Free-Electron Lasers: Present Status and Future Prospects

KWANG-JE KIM AND ANDREW SESSLER

Free-electron lasers as scientific instruments are reviewed. The present status and future prospects are delineated with attention drawn to the size, complexity, availability, and performance capability of this new tool.

THE FREE-ELECTRON LASER (FEL) WAS PROPOSED BY JOHN Madey in 1970 (*1*), although earlier work, relevant to the concept, had been done by Motz (*2*) and by Phillips (*3*). Experimental demonstration was achieved by Madey and his associates in 1975 and 1976 (*4*). Since that time, FELs of diverse configurations have been operated at several laboratories around the world. At present, FEL development is focused in two directions: in the construction of reliable FELs for scientific research in the infrared (IR) region and in the extension of FEL capability to vacuum ultraviolet (VUV) and even shorter wavelengths. In this article we shall briefly review the principles of an FEL, putting emphasis on those aspects that limit performance. Then we shall discuss the applications, present status, and future prospects of FELs.

Brau (*5*) has described the history, the basic principles, various experiments, and potential applications of FELs. The textbooks on FELs (*6*) provide even more material, and there have been a number of other review articles (*7, 8*). In addition, the interested reader may consult the Proceedings of the International FEL Conferences (the 12th will be held this year) where many of the original research papers have been published (*9*).

Principles of the FEL

An FEL produces coherent radiation from a beam of free electrons rather than from electrons bound into atoms or molecules, as in a conventional laser. The electrons are passed through a transverse magnetic field alternating in sign along the direction of the electron's motion. The device that produces the periodic magnetic field is known as a wiggler (or sometimes an undulator). The configuration is shown diagrammatically in Fig. 1, which also shows the resonant optical cavity for the output radiation. The resonance condition involves the electron energy, γ (in units of the electron rest energy mc^2, where m is the electron mass and c is the speed of light); the magnetic period length, λ_w; the wiggler field strength, B; and the output radiation wavelength, λ. This relation is:

$$\lambda = (\lambda_w/2\gamma^2)(1 + a_w^2) \qquad (1)$$

where the wiggler peak field strength, B, is expressed by (meter-kilogram-second units)

$$a_w = eB\lambda_w/(2^{3/2}\pi mc) \qquad (2)$$

The tremendous interest in FELs derives from this resonance condition, namely, the easy tunability of an FEL and the wide range of wavelengths that are available to the FEL. There are three ways to tune an FEL: (i) it is possible to design wigglers having a range of wiggler period lengths (usually in the centimeter range); (ii) it is easy to generate electron beams having various energies (in γ units, from near unity to thousands); and (iii) it is possible to change the wiggler magnetic field.

Thus, as compared to a conventional laser, which is tied to the natural resonance frequency of the atom or molecule, for an FEL all frequencies are possible. The electromagnetic spectrum is shown in Fig. 2, where we also show some alternative sources of radiation. One can see that sources are lacking both in the IR region (1 μm $\leq \lambda \leq$ 1 mm) and in the UV and shorter wavelength region ($\lambda \leq$ 1000 Å). FELs could presumably fill these gaps. In Fig. 3 we show the performance of FELs to date; the features of operation in different wavelength ranges and tunability have already been demonstrated.

The wiggler can be constructed from either electromagnets or permanent magnets. Attention must be given to the field quality and alignment of the wiggler. The development of high-field, short-period wigglers, made with permanent magnets, has been an important factor in constructing efficient FELs. One can easily change the magnetic field of a permanent magnet wiggler by changing the wiggler gap

An FEL can be operated either as an oscillator, as we show in Fig. 1 where an optical cavity is indicated, or as an amplifier. Most FELs are operated in the oscillator mode, and attention must be given to mirror properties. In an amplifier mode, the gain in a single traverse needs to be significant, and this requires an intense electron beam. (In an oscillator, the gain per pass only needs to be larger than the loss per pass.)

In the amplifier mode, because no mirrors are involved, operation can be obtained in short-wavelength ranges where high reflectivity mirrors are difficult to construct. Either an input signal may be used, which can readily be done for longer wavelengths, or amplification can be made to grow from noise by means of self-amplification of spontaneous radiation (SASE). In the short-wavelength range, where even low-power input signals are not available, an FEL must rely on growth from noise.

As an electron moves down the wiggler of an FEL, it loses energy to the growing electromagnetic wave and, consequently, no longer satisfies the resonance condition. As a result, the FEL stops working; that is, "reaches saturation." This can be avoided if the wiggler field, B, is varied to match the changing resonance condi-

The authors are physicists at the Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.

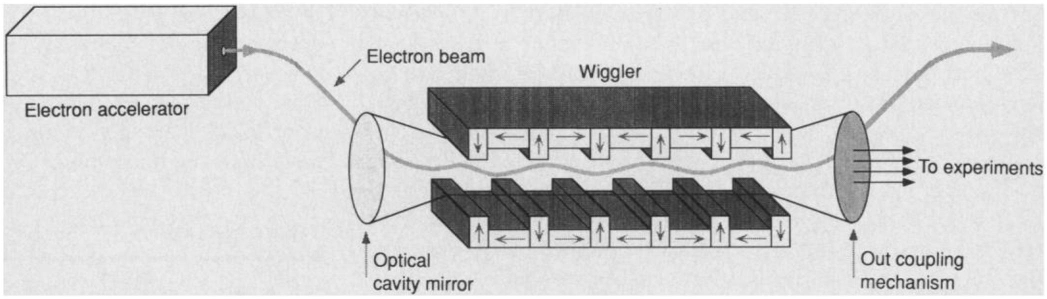

Fig. 1. A schematic diagram of a free-electron laser. A beam of electrons is generated in the electron accelerator and then passed through a region of alternating direction magnetic field (wiggler). Coherent light is generated and contained in an optical cavity defined by the mirrors. Care must be given to generating, focusing, and transporting the electron beam, as well as to proper treatment of the light beam.

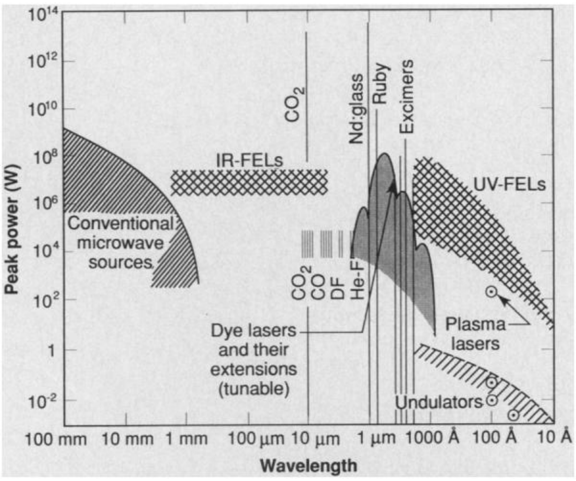

Fig. 2. FELs have already provided tunable, coherent radiation in the IR and UV spectral ranges. The diagram shows the power and range of some other sources of radiation: conventional microwave sources (tubes, klystrons, gyrotrons); lasers; plasma lasers (indicated by ⊙); undulators on third-generation synchrotron radiation facilities. There are wide ranges of the spectrum where there is need for the FEL. Possible FEL performance is indicated by the cross-hatched regions.

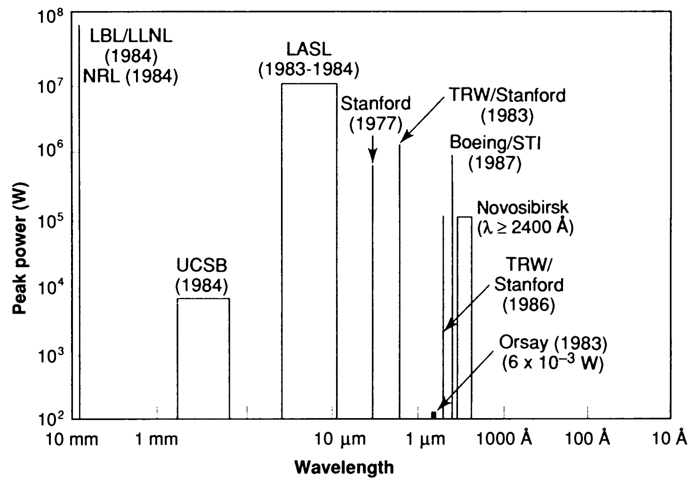

Fig. 3. Achieved FEL performance as a function of wavelength, showing the wide range of wavelengths in which FELs have been operated, as well as the wide tunability ranges realized. Abbreviations: LBL, Lawrence Berkeley Laboratory; LLNL, Lawrence Livermore National Laboratory; NRL, Naval Research Laboratory; LASL, Los Alamos Scientific Laboratory; UCSB, University of California at Santa Barbara; STI, Spectra Technology, Inc.

tion. With this so-called "tapering," the FEL continues to operate even when the wiggler is very long. Tapering is important for some high-gain amplifier operations.

An FEL "works well" provided certain conditions on the quality of the electron beam are satisfied. In the past, essentially all the difficulties with FELs have not been due either to technological problems in the FEL or to theoretical problems concerning FEL operation, but rather to the fact that the electron beam was not of sufficient quality, that is, the beam did not satisfy the conditions required for operation of an FEL. As the technology of electron beams improves, one can expect to see ever more powerful FELs, devices that span an even larger range of wavelengths and produce even more power.

Roughly, beam quality is described by two quantities: beam energy spread, $\Delta\gamma/\gamma$, and beam emittance, ϵ. The energy spread is a measure of longitudinal spread, and ϵ, the emittance, is a measure of the transverse spread. The emittance, ϵ, is the area of the transverse phase space occupied by the electron beam; in terms of beam radius, a, and beam angular divergence, θ, it is given by $\epsilon = \pi a \theta$.

What are the conditions on electron beam quality? An optical beam has an emittance of order λ. Thus, it is necessary that the electron beam emittance be matched to the optical beam; that is, $\epsilon \leq \lambda$. The FEL gain bandwidth is $1/2N$, where N is the number of periods in the wiggler. It is necessary to have the energy spread less than gain bandwidth; namely, $(\Delta\gamma/\gamma) \leq 1/2N$.

In addition to these two conditions on beam quality, there is a condition on beam current. That condition is related to the required gain and therefore depends on the mode of operation of the FEL. We shall not go into details here, but roughly the requirement is a few amperes for an oscillator and a few hundred amperes for an amplifier.

Applications

There are many applications envisioned for FELs. (We say "envisioned" because, so far, there have been very few actual uses of FELs.) A number of conferences have been devoted to the subject (*10*). In Table 1 we list some of these potential applications.

Microwave. High power from an FEL operating in the mirowave range has already been demonstrated. Thus, applications requiring this capability, such as plasma heating in tokamaks or acceleration of particles in conventional linacs, are near at hand. For plasma heating, the primary physics issue is the plasma response to the high peak power of an FEL (which necessarily brings in nonlinear effects that may or may not be advantageous), in contrast with conventional (almost d-c) gyrotrons. There are, also, economic considerations.

In the accelerator application, FELs become the microwave sources and therefore make possible operation in the high-frequency range (up to approximately 30 GHz, compared with 3 GHz in the large accelerator at Stanford) where conventional klystrons are no longer effective. The primary issue is economic, and, to this end, two-beam accelerators have been developed. They use a drive beam for powering the FEL and a second beam that is accelerated to high energy. Two-beam accelerators are expected to increase efficiency (and hence reduce operating cost) while tolerating a larger capital cost, but, because they have various novel features, their development involves new physics issues, which are, only now, being studied.

Infrared. Many of these applications can be expected rather soon; that is, they require radiation in the IR (which is relatively easy to come by), but they do not require high power. Nevertheless, these applications require facilities that take account of the user needs in such things as stability, linewidth, reliability, ease of tuning, and so forth. Radiation from an IR FEL can be used to manipulate molecular vibrations and chemical reactions in both the condensed and the gas phases. The IR pulses will make possible new studies on intramolecular vibrational energy transfer by means of IR multiphoton excitation and dissociation, a technique thus far limited to the molecular species that can be excited by CO_2 lasers. With broadly tunable IR FELs, the technique can be extended to practically all molecular species. The new studies will provide valuable information on, for example, the combustion phenomena. High average-power IR FELs would ultimately allow materials to be synthesized from across a wide range of the periodic table. The pump-probe type experiments involving an IR FEL and a second light source (which can be another FEL, a conventional laser, or a synchrotron light source), will allow quantitative studies of many surface phenomena, such as time-dependent redistribution of surface molecules, diffusion, desorption, and so on. Measurement of the band gap of the high T_c (T_c is the superconducting transition temperature) superconductor will be possible because of the high intensity of the IR FEL radiation.

Many military and medical applications require high power at short wavelengths (about 1 μm). This level of operation has not yet been achieved by FELs, and thus these applications still lie in the future.

Short wavelengths. The applications in the UV and the x-ray range are most attractive and are driving the FEL physicist to learn how to operate at very short wavelengths. For example, there is great desire to reach the "water window," between 24 and 44 Å, where biological materials can be studied in their natural aqueous environment. Also, there is great interest in obtaining sufficiently narrow bandwidth and intensity for probing the fine details of the chemical

Table 1. FEL applications.

1. Condensed matter studies
   - Surface science (IR)
   - Semiconductors (IR)
   - Superconductors (IR)
   - Magnetic properties (IR, soft x-rays)
2. Nonlinear plasma studies
   - Heating (microwave)
   - Current drive in tokamaks (microwave)
3. Nonlinear quantum electrodynamics studies (1 or 10 μm)
4. Nonlinear optics and nonlinear microwaves
5. Inertial fusion (~1/2 μm)
6. Chemistry
   - Molecular excitations (IR)
   - Dynamic reactions (1 to 10 μm)
   - Crossed photon-molecular beams (1000 to 2000 Å)
7. Biology
   - Microscopy (40 Å)
   - DNA studies (5 Å and IR)
   - Cell response (IR)
8. Medicine
   - Surgery (1 to 10 μm)
   - Photoreactions (IR)
9. Accelerators
   - Inverse FELs
   - Two-beam accelerators (1 to 3 cm)
10. Chemical production (VUV)
    - Fixing polymers
    - Making drugs
11. Isotope separation (IR)
12. Lithography (10 Å)
13. Military uses (IR, visible)

Table 2. Worldwide FEL projects.

China
Shanghai (diode, RF linac)
IAE, Beijing (RF linac)
IHEP, Beijing (RF linac)
Chengdu (induction linac)
England
Glasgow (RF linac) (project terminated)
France
Orsay, ACO (storage ring) (project completed)
Orsay, Super ACO (storage ring)
Orsay, CLIO (RF linac)
Bruyères (RF linac)
Palaiseau (diode)
Lille/Dijon (electrostatic)*
Bordeaux (induction linac)
Germany
KFI, Darmstadt (superconducting)
Dortmund DELTA (storage ring)*
Israel
Technion (diode)
Weizmann (electrostatic)
Italy
ENEA, Frascati (microtron)
INFN, Frascati, ARES (superconducting RF linac)
Milan, ELFA (superconducting linac)*
Padua (electrostatic)*
Japan
JAERI (superconducting RF linac, induction linac)
Narashino (microtron)
Mitsubishi (RF linac)
University of Tokyo (RF linac, storage ring)
Osaka (induction linac, diode)
ISIR (RF linac)
ETL (storage ring)
KEK (induction linac)
Netherlands
FOM, Rijnhuizen FELIX (RF linac)
Twente (microtron)
United States
Stanford, SCA (superconducting RF linac)
Stanford, Mark III (RF linac) (project completed)
Duke (RF linac)
Duke (storage ring)
Los Alamos (RF linac)
Boeing (RF linac)
University of California, Santa Barbara (electrostatic)
Naval Research Laboratory (diode) (project completed), (induction linac)
Columbia (diode)
Livermore, ELF, Paladin (induction linac) (project completed), MTX (induction linac)
National Institute of Standards and Technology–Naval Research Laboratory (microtron)
Vanderbilt (RF linac)
University of Florida, CREOL (electrostatic)*
Brookhaven (storage ring) (project terminated), (RF linac)
Massachusetts Institute of Technology (diode, induction linac)
Hughes (diode)
Lawrence Berkeley Laboratory (RF linac)*
University of California, Los Angeles (RF linac)*
Bell Labs (microtron)
U.S.S.R.
INP, Novosibirsk (storage ring)
Erevan (microtron)

*Proposed.

dynamics of dilute samples, in obtaining sufficient spatial coherence for holography, and in obtaining sufficient power at short wavelengths to permit projection lithography and material processing. Some capabilities, in coherence and in power, in the short-wavelength region will be available soon with the completion of the advanced synchrotron radiation facilities under construction at several laboratories around the world (see Fig. 2) (*11*). Experience in dealing with intense short-wavelength radiation with these sources will provide a base for the more challenging experiments possible with the more intense and coherent FEL sources.

Present Status

The considerable interest in the FEL is apparent from a list of worldwide activities (Table 2). This compendium lists ongoing projects, past projects, and future projects. The purpose of the table is to give a feeling for the range and diversity of the activities.

The projects use just about every kind of electron accelerator known. That is in part a result of history (what an institute happens to have and what it has expertise in), and in part a result of the fact that it is not yet clear what is the most suitable accelerator for a particular kind of FEL.

We have selected a few representative projects and presented more information about them in Table 3. These are all operating FELs, so the performance characteristics are very much real values and not merely design expectations. We have listed the wavelength range, the linewidth of the radiation, the pulse structure, the energy per pulse, and the average power. The reader can compare this performance with that of other sources and consider experiments now possible that previously were not so. These projects are the base upon which worldwide enthusiasm for new FEL projects has been built.

In Fig. 4 we show the FEL undulator installed on the Super ACO at Orsay. The installation is large, complicated, and expensive. This particular facility is a bit larger than those FEL facilities in the IR region (the Orsay facility is primarily a synchrotron radiation facility serving many users), but the general impression is correctly given.

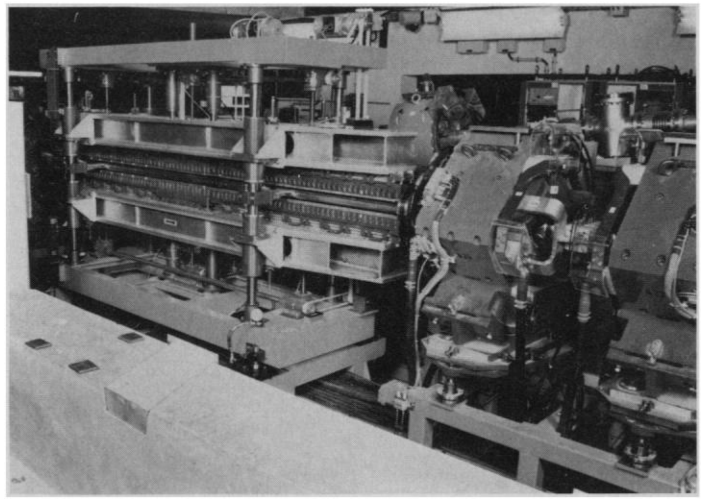

Fig. 4. The FEL in the Super ACO storage ring at Orsay. The facility is complicated and represents a considerable investment. That is generally true of FELs; they are not inexpensive, and it seems most unlikely that they will ever become tabletop in size like ordinary lasers.

Future Prospects

In the future, FEL development will probably proceed along two separate paths. In the IR region, where the technologies for the accelerator and optical cavities are available, the emphasis will be on constructing user facilities. In the short-wavelength region, the emphasis will be on the development of technology.

IR FEL user facilities. IR FELs have been built and operated; but these first devices were oriented toward learning about FELs rather than toward serving a community of users. The challenge in the future will be to build an FEL that satisfies a unique set of criteria required for a user facility. We list parameters of four representative new facilities in Table 4. The first three facilities in this table are under construction. The last one is in the proposal stage, but it is listed here as it is a representative of the present state of the art and shows what can be expected. It is likely that all of these facilities will operate rather reliably, in a stable manner, and for a very large percentage of scheduled operating time.

An important criterion for an FEL user facility is the stability of the FEL output, in wavelength, in intensity, and in direction. Thus the choice of the accelerator system and design must be made with the view of ensuring the required stability. The jitter in electron beam parameters, such as the electron beam energy, charge, timing,

Table 3. Representative operating FELs.

Parameter	Los Alamos	Stanford Mark III	Santa Barbara	Stanford SCA	Novosibirsk	Orsay
Accelerator	RF linac (standing wave)	RF linac (traveling wave)	d-c	Superconducting linac	Storage ring	Storage ring
Electron energy	23 MeV	45 MeV	3 MeV	66 and 115 MeV	350 MeV	150–240 MeV
Wavelength range	10–45 μm	2–8 μm	130–400 μm	0.5–3.0 μm	2400–6900 Å	5700–6400 Å
Bandwidth ($\Delta\lambda/\lambda$)	0.3%	0.5%	0.1%*	0.1%	0.01%	0.01%
Micropulse duration	8 ps	1–2 ps	3 μs	2–4 ps	75 ps	<300 ps
Repetition rate†			50 Hz		8 Mhz	27 MHz
Micropulse	22 MHz	2.8 GHz		12 MHz		
Macropulse	1 Hz	15 Hz		10–20 Hz		
Micropulse energy	200 μJ	5–7 μJ	4.5 mJ	1–5 μJ	1–100 nJ	2–5 nJ
Average output power	1 W	3 W	0.23 W	10 W	6 mW	3 mW

*Including jitter. †A pulse from an FEL driven by an rf linac will consist of a macropulse containing many micropulses.

Table 4. Parameters of some planned facilities (IR).

Parameter	FELIX (*15*)	NIST-NRL (*16*)	CLIO (*17*)	CDF (*18*)
Accelerator	RF linac	Microtron	RF linac	RF linac
Electron energy	15–45 MeV	185 MeV	30–70 MeV	56 MeV
Wavelength range	5–160 μm	0.2–10 μm	2–20 μm	3–50 μm
Micropulse duration	3 ps	3 ps	10–15 ps	10 ps
Macropulse duration	20 μs		10 μs	100 μs
Repetition rate*		74 MHz		
Micropulse	1000 MHz		30–500 MHz	37 MHz
Macropulse	10 Hz		50 Hz	60 Hz
Micropulse energy	25 μJ	0.1–3.0 μJ	100 μJ	200 μJ
Average output power	5 W	25–200 W	10–100 W	20 W

*As clarified in the footnote to Table 3.

and so on, needs to be tightly controlled by using feedback and feed-forward correction. Thus, for example, the fluctuation in the electron beam energy for the Combustion Dynamics Facility (*15*) will be reduced to less than 0.05%.

Another important criterion is the ease of wavelength coverage and tuning; the facility must provide a wide wavelength coverage with minimum interruptions to the users. It is more or less straightforward to change the electron energy or the wiggler gap. It is less straightforward to design a broad-band optical system that includes the optical cavity, output coupling, and beam transport from the FEL to the experimental station. Work in this direction is just beginning and can be expected to advance significantly in the future.

FELs for 1000 Å or shorter wavelengths. The short-wavelength record in FEL is 2400 Å obtained at Novosibirsk. Realizing FELs for short wavelengths is difficult because the electron beam requirements are more demanding: these include higher energy, higher current, smaller emittance, and smaller energy spread. Also, high-reflectivity mirrors suitable for optical cavity are currently not available. In spite of these difficulties, several laboratories are engaging in research for the development of short-wavelength FELs because the scientific payoffs are great (*12, 13*).

Among different accelerators, electron storage rings appear to be the most promising source of electron beams for short-wavelength FELs. The unique radiation damping mechanism improves, and maintains, beam quality in the storage ring. The accelerator community has gained considerable experience recently in the art of building high brightness electron storage rings in connection with the advanced light source projects at several places around the world. The drawbacks of the storage ring–based FELs are that the storage rings are big and expensive and that the average output power tends to be limited because the damping is a slow process.

Another approach is to use radio-frequency (RF) linacs. In that case, it is necessary to start out with a good emittance beam, since there is no damping mechanism. The recent development of laser-driven RF photocathodes (*14*) appears to make possible the generation of such low emittance, yet intense, beams. It is upon this new technology that the linac FELs, for very short wavelengths, are based. The linac technology benefits from high-energy physics linear collider projects.

Multifacet mirrors and multilayer mirrors are currently under development for use in short-wavelength FELs. The use of mirrors can be entirely avoided if FELs are run in the amplifier mode. As the

Table 5. Parameters for representative short-wavelength FEL projects.

Parameters	Los Alamos National Laboratory (*19*)	Duke (*20*)	Lawrence Berkeley Laboratory (*21*)	Brookhaven National Laboratory (*22*)
Accelerator	RF linac	Storage ring	Storage ring	Superconducting linac
Electron energy	100–500 MeV	800–1000 Mev	750 MeV	250 MeV
FEL type	Oscillator	Oscillator	Amplifier	Amplifier
Wavelength	10–4000 Å	50–4000 Å	400 Å	1000–3000 Å
Micropulse duration	10–30 ps	300 ps	100 ps	5 ps
Repetition rate*		3 MHz	10 Hz	3–10 kHz
Micropulse	10–100 MHz			
Macropulse	30 Hz			
Peak output power	1–10 MW	10 kW	50 MW	300 MW
Average output power	1–10 W	10 W	50 mW	15 W

*As clarified in the footnote to Table 3.

input radiation, if available at all, is usually quite weak in the short-wavelength region, the FEL in the amplifier mode is inherently a high-gain device. In the case of extreme high gain (one million or larger), the FEL can amplify the initial noise signal (the undulator radiation) to intense, coherent radiation. Although operation in this (SASE) regime requires neither mirrors nor coherent input signals, the requirements on the electron beam qualities and the wiggler construction are very demanding.

Considerable effort is being directed toward the development of short-wavelength undulators. This development is important for short-wavelength FELs as, the smaller λ_w is made, the less energetic are the electrons that are required for a given optical wavelength. At present, undulators with wavelengths λ_w of about ~1 cm are being developed that use either permanent magnets, superconducting magnets, or electromagnetic (iron) magnets.

Laboratory and theoretical work is being undertaken on the development of even shorter wavelength ($\lambda_w \approx 1$ mm) undulators ("microundulators"), gas-loaded FELs, plasma-loaded FELs, and two-stage FELs. All of this work is motivated by the desire to reach short wavelengths in an economic and reliable manner. However, none of these developments have yet reached the stage of being incorporated into projects.

In Table 5 we list the parameters of some short-wavelength FEL projects. The Duke facility is being constructed, Los Alamos National Laboratory is building a linac to test the concept, and the other two projects are in a very preliminary stage. The Lawrence Berkeley Laboratory facility uses an amplifier, rather than an oscillator, so as to avoid the use of mirrors. The consequence is that the storage ring peak current must be very large and the FEL wiggler very long and of high field. The last requires a small gap, so small that the wiggler must be put into a special bypass section of the storage ring (so as to avoid drastic reduction of the electron beam lifetime); the electron beam is switched into the bypass once per damping time.

Conclusions

It has been two decades since an FEL was first conceived. During that time, many different FELs have been built, operated, and analyzed, and as a result the understanding of FELs has been greatly advanced. Only a few experiments have so far been done using the photons from an FEL, but a number of "user facilities" (in the IR) are now under construction, and the next decade should witness a flowering of experiments using the unique capabilities of FELs. In addition, the FEL appears to be capable of producing UV, VUV, and even x-ray radiation. Work on this frontier is ongoing, but no "user facilities" can be expected until sometime after this decade.

REFERENCES AND NOTES

1. J. M. J. Madey, *J. Appl. Phys.* **42**, 1906 (1971).
2. H. Motz, *ibid.* **22**, 527 (1951).
3. R. M. Phillips, *IRE Trans. Electron Devices* 7, 231 (1960).
4. L. R. Elias *et al.*, *Phys. Rev. Lett.* **36**, 717 (1976); D. A. G. Deacon *et al.*, *ibid.* **38**, 892 (1977).
5. C. A. Brau, *Science* **239**, 1115 (1988).
6. T. Marshall, *Free-Electron Lasers* (Macmillan, New York, 1985); C. Brau, *Free-Electron Lasers* (Academic Press, New York, 1990).
7. W. B. Colson and A. M. Sessler, *Annu. Rev. Nucl. Sci.* **35**, 25 (1985); A. M. Sessler and D. Vaughan, *Am. Sci.* **75**, 34 (1987); B. E. Newnam, Ed., *Free-Electron Lasers* (Critical Reviews of Optical Science and Technology, SPIE 738, International Society for Optical Engineering, Bellingham, WA, 1987); H. P. Freund and R. K. Parker, *Sci. Am.* **260**, 84 (April 1989).
8. J. M. Ortega, *Synchrotron Radiat. News* **2** (no. 2), 18 (1989); *ibid.* (no. 3), p. 21; *ibid.* **3** (no. 1), 24 (1990).
9. Proceedings of the 10th International Free-Electron Laser Conference, Jerusalem, 29 August to 2 September 1988 [*Nucl. Instrum. Methods Phys. Res. A* **285** (nos. 1 and 2) (1989), and previous conferences referenced therein].
10. Proceedings of the Workshop on Applications of Free-Electron Lasers, Castelgandolfo, Italy, 10 to 12 September 1984, D. Deacon and A. De Angelis, Eds. [*Nucl. Instrum. Methods Phys. Res A* **239** (no. 3) (1985)]; "Free-electron laser applications in the ultraviolet" (*1988 Tech. Dig. Ser.*, vol. 4, Optical Society of America, Washington, DC, 1988); D. Prosnitz, Ed., "Free-electron lasers and applications," *Proc. Soc. Photo-Opt. Instrum. Eng. 1227* (1990).
11. D. Attwood, K. Halbach, K.-J. Kim, *Science* **228**, 1265 (1985).
12. J. M. J. Madey and C. Pellegrini, Eds., *Free Electron Generation of Extreme Ultraviolet Coherent Radiation* (AIP Conference Proceedings 118, American Institute of Physics, New York, 1984).
13. B. E. Newnam, *Nucl. Instrum. Methods Phys. Res. B* **40/41**, 1053 (1988); C. Pellegrini, *ibid. A* **272**, 364 (1988).
14. J. S. Fraser, R. L. Sheffield, E. R. Gray, P. M. Giles, in *Proceedings of the 1987 IEEE Particle Accelerator Conference*, 16 to 19 March 1987, Washington, DC, E. Lindstrom and L. Taylor, Eds. (IEEE 87CH2387-9, IEEE, New York, 1987), p. 1705.
15. P. W. Van Amersfoot *et al.*, "The FELIX Project Status Report," April 1988 (*Rijnhuizen Rep. 88–176*, FOM-Instituut Voor Plasmafysica, Rijnhuizen, Netherlands, 1988).
16. X. K. Maruyama *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **259**, 259 (1987); C.-M. Tang *et al.*, *J. Appl. Phys.* **63**, 5233 (1988); S. Penner, Ed., "NBS-NRL Free-Electron Laser Conceptual Report" (National Bureau of Standards–Naval Research Laboratory FEL Collaboration, Gaithersburg, MD, March 1988).
17. J. C. Bourdon *et al.*, "CLIO: Free-electron laser in Orsay," in *Proceedings of the 1988 European Particle Accelerator Conference*, 7 to 11 June 1988, Rome, S. Tazzai, Ed. (World Scientific, Teaneck, NJ, 1989), p. 314.
18. *Conceptual Design Report, Combustion Dynamics Facility/LBL Report* (Lawrence Berkeley Laboratory, Rep. PUB-5250, Berkeley, CA, 1990).
19. B. Newnam, in *Proceedings of the 1988 Linac Conference*, 3 to 7 October 1988, Williamsburg, VA, CEBAF-89-001 (Continuous Electron Beam Accelerator Facility, Newport News, VA, 1989), p. 290.
20. J. E. Le Sala, D. A. G. Deacon, J. M. J. Madey, *Nucl. Instrum. Methods Phys. Res. A* **250**, 262 (1986).
21. J. Bisognano *et al.*, *Particle Accel.* **18**, 223 (1986).
22. I. Ben-Zvi, personal communication.

23. We thank our many colleagues in the FEL community upon whose work this article is based. Supported by the U.S. Department of Energy through the Lawrence Berkeley Laboratory under contract DE-AC03-76SF00098.