a dense plasma, the resonant electrons will absorb all of the energy of the microwave field and immediately diffuse and convert it to the other plasma particles. Besides having important implications for fusion-power technology, the application of the FEL to electron-cyclotron heating (ECH) may have an impact on plasma-physics research. The potential for using microwaves to heat plasmas has long been known but has been thwarted by the technology limits of the microwave-generating (gyrotron) tubes. As the frequency and power-per-unit requirements have grown, the tubes designed to heat plasma have become increasingly difficult and expensive to build. At present, 100-kW tubes at 140 GHz (~2 mm wavelength) are available. However, the generation of fusion power will require 1-MW units (average power) at 250 to 350 GHz; for tube technology, this requirement appears impractical, at least at reasonable cost. The advantage of FELs is that the high power per unit is an inherent feature of their design.

The results we have achieved with an FEL at the Laboratory's Experimental Test Accelerator (ETA) have reawakened interest within the fusion community in the possibility of heating plasmas at cyclotron frequencies.

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Advantages of Applying the FEL to Electron-Cyclotron Heating

The magnetic field in a toroidal plasma varies monotonically across the plasma column, so the frequency of the electron gyromotion depends on the location. Since the microwave frequency is resonant with the gyromotion of electrons, the absorption of power from the microwave field is localized. The magnetic field variation is sufficiently large that the absorption width around the local resonance layer is very narrow.

The consequent possibility of controlling the power-deposition profile could translate to better plasma confinement, a fundamental challenge for designers of fusion-energy machines. This possibility rests on the expectation that plasma current, temperature, and density profiles might be controlled by the power-deposition profile, and on the ability to control certain plasma instabilities that have proved deleterious to confinement in the past. Another intriguing possibility is that the plasma current that flows around the toroidal tokamak could be sustained by the microwaves; as a result, the tokamak could be converted from its present pulsed operation to a more desirable steady-state operation. In our experiments, we will attempt to drive a portion of the total current and demonstrate the validity of current drive theories.

There are, of course, other means than microwaves to drive current in a plasma, but few will work in reacting plasmas. For example, alpha particles generally damp the waves in all ion-wave schemes. However, with microwave ECH, there is no alpha-particle damping.

The technology advantages of electron heating with high-power microwaves (with FELs or otherwise) are impressive. For example, the access port for introducing microwaves into the vacuum vessel can be very small compared to the port size needed for other methods of heating. That is because the average power flux of the microwave source is usually very high, typically $100 \text{ kW/cm}^2$; this compares to values of 1 to 10 kW/cm$^2$ for ion-wave and neutral-beam heating methods.

Other advantages of heating with microwaves are that they produce minimal edge effects as they pass through the plasma, and they preclude the need for antenna structures within the vessel. For ion-heating systems, these antennas are a source of impurities when bombarded by high-energy particles, a problem that will be exacerbated by the hotter and denser deuterium-tritium plasmas of future experiments.

In steady-state microwave systems, a ceramic window at the entrance to the vacuum vessel is required to exclude neutral gas from regions in the waveguide where there is a harmonic resonance. Breakdown can occur in the waveguide at these harmonic resonance locations. However, an FEL producing pulsed microwave fields could transmit high-average-power pulses (of several megawatts) into the vacuum vessel with no ceramic window; the window would be unnecessary because the plasma would not break down within the short (50-ns) pulse time.

Cost considerations also favor the FEL for plasma heating. We anticipate that FELs designed specifically to generate microwaves at millimetre wavelengths could deliver an average power of 3 to 5 MW per unit and cost roughly $3 per watt of delivered power. This cost is one-third to one-half that for systems based on microwave-generating tubes, and it is at least as low as for any other technology.

Proposed Electron-Cyclotron Heating Experiments

Experiments will be carried out at LLNL to demonstrate that FEL-generated microwaves can be used for both electron heating and current drive in tokamak plasmas. These experiments will address two issues simultaneously: how pulsing of the high-intensity field affects power-absorption, and the physics of the plasma response to high-power microwave heating. Our inquiries into the effect of the intense energy pulses will seek answers to two questions: will the microwave power reach the resonant layer, and will it be absorbed there? (Figure 1 shows our proposed experimental facility.)

Theory suggests that a variety of three-wave parametric processes could be excited in the plasma, some that would lead to only partial absorption of the microwaves before they reached the resonant layer and others that would reflect or backscatter the microwaves. Specific calculations show that only Brillouin backscatter is potentially important. However, even that process, and all other convective-wave processes, should be eliminated by the mild diffusion of the microwaves expected from density fluctuations known to occur at the edge of the plasma.

At resonance, the large-amplitude microwave pulses cause nonlinear electron-orbit perturbations, thus making inapplicable linear-absorption theory for wave interactions at the electron-cyclotron frequency. Our calculations show that complete absorption can occur, but at plasma densities about three times higher than linear theory predicts. Furthermore, the absorption depth and electron-velocity distribution function are both modified from that predicted by linear theory. Experiments are needed to confirm these effects.

During the past five years, experimenters have found that virtually all forms of auxiliary power introduced into a tokamak will degrade plasma confinement if the auxiliary power density exceeds that produced by the resistive (ohmic) current in the plasma. This has been true of neutral-beam heating, lower-hybrid (ion) heating, ion-cyclotron wave heating, and, to some extent, ECH. There are exceptions in the case of ECH that suggest it is the best form of auxiliary heating. Experiments in which auxiliary power density exceeds...
Fig. 1
Sketch of the facility for the Microwave Tokamak Experiment (MTX). On the upper left is the tokamak machine in which the electron-cyclotron heating experiments will be carried out. On the lower left, within the vault of the existing Mirror Fusion Test Facility (MFTF), is the ETA II, containing the electron-beam accelerator and FEL wiggler. (The ETA II is to be constructed upon removal of its predecessor, the ETA.) The tokamak, to be located within the main MFTF building, but outside the MFTF vault, will have its own shielding walls. Power from the FEL will be transmitted about 19 m to the tokamak through a quasi-optical, microwave-transmission system that will consist of an evacuated 0.6-m-diam ducting network enclosing four focusing mirrors. The microwave beam will then be focused to enter the tokamak machine through a narrow (4-cm-diam) port.
the plasma's ohmic power density are needed to verify the advantages of high-power ECH for plasma confinement.

It is known that, for any given frequency, there is a plasma density at which the microwaves will be cut off, and the cutoff density increases with the square of the frequency. Until now, experiments have been limited to the plasma cutoff densities that correspond to the frequencies available from microwave tubes. However, FEL-generated high-frequency waves would allow us to do experiments at plasma densities an order of magnitude higher than before—that is, at densities suitable for reactor operation.

Effective reactor operation requires that the plasma pressure be very high, typically 10% of the confining magnetic pressure. To operate at these plasma pressures and to avoid limitations imposed by wave-propagation fundamentals, heating must be done at the second harmonic of the cyclotron frequency. Since the fundamental frequency for each 1 T of the confining magnetic field is 28 GHz, the second harmonic for the typical 6-T tokamak field is 336 GHz, a frequency too high for conventional microwave sources but easily produced by an FEL.

**Electron-Cyclotron Heating Facilities**

For our planned experiments, we will use the new ETA II facility at LLNL (see the article on p. 14) and the Alcator-C tokamak, now at the Massachusetts Institute of Technology (MIT). Upon completing their work with the tokamak, at the end of 1986, MIT researchers will ship it to the Laboratory. The entire endeavor will be called the Microwave Tokamak Experiment (MTX). Our schedule calls for us to begin tokamak checkout in April 1988 and microwave system checkout during the summer of 1988. Heating experiments should begin in the fall of 1988.

A sketch of the proposed facility (Fig. 1) shows the ECH experimental area containing the MTX, and the ETA II containing the high-energy (7- to 10-MeV) electron-beam accelerator and the FEL magnet series. The east end of the vault of the Mirror Fusion Test Facility (MFTF) is also visible. The electrical and electronic support equipment is not shown.

The MTX will be located in the high-bay area of the MFTF main experiment building, at the east end of the vault and just beyond the concrete shield that houses the ETA II. The output end of the FEL will then be situated approximately 19 m from the MTX. Power from the FEL will be transmitted to the tokamak through a quasi-optical, microwave transmission system, which would consist of a network of 0.6-m-diameter ducts enclosing four mirrors that focus and direct the FEL microwave beam. The beam will be focused to enter the tokamak vacuum vessel through a narrow (4-cm) port.

At the plasma densities planned for the experiment (approximately 2 to $6 \times 10^{14}$ particles/cm$^3$), power absorption should be good if the microwaves we launch through a horizontal port into the torus have their electric field aligned with the tokamak's magnetic field (we refer to this condition as "ordinary wave propagation"). The MTX tokamak can be operated to a 10-T magnetic field, allowing the use of high-frequency microwaves in the millimetre and submillimetre range.

**FEL and ECH: Future Directions**

Success in these experiments will demonstrate the usefulness of the FEL technology for driving and sustaining reactor plasmas. Good results will also provide a physics base for assessing the FEL's utility in devices for generating fusion power. If this technology fulfills its potential for driving current, controlling instabilities, and improving plasma confinement, ECH could become the method of choice for heating plasmas to ignition and for sustaining the plasma current in tokamaks.
FEL Technology and High-Power Accelerators
We are developing the theory and technology for a compact linear accelerator with a high acceleration gradient and an output energy of about $10^{12}$ eV (1 TeV). Two of these accelerators would eventually be set facing each other and operated simultaneously as a linear particle collider, with a center-of-mass energy during collisions of 2 TeV.

To achieve the necessary acceleration gradients, we are now proceeding with the concept of the two-beam accelerator (TBA), originally proposed by A. M. Sessler in 1982 (see Ref. 2). Other workers and laboratories in the physics research community are doing basic analysis and design for the TBA concept; a sample set of parameters for a TBA design developed by J. S. Wurtele and A. M. Sessler appears in Table 1.

In concept, the TBA employs a main high-energy-beam linear accelerator driven by a FEL which runs parallel to it and serves as the power source for acceleration. The main accelerator, like that used at the Stanford Linear Accelerator Center (SLAC), is a disk-loaded waveguide powered by microwaves. The innovative feature of the TBA is that it uses an FEL, rather than klystrons or gyrotrons, as the source of the microwaves. With a TBA, power would be tapped off periodically along the FEL wiggler and fed across to the main accelerator. The FEL is designed so that its microwave power increase per unit length is equal to the average power extracted per unit length.

The advantage of employing the FEL—besides its relative simplicity—is its unique, inherent ability to generate economically very high power at very high frequencies. The simplicity of the FEL precludes the need for the thousands of individual microwave generators called for in conventional accelerator designs.

### Designing Higher-Gradient Accelerators
Many members of the high-energy-physics community feel that development of a linear collider operating at the TeV level is the next major step in accelerator technology. Achieving the 1-TeV beam energy with an accelerator of reasonable length, say, a few kilometres or less, will require an average acceleration gradient of at least 200 to 400 MV/m, which should be possible at an operating frequency in the 30-GHz range. Present techniques, such as those employed at the SLAC, produce an average acceleration gradient of only $\sim 17$ MV/m at $\sim 2.8$ GHz.

The major factor that limits operation of a microwave-driven

<table>
<thead>
<tr>
<th><strong>Table 1 Parameters for a 1-TeV on 1-TeV two-beam accelerator collider.</strong></th>
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<tbody>
<tr>
<td><strong>FEL: low-energy beam</strong></td>
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<tr>
<td>Average beam energy</td>
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<tr>
<td>Beam current</td>
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<tr>
<td>Beam power</td>
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<td>Beam energy</td>
</tr>
<tr>
<td>Bunch length</td>
</tr>
<tr>
<td>Wiggler wavelength</td>
</tr>
<tr>
<td>Average peak wiggler field</td>
</tr>
<tr>
<td>Power production</td>
</tr>
<tr>
<td>Prime-power input</td>
</tr>
<tr>
<td><strong>Periodic section of HGS</strong></td>
</tr>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>Gradient</td>
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<tr>
<td>Stored energy</td>
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<tr>
<td>Microwave fill time</td>
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<td><strong>HGS: high-energy beam</strong></td>
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<td>Length</td>
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<td>Repetition rate</td>
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<td>Injection energy</td>
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<td>Luminosity</td>
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<td>Beam height</td>
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<td>Beam width</td>
</tr>
<tr>
<td>Single-beam power</td>
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<tr>
<td>Number of particles</td>
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<td>Disruption parameter</td>
</tr>
<tr>
<td>Beamstrahlung*</td>
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<tr>
<td>Total efficiency (from primary power input to high-energy beam)</td>
</tr>
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*The fractional beam-energy spread caused by electromagnetic radiation produced when beams collide.
accelerator is surface-to-surface electric-field breakdown within the structure. This theoretical upper limit for operation is shown in Fig. 2, which is a plot of the maximum electric-field gradient at an accelerator structure versus frequency (and wavelength) for rf-accelerating structures made of copper. In the commonly used disk-loaded waveguide geometry, the average beam-acceleration gradient is only about half the maximum gradient of the electric field at the surface.

Two points recently established by experiment are shown in Fig. 2 along with the SLAC operating point. Also shown are two lines representing presently understood operating limits:

\[ \text{Surface-field-breakdown limit (} \propto f^{0.88} \text{)} \]
\[ \text{Surface-heating limit (} \propto f^{0.12} \text{)} \]
\[ \text{Kilpatrick limit (} \propto f^{0.5} \text{)} \]

Figure 2 makes it clear that the desired high gradients should be achievable since gradients scale almost linearly with frequency. Thus, to achieve the dramatically increased acceleration gradients (and, in turn, achieve the 1-TeV operating energy), we must take a new approach to the basic accelerator design.

Finding a Suitable Microwave Generator

Although the advantage of operating at higher microwave frequencies has long been recognized, there have been no suitable high-power sources at, say, 1-cm wavelength until the recent development of gyrotrons and FELs. Gyrotrons are still being developed and may eventually prove to be a practical power source for some linear accelerators. However, their maximum power output at 1-cm wavelength seems likely to remain below 200 MW. Consequently, a 1-TeV machine would require thousands of such power sources, all properly locked in phase. Obviously, such a device would be impractical.

A promising alternative power source for achieving high acceleration gradients at high frequencies is the FEL, which can produce in excess of 1000 MW of average power at 1-cm wavelength. Our current theoretical and experimental work on the TBA is...
based on the FEL's ability to supply this high microwave power. The TBA (Fig. 3) consists of a high-gradient, electron-beam-accelerator structure (HGS) periodically coupled to an FEL as a source of high-power microwave energy.

It is interesting that there is an inverse relationship between the basic functional concepts of the FEL and of the HGS: whereas the microwave field of the FEL wiggler obtains its drive power from an electron beam, the electron beam of the HGS obtains its drive power from a microwave field. This relationship has been likened to the operating principle of the transformer, wherein the microwave field is analogous to the transformer's magnetic coupling field.

Although the FEL electron beam loses energy in the process of generating the high-power microwave field, the energy can be replenished by induction accelerator units placed periodically along the length of the FEL wiggler. Recent computer studies show that the current and beam quality could be largely sustained in a FEL wiggler several kilometres long.

**Research on Ultrahigh-Gradient Structures**

An initial goal of our TBA development program is to demonstrate ultrahigh gradients in an actual accelerating structure to test the scaling presented in Fig. 2 for electric-field breakdown. Toward this end, we have constructed a seven-cell, high-gradient test unit similar to a portion of the HGS (eventually, the periodic section will have ~34 cells). The unit was designed for testing at the Electron-Laser Facility (ELF, described in the article on p. 14).

The seven-cell unit (see Fig. 4) is a copper 2π/3-mode structure. All cavity and input/output coupler dimensions were scaled down from a section of the SLAC accelerator structure by the ratio of 12.11 (34.6 + 2.856 GHz). The cavities are all of equal diameter and length. The test unit was tuned to a frequency of 34.6 GHz to match that of the FEL magnetron driver.

**Fig. 3**

Diagram of the TBA concept. The TBA consists of a high-gradient, electron-beam accelerator structure (HGS) with a FEL wiggler running parallel to it and serving as its microwave-accelerating power source. The HGS is the same type of accelerator employed at the SLAC, a disk-loaded waveguide powered by microwaves. Power from the FEL is tapped off periodically along its length and fed across to the HGS. To replenish the energy given up by the FEL beam to the microwave field, induction-accelerator units are placed periodically along the FEL wiggler. The FEL is designed so that its microwave power increase per unit length is equal to the average power extracted per unit length. Recent computer studies have shown that the FEL wiggler can be several kilometres long without significant degradation of beam quality or current.

**Fig. 4**

Seven-cell, high-gradient test unit. Referring to Fig. 3, the test unit would be analogous to a portion of the HGS. In its final form, the periodic section would have ~34 cells. All cavity and input/output coupler dimensions were scaled down from a section of the SLAC accelerator structure by the ratio of 12.11. The cavities are all of equal diameter and length, and were dimple-tuned to a frequency of 34.6 GHz to match the FEL magnetron driver. In this unit, the highest surface electric-field gradient is produced in the input cavity; its predicted maximum value is calculated to be 1.52 GV/m for a power level of 100 MW. In power tests at the ELF, we achieved an average accelerating gradient of ~150 MV/m; this result is very encouraging considering the marginal vacuum conditions available at the time and the routine metallurgy employed in the test unit.
In the test unit, the highest surface electric-field gradient is produced in the input cavity. The gradient value was calculated to be 1.52 GV/m for a power level of 100 MW, and was obtained by using 1.95 for the ratio of the peak field gradient at the surface to average acceleration gradient. In this calculation, the surface field varies as the square root of the power passing through the structure.

Normally, new accelerator structures are preconditioned with pulsed rf, the power level being increased slowly to the rated value; the purpose of preconditioning is to burn off submicroscopic irregularities on the accelerator surface. This may take several days or more at repetition rates up to 360 pulses per second. Since we had no suitable microwave pulsing source of high power and high repetition rate, we could not precondition our test unit. During tests with the ELF, we increased the power to the test unit until the first evidence of electric-field breakdown appeared. This was indicated by changes in the shape of the microwave pulse transmitted through the test unit and by photomultipliers detecting the light from internal arcing. We did not observe significant improvement in breakdown resistance for the time we tested, although our short schedule did not allow thorough testing. Furthermore, in the test setup at the ELF, the vacuum in the test unit was only marginally sufficient, typically in the 2-mPa range.

The peak measured output-power level to the dummy load (see Fig. 4) was 3.1 MW. Allowing for a measured 3.0-dB total insertion loss for the seven-cell HCS test unit, the calculated corresponding peak field in the input cavity is \( \sim 380 \) MV/m. This is equivalent to an average accelerating gradient of \( \sim 190 \) MV/m. Considering the marginal vacuum conditions and the fact that no special fabrication techniques or metals of unusually high quality were used, this result is very encouraging.

New accelerator units are being constructed of the best copper and with the best fabrication techniques. These units will undergo a thorough high-temperature bakeout and will be tested at a vacuum level of 0.01 mPa or better. We expect to demonstrate maximum surface gradients significantly higher than the value quoted above. Because the lack of a suitable pulsing source will continue to preclude normal rf preconditioning for some time, we are investigating other preconditioning methods.

Another HGS design feature that we will soon test at the ELF is a "septum coupler." Power must be periodically extracted from the FEL and coupled to the HGS without disturbing the FEL's modal power distribution. Essentially all of the microwave power in the FEL must be maintained in the \( \text{TE}_{01} \) mode; any coupling discontinuities that converted power to other modes will reduce total efficiency. Standard directional coupling appears inadequate in view of the FEL's oversized interaction waveguide. To minimize mode conversion, we propose to introduce into the FEL waveguide angled septa that will function as scoops for gracefully removing a fraction of the flowing microwave power. The septa are tapered to fundamental waveguide size so that power can be extracted from the FEL and transported to the HGS without mode conversion. The tests of the septum coupler section are intended to uncover ill effects, if any, induced by the coupler on microwave mode and harmonic content, and on electron-beam stability.

**FELs and Accelerators: Future Directions**

Future research on the application of FELs in accelerators will be three pronged. First, we must optimize the design for the FEL’s beam-reacceleration cavity. Its overall beamline insertion length must probably be held to a few centimetres to avoid seriously degrading the TBA's high average acceleration gradient. Moreover, the microwave power loss in crossing the reacceleration gap should be only a few percent. Initial
measurements of gap loss indicate that special focusing or guiding will be required to keep power loss down at an acceptable level.

Second, we must improve the luminosity of the beam. The desired high-energy beam luminosity (see Table 1) is difficult to achieve when accelerating single electron bunches. The situation is mitigated by the acceleration of bursts of multiple bunches. This mode of operation has yet to be fully analyzed and optimized.

Third, we must address the issues of phase stability and control, perhaps the largest outstanding TBA design challenge. Analytical studies of the sensitivity of microwave phase to errors in operating parameters are proceeding at Lawrence Berkeley Laboratory. With no correction, the phase errors resulting from very small, but realistic, deviations from ideal operating conditions are unacceptably large. We require a phase-stabilizing scheme that is automatic and nearly instantaneous in response. The only phase-correcting feedback system proposed to date is cumbersome and costly. We are continuing the search for a more practical solution.

**Summary**

Among the several applications for the free-electron laser that we are investigating, two are the auxiliary heating of plasmas at cyclotron frequencies, and the high-frequency, high-power drive for a two-beam, high-gradient linear accelerator. We have proposed experiments to demonstrate that FEL-generated microwaves can be used for both heating and current drive in tokamak plasmas. In our accelerator research, we have demonstrated ultrahigh gradients in a short test unit. Also, we have made progress on several design concepts and have identified some of the problems that will have to be surmounted.

**Key Words:** accelerator; electron-cyclotron heating (ECH); Experimental Test Accelerator (ETA); free-electron laser (FEL); high-gradient, electron-beam-accelerator structure (HGS); particle collider; tokamak.

**Notes and References**


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

Laboratory physicists and engineers discuss development issues and applications of the free-electron laser.

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Physics of the Free-Electron Laser

In free-electron laser (FEL), energy from a beam of electrons is converted into coherent light. A periodic, linear array of magnets (a "wiggler") causes the electrons to bunch into a series of thin "pancakes" along the beam and to emit light. If the magnetic field strength or period of the wiggler magnets is decreased (tapered) along the beam path, the electrons will continue to interact with the light with increasing conversion efficiency.

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Induction Linear Accelerator for the Free-Electron Laser

Our future work with the free-electron laser (FEL) requires an induction linear accelerator that will produce a very bright beam at high repetition rates and that will serve as the electron source and driver for the FEL. We have recently designed a new injector, accelerator cells, and a pulsed-power drive for the accelerator.

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Experiments with the Free-Electron Laser

We have been experimenting with a free-electron laser (FEL) concept that draws energy from an intense beam of high-energy electrons to amplify coherent microwaves and laser light. Our FEL experiments in the microwave regime used 30-ns bursts of 3.5-MeV electrons from our Experimental Test Accelerator and produced up to 1-GW pulses of 34.6-GHz microwaves with a conversion efficiency of 34%. We are building a 25-m experimental FEL (Paladin) to amplify 10.6-μm infrared light from a carbon dioxide laser. Paladin will use the pulsed 50-MeV beam of our Advanced Test Accelerator and shaped magnetic fields for focusing. Paladin will allow us to study "gain guidance" and electron light piping as means of exceeding the diffraction limits in order to increase the output power.

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Optical Systems for the Paladin Experiment

To demonstrate an amplifier for an optical free-electron laser, we must have an input beam of coherent light oscillating in the correct mode and appropriate optical diagnostic instrumentation. Most of the energy of the input beam must be in the fundamental TEM₀₀ mode, a very stringent limit on beam quality. For our initial experiments with a short wiggler, we will need an input energy of about a megawatt. In later experiments in the high-intensity regime with wigglers up to 25 m long, we expect to use an input beam power of a gigawatt. The optical systems we have designed for the Paladin experiment will deliver a stable input beam and provide a flexible set of output diagnostic measurements.

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Two Applications for the Free-Electron Laser

The Laboratory is currently working on two applications exploiting the high-power, high-frequency capabilities of the free-electron laser: auxiliary heating of plasmas at cyclotron frequencies, and the high-frequency, high-power drive for a two-beam, high-energy-gradient linear accelerator. Experiments have been proposed to demonstrate that FEL-generated microwaves can be used for both heating and current drive in tokamak plasmas. An initial goal in the accelerator research program is to demonstrate ultrahigh gradients in a short test unit, which is a functional analog of one periodic section of the actual accelerating structure. Design concepts and problems are presented for both projects.

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price codes: printed copy A62, microfiche A01