Laser Focus World

Electrostatic free-electron lasers have many uses

Already a research tool, free-electron lasers could find applications in medicine and industry.

By Avraham Gover, Aharon Friedman, and Adam T. Drobot

Free-electron lasers based on electrostatic accelerators (ESA-FELs) promise new and exceptional sources of coherent electromagnetic radiation over a wide portion of the electromagnetic spectrum. These lasers have the potential for high average power and very high efficiency. Consequently, we predict that the development of ESA-FEL technology will result in many new industrial, scientific, and military uses.

An FEL consists of an electron source, an accelerator and transport system, and an interaction region, where the radiation is produced and radiative energy is extracted from the electron beam. The lasing mechanism in an FEL results from an interaction between free electrons and a magnetostatic wiggler field. The basic emission process is stimulated synchrotron radiation. When the wiggler period and electron energy are chosen to satisfy conditions of synchronism and proper electron phasing, the electron beam favors the transfer of energy to the radiation field (see Fig. 1).

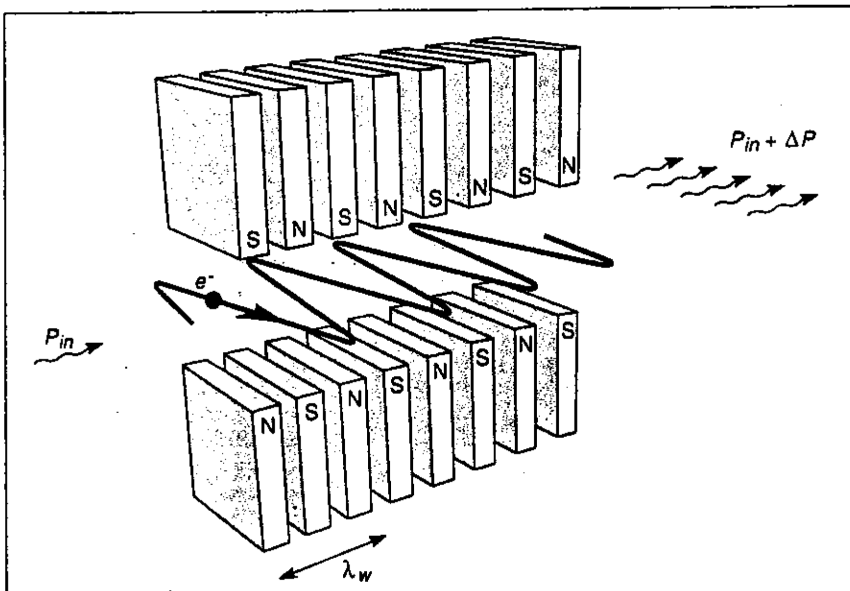

FIGURE 1. FEL lases when free electrons interact with magnetostatic wiggler field.

Operation of FELs has been demonstrated in the last decade at wavelengths ranging from microwave to UV light. FELs have been constructed with different kinds of particle accelerators, including RF accelerators, induction linacs, storage rings, and pulsed-line accelerators.[1] As the technology of FELs has matured, their ability to produce high power levels with high efficiency, while maintaining high coherence and wavelength tunability, has become evident. State-of-the-art FELs based on energy-recovery electrostatic accelerators have a remarkable advantage in power and efficiency and can fundamentally change the economics of producing coherent radiation, especially in the long-wavelength (IR to millimeter-wave) part of the spectrum.

With an energy-retrieval scheme, overall wall-plug energy-conversion efficiencies in excess of 50% may be possible, as is achievable in microwave devices.[2] High-average-power levels in the megawatt range are foreseen, and the coherence and optical quality of the produced radiation are expected to compete with those of conventional lasers.[3]

ESA-FELs

A particular scheme for an ESA-FEL based on a modified straight-geome-

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■ FREE-ELECTRON LASERS

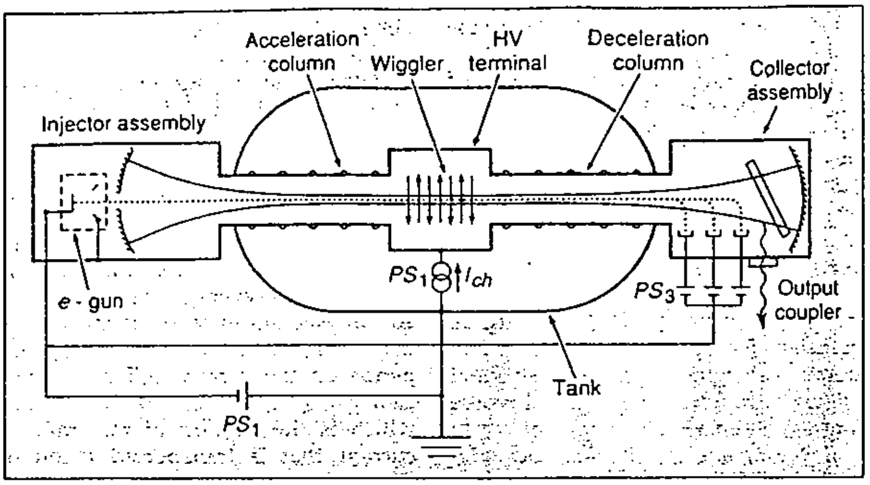


FIGURE 2. Electronic circuit of an FEL oscillator is based on a straight-geometry tandem electrostatic accelerator.

try tandem van de Graaff accelerator is shown in Fig. 2.[4] The accelerator is installed in a large tank that contains pressurized gas for electric insulation. In the center of the tank, a terminal is charged to high voltage (in the 5–25-MV range) by a current I_{ch}. The current source can be electromechanical, such as rotating belts, or in the form of chains, or it can be an electronic source made of a cascade of capacitors and diodes, as in the Crockford-Walton accelerator or a Dynamitron.[5] The electrons are brought into the high-voltage (HV) terminal through an acceleration column, and are extracted from it through a deceleration column.

The electrostatic accelerator is a conservative system—electrons accelerated and then decelerated through it do not draw energy from it. The simple, straight geometry helps maintain the electron-beam quality throughout the system. However, there is always some inevitable leakage of electrons from the imperfect beam into the system's walls, which may result in a drop in the terminal's voltage. Thus, for operation at steady state, a current (I_{ch}) equal to the total leakage current plus the "bleeding current" through the acceleration column resistors must be supplied throughout the operation of the device.

A wiggler magnet, a structure that produces a strong periodic transverse magnetic field in the interaction region, is placed in the HV terminal. As the electron beam passes through the wiggler field, it experiences transverse oscillations and emits undulator-synchrotron radiation in the forward direction. With the trapping of the emitted spontaneous radiation inside an optical resonator, a stimulated-emission process is enabled, and a coherent radiation field builds up in the optical resonator. When the laser oscillation threshold is exceeded, each electron emits multiphoton radiation (thousands to millions of photons), thus transforming a substantial fraction of its kinetic energy into the radiation field of the resonator.

The remainder of the electron-beam kinetic energy, which was not radiatively extracted, is not lost. The wasted beam is decelerated along the deceleration column and collected by a multistage segmented collector. The collector segments are biased in a way that replicates the energy distribution of the electron beam after the interaction with the radiation field in the wiggler region. With proper design, all the electron beamlets impinge on the collector segments with only small excess kinetic energy, and thus, the main source for energy waste, which is the heat production on the collectors, is diminished.

Clearly, the source of the radiative power in this scheme is the collector power supply and not the accelerator charging mechanism. The collector power supply operates at voltages corresponding to the energy loss of the electrons (tens to hundreds of kV) and currents equal to the current transported through the accelerator (on the order of amperes).

Characteristics and trade-offs

Wavelength. The ESA-FEL is expected to be an excellent high-power source in the far-IR and near-mm wavelengths. Realization of ESA-FEL devices in the optical regime is more difficult due to the relatively low acceleration energy available with electrostatic accelerators.

The operating wavelength of FELs is determined by the Doppler-shift relation

$$\lambda = \frac{1 + \bar{a}^2_w}{2\gamma^2} \frac{\lambda_w}{n}$$

where $a_w = e\,\bar{B}_w\lambda_w/(2\pi mc)$, $\bar{B}_w$ is the magnetic field of the wiggler and λ_w its period, $\gamma = E/mc^2$ is the relativistic Lorentz factor and $n = 1, 3, 5 \ldots$ is the harmonic order of the FEL operation. State-of-the-art electrostatic accelerators have energies of $E \leq 25$ MeV ($\gamma < 50$), and conventional wiggler technology provides wiggler strengths of $-\bar{B}_w \leq 1$ Tesla and wiggler periods of $\lambda_w \geq 25$ mm. These parameters are compatible with design requirements of FELs in the far-IR and millimeter-wavelength regime in such applications as electron-cyclotron resonance heating of confined plasma for thermonuclear fusion and for material processing.

There are numerous applications of high-power coherent radiation at optical wavelengths. However, operation of an ESA-FEL in the optical regime (at wavelengths below 6 μm) requires improvement in the technology of either high-energy accelerators or short-period wigglers. Increase of electrostatic accelerator energies to 50 MeV ($\gamma = 100$) is conceivable and will be sufficient for operation in the optical frequency regime with conventional wigglers, but will inevitably involve large size and weight.[6]

Development of short-period wigglers ($\lambda_w < 5$ mm), and strong wigglers operating at harmonic frequencies, is less expensive and has a higher payoff. Various schemes for short-period wigglers have already been proposed, including superconductor magnets, electromagnetic pumps,[7] conventional permanent magnets,[8] and electromagnets (see Fig. 3).[9,10] Such wigglers will make it possible to operate in the optical frequency regime with conventional accelerators of 10–20-MeV energy.

Power. The average optical power generated by the FEL is given by

$$\Delta P_{av} = I_{av}\,\Delta E_{av}/c$$

where I_{av} is the average electron-beam current flowing through the wiggler and ΔP_{av} is the average energy extracted per electron in favor of the radiation field. The average current I_{av} de-

Table 1. Radiative power generation by ESA-FELs

ΔE_{av} (MeV)	I_{ch} (mA)	η_{coll} (%)	I_{av} (amp)	ΔP_{av} (MW)	$^*\Delta P_{peak}$ (MW)	I_{peak}	$^{**}P_c$ (GW)
0.5	1/10/100	99/90/0	0.1	0.05	0.5	2	0.1
0.5	1/10/100	99.9/99/90	1.0	0.5	10.0	20	1.0
0.5	10/100	99.9/99	10	5 CW aver.	100 pulsed	200	10 Q-switched

* assuming duty cycle 5%
** assuming round-trip reflectivity 99%

pends on the current collection efficiency η_{coll} of the accelerator system, which is the fraction of the emitter current that is transported through the accelerator without interception all the way to the collector. At steady state, the leakage current $I_{av}(1 - \eta_{coll})$ equals the charge current I_{ch}. Consequently,

$$I_{av} = \frac{I_{ch}}{1 - \eta_{coll}}$$

Table 1 presents three exemplary sets of parameters that demonstrate the potential of high-power operation. With these parameters, average optical power in the range ΔP_{av} = 0.05–5 MW can be produced by the device in CW operation. Because the system is predominantly limited by average current, one can obtain higher peak powers by pulsing the electron-beam gun. The table lists the corresponding pulse-power levels ΔP_{peak} = 1–100 MW for an assumption of 5% duty factor. Even higher-pulsed power levels (at a lower repetition rate) can be obtained by instantaneously dumping out all the power stored in the cavity (P_c) in a Q-switched operating mode. The stored power levels, P_c = 0.1–10 GW, are attainable with an assumption of cavity round-trip reflectivity R = 99%.

State-of-the-art operation

Although the technology of ESA-FEL is in its infancy, the depressed collector was developed four decades ago in connection with microwave tubes, which can operate with efficiencies exceeding 50%. A research group at the University of California at Santa Barbara (UCSB) demonstrated the extension of this kilovolt-range technology to the megavolt regime in 1983.[12] They subsequently demonstrated free-electron lasing, first at λ = 400 μm, with E = 3 MeV[2], and later at λ = 120 μm, with E = 6 MeV. The FEL operated at the tens-of-kilowatts power range with tens-of-microseconds pulse duration. The pulsed current circulated in the system was in the ampere range, with a collection efficiency during operation of η_{coll} = 95%–97%.

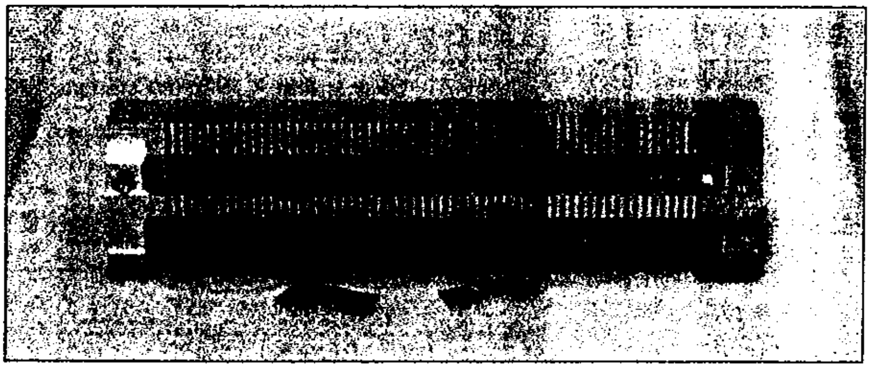
The UCSB experiment is, so far, the only demonstration of an ESA-FEL. There is not as yet an experimental demonstration of a straight-geometry tandem FEL as shown in Fig. 2, but there is ongoing development based on such a configuration at UCSB,[8] in the Weizmann Institute of Science in Israel,[4] and in the Institute Nationale Fizika Nucleare (Milan, Italy).[5] The demonstration and evaluation of FEL operation in this positively charged HV terminal configuration is anticipated with great interest because it can provide higher voltage, higher current, and higher collection efficiency than the folded-geometry tandem configuration used in the UCSB experiment. Thus, it is the best scheme for the short-wavelength high-power operation range.

Table 2. Applications of high-power FELs

Application	Short wavelength	High power	High efficiency	Tunability	High spatial coherence	Narrow spectral width
Material biological research	30–1000 μm***	0.1–1000 W***		Yes***	Yes***	Yes***
Medical	vis-IR**	1–50 W***		Yes***		
Tokmak ECRH[1]	0.5, 1 mm***	1–20 MW***	>40%***	5–10%/ms***		
Material processing (thermal)	10–1000 μm***	>5 KW***	>20%***			
Material processing (quantum)	UV-vis*	1–100 KW***	>3%***	Yes***		Yes***
Photochemical isotope separation	0.15, 0.3, 0.5 μm (16–200 μm)*	100 KW**	>1%***	Yes***		Yes***
Lidar remote sensing	vis-IR***	1–100 KW***		Yes***	Yes***	Yes***
Atmos./space energy transmission/ propulsion	vis-IR*	10–100 MW*	>50%**		Yes***	
Inertial fusion	0.3–0.5 μm*	10 TW peak*	>5%**		Yes***	

* requires substantial technology development
** attainable with moderate development effort
*** presently attainable

[1]Tokmak-magnetic fusion device
ECRH-electron cyclotron resonance heating



MIT/ODETICS

FIGURE 3. Electromagnet microwiggler with period λ_w = 2.4 mm has been developed by the Massachusetts Institute of Technology (Cambridge, MA) and Odetics (Anaheim, CA).

Projected applications

High-power electrostatic accelerators can be used in applications that take advantage of the high average power, high efficiency, and tunability of the source, and, on the other hand, can tolerate the large size and immobility of the system. The anticipated system cost is expected to be high (millions of dollars per unit). On the other hand, due to the high conversion efficiency of the device, the photon-production cost is expected to be low and eventually limited by electric-power cost.

Some present and possible future uses for high-power FELs are listed in Table 2. The symbols represent estimates of the availability of the required operating parameters for different applications and are extrapolations from current technology. Undoubtedly, the first applications of ESA-FEL would be for scientific (material and biological) research.

In fact, the UCSB FEL currently operates as a user facility and has provided coherent far-IR radiation for numerous experiments in biology, medicine, and solid-state research since 1987.

The mid-IR range of the spectrum (10–1000 μm) can be attained with state-of-the-art accelerators and wigglers. Numerous solid-state elementary excitations and electronic levels can be studied spectroscopically at this wavelength region, taking advantage of the tunability and coherence of the source (of recent interest are high-T_c superconducting materials with band structure in the 8–140 MeV.[11] The high (kW) power of the device also allows application to nonlinear spectroscopy. Biomedical studies include excitation of vibrational modes in DNA and investigation of laser-tissue interaction. The control over pulse duration and pulse structure, combined with the frequency tunability, gives the ESA-FEL a distinct advantage in these applications.[12]

Other applications listed in Table 2 require development to bring the ESA-FEL to operation closer to the limits of its technical potential. These applications require either the extension of the operating wavelength to shorter wavelengths or the increase of its operating power, or both.

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