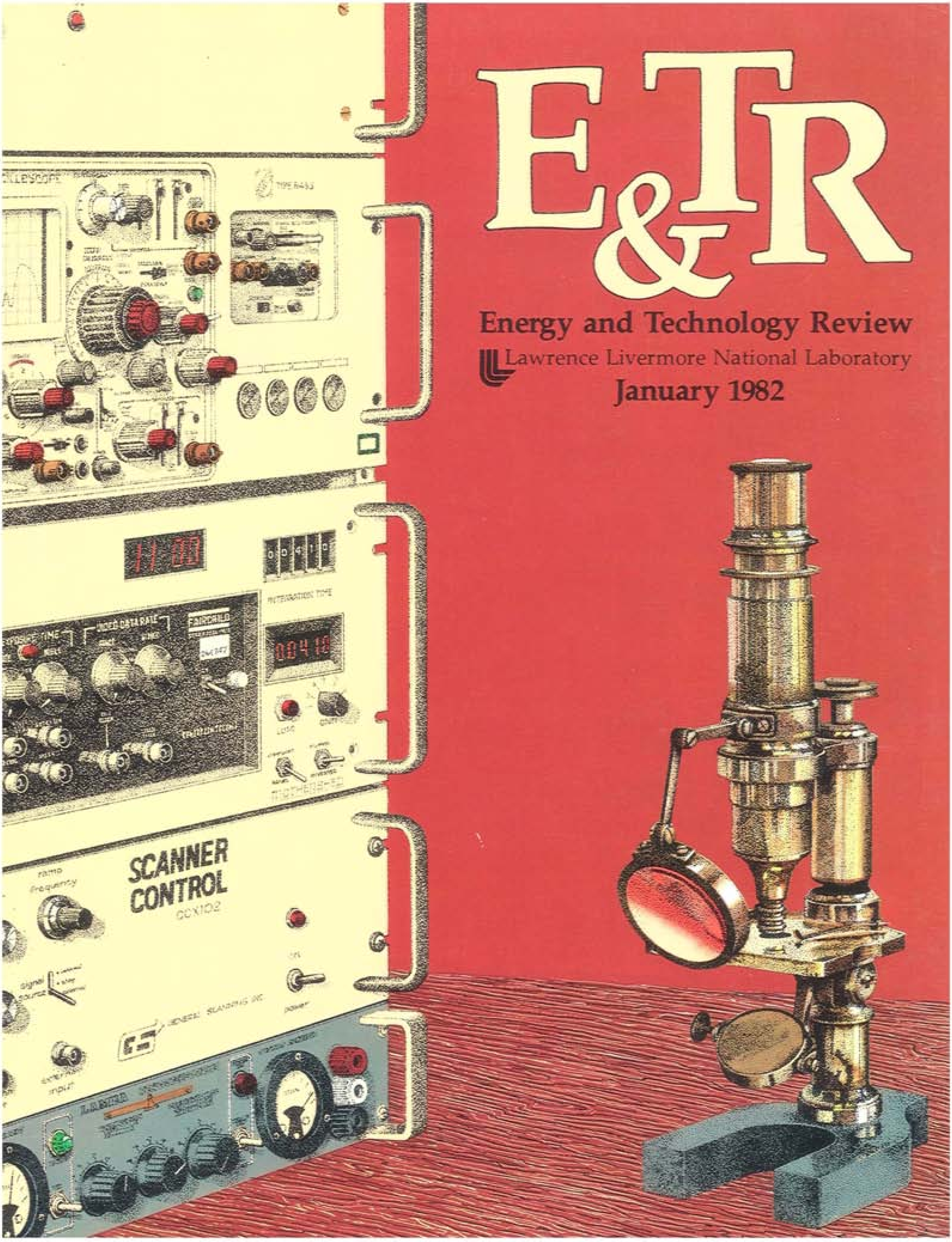
E&TR

Energy and Technology Review

Lawrence Livermore National Laboratory

January 1982



The Free-Electron Laser Amplifier

Recent experiments have shown that the energy in a high-quality electron beam can be directly converted to laser radiation; analysis suggests that this process may be suitably efficient and scalable in power for use in the production of power by inertial confinement fusion. We are conducting computer simulation studies of the conversion process.

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The manifold and expanding applications of laser technology now include optical communications, photochemistry, weapon systems, and inertial confinement fusion (ICF) research. Many of these applications require an intense, highly efficient source of laser radiation. In conventional lasers, population inversions between characteristic states of a solid, liquid, or gaseous medium are created by various means of excitation such as electrical discharge or chemical or optical pumping. The excitation energy is then extracted as coherent light. As these energy transformation processes usually entail unavoidable energy losses, they impose limits on the efficiency and power capability of such lasers. One way to bypass these problems is to convert electrical energy directly to coherent radiation.

A promising technology for direct energy conversion, still in the exploratory stage, is the free-electron laser (FEL). The FEL operates on principles radically different from those of conventional lasers by directly converting kinetic energy in a high-energy (relativistic) electron beam into coherent radiant energy.[1]

Direct conversion already has produced coherent radiation in the longer-wavelength (radio wave and microwave) regions of the electromagnetic spectrum. Figure 1 shows the efficiency of converting electron-beam energy into radiation in electromagnetic generators of various types. Long-wavelength radiation is now produced with very high (70%) efficiency by radio tubes, gyrocons, and klystrons. Gyrocons and traveling-wave tubes have demonstrated efficiencies of 20% to 60% in the microwave region, with even higher efficiencies projected. The FEL is the short-wavelength analogue of these devices.

We are doing computer-simulation studies of the FEL to investigate its potential for increasing the power output of conventional lasers. Should electron-beam accelerators with the appropriate characteristics prove feasible, we envision FEL systems capable of efficiently generating high-power coherent radiation spanning the spectral region from the far infrared to the ultraviolet. Our studies of the FEL suggest that, in the shorter-wavelength region from 10 to 10^{-1} μm, conversion efficiencies approaching 30% may be achievable.

The development of low-cost and efficient short-pulse lasers in the ultraviolet and visible regions is a technology of particular interest in ICF research. Most current FEL research is sponsored by the Department of Defense and centers on the use of radiofrequency linear accelerators more suited to applications requiring low peak power and high average power. In the Laboratory's Laser Fusion Program, we are examining the use of FELs based on linear induction accelerators producing high peak power as a driver for inertial confinement fusion reactors.

ICF research at LLNL[2] has reached the point where we can estimate performance specifications for an ICF reactor capable of generating power on a commercial scale. The production of economically competitive ICF power requires, among other things, the availability of a

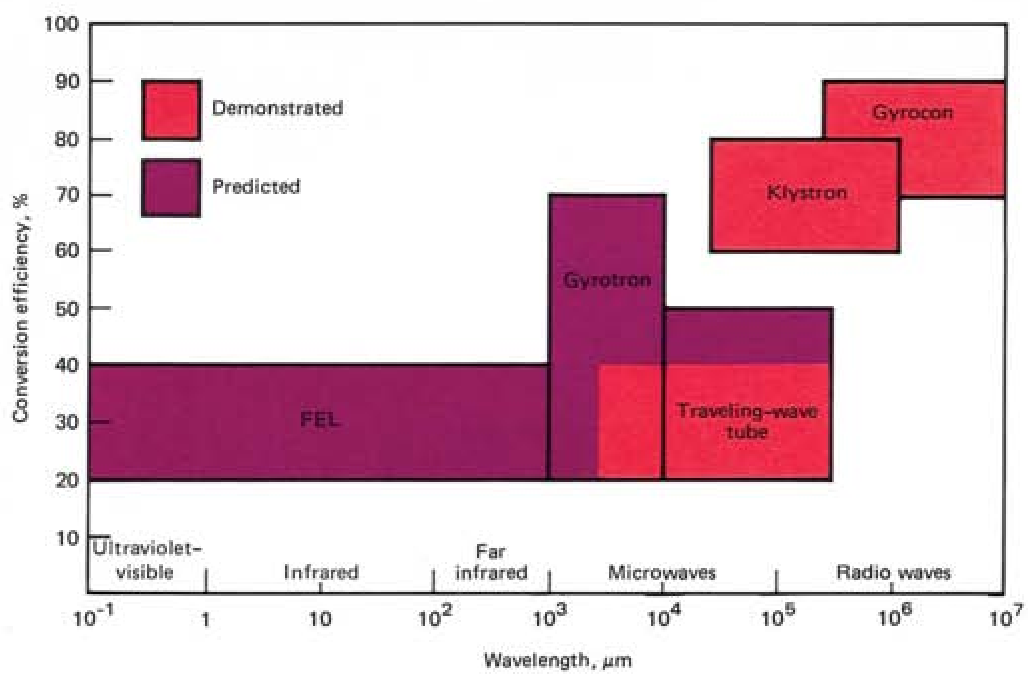


Fig. 1

Efficiency of electromagnetic generators of various types in converting electron-beam energy to radiation. The conversion efficiencies shown are for an electron beam alone; overall system efficiency for an FEL would be somewhat lower (10 to 20%).

relatively inexpensive (≤$100/J) and efficient (≤10%) driver capable of delivering a several megajoule pulse of 10- to 20-ns duration to a target one-half centimetre in diameter several times per second.

Although conventional lasers eventually may reach such performance levels, at present they are relatively inefficient (1% to 10% conversion efficiency) and expensive ($300 per optical joule). More efficient methods of energy conversion are needed to close the present gap between laboratory devices and commercial power applications. Our studies suggest that the FEL may attain conversion efficiencies of 15% to 20% at a cost of $100 per optical joule.

Mechanism of Energy Conversion

The basic operating principle of the FEL is to amplify the intensity of a propagating laser field by using the radiation emitted from high-energy electrons. Consider, for simplicity, the case of a single electron. To directly convert the kinetic energy of an electron to radiation, it is necessary to perturb the electron's motion. This can be done by passing it through a magnetic field that is static in time but periodic (alternating) in space. An electron entering such a field acquires a transverse oscillatory motion (Fig. 2). In the FEL, the field is produced by a series of magnets called a "wiggler."

A laser beam entering the wiggler from the same direction as the electron is polarized so that the electrical component of the laser's radiation field acts to retard the electron's oscillatory motion (see box on p. 22). The kinetic energy lost by the electron (in the form of radiation) as it decelerates is transferred to the laser's radiation field. The net result is that the electron is traveling a little slower at the output end of the device than when it entered, and the intensity of the laser field has been amplified.

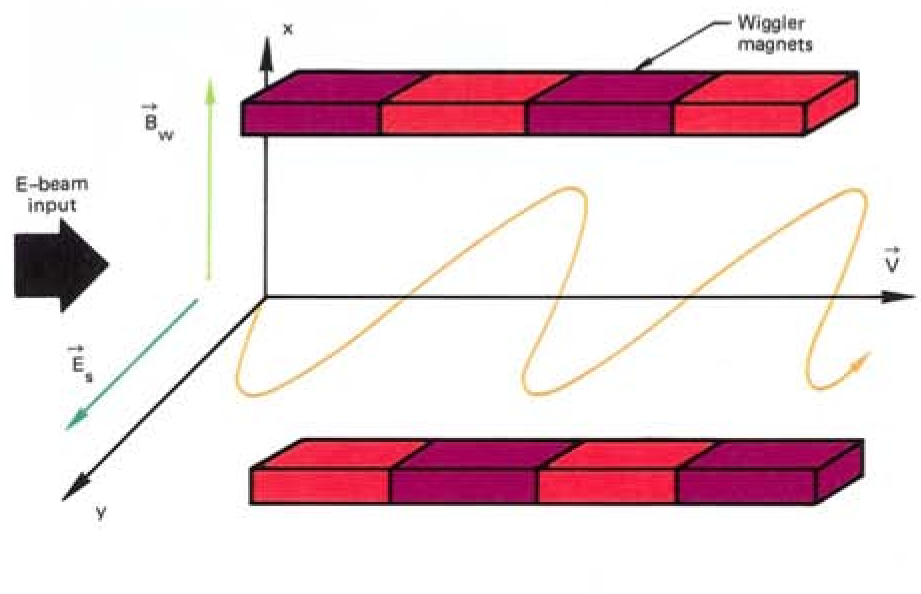
To achieve a net transfer of energy from an electron to the laser field, it is necessary to maintain a precise relationship among the velocity of the electron, the spacing (or period) and strength of the wiggler magnetic field, and the wavelength of the laser field. This is called the synchronism condition. At nonrelativistic electron energies, this condition specifies that the spacing of the wiggler field must be approximately the same as the wavelength of the laser field. By designing the wiggler spacing and adjusting the electron velocity appropriately, we can cause electrons to radiate at the frequency of the laser field.

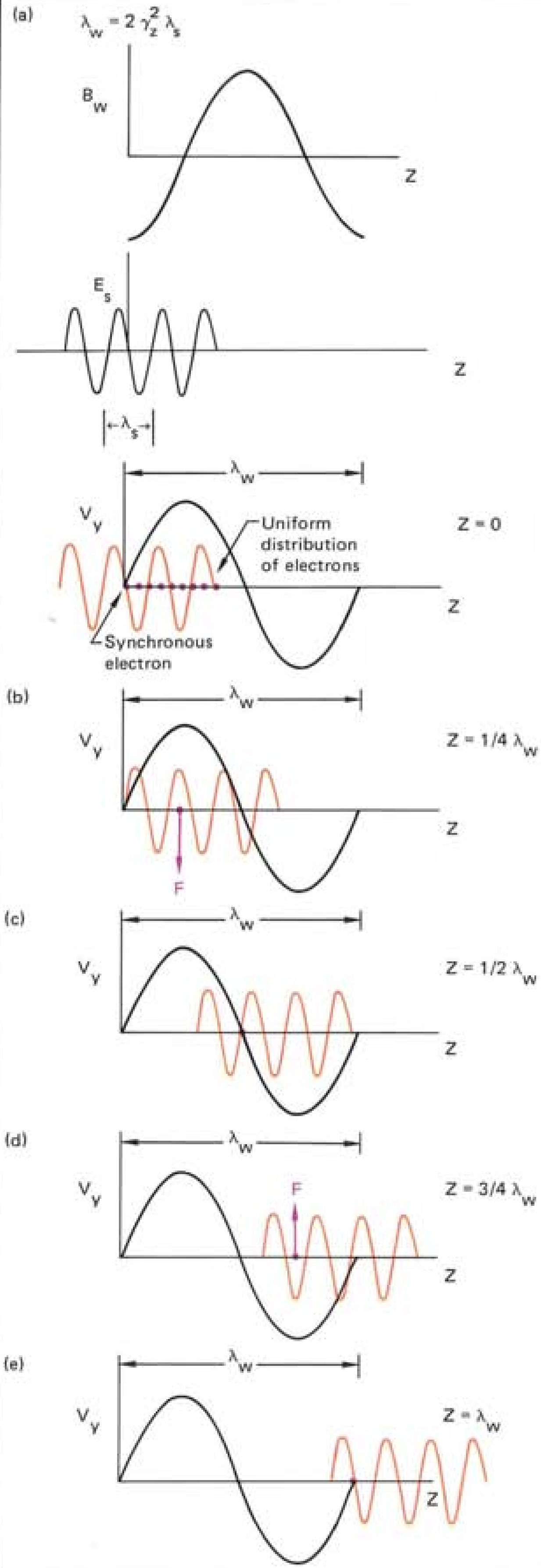
However, because of the technical difficulty of fabricating very small magnets, the radiation that can be amplified at nonrelativistic electron energies is limited to wavelengths longer than several millimetres, considerably greater than those necessary with laser fusion devices. The problem, then, is to find a technique for generating radiation at the requisite wavelengths within the contraint imposed by magnet size.

This problem can be solved by giving the electron an initial velocity high enough so that relativistic effects become important. Two effects predicted by the special theory of relativity come into play at this point. One is the Lorentz contraction (see box on p. 28). This effect causes the spacing of the magnetic field to appear much shorter (contract) in the frame of reference of an electron moving through the wiggler. Simultaneously, in the laboratory's frame of reference, the wavelength of radiation emitted by the electron undergoes a relativistic Doppler shift, causing it to appear shorter. With careful adjustment of the electron's initial velocity, the electron will emit radiation at a wavelength corresponding to the

Fig. 2

Mechanism of energy transfer in the FEL. An electron is injected (in the z direction) into the field, B_w, of a periodic array of magnets (the "wiggler"), which imposes a transverse oscillatory motion on the electron (in the y direction) as it traverses the array. This oscillatory motion causes the electron to emit electromagnetic radiation. The kinetic energy lost by the electron is transferred to a co-propagating electromagnetic (laser) field (E_s).





Deceleration of an Electron by an Electromagnetic Field

A laser beam entering the wiggler from the same direction as the electron is polarized so that the electrical component of the laser's radiation field acts to retard the electron's oscillatory motion. The kinetic energy lost by the electron (in the form of radiation) as it decelerates is transferred to the laser's radiation field. The net result is that the electron is traveling a little slower at the output end of the device than when it entered, and the intensity of the laser field has been amplified.

(a) The initial wiggler magnetic field, B_w, laser electric field, E_s, of wavelength λ_s, and velocity of the electron V_y. As the electric field at the position of the synchronous electron is zero, the laser's field does no work on the electron.

(b) The synchronous electron has now traveled 1/4 of a wiggler spacing, λ_w. The electric field and the electron's velocity are now both positively directed, so that the laser field exerts a decelerating force on the electron, effectively transferring energy from the electron to the laser field.

(c) The electron has traversed 1/2 of a wiggler spacing. The laser field seen by the electron is now zero, so that no net force is exerted on the electron.

(d) The electron has traversed 3/4 of a wiggler spacing. The laser field and the electron's velocity are now both negatively directed. Once again, a decelerating force acts on the electron, transferring energy from the electron to the laser field.

(e) The electron has now traveled one full wiggler spacing, and the situation is again as in (a). The laser field has traveled one wiggler spacing plus one laser wavelength while the electron has traveled one wiggler spacing. (This synchronism requires that $\lambda_s = \lambda_w/2\gamma_z^2$, as in the relativistic case; see box on p. 28) Net energy has been transferred from the electron to the laser field, and the cycle begins again.

wavelength of the laser field, thereby amplifying the intensity of the field.

The synchronism requirement raises an additional design issue. As an electron travels through the wiggler and loses energy, its velocity decreases. The design of the wiggler must be adjusted to ensure that the spacing of the wiggler field remains the same as the wavelength of the laser field in the electron's frame of reference. The solution is a variable (tapered) wiggler, whose magnetic-field-reversal spacing changes as a function of distance along its length.

Extension of the Concept to Many Electrons

Developments in accelerator technology must accompany development of the FEL. Important constraints are imposed on this technology when the FEL concept is extended from a single synchronous electron to the case of many electrons in an actual electron beam. At present, we are using computer simulations to estimate the efficiency with which energy can be extracted from an electron beam by the FEL amplifier.[3]

Although the synchronism condition described above applies well to monoenergetic electron beams that are tightly clustered in space, real beams will have initially a uniform distribution along the axis of the FEL. This suggests that many electrons will fail to satisfy the synchronism condition, seriously reducing the efficiency of energy extraction.

Fortunately, there is a mitigating mechanism. Recent studies indicate that if the laser (electromagnetic) field is quite strong, any electron with an energy close to the synchronous energy will, on the average, lose energy at the same rate as a synchronous electron.[4] The laser field, in effect, selects electrons with the proper phase relationship. Entire ensembles of electrons may then interact coherently with the laser field, permitting high energy-extraction efficiencies. Our simulation studies are designed to verify this phenomenon.

Our studies have predicted the dynamic behavior of a typical electron cluster in a FEL. Figure 3a shows initial energies and positions of a cluster of 500 electrons one optical wavelength long as

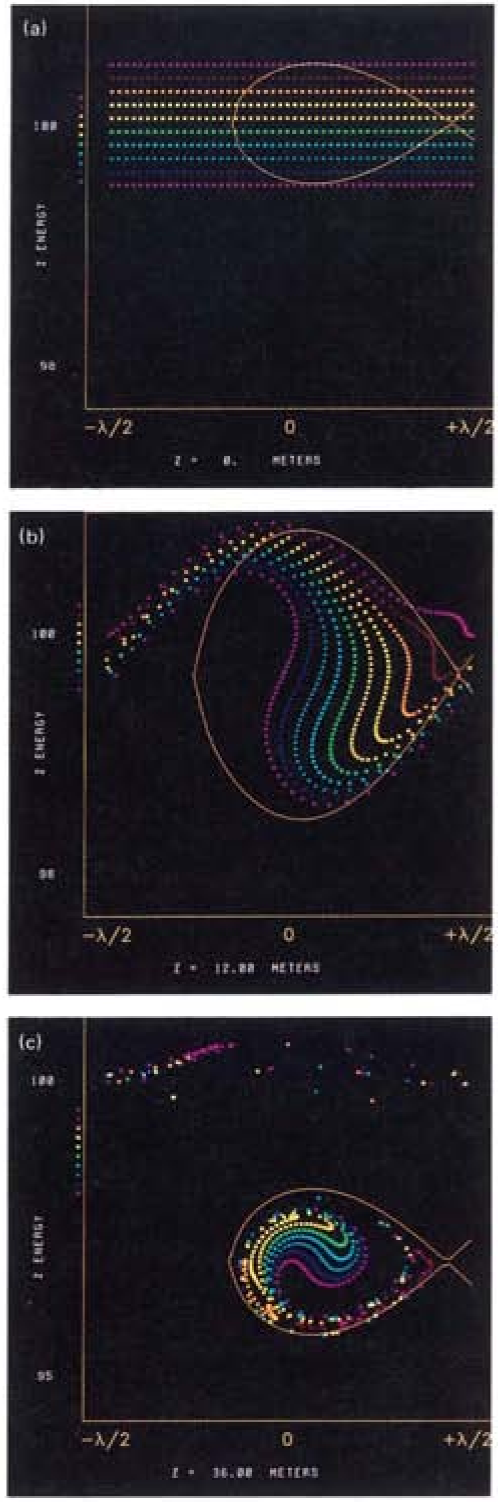


Fig. 3

(a) A cluster of 500 electrons one optical wavelength long as it enters the wiggler. The fish-shaped curve is called a "bucket." Electrons sufficiently close to the synchronous electron located at the center of the bucket lose energy at the same rate it does. (b) The same cluster of electrons after it has traveled 12 m down the wiggler. Some electrons have gained and others have lost energy; the net result is a minimal transfer of energy to the laser field. (c) 36 m down the wiggler, the electron cluster has divided; one cluster retains the initial energy and a second cluster has been trapped in the bucket and decelerated, thereby transferring large amounts of energy to the laser field.

it enters the wiggler. The fish-shaped curve surrounding most of the electrons is known as a "bucket." Our approximate calculations indicate that the electrons within the bucket should be close enough to the synchronous electron to lose energy at the same rate as it does. Figure 3b shows the same cluster of electrons after it has traveled 12 m down the wiggler. Some electrons have gained and others have lost energy; the net result at this point is a minimal transfer of energy to the laser field. In Fig. 3c, however, 36 m down the wiggler the electron cluster has divided. One cluster retains the initial energy and a second cluster has been trapped in the bucket and decelerated, thereby transferring large amounts of energy to the laser field.

Our one-dimensional model did not simulate the normal diffraction of the laser field or its refraction by the electron cluster. We are refining a two-dimensional model that will enable us to simulate propagation of the optical beam through the FEL and will include diffraction and refraction effects. Our preliminary results, shown in Fig. 4, suggest that the optical beam will propagate satisfactorily even if the wiggler is very long.

Designing a Fusion-Class FEL System

We have also used our one-dimensional model to simulate fusion-class FEL devices. The results indicate that high extraction energies can be most economically achieved if the laser operates at very high intensities (greater than 10 TW/cm^2). Such intensities would eliminate the need for final focusing optics—a source of significant energy

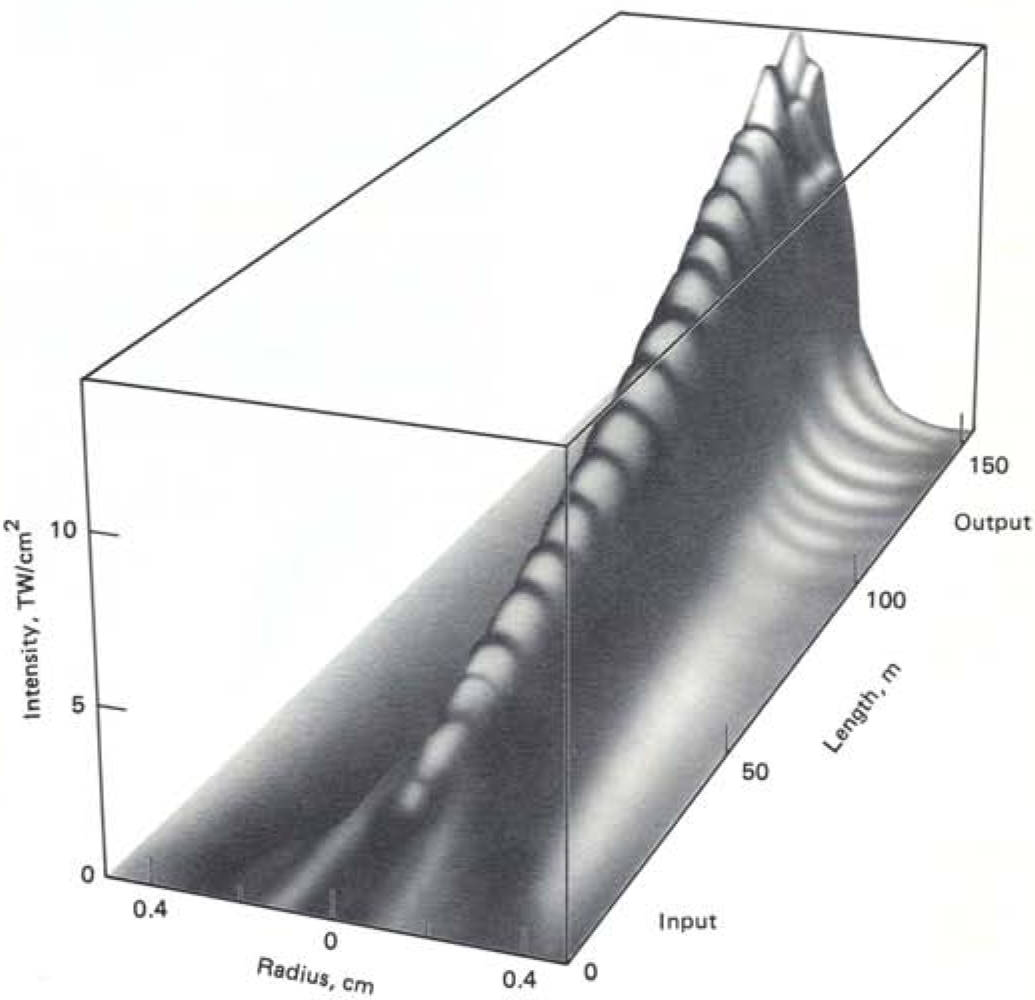


Fig. 4

Intensity of the laser field predicted by our two-dimensional FEL simulation. The long axis shows distance down the amplifier. Results indicate that the beam will propagate through a long amplifier.

losses in conventional laser systems—by enabling propagation of the laser beam directly onto a fusion target. This means that we would need an output beam width roughly equal in diameter to the target.

The performance specifications of a typical FEL driver for an ICF system are listed in Table 1, which includes the corresponding parameters of an electron accelerator. This particular device was designed for a near-ultraviolet (250-nm) laser. In a one-dimensional simulation, the output of each amplifier is 100 kJ in 15 ns. The variable-wiggler FEL amplifier is 120 m long and consists of an array of samarium-cobalt permanent magnets with a maximum field strength of 5 to 10 kG at the pole faces. Figure 5 gives a cutaway view of the device.

We have examined the requirements for an accelerator capable of delivering electrons to the FEL with the necessary energy and are studying two candidate systems. The first, technically the least

Table 1 Performance specification for a near-ultraviolet (250-nm) FEL fusion driver.

Parameter	Value
Amplifier	
Length, m	120.0
Wiggler spacing, cm	15.0
Wiggler field (variable, kG)	2.5-5.0
Beam intensity	
In, GW/cm^2	10.0
Out, TW/cm^2	42.0
Energy out, kJ (15 ns, 0.5-cm diam)	100
Accelerator	
Voltage, GeV	1.1
Current, kA	20.0
Energy spread, %	0.5
Emittance (normalized), rad-cm	0.1
Pulse length, μs	0.5-0.6

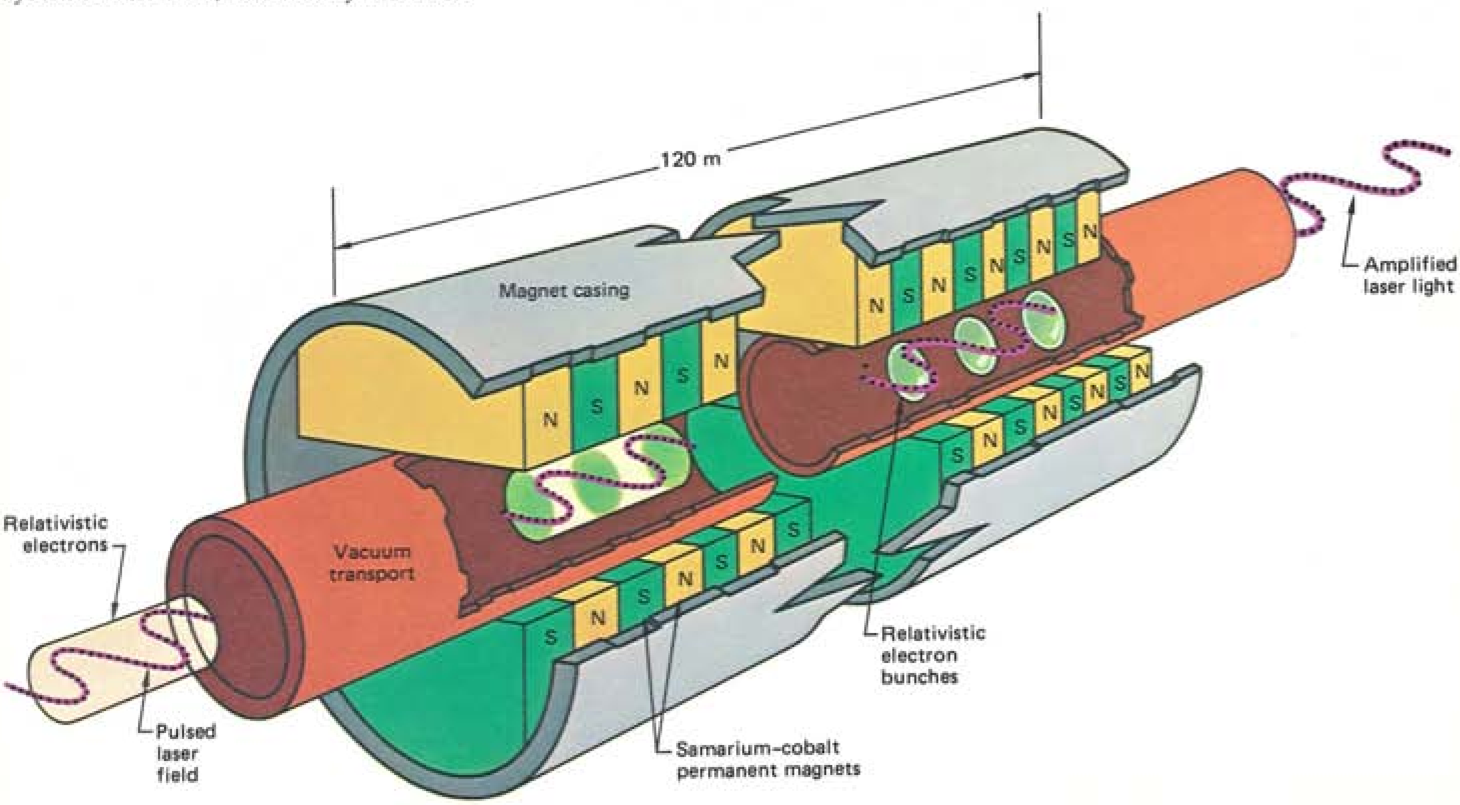


Fig. 5

Artist's conception of a typical FEL device. The wiggler consists of a series of a series of samarium-cobalt magnets 120 m long. A beam of high-energy (relativistic) electrons enters the device together with a pulsed laser field. At a certain distance along the wiggler, the kinetic energy of the electrons (now bunched as described in Fig. 3) is transferred to the laser field.

To achieve the roughly 3-MJ output required for an ICF power plant, it would be necessary to couple as many as 30 . . . 100-kJ FEL amplifiers configured to converge on a fusion target.

demanding, is a 1.1-GeV linear induction accelerator. In a linear induction accelerator, the electron beam passes through the centers of a linear array of toroids (cores) of magnetic material (ferrite). Each core is a transformer in which a pulsed power source drives the primary winding and the electron beam forms the secondary "winding." The voltage of each core is added to the electron beam as it passes down the accelerator.

At present, the most powerful accelerator of this type is the 50-MeV, 10-kA Advanced Test Accelerator (ATA) now under construction at LLNL.[5] A 1.1-GeV, 20-kA linear induction accelerator would require a significant advance over the ATA with regard to voltage and emittance. (Emittance is related to both the degree of synchronism achievable and to the fraction of electrons in a cluster that end up in the decelerating bucket.) The required voltage and current can be provided by a relatively straightforward increase in the amount of magnetic material used, pulsed power, and accelerator length. Further development would be required to satisfy the emittance requirement.

Our second candidate accelerator, attractive because of its lower cost and potentially higher efficiency, is a 1.1-GeV betatron accelerator. As in the linear induction accelerator, the electron beam forms the secondary of a transformer. In the betatron, however, electrons are accelerated in an evacuated ring. A set of bending magnets forces the beam to circulate around the betatron's magnetic core material for several thousand transits.

Use of the betatron as an electron source raises three major technical problems related to injecting electrons of sufficiently high energy into the betatron ring, extracting the high-energy beam from the ring, and maintaining beam stability in the ring during acceleration.

The injection problem can be addressed by injecting electrons into the betatron at 50 to 100 MeV from a linear induction accelerator with a pulse length equal to the transit time around the ring. The electron beam can be extracted from the betatron ring with a magnetic switch, but the strength and volume of the required magnetic field limits the rise time of the switch to 30 ns, leading to a loss of electrons. However, the most crucial problem with the betatron remains the instability of the circulating beam at low electron emittance. This may prove intractable.

To achieve the roughly 3-MJ output required for an ICF power plant, it would be necessary to couple as many as 30 of the 100-kJ FEL amplifiers shown in Fig. 5, configured to converge on a fusion target. Figure 6 schematically represents one half of such a device (the electron

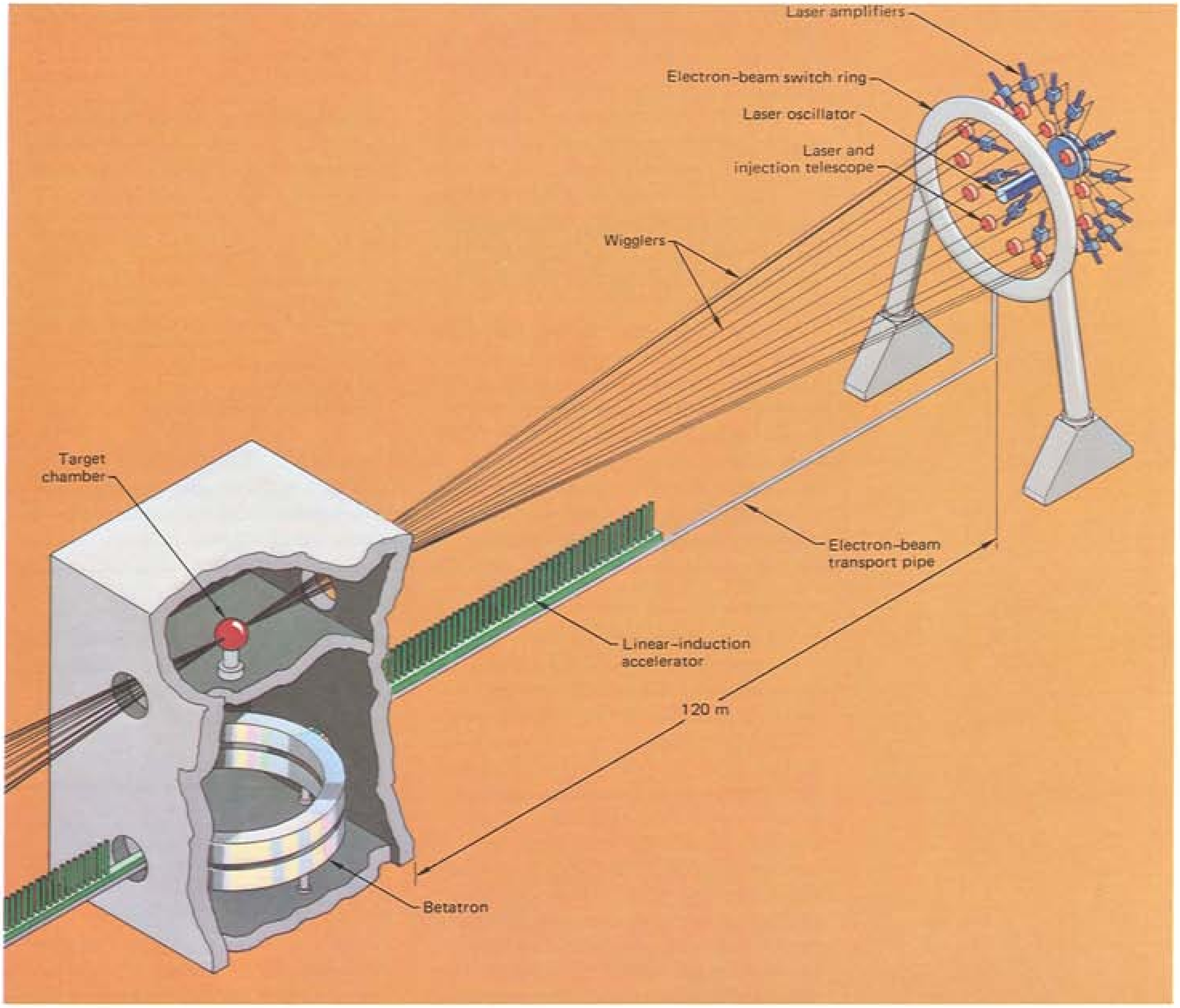


Fig. 6

Schematic drawing of a hypothetical 3-MJ ICF power plant using FEL technology. Up to 15 FEL amplifiers are configured to converge on a fusion target. The wigglers consist of laser pipes surrounded by magnets. The laser preamplifier subsystem consists of up to 15 small krypton-fluorine lasers. A grazing-incidence optical telescope in each preamplifier focuses the laser beam to provide 150 J/cm^2 as the beam is injected into the pipe aperture. All optical components are more than 130 m from the target chamber. The electron source is a 1.1-BeV betatron. Preaccelerated electrons enter the betatron from a 50-MeV linear-induction accelerator, are accelerated, and exit into a switch ring. Fast (3-ns) magnetic switches in the ring divide the relatively long accelerator pulse into as many as fifteen 15-ns flat electron-beam pulses. These shortened pulses are then magnetically guided into the wigglers.

Relativistic Effects for a Moving Electron

The Lorentz contraction is predicted by Einstein's special theory of relativity. Consider an electron moving with a velocity v_z relative to an object (in this case, the wiggler) of spacing λ_w (as measured by a stationary observer). In the electron's frame of reference, the wiggler will appear to have a length $\lambda'_w = \lambda_w/\gamma_z$, where

$$\gamma_z = \frac{1}{[1-(v_z/c)^2]^{1/2}} ,$$

c being the speed of light. Thus, the apparent spacing of the wiggler will decrease in the electron's frame of reference.

In classical physics, the Doppler shift is the phenomenon whereby, for example, the whistle of a train moving toward a stationary observer appears to have a higher frequency than if the train were moving away. In the relativistic analogue of this effect, if radiation has a wavelength λ'_s in a moving frame of reference, it will have a wavelength

$$\lambda_s = \lambda'_s/2\gamma_z ,$$

in the frame of reference of a stationary observer (see box on p. 22).

To apply these effects to the FEL, we assume that in the electron's frame of reference the radiation wavelength is the same as the spacing of the wiggler, so that

$$\lambda'_s = \lambda'_w .$$

Applying the Doppler and Lorentz effects to translate this relationship to the laboratory's frame of reference, we obtain

$$2\gamma_z\lambda_s = \lambda_w/\gamma_z ,$$

or

$$\lambda_s = \lambda_w/2\gamma_z^2 .$$

As γ_z may easily have a value of several hundred, a 4-cm wiggler spacing could produce radiation in the visible region of the spectrum (500 nm).

source is a betatron plus a linear induction accelerator). Up to 15 evacuated laser pipes surrounded by wiggler magnets converge in a cone aimed at the target.

The laser preamplifier subsystem consists of up to 15 small krypton-fluorine lasers, one for each laser pipe. A grazing-incidence optical telescope in each preamplifier focuses the laser beam to provide 150 J/cm^2 as the beam is injected into the pipe aperture, without exceeding 10 J/cm^2 at any optical surface. The laser output of each preamplifier proceeds directly through its pipe to the target. The only optical components in the system are in the laser preamplifiers and the telescopes, both of which are more than 130 m from the target chamber.

We estimated component and total costs for a 3-MJ ICF power plant based on the two candidate systems described above (Table 2). An eventual choice among candidate technologies will depend, among other things, on success in solving the associated technical and

Table 2 Nominal subsystem costs for two candidate 3-MJ FEL fusion drivers.

Subsystem	Linear induction accelerator, $ million	Betatron, $ million
Accelerator	235	165
Magnets	15	15
Pumps	10	10
Oscillators	5	5
Building	75	75
Total	340	270
Total/MJ	110	90

Table 3 Estimated technology efficiency of two candidate systems for a near-ultraviolet (250-nm) free-electron laser fusion driver.

Technology	Linear induction accelerator, %	Betatron, %
Pulsed power to B-field[a]	60	80[b]
Transfer to e-beam[c]	85	90
Stacking[d]	85	75
Fill factor[e]	80	80
FEL extraction[f]	38	38
Overall	13	16
Overall[g]	14	18

[a]Transfer efficiency from the wall plug to the accelerating magnetic field.
[b]Probably requires some recovery of energy stored in the magnetic field.
[c]Field energy coupled into the electron beam.
[d]Energy loss incurred by dividing one long pulse into many short pulses and then recombining (stacking) the latter on the target.
[e]Optimistic estimate of spatial overlap of the electron and laser beams; this will be revised as a result of our two-dimensional propagation studies.
[f]Calculated from our one-dimensional simulation.
[g]Includes recovery of thermal energy from spent electron beam.

engineering problems and on the impact of solutions on relative costs.

Table 3 gives the estimated efficiency of several technologies used in the linear-induction accelerator and betatron designs. At this point, the betatron design appears to have an overall efficiency edge of about 20% over the linear-induction accelerator design. The efficiency of both designs might be increased slightly by thermally converting the spent electron beam to electricity at 30% efficiency. Directly recovering the energy in the spent beam would be more efficient than thermal conversion but probably would be very expensive. Some of these estimates may be revised as a result of our two-dimensional propagation studies.

Conclusions

Preliminary experiments suggest the feasibility of the FEL as a source of high-power coherent radiation. The basic technology is now undergoing intensive research and development in the laser community. Favorable resolution of the challenging technical issues would open a new range of commercial and military applications for laser-based systems. We believe that prospects are encouraging for the eventual development of FEL amplifiers with the short wavelengths and high peak power required for a commercial-scale ICF power plant. Our studies suggest that such plants could combine high conversion efficiency with relatively low cost.

Key Words: electron-beam accelerator; energy conversion; free-electron laser; intertial confinement fusion.

Notes and References

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