Review of Free-Electron Lasers
(Single-pass) *

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Abstract

The fact that six new free-electron laseres (FEL) became operative within the last twelve months – with some more to follow in the near future – clearly indicates the progress that has been made in this field during the last years. Although free-electron lasers are conceptually simple devices, experience exhibits that the production of high quality, relativistic electron beams is a stringent prerequisite for a reliable working facility. A survey will be given concerning single-pass free-electron lasers that are currently being assembled or are already in use driven by rf linacs, microtrons and electrostatic accelerators. Undulators employed for the conversion of energy stored in the electron beam into photons and optical cavities needed for amplification of the radiation are discussed only briefly.

1 INTRODUCTION

Since the first successful operation of a free-electron laser (FEL) in 1976 about fifteen facilities have managed to lase so far – six of them within the last ten months. As a matter of fact there exist currently more than 40 FEL projects worldwide and beyond that about ten more proposals are waiting for financial support. This clearly indicates the large interest in a tunable and potentially powerful source of coherent radiation over a broad range of wavelengths from the far-infrared to the far-ultraviolet regions of the spectrum.

Since it is felt that the basic physics behind the operation of an FEL is in general understood, more and more efforts are concentrating on the utilization of improved electron accelerators with respect to the beam quality, the use of high brightness injection, more compact devices and hopefully also less expensive arrangements. However, the future of the free-electron laser will depend only on its availability for applications also beyond strategic defense needs.

The present paper is trying to give an adequate report of the status in the field of the single-pass free-electron lasers. After a short introduction combining the few essential relations governing the lasing process (Sect. 2) a survey will be given that summarizes the essentials for the realization of FELs using rf and electrostatic accelerators and microtrons (Sect. 3). Applications performed already or planned using photons produced by FELs are subject of Section 4, which is followed by a few concluding remarks (Sect. 5).

2 BASIC PRINCIPLES

A free-electron laser is a device consisting of an electron beam, an unducator magnet array and an optical resonator defined by two reflecting mirrors (Fig. 1). In case of a linear undulator the magnets are arranged with their poles alternating in a linear polarized field with a wavelength of a few centimeters. The undulator has typically a length of a few meters corresponding to about one hundred periods. As the electrons proceed down the undulator, they are forced by the magnetic field to perform a periodic oscillation in space and thus radiate. This process is the so-called spontaneous emission. The wavelength of the emitted photons is given by the relationship [1,2]

$$\lambda_L = \frac{\lambda_u}{2\gamma^2}[1 + (\frac{eB_u\lambda_u}{2\pi m_0 c})^2 + \gamma^2\theta^2], \qquad (1)$$

where λ_L is the laser wavelength, λ_u is the period of the undulator, e is the electron charge, B_u is the rms field amplitude, m_0 is the rest mass of the electron, c is the velocity of light, γ is the energy of the electron in units of the rest mass and θ is the angle between the direction of the electron beam and the undulator axis. This last term inside the bracket takes into account the possibility of off-axis propagation of the electron beam.

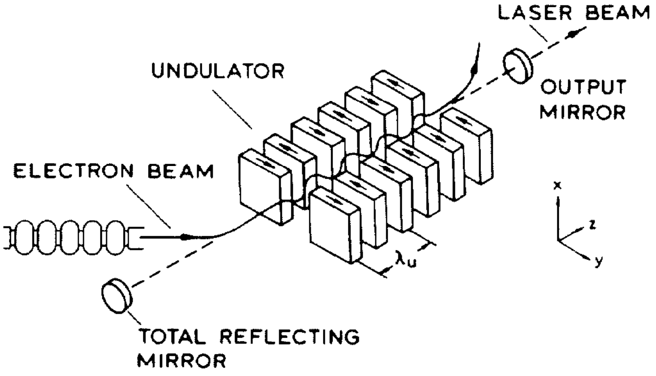

Fig. 1: Schematic diagram of a free-electron laser. A beam of relativistic electrons is directed through an alternating polarized magnetic field.

In order to achieve amplification of the spontaneous emission a partially reflecting downstream mirror and a

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totally reflecting upstream mirror (see Fig. 1) are chosen with respect to the reflectivity, curvature and position in such a way that the following electron pulse enters the undulator at the same time as the photon pulse created by the previous electron pulse. Under resonance conditions the interaction of the electrons with the combination of the electromagnetic wave and the magnetic undulator field – the so-called ponderomotive potential – causes the electrons to move from their random positions to form bunches spaced as the laser wavelength. Thus, instead of emitting their radiation at random, they radiate in phase with the laser beam. By adding the radiation coherently the laser beam emerges from the undulator stronger than when it entered. According to elementary one-dimensional theory the small signal gain which is given by the expression [3,4]

$$\begin{aligned} G &= 0.135\frac{8N(\pi e K L)^2 \quad \hat{I} \quad |J_0(\xi) - J_2(\xi)|^2}{4\pi\epsilon_0\gamma^3 m_0 c^2\, ec A_e} \times F \\ &\quad \times \frac{C_B}{(1+\frac{2N\lambda_u}{3\ell_e})(1+{\mu_\epsilon}^2)(1+{\mu_\Delta}^2)} \end{aligned} \tag{2}$$

where N denotes the number of undulator periods, $K = eB_u\,\lambda_u/2\pi m_0 c$ which is identical to the second term in Eq. 1, L is the total length of the undulator, $\hat{I}$ the peak current, J_n are Bessel functions, F is the filling factor defined by the spatial distribution of the electron beam A_e divided by the according size of the optical beam A_0 i.e. $F = A_e/A_0$, if $A_e < A_0$, ℓ_e is the electron pulse length, μ_ϵ takes into account the finite emittance of the beam and is given by the expression $\mu_\epsilon = 2\sqrt{2}\cdot K\epsilon_n^y L/(1+K^2/2)\lambda_u^2$ where ϵ_n^y denotes the normalized emittance of the electron beam in y direction, and μ_Δ describes the energy spread $\Delta E/E$ of the beam given by the relation $\mu_\Delta = 4N\Delta E/E$. The correction term C_B, finally, describes the decrease of the small signal gain caused by the inaccuracy of the magnetic field of the undulator as well with respect to its maximum value on the axis as to its periodicity.

In order to establish a lasing system it is thus required that the average net gain per bounce of radiation in the optical resonator exeeds the losses inside the cavity. For the remaining net gain G_n we then obtain – assuming that the gain does not change as the signal grows, which is valid only for small signals – after M bounces of the radiation between the mirrors an increase of power $P(M)$ according to

$$\frac{P(M)}{P_0} = (1+G_n)^M . \tag{3}$$

The basic features that characterize the outstanding capabilities of free-electron lasers are readily deduced by inspection of Eqs. (1)—(3) . Since the K value for undulators is in general chosen to be of the order of one, the laser wavelength is determined by λ_u and γ only (Eq. 1). By variation of γ or B any wavelength can be selected . In order to obtain shorter wavelengths, γ cannot be increased arbitrarily since the small signal gain decreases with γ^3, which will finally prevent the system from lasing (Eq. 2).

The requirements for the electron beam can thus be summarized to the following aspects:

$$\begin{array}{llcccr} * & \text{energy} & : & \gamma & > & 10 & (4) \\ * & \text{current} & : & \hat{I} & > & 1\ \text{A} & (5) \\ * & \text{emittance} & : & \epsilon_\mu^y & < & \frac{\lambda_u^2}{K}\,\frac{1+\frac{K^2}{2}}{2\sqrt{2K}} & (6) \\ * & \text{energy spread} & : & \Delta E/E & < & \frac{1}{4N} & (7) \\ * & \text{pulse length} & : & \ell_e & > & N\cdot\lambda_L & (8) \end{array}$$

where the first condition is stringent in order to avoid slippage i.e. an imperfect longitudinal overlap between electron and photon pulse due to electrons slipping behind. For realistic conditions e.g., K=1, L=3 m, N=100, λ_u =1.5 cm and γ=100 one obtains for the restrictions (6) to (8) at λ_L=1.5 μm the following conditions:

$$\begin{array}{lcl} \epsilon_\mu^y & < & 50\ \pi\text{mm mrad} \\ \Delta E/E & < & 2.5\cdot 10^{-3} \\ \ell_\epsilon & \approx & 150 \quad \mu\text{m}. \end{array}$$

3 FEL FACILITIES

Since the first successful operation of a free-electron laser in 1976 by Madey and his coworkers [5] about fifteen free-electron lasers have lased in the short wavelength region, and a number of others have been operated in the microwave region [6]. The shortest wavelength reached so far (240 nm) was obtained with the facility set up at the storage ring VEPP-3 in Novosibirsk [7]. The highest power (1 GW) has been achieved with the induction linac ETA at Livermore [8] at a very long wavelength (9 mm). Since almost all undulators have a wavelength of a few centimeters, the wavelenth of the free-electron laser is largly determined by the electron energy. As a result, since each type of accelerator is most useful over a certain energy range, it is possible to correlate each type of accelerator with a wavelength range over which it is most useful (Fig. 2).

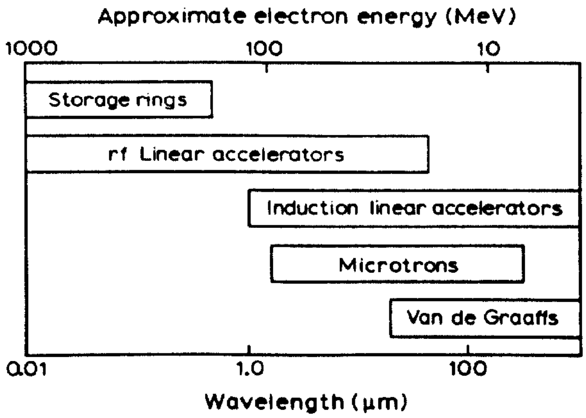

Fig. 2: Various types of accelerator technology for different electron energy ranges and accordingly different laser wavelength regions.

Currently there are more than forty FEL installations worked on some of which have already lased. The following types of accelerators are used [9]: *rf-linac* (19), *storage ring* (7), *Marx generator* (6), *induction linac* (5), *electrostatic accelerator* (2), *and microtron* (2). About ten more projects are in the planning phase or are waiting for financial support. The forty-one actie FEL experiments are distributed among the following nine countries: *USA* (14), *Japan* (12), *France* (5), *Germany* (3), *Netherlands* (2), *Italy* (2), *CIS* (1), *Israel* (1) *and China* (1).

In Europe a network was established between the following institutions: *FOM-Institute for Plasma Physics Rijnhuizen, Herriott-Watt University, Dundee Institute of Technology, University of Oxford, LURE Orsay, Universite des Science et Techniques de Lille-Flandres Artois, Frascati Research Centre, Technische Hochschule Darmstadt and Universiteit te Twente.* Since the beginning of this network the facilities in Rijnhuizen [10] and Paris [11] have lased recently for the first time while the FEL at Darmstadt [12] is expected to lase later this year.

It becomes apparent from the above list of accelerator technology involved that most free-electron lasers are driven by rf accelerators. These accelerators are characterized by high energy and medium current, since the improvements in electron injector technology have increased the currents to a sizable amount and also the electron beam quality. In Table 1 some of the essential features of these 19 projects are summarized. A few aspects should be emphasized. With respect to the technical details the different rf-linac projects span over the following ranges:

*	frequency	0.433	$< f <$	3.0	GHz
*	energy	13	$< E_0 <$	79	MeV
*	peak current	2.7	$< \hat{I} <$	500	A
*	average current	$5 \cdot 10^{-2}$	$< \bar{I} <$	400	mA
*	FEL wavelength	1	$< \lambda_L <$	60	μm
*	FEL peak power	10^{-3}	$< P <$	4000	MW

The second most often applied technology involves the use of storage rings [13]. Because they work best at high electron energy over 100 MeV and have good electron-beam quality, storage rings are well suited to free-electron laser operation at short wavelengths.

In Table 2, finally, the additional fifteen projects using induction and electrostatic linacs and microtons are listed as well. All three types of accelerators have successfully been used for free-electron laser experiments. The outstanding feature of induction linacs is the very large current they can accelerate, typically as much as 10 kA in pulses lasting about 50 ns. The above mentioned facility at Lawrence Livermore National Laboratory will soon be able to increase the output peak power to 2–3 GW (ref. [9]). The simplicity and reliability of an electrostatic accelerator has efficiently been used at the University of California in Santa Babara for experiments dealing with FEL physics and research in solid state physics and biophysics as well. In the near future this facility will be able to offer laser beams in the broad region from 30 μm to 1.7 mm. Finally, it should be mentioned that last year at Bell Labs in Murray Hill a microtron driven FEL has managed to lase for the first time. Although the difficulties involved for FELs with microtrons are not trivial, this principle contains fascinating aspects since it can greatly reduce cost and size of the accelerator: a 20 MeV accelerator can fit into a few square meters of space.

The large success in FEL technology results not only from the advances in accelerator technology during recent years but also from the development of more and more sophisticated undulators and resonators. While all rf accelerator driven facilities make use of permanent magnet material, also electromagnetic helical devices have been built and partially also already successfully tested. The majority, however, makes use of permanent material predominantly in two versions with the following specifications:

*	configuration	Halbach, Hybrid
*	magnetic material	SmCo, NdFeB
*	periodicity	$1 < \lambda_u < 6$ cm
*	length	$1 < L < 5$ m
*	maximum B field	$0.1 < B < 0.6$ T
*	gap	variable

With respect to the resonators the following classification holds for the nineteen projects listed in Table 1:

*	resonator length	$2 < L_r < 22$ m
*	mirror material	metal (Ag/Cu, Cu) dielectric (CaF_2, ZnSe)
*	mirror transmission	$0.5 < T < 10$ % .

4 APPLICATIONS

Since the first successful operation of a free-electron laser in 1976, numerous proposals for its application have been suggested. They all concentrate around the unique features of this type of laser as there are: *wavelength region, tunability, time structure, peak power and coherence.*

It took more than ten years until the first publication using an FEL has come out. Until now about 25 scientific papers were published [14] which is still a very small number compared to the vast body of publcations dealing with the physics or development of FELs itself [6]. The scientific work performed with FEL radiation has so far taken place at the three facilities of the University of California in Santa Barbara, the Mark III - FEL (now at Duke University) and the SCA-FEL at Stanford.

The published applications at UCLA deal with problems related to subjects in solid state physics, semiconductors and magnetic excitations. The experimental results related to semiconductors cover a wide range of applications including photoconductivity, photodetectors, impurity hopping and the photo-Hall-effect. The magnetic excitations were studied with respect to their frequency shifts in magnetic fields and to their transport behaviour. Some of the applications make use of the *picosecond time structure* of the photon beam which has opened the field for FEL-coherent transient spectroscopy.

Table 1: Free-electron lasers driven by linear accelerators

		Electron energy [MeV]	Frequency [MHz]	Pulse length [ps]	Repetition rate [μs]	$\hat{I}$ [A]	$\bar{I}$ [mA]	Wave-length [μm]	Emitted peak power [MW]
Los Alamos	APEX[a]	47	1300	10–20	100	300	100	2.8	150
Boeing	APLE	36	433	70	8300	450	230	10.6	782
Los Alamos	AFEL	40	1300	13	20	180	250	0.36;3.7	30;75
Vanderbilt[a]		20–45	2856	2	7	40	200	2–10	3
Stanford[a,b]		10–70	1300	3	1000–10000	6	0.2	1-25	10
Durham	Mark III[a]	25–45	2857	1–4	0.5–9	40	250	1.4–8.1	2
Rockwell		83.5	2857	10–30	3.7	500	400	1.06	4000
UCLA	KIAE	25	2856	4	4	200	$5\cdot10^{-6}$	5–10.6	0.001
IAERI	SCARLET[b]	13.5	499.8	4000	1000	10	4	41.7	1
Osaka	ISIR	38	1300	20–30	2.5	50		10–60	
Tokyo	UT-FEL	15	2856	2	6	40	200	40–50	24
Osaka		7	2856	2	10	100			
LURE	CLIO[a]	30–74	3000	10	10	100	250	2–20	10
Bryères-le-Chatel	ELSA	20	433	30–200	200	300	200	15–25	50
Rijnhuizen	FELIX[a]	15–49	3000	6	20	70	200	8–80	0.1
Twente	TEU-FEL	31	1300	20	10	100	160	10;180	15
Rome	LISA[b]	25	500	8	1000	5	2	16	1
Beijing		30	2856	4	5	20	220	7–25	
Darmstadt	S-DALINAC[b]	35–50	2997	1.9	cw	2.7	0.05	2.5–6	0.1

[a]: systems have lased

[b]: superconducting accelerator

The research at both centers has covered applications in molecular and biology as well. The experimental results in biology concentrate on the change in the behaviour of biological samples under *high power FIR excitation* in a *narrow band width* around *selected frequencies*.

It can be stated that large efforts are made currently worldwide to provide photon beams for research using FELs. This includes the enlargement of the existing user facility in Santa Barbara which will be soon able to offer FEL produced photon beams continously from 30 μm to 1.7 mm. This is also indicated by the call for proposals for experiments at the Vanderbilt University Free-Electron Laser Center that went into operation last year which is dedicated to the application to research in medicine, biology and material science. The tremendous effort started in Japan last year with a 80 Mio Dollar support for FEL developments for applications in predominantly material science related topics clearly indicates the importance given to this field.

Finally the European situation ought to be mentioned at least briefly. Although the FEL at the Laboratoire pour l'Utilisation du Rayonnement Electromagnetique (LURE) has been lasing as early as 1983 at the ACO storage ring, no experiments using the radiation have been performed so far. The European network mentioned above will provide FEL beams at several sites. With the first successful lasing at Rijnhuizen in September 1991 and at the CLIO project of LURE in January 1992 already two of the four facilities can provide the photon beams asked for. The IR FEL at Darmstadt has until now been tested with respect to the emission of the spontaneous radiation and is expected to lase later this year. The scientific programs set up at the laboratories in Paris, Rijnhuizen and Darmstadt indicate a large variety of applications that will be performed.

5 SUMMARY

The more than forty FEL facilities presently under construction or already working will for the first time deliver photon beams covering a broad range of wavelengths from 240 nm to 9 mm power and a variety of time structures. Power levels up to 4 GW will be achievable and the first successful manipulation of the undulator gap carried out recently [15] will favour experiments that require rapid tunability of the photon wavelength. The first microtron driven FEL opens new possibilities for future developments of compact devices. A tendency for the development of devices which will lase at even lower wavelengths is observed with application of microundulators and the utilization of higher harmonics. The injection and extraction of the electron beam via the resonator mirrors is planned and the trend for compact machines at low costs (less than 500 thousand US $) is propagated.

It is widely felt that this huge impact will undoubtedly answer the question whether the FEL can be the laser system of the next century at all. This will depend on the fact if the systems can furnish the desired beams within the parameter set asked for and reliably over the needed time and if the experiments and applications planned yield the

Table 2: FEL facilities using induction and electrostatic accelerators, microtrons and Marx generators

		Electron energy	Pulse duration	Peak current	Laser wavelength	Peak Power
A. Induction accelerator						
Livermore	(ETA II)[a]	7 MeV	50 ns	3 kA	2 mm	3 GW
Osaka	(SHVS)[a]	6 MeV	100 ns	5 kA		0.1 GW
Tsukuba[a]		0.8 MeV	80 ns	2.7 kA		10 MW
JAERI	(LAX-1)	1 MeV	150 ns	3 kA		
Le Barp	(LELIA)	4.5 MeV	60 ns	1.5 kA		
B. Electrostatic accelerator						
Santa Barbara[a]		6 MeV	1–20 μs	2 A	30 μm–1.7 mm	5 kW
Tel Aviv		5 MeV	65 μs	2 A	300–3000 μm	
C. Microtron						
Muray Hill[a]		19 MeV		2 A	160–250 μm	100 W
Frascati	(ENEA)	6 MeV		5 A	500 μm	1 MW
D. Marx generator						
New York (Columbia Univ.)[a]		1 MeV	150 ns	200 A	1–2 mm	5 MW
College Park (Univ. o. Maryland)		0.44 MeV	80 ns	10 A	3 mm	140 W
Le Barp	(ONDINE)	2.5 MeV	50 ns	1000 A		
Osaka	(ELSA)[a]	0.6 MeV	8 μs	200 A		20 kW
Osaka[a]		0.6 MeV	1 μs	20 A		100 kW
Stuttgart	(DLR)	1 MeV	100 ns	25 kA	1–3 mm	10 MW

[a]:systems have lased

desired results, which can not be obtained with commercial laser systems. At the present time this appears to be most likely for applications in the field of medicine and material sciences.

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