Chapter 7
Free Electron Lasers

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Abstract Free electron lasers are electron beam-based sources of coherent, high-power tunable radiation which can, in principle, be designed to operate at any wavelength ranging from mm waves to X-rays. In recent years, these devices have successfully been operated at THz and hard X-ray wavelengths where conventional sources of radiation are either not available or are not very efficient. This chapter briefly discusses the principle of operation and important subsystems of FELs, their special features, and the typical characteristics of some operational FELs. A review of the present status of activity in India and abroad is also discussed briefly.

Keywords Basics of free electron laser (FEL) • Components of FEL • FEL radiation characteristics • Terahertz sources • Present status of FELs in world

7.1 Introduction

A free electron laser (FEL) is a source of high-power coherent electromagnetic (EM) radiation in which "free electrons" in a relativistic electron beam from an accelerator are propagated through a spatially periodic arrangement of magnets, called an undulator. A fraction of the kinetic energy of the relativistic electrons is converted to electromagnetic waves of wavelength (λ_L), which depends upon the wavelength, or period, of the spatially periodic magnetic field (λ_U), the relativistic gamma factor (γ) of the electrons, and the undulator parameter ($K_U = eB_U\lambda_U/2\pi mc$) as given by the expression

$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left(1 + K_U^2\right). \tag{7.1}$$

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As seen from Eq. (7.1), the wavelength λ_L of radiation from an FEL can be tuned over a large range of wavelengths by varying the energy of the electron beam, γ, or the undulator parameter, K_U.

The basic principle of operation of an FEL is similar to that of microwave sources like klystrons and traveling wave tubes, which also employ an electron beam for the generation of electromagnetic radiation. However, these devices employ a nonrelativistic electron beam propagating through a slow-wave structure supporting transverse magnetic (TM) modes. Since the transverse dimensions of slow-wave structures and waveguides scale inversely with wavelength of the radiation to be generated, these devices face problems of beam purity and power-handling capacity for operation at submillimeter and shorter wavelengths. In an FEL, the interaction inside the undulator is between a beam of relativistic electrons and a freely propagating transverse electromagnetic (TEM) mode. Hence, there is neither an adverse scaling of transverse dimensions of the device with the wavelength of operation nor a limit on power-handling capacity for the device since the electron beam itself is a broken-down medium. Successful lasing in an FEL critically depends upon the quality of the electron beam as well as on the quality of undulator magnetic field, and both requirements become more stringent for operation at shorter wavelengths.

Since the principle of operation of an FEL is uniform for all wavelengths, an FEL can in principle be tuned over a wide-wavelength range provided the requirement of qualities of electron beam and undulator field are fulfilled. For example, the FEL at the Free Electron Laser Institute (FELI) in Japan operates from 0.23 to 100 μm using five undulators. The pulse structure of EM radiation from an FEL mimics the pulse structure of the electron beam and has no dependence upon the wavelength of operation. Since most operating FELs employ radio-frequency (RF) linear accelerators (linacs), the electron beam from these devices has pulse widths that are typically a few percent of the time period of RF employed in the accelerator. For example, FELs operating with S-band linacs at 2856 MHz usually generate trains of pulses 5–10 picosecond long for a macro-pulse duration of a few microseconds repeating at few Hz to few tens of Hz. With the recent progress in pulse compression techniques for electron beams from accelerators, FELs have also been operated at pulse widths as short as a few tens of femtosecond.

The size of an FEL is large as compared to that of conventional lasers and microwave sources since they employ a long undulator and an accelerator to generate the relativistic electron beam. FEL facilities also require a radiation shielded area since the electron beam produces significant amount of harmful Bremsstrahlung X-rays when it is dumped after emerging out from the undulator. FELs therefore do not compare favorably with conventional lasers and microwave sources at wavelengths where these sources operate efficiently but are preferred at wavelengths where these conventional sources do not operate, for example, in the terahertz (THz) and X-rays wavelength regimes.

The next section discusses a standard configuration of an FEL and salient features of some of its important subsystems. The basic principle of operation of an FEL is discussed in detail in Sect. 7.3 where the method of buildup of coherence in an

FEL, which makes it different from a synchrotron radiation source, is also discussed. Section 7.4 discusses some important advantages FELs have over other conventional radiation sources, which have made FELs popular, particularly in certain wavelength regions where conventional radiation sources are either not available or are not very efficient. This is followed by a brief review of the current status of FEL activity across the world and in India in Sect. 7.5 followed by a concluding paragraph in Sect. 7.6.

7.2   Important Subsystems

Figure 7.1 shows a typical schematic of an FEL with its three important subsystems – an electron accelerator, an undulator, and the optical cavity formed using two mirrors on either side of the undulator.

7.2.1   Electron Accelerator

Most present-day FELs use radio-frequency linear accelerators (RF linacs) that range in energies from a few MeVs for long-wavelength FELs to few tens of GeVs for hard X-ray FELs. Though there are FELs operating with other kinds of accelerators too like DC accelerators, induction linacs, storage rings, etc., the discussion in this chapter is limited mainly to RF linac-based FELs.

The parameters qualifying an accelerator are electron beam energy W, electron beam current I_b, relative energy spread in the electron beam dW/W, and emittance
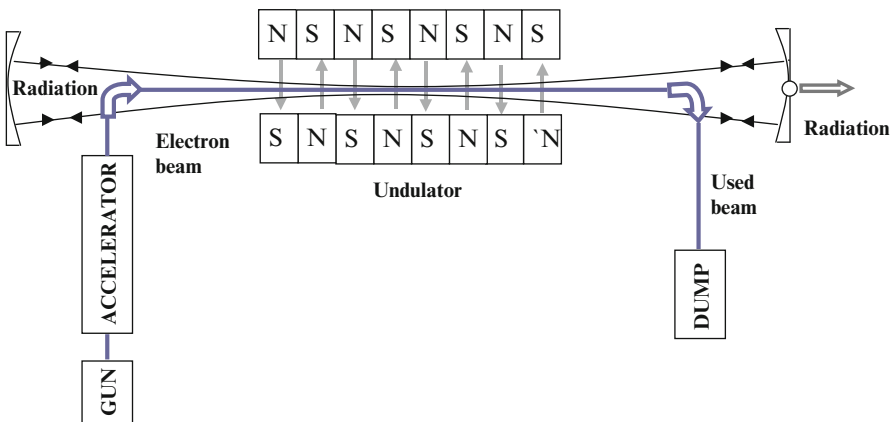

Fig. 7.1 Schematic of an FEL showing its important subsystems and method of out-coupling of radiation from its optical cavity

ε of the electron beam. In its simplest form, emittance of an electron beam from an accelerator can be defined as a product of its radius at waist and asymptotic divergence. In addition to these, another critical parameter is the pulse-to-pulse mean energy jitter, which depends mainly upon the stability of the RF system powering the RF linac. While energy of the electron beam determines the wavelength of operation of the FEL and peak current determines the gain, the relative energy spread and emittance of the electron beam critically affect the process of lasing. Long-wavelength FELs are more tolerant to large values of emittance and relative energy spread. For short-wavelength FELs, these parameters become the limiting factors and present-day X-ray FELs like the Linac Coherent Light Source (LCLS) at Stanford operate with an accelerator that is state of the art for the electron beam delivered by it.

The choice of the accelerator for an FEL is dictated by its operating parameters. The most popular choice of electron linacs for FELs are the conventional normal conducting (NC) disk-loaded traveling wave (TW) RF linacs, which have been used in FELs with wavelength ranging from hundreds of microns (THz FELs) to X-rays (X-ray FELs). FELs designed to operate at very high average power are also built using superconducting radio-frequency (SCRF) cavities to reduce power loss in the RF cavities. The length of the accelerator is dictated by the beam energy required. For THz FELs requiring a few MeV energy electron beam, the accelerator length could be of the order of a meter, while for hard X-ray FELs which need close to 15 GeV electron beams, the length of the accelerator is hundreds of meters.

Since electrons from an RF linac need to be propagated through an undulator in an FEL, the accelerator here includes a magnetic transport line to focus and transport the electron beam from the exit of the RF linac to the entry of the undulator. The principle of the transport line, which comprises focusing, defocusing, and bending magnets, is similar to that of an optical beam transport system with lenses and mirrors. Electron beam diagnostic elements, required to monitor the electron beam at different locations, are included in the beam transport line.

7.2.2   Undulator

An undulator is a spatially periodic arrangement of magnets that generates a magnetic field of amplitude B_U and periodicity λ_U with a field distribution that is static in time but varies sinusoidally in space. Undulators can be built using pure permanent magnets, pure electromagnets, or a combination of permanent magnets and electromagnets as in hybrid undulators. Permanent magnets are preferred where operation with short undulator period is desired. Since the polarization of radiation from an undulator is identical to that of the undulator magnetic field itself, various configurations of magnets have been proposed to obtain different polarizations of the undulator magnetic field varying from linear to elliptical to variable polarizations. The most popular undulator configurations employed worldwide are the Halbach configuration for linearly polarized undulators and the APPLE-II configuration for variable-polarization undulators.

Fig. 7.2 Typical arrangement of permanent magnets in an undulator employing the Halbach configuration. Each rectangle refers to one magnet with the arrow within showing the direction of magnetization
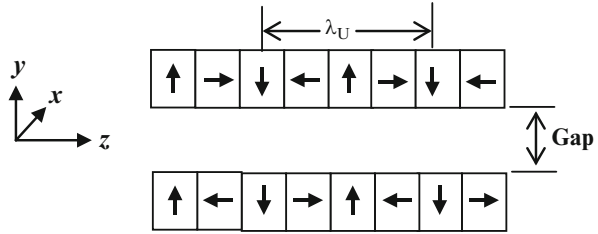

Figure 7.2 shows a typical arrangement of permanent magnets first proposed by Halbach for the generation of a sinusoidally varying linearly polarized undulator magnetic field along the undulator axis given by

$$\boldsymbol{B}_U = B_U \sin\left(k_U z\right) \boldsymbol{y}, \tag{7.2}$$

where $k_U = 2\pi/\lambda_U$. This desired sinusoidal on-axis field distribution is obtained by arranging two rows of magnets equidistant from the axis with the orientation of individual magnets in each row as shown in Fig. 7.2. The electrons propagate along the z direction and the magnetic field is along the y direction. The length of the bar magnets along the x direction is chosen such that there is uniform B_y field over the full size of the beam along this direction. In other words, the "good field region" along the x direction should be larger than the size of beam in this direction. The field strength of an undulator is characterized by the undulator parameter $K_U = eB_U\lambda_U/2\pi mc$. For FELs, K_U is typically of the order of 1 or slightly less than 1 and the magnetic arrangement is called as an undulator. When $K_U \gg 1$, as in synchrotron radiation sources (SRS), the device is called as a wiggler.

7.2.3 Optical Cavity

In an oscillator configuration of an FEL, the undulator is located between two mirrors which form an optical cavity like a Fabry-Perot resonator as shown in Fig. 7.1. Radiation emitted by the first bunch of electrons propagating through the undulator is reflected back and forth inside the optical cavity for repeated interaction with subsequent bunches of electrons ultimately leading to lasing as discussed in the next section. Out-coupling of FEL radiation from the optical cavity is accomplished either by making the downstream mirror partially transmitting or by making a small hole in the downstream mirror to out-couple a fraction of power at every reflection. In an FEL, it is important to align the axis of the optical cavity with that of the undulator for maintaining overlap between the electron and the optical beams for efficient energy exchange between the two.

Except for FELs at X-ray wavelength where operation in oscillator configuration is not possible for want of mirrors, FELs at other wavelengths can be operated in both oscillator and amplifier configurations.

7.3 Principle of Operation

The principle of operation of an FEL is presented in many books and articles using different approaches. In this section, we discuss the operating principle using the approach followed in references [1] and [2] with some discussions based on [3]. Consider a beam of relativistic electrons propagating in the z direction along the axis of an undulator supporting a spatially periodic magnetic field given by Eq. (7.2). The magnetic field here is in the y direction and the electrons experience a Lorentz force in the x direction. Since the magnetic field of the undulator is static in time but spatially periodic along the z direction, the direction of the Lorentz force also changes with the same periodicity causing the electrons to execute a snakelike "wiggly" motion in the x-z plane as they propagate along the axis of the undulator. Since the magnetic field of the undulator along the y direction has a phase dependence of $\sin(k_U z)$, as shown in Eq. (7.2), the electrons propagating through the undulator acquire an x component of velocity with a phase dependence given by

$$v_x = v_x \, \sin\left(k_U z\right) x. \tag{7.3}$$

As a consequence of this wiggly motion, the electrons initially moving with a constant velocity along z direction now become accelerated charged particles which emit radiation as dictated by laws of electrodynamics, with the wavelength of radiation given by Eq. (7.1). An electron beam from an RF linac comprises a large number of electrons in each bunch, which we assume are distributed uniformly along the length of each bunch. All electrons radiate randomly as they propagate through the undulator with no definite phase relationship between radiation emitted by different electrons. The net radiation coming out of the undulator is essentially this "spontaneous emission" with a pulse length equal to the bunch length of electrons from the RF linac. From the principle of superposition, the power in the radiation P_R is proportional to N_e, the number of particles in the bunch. The phenomenology of this process is the same as that of radiation from synchrotron radiation sources.

The amplitude of transverse oscillations executed by an electron inside the undulator is given by K_u/γ. For $K_u \sim 1$, which is the case for most FELs, the amplitude of transverse oscillations of the electrons is $\sim 1/\gamma$. A charged relativistic particle emits radiation in a direction perpendicular to the oscillation of the particles with the intensity of radiation peaking at 90° to the oscillatory motion and concentrated in a narrow cone with a semi-angle $1/\gamma$. Since the amplitude of the electron's transverse oscillations is also $1/\gamma$, an observer at the end of the undulator receives radiation from the full transverse oscillation executed by the electron. This overlap between transverse oscillations and the radiation cone of semi-angle $1/\gamma$ also helps in the buildup of coherence in an FEL, as discussed later in this section.

The electrons undergo transverse oscillations and radiate as per laws of electrodynamics only when they propagate through the length of the undulator $L_u = N_u \lambda_u$, where N_u is the number of undulator periods. Consequently, the electrons radiate only for a finite time and the Fourier transform of this radiation gives the spectral

width of undulator radiation, which is equal to $1/2N_u$. Typically, the undulator for an IR or terahertz (THz) FEL has about 50 periods, which means that the line width of radiation is of the order of 1 %.

A synchrotron radiation source (SRS) with a wiggler, which is similar in construction to an undulator, also works on the same principle discussed above for the generation of spontaneous, or incoherent, radiation. However, the buildup of coherence in an FEL results in high brightness of radiation that is greater by orders of magnitude as compared to that from SRS. As discussed earlier, the electron excursion in the transverse direction in an FEL is of the order of $K_u/\gamma = 1/\gamma$, which is the same as the semi-angle of the cone in which spontaneous radiation is emitted. As the electrons propagate through the undulator, they stay within the radiation cone and there is a second-order interaction between the radiation field and the transverse oscillations of the electrons due to the undulator, leading to the buildup of coherence. In a SRS with a wiggler, $K_U \gg 1$ and the transverse electron excursion is much greater than the semi-angle of the cone in which spontaneous radiation is emitted. Hence, there is poor overlap between the radiation and electrons as they propagate through the wiggler resulting in no buildup of coherence.

In order to understand the buildup of coherence in an FEL, consider a configuration where in addition to the undulator magnetic field discussed earlier, the electron beam also sees an electromagnetic wave whose field components can be represented as

$$\boldsymbol{E}_R = \boldsymbol{x}\ E_R \cos(k_R z - \omega_R t + \phi_R),$$
$$\boldsymbol{B}_R = \boldsymbol{y}\ B_R \cos(k_R z - \omega_R t + \phi_R). \tag{7.4}$$

Here, E_R and B_R are the electric and magnetic fields, respectively, of the radiation generated at a frequency $f_R = 2\pi/\omega_R$ with a wave vector $k_R = 2\pi/\lambda_R$, λ_R being the wavelength of radiation emitted, and ϕ_R is an initial phase. This electromagnetic field could be present in the undulator either due to the incoherent spontaneous radiation emitted by electrons as discussed earlier or due to a seed radiation in an amplifier configuration. The amplitudes (E_R and B_R) and phase ϕ_R are slowly varying down the undulator.

The first-order Lorentz force experienced by an electron due to the undulator magnetic field imparts to it a velocity v_x given by Eq. (7.3). Since this "wiggling" electron and the spontaneous radiation emitted by it co-propagate down the undulator with overlap maintained between the two as discussed earlier, exchange of energy between the electric field $\boldsymbol{x}E_R$ of the radiation and the $\boldsymbol{v_x}$ motion of the electrons in the undulator is given by

$$mc^2 \frac{d\gamma}{dt} = e\,\boldsymbol{E}_R.\boldsymbol{v_x}. \tag{7.5}$$

From Eqs. (7.3), (7.4), and (7.5), one obtains

$$\frac{d\gamma}{dt} \propto -\cos(k_R z - \omega_R t + \phi_R)\ \sin(k_U z). \tag{7.6}$$

The right-hand side of this equation can also be written as $\{sin(k_R z - k_u z - \omega_R t + \phi_R)$ $- sin(k_R z + k_u z - \omega_R t + \phi_R)\}$, where both the sine terms oscillate between $+1$ and -1 averaging out to zero as the electron moves down the undulator. By suitably choosing an electron velocity $v_{z0} = \omega_R/(k_R + k_U)$, the second term in the phase dependence above is almost constant or slowly varying and does not average out to zero. Hence, a net energy exchange between radiation and the electron is possible in this case.

This is better understood if we look at the interaction of an electron moving with a constant velocity along the "z" direction with a co-propagating wave having a component of electric field along the z direction and a phase velocity v_ϕ. If the electron velocity is very different from the phase velocity of the wave, it sees random fluctuating phases of the electric field of the co-propagating wave. Hence, the net effect on the electron due to the electric field of the co-propagating wave averages out to zero. On the other hand, if the electron has a velocity equal to the phase velocity of the co-propagating wave, it sees the same phase of the electric field as they co-propagate, and depending upon the value of phase of the field, it can gain energy from the wave, lose energy to the wave, or remain unaffected. The interaction between the electrons and the ponderomotive wave is similar to the above analogy, and it is possible for the electron to lose energy to the ponderomotive wave, which ultimately results in growth of radiation.

The quantity $\psi = (k_R z + k_u z - \omega_R t)$ is called as the phase of a ponderomotive wave driven in the electron beam due to the second-order interaction between the v_x component of velocity acquired by the electrons in the undulator and the electric field of the radiation wave. Depending upon the quantity $\psi + \phi_R$, an electron can either gain or lose energy to the radiation. The electron beam from the accelerator initially has electrons distributed uniformly in phase. Hence, as this beam propagates down the undulator with a velocity $v_{z0} = \omega_R/(k_R + k_u)$, electrons lying in a phase 0 $(\pm 2n\pi,$ where n is an integer$)$ to π $(\pm 2n\pi)$ lose energy, while the others lying between π $(\pm 2n\pi)$ and 2π $(\pm 2n\pi)$ are accelerated, resulting in no net energy exchange. If the electron distribution can be modified to have electrons only between phases 0 to π, 2π to 3π, and so on, all electrons will lose energy to the ponderomotive wave, which in turn will result in growth of radiation.

In an FEL, this desired redistribution of electrons within each bunch from the accelerator occurs as the bunch travels through the undulator. The first-order Lorentz force experienced by the electrons due to the undulator magnetic field causes them to experience a force in the x direction, and they acquire a velocity v_x in that direction. As these "wiggling" electrons and the spontaneous radiation emitted by them co-propagate down the undulator, they experience a second-order Lorentz Force due to an interaction of their v_x motion with the B_y magnetic field of the electromagnetic wave given by Eq. (7.4). This results in a "ponderomotive" force along the z direction with a time and space dependence given by $sin(k_u z) \, cos(k_R z - \omega_R t + \phi_R)$. If the initial electron velocity is chosen appropriately as discussed above, there is a net force along the z direction causing a redistribution of the initially uniform distribution of electrons in each bunch leading to micro-bunching around the phases 0, 2π, 4π, etc., with the separation between bunches given by $2\pi/(k_U + k_R)$.

Fig. 7.3 Bunching of electrons by the ponderomotive wave. "A" shows an un-bunched electron beam with uniform distribution of electrons (gray) over all phases of the ponderomotive wave and "B" shows electrons bunched around phases $0, \pi, 2\pi$, etc.

Figure 7.3 shows the redistribution of charge leading to micro-bunching. Since $k_R \gg k_U$, the bunch spacing $\sim \lambda_R$ and radiation from the micro-bunches are in phase leading to coherence. From the principle of superposition, the radiated power P_R in this case is proportional to N_e^2, which gives orders of higher brightness for the radiation emitted by the FEL as compared to synchrotron radiation sources. For example, an electron bunch with 0.1 nC charge propagating through an undulator contains $\sim 10^8$ electrons and spontaneous emission power from this electron bunch is proportional to this number of electrons. Development of micro-bunching in an FEL as discussed above ideally results in development of full coherence in the output radiation giving a gain of 10^8 as compared to the spontaneous emission output from the same bunch.

From the laws of electrodynamics, growth of electromagnetic radiation at a given angular frequency ω and wave number k requires a driving current having the same Fourier components (ω, k). Hence, the initially uniform distribution of electrons in each bunch from an accelerator in an FEL has to be modified by micro-bunching to obtain a current density with the required Fourier components (ω_R, k_R). For example, consider an FEL operating in the infrared region with a wavelength of 30 μm or a frequency of 10 THz corresponding to a time period of 0.1 picosecond(ps). At this time scale, the 10 ps long beam from the accelerator is like a uniform distribution without any component of current at the desired frequency. Micro-bunching is required in each bunch from the accelerator on a time scale shorter than 0.1 ps to generate a current density at the radiation frequency to drive this electromagnetic radiation. The ponderomotive wave driven in the electron beam due to the interaction of the electrons with the undulator and radiation fields generates the required micro-bunching leading to growth of radiation in an FEL.

In order to study the growth of radiation in an FEL, one needs to solve the electromagnetic wave equation with the driving terms on the right-hand side as shown in Eq. (7.7).

$$\nabla^2 A_R - \frac{1}{c^2} \frac{d^2 A_R}{dt^2} = -J. \tag{7.7}$$

Here, $A_R (\omega_R, k_R)$ is the vector potential associated with the electromagnetic wave, or the FEL radiation, and $J(\omega_R, k_R)$ is the current density having the same Fourier components as that of the electromagnetic wave in order to drive it. Determination of this current requires the study of electron motion in the FEL, which again

depends upon the evolution of the electric and magnetic fields of the electromagnetic radiation in the FEL. Hence, analytical treatment of an FEL involves the solution of coupled equations governing the motion of particles and the growth of radiation in the device, which is presented very lucidly in references [2, 3]. Many numerical codes have been developed to study FEL interaction considering the contribution due to three-dimensional space and time-dependent effects in the device, and contemporary FELs are designed using one or many of these codes.

7.4 Why Are FELS Attractive?

7.4.1 Tunability

The most attractive feature of an FEL is its tunability. It is evident from Eq. (7.1) that the wavelength of radiation, (λ_L), can be tuned either by varying the γ (energy) of the electron beam coming from the accelerator or by varying the undulator parameter K_U. While the former is easier and can be achieved by varying the RF power fed to the linac, the latter involves changing the gap between undulator jaws to vary the undulator field strength, thereby changing the undulator parameter. A classic example of this tunability is the FEL at the Institute for FEL at Osaka in Japan where radiation from 0.23 μm to 100 μm wavelength is generated using five undulators. Tunability is very important for experiments where very fine lines are to be discriminated.

7.4.2 Choice of Pulse Structure

The pulse structure of the radiation generated by an FEL mimics the pulse structure of the electron beam propagating through the undulator. Consequently, FELs can operate with any desired pulse structure independent of the wavelength of operation. This is achieved by tailoring the pulse structure of the electron beam from the accelerator for the intended application.

7.4.3 High-Power Operation

Ideally, there is no upper limit on the power output that can be obtained from an FEL. This is due to the fact that the active medium in an FEL is the electron beam, which itself is an ionized medium which cannot be broken down further as in atomic and molecular systems subjected to high electric fields during operation at high powers. Further, the electron beam transfers only a small fraction of its energy to

the FEL radiation with the remaining energy in the beam being brought out of the interaction region and dumped in a suitably designed beam dump. Consequently, there is no problem of heat removal from the machine since all energy is removed at the speed of light. X-ray FELs have demonstrated GW of peak power in fs pulses while a long-wavelength FEL has been successfully operated at 10 kW CW average power. Progress on the power output from FELs is dependent upon the progress in accelerator technology.

7.4.4   Mirror-Less Operation at X-Ray Wavelengths

As one moves to wavelengths shorter than 100 nm, it is difficult to have mirrors that can be used to make the optical cavity of an oscillator. With FELs, there is a regime of operation called as the high gain regime where, in a single pass through the device, a high-intensity bunch of electrons can drive an FEL to reach saturation over an undulator length of few 10s of meters. This regime of operation is very popular in X-ray FELs operating in the self-amplified spontaneous emission (SASE) mode where an intense (kA of peak current), energetic (few GeV for X-rays) electron bunch is propagated through an undulator that is 30–40 m long. The initial spontaneous emission from the electron bunch is amplified as it propagates through the undulator with continuous interaction between the radiation and electron bunches resulting in saturation of lasing action after which very high-peak-power, coherent X-ray radiation with intensities that are orders of magnitude higher than those possible from present-day synchrotron radiation sources are obtained. Many versions of this mode of operation, including those employing a seed laser with harmonic generation, have been proposed and are being tried out to improve the performance of these X-ray FELs. It may be noted that SASE mode of operation has been successfully demonstrated at longer wavelengths also. However, due to the availability of mirrors at these wavelengths, the oscillator configuration is more popular at these wavelengths.

7.5   Present Status of FELs

After the first successful operation of an FEL in 1976 by John Madey and his group at Stanford University, where they demonstrated operation of an FEL in an amplifier configuration at infrared wavelength, the same group also demonstrated operation in an oscillator configuration at the same wavelength using an optical cavity. The first operation of an FEL in the optical regime was at Orsay in France where a storage ring FEL on the ACO storage ring produced red color light. While the undulator used in this FEL is similar to that used in other FELs, the electron accelerator here is a synchrotron instead of a linear accelerator (linac), which is the most popularly employed injector for FELs. FELs have subsequently been operated at practically all

wavelengths with major emphasis being wavelengths where conventional lasers and microwave sources are not very efficient [4]. Current trends on FEL development are therefore focused mainly on two wavelength regimes – IR/terahertz (THz) and V-UV/X-ray wavelengths.

With a lot of interest focusing around THz radiation for scientific as well as for security-related applications, many FELs have been built or proposed in the last decade at these long wavelengths. Depending upon the application, these FELs operate either with short pulse and high-peak powers required for scientific applications or at high CW average powers for imaging or homeland security-related applications. A THz FEL has been successfully operated at Novosibirsk in Russia at a CW average power level of 400 W in what is called as an energy recovery linac (ERL) configuration using normal conducting linacs. Similarly, an FEL using a similar ERL configuration but with superconducting cavities has been successfully operated at the Jefferson Lab in the United States at CW average power levels of more than 10 kW.

Recently, with growing interest in high brightness sources of hard X-rays, many short-wavelength FELs have been built/proposed. The first such X-ray FEL is the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center in the United States which has successfully demonstrated lasing at 1.5 Å with bright femtosecond (fs) pulses of X-ray radiation which have been used for a variety of research applications. The SACLA X-ray FEL in Japan has also lased recently producing bright beams of hard X-rays. Similar X-ray FELs are also being built in Europe (X-FEL), Paul Scherer Institute in Switzerland, Pohang Light Source in Korea, etc. and greater details about these FELs can be obtained from their respective websites. These FELs are the state of the art in FEL research since successful building and commissioning of these devices involves many cutting-edge technologies like advanced electron beam generation and manipulation techniques, beam diagnostics, very stable RF and control systems, etc. The operating parameters of LCLS are typical of such X-ray FELs: $\lambda \sim 1.5$ Å, pulse width $\sim$100 fs, peak brightness $\sim 12 \times 10^{32}$ photons/s/mm^2/mrad^2/0.1 % BW, and peak coherent power $\sim$9 GW.

Significant work has also been done on new and improved configurations of FELs to tap the progress made in science and technology of accelerators. While LCLS utilizes conventional normal conducting linacs, the X-FEL project proposes to use superconducting RF technology for the injector linac which will enable them to operate with a higher duty cycle. Superconducting RF technology is also being exploited to build energy recovery linacs that operate at close to 99 % efficiency. Such a configuration has already demonstrated 10 kW CW average power at IR wavelength, which is very useful for homeland security applications. On the X-ray FEL front, various schemes like high-gain harmonic generation (HGHG), high harmonic generation (HHG), and FEL oscillator configuration using an optical cavity with Bragg crystal mirrors are being tried out, or have been proposed in projects like the FERMI and SPARC FELs in Itlay, Dalian and SDUV FELs in China etc.

In India, experimental activity related to FELs was initiated at the Institute for Plasma Research (IPR), Ahmedabad, and at the University of Pune in the 1990s.

While activity at Pune University initially focused on building an undulator for use in an FEL, the activity at IPR, Ahmedabad, was on propagation of a sheet electron beam generated by their injector through a planar, five-period undulator to generate mm waves. This was successfully accomplished by them in 1996 [5]. Significant theoretical studies on FELs have been performed at the Indian Institute of Technology (IIT), Delhi, University of Lucknow, and at the Devi Ahilya Vishwavidyalaya (DAVV), Indore. DAVV, Indore, has recently initiated experimental activity related to development and characterization of prototype undulators for FELs.

The Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, initiated activities on FELs in late 1990s, beginning with theoretical studies on different types of FEL configurations and for the design of an FEL at far-infrared wavelengths. Subsequently, the first project to build a far-infrared FEL was taken up in the year 2002 which envisaged the setting up of a THz FEL designed to lase at 80–150 μm wavelength using an electron beam of energy 7–10 MeV and a 2.5 m long pure permanent magnet undulator (NdFeB) with a period of 5 cm. This effort involved the in-house development of all important subsystems – the injector linac [6], the undulator [7], the optical cavity, the electron beam transport line, and the RF system. This FEL, called as the compact ultrafast terahertz FEL (CUTE-FEL), was commissioned in 2010 and the first spontaneous THz radiation from the device was observed in 2011. Subsequently, with improvements in the injector system of the FEL, first signature of nonlinear dependence of radiated power on the electron beam current has been observed in 2012 [8]. Efforts are underway to further increase the nonlinearity and move toward saturation with the commissioning of a crucial RF power amplifier for the pre-buncher cavity.

Efforts are also presently underway on building an infrared FEL (IR-FEL) designed to lase at 15–30 μm wavelength using an injector linac of 15–25 MeV energy and a 2.5 m long pure permanent magnet undulator with 5 cm period. This IR-FEL is proposed to be used for materials science research by an in-house group for which a user facility is presently being developed.

7.6 Conclusions

FELs are electron beam-based sources of intense, coherent, tunable electromagnetic radiation which can, in principle, operate over a wide-wavelength region from THz to hard X-rays. On account of being coherent, the radiation power output from an FEL is many orders of magnitude higher than that possible using a synchrotron radiation source operating at the same wavelength. Though they are operationally not as simple and compact as conventional lasers or microwave sources, they have certain unique characteristics like tunability, uniformity of operation principle over all wavelengths, high-power-handling capacity, etc., that make them very popular at wavelengths where the conventional sources are either not available or not very efficient. Many user facilities based on FELs are in operation today at wavelengths ranging from far-infrared to soft and hard X-rays.

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