Lasers, Free-Electron

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Abstract
Free-electron lasers are radiation sources, based on the coherent emission of synchrotron radiation of relativistic electrons within an undulator or wiggler. The resonant radiation wavelength depends on the electron beam energy and can be tuned over the entire spectrum from micrometer to X-ray radiation. The emission level of free-electron lasers is several orders of magnitude larger than the emission level of spontaneous synchrotron radiation, because the interaction between the electron beam and the radiation field modulates the beam current with the periodicity of the resonant radiation wavelength. The high brightness and the spectral range of this kind of radiation source allows studying physical and chemical processes on a femtosecond scale with angstrom resolution.

Keywords
free-electron laser; undulator; microbunching; SASE FEL; FEL oscillator; FEL amplifier; FEL parameter; gain length.

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1 Introduction

A free-electron laser (FEL) [1] transforms the kinetic energy of a relativistic electron beam produced by a particle accelerator like a microtron, storage ring, or radio Q2 frequency (RF) linear •accelerator into electromagnetic (EM) radiation. The transformation occurs when the beam goes through an alternating magnetic field, produced by a magnet called an *undulator* [2], that forces the electrons to move in an oscillatory trajectory about the axis of the system, as shown in Fig. 1. An electromagnetic wave propagates together with the electron beam along the undulator axis, and interacts with the electrons.

The undulator magnet is a periodic structure in which the field alternates between positive and negative values and has zero average value. It produces an electron trajectory having a transverse velocity component perpendicular to the axis and parallel to the electric field of the wave, thus allowing an energy exchange between the two to take place. One can either transfer energy from the beam to the wave, in which case the device is an FEL, or from the wave to the beam, in which case it is an inverse FEL (IFEL) [3]. In the second case, the system is acting like a particle accelerator and can be used to accelerate the electron beam to higher energies.

The energy transfer can take place only if a condition of synchronism between the wave and the beam oscillations is satisfied (Sect. 2.2). This condition gives a relationship between the radiation wavelength λ, the electron beam velocity β_z along the undulator axis (measured in units of the light velocity c), and the undulator period λ_0:

$$\lambda = \frac{\lambda_0(1-\beta_z)}{\beta_z} \qquad (1)$$

For relativistic electrons, this condition can also be written in an approximate, but more convenient, form using the beam energy γ (measured in the rest energy units $E = mc^2\gamma$):

$$\lambda = \left(\frac{\lambda_0}{2\gamma^2}\right)(1 + a_w^2). \qquad (2)$$

The dimensionless quantity

$$a_w = \frac{eB_0\lambda_0}{2\pi mc} \qquad (3)$$

is the undulator vector potential normalized to the electron rest mass mc^2; e is the electron charge and B_0 is the undulator peak magnetic field. (Here, and in the rest of the paper, we use MKS units.) The quantity a_w is called the *undulator parameter*,

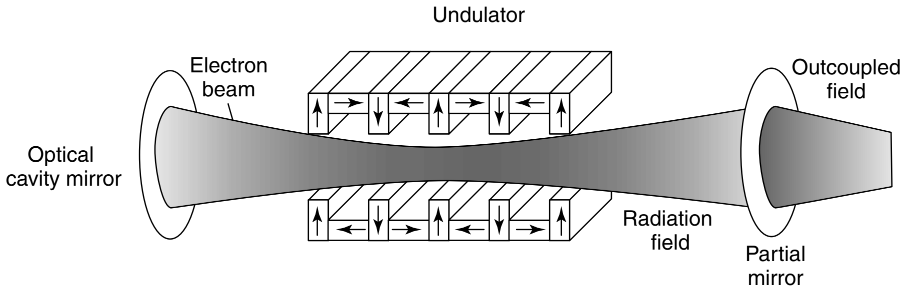

Fig. 1 Schematic representation of an FEL oscillator, showing its main component: the electron beam, undulator magnet, and optical cavity. The undulator shown is a permanent-magnet planar undulator. The arrows indicate the magnetic field direction. In an FEL amplifier of SASE FEL setup the optical cavity is omitted. The FEL amplifier is seeded by an external radiation field

which is the normalized vector potential of the undulator field. The undulator can be of two types: helical and planar (Sect. 2). Equation 2 is valid for a helical undulator. In the case of a planar undulator, Eq. 2 is still valid if we replace the undulator parameter with its rms value $a_w/\sqrt{2}$.

Because of the dependence of the radiation wavelength on the undulator period, magnetic field, and electron-beam energy – quantities that can be easily and continuously changed – the FEL is a tunable device that can be operated over a very large frequency range. At present, the range extends from the microwave to the UV [4]. A new FEL is now under construction in the United States [5] to reach the X-ray region, about 0.1 nm. A similar program is being developed in Germany [6], and other FEL to cover the intermediate region between 0.1 nm and the UV [7] are also being considered by several countries.

The efficiency of the energy transfer from the beam kinetic energy to the EM wave is between 0.1 to a few percent for most FELs, but it can be quite large, up to about 40%, for specially designed systems. The beam energy not transferred to the EM wave remains in the beam and can be easily taken out of the system, to be disposed of, or recovered elsewhere. This fact suggests that high- to average-power FELs can be designed without the problem, common in atomic and molecular lasers, of heating the lasing medium.

The time structure of the laser beam mirrors that of the electron beam. Depending on the accelerator used, one can design systems that are continuous-wave (cw) or with pulses as short as picoseconds or subpicoseconds.

Tunability, high efficiency, and time structure make the FEL a very attractive source of coherent EM power. In some wavelength regions, like the X-ray, the FEL is unique. Its applications range from purely scientific research in physics, chemistry, and biology to military, medical, and industrial applications.

FELs originate in the work carried out in the 1950s and 1960s on the generation of coherent EM radiation from electron beams in the microwave region [2, 8]. As scientists tried to push power sources to shorter and shorter wavelengths, it became apparent that the efficiency of the microwave tubes, and the power they produced, dropped rapidly in the millimeter region. It was then realized that this problem could be overcome by using an undulator magnet to modify the beam trajectory [1], making it possible for the beam to interact with a wave, away from any metallic boundary. Two pioneering experiments at the Stanford University [9, 10] proved that the FEL is a useful source of coherent radiation.

The current disadvantage of FELs is the greater complexity and cost associated with the use of a particle accelerator. For this reason, the use and development of FELs are mainly oriented to the following:

1. portions of the EM spectrum, like the far infrared (FIR), or the soft and hard X-ray region, where atomic or molecular lasers are not available or are limited in power and tunability;
2. large-average power, high-efficiency system.

An order-of-magnitude comparison of the peak brightness obtained or expected

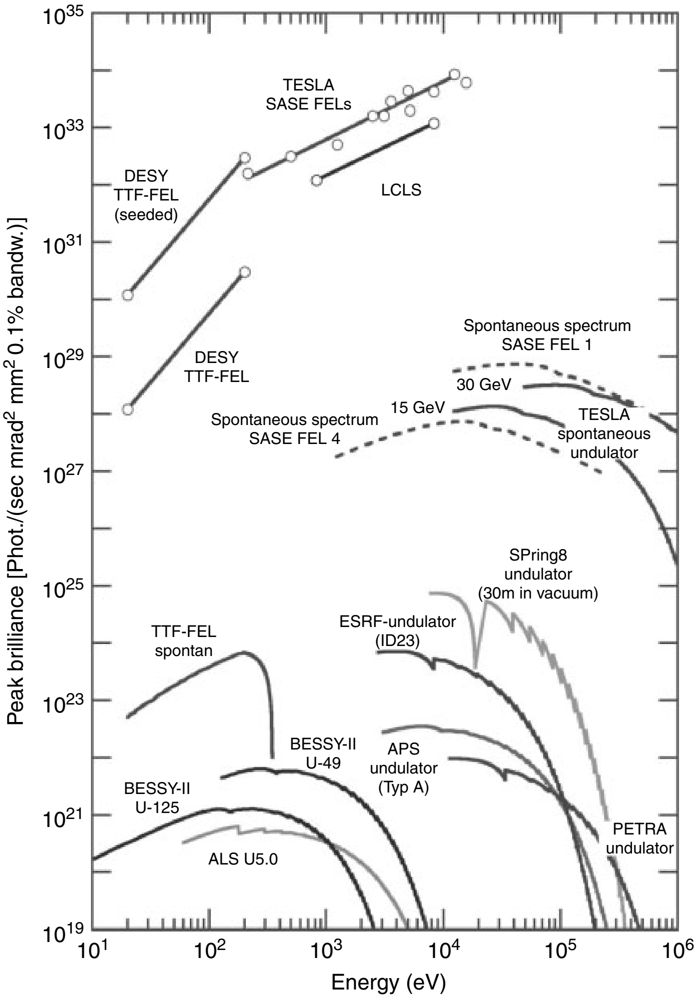

Fig. 2 Peak brightness of free-electron lasers in the VUV and X-ray regime, compared to 3rd generation light sources [11]

for the FEL, compared to other sources of EM radiation, is given in Fig. 2, pointing out again the interest for FELs in the soft-to-hard X-ray regions.

In Sect. 2 of this article, we discuss the general physical principles of FELs and the properties and characteristics of their main components, that is, the undulator magnets, electron beams, and optical systems. We also describe the main properties of the spontaneous radiation from an undulator, the process leading to the amplification of radiation, the high-gain and small-signal-gain regimes, diffraction effects, saturation effects, the limits on the system efficiency, the dependence of gain on beam parameters.

In Sect. 3, we give a short review of the experimental results obtained to date for various FELs. The future development of FELs is described in Sect. 4.

2
Physical and Technical Principles

An FEL has three fundamental components: an electron beam of given energy and intensity and the associated accelerator used to produce it; the undulator magnet; and the EM wave and the associated optical components controlling its propagation. A schematic representation of an FEL is given in Fig. 1.

The accelerators used to provide the electron beam are of many types: electrostatic, induction line, radio-frequency (rf) linear accelerator, pulsed diode, or storage rings. Some of their basic characteristics, their energy ranges, and the FEL wavelengths for which they are more commonly used are given in Table 1.

Undulator magnets are of two main types: helical or planar. In the first case, the magnetic field vector rotates around the axis as a function of axial distance; in the second case, its direction is fixed, and its amplitude oscillates along the axis. These magnets can be, and have been, built using a wide variety of technologies: pulsed or DC electromagnets, permanent magnets, and superconducting magnets. The field amplitude can vary from a fraction of a tesla to over 1 T, and the period from 1 cm to many centimeters. A great effort is under way to develop undulators with periods in the millimeter range; these would allow a reduction of the beam energy for a given radiation wavelength, thus reducing the cost and complexity of the FEL. A helical undulator was used by Madey and coworkers [9] in the first FEL. This undulator was a superconducting magnet, built with two helical windings with current flowing in opposing directions.

The FEL can be operated as an oscillator, using an optical cavity to confine the radiation in the undulator region, as shown in

Tab. 1 Particle accelerators for FELs

	Energy	*Peak current*	*Pulse length*	*FEL wavelength*
Electrostatic	1–10 MeV	1–5 A	1–20 μs	mm to 0.1 mm
Induction linear accelerator	1–50 MeV	1–10 kA	10–100 ns	cm to μm
Storage ring	0.1–10 GeV	1–1000 A	30 ps–1 ns	1 μm to nm
RF linear accelerator	0.01–25 GeV	100–5000 A	0.1–30 ps	100 μm to 0.1 nm

Fig. 1, or it can be used as an amplifier. Oscillator–amplifier combinations [master oscillator, power amplifier (MOPA)], as well as systems in which one amplifies the electron spontaneous radiation emitted in traversing the undulator [self-amplified spontaneous radiation (SASE) [12]], have been used.

The performance characteristics of some of the existing FELs are discussed in detail in Sect. 3.

2.1 Undulator Spontaneous Radiation

For this discussion, we use a reference frame with z along the undulator axis and x and y perpendicular to z. For a helical undulator, the field near the axis z is given by

$$\vec{B} = B_0 \left[\vec{e}_x \cos\left(2\pi \frac{z}{\lambda_0}\right) + \vec{e}_y \sin\left(2\pi \frac{z}{\lambda_0}\right) \right], \tag{4}$$

where $\vec{e}_x$, $\vec{e}_y$, and $\vec{e}_z$ are unit vectors along the x, y, and z axes. The electron velocity in this field, in units of c, is

$$\vec{\beta} = \frac{a_w}{\gamma} \left[\vec{e}_x \sin\left(2\pi \frac{z}{\lambda_0}\right) + \vec{e}_y \cos\left(2\pi \frac{z}{\lambda_0}\right) \right] + \vec{e}_z \beta_z. \tag{5}$$

The amplitude of the transverse velocity is a_w/γ. This quantity also represents the maximum angle between the electron trajectory and the undulator axis. For relativistic beams, this quantity is much less than 1, and the longitudinal velocity is near 1. Notice that in the case of a helical undulator, the axial component of the velocity, β_z, remains constant. For a planar undulator, only one of the two transverse components in Eqs. 4 and 5 is nonzero. In this case, the longitudinal velocity is not constant; in fact, it can be written as the sum of a constant term plus one oscillating at twice the undulator period. The electron trajectory in a helical undulator is a helix of radius $a_w \lambda_0 / 2\pi\gamma\beta_z$ and period equal to the undulator period. For a planar undulator, it is a sinusoid in the plane perpendicular to the magnetic field.

When traversing the undulator, the electrons are subject to an acceleration and radiate EM waves. This spontaneous emission is fundamental to the operation of an FEL. One relativistic electron traversing an undulator magnet emits radiation in a narrow cone, with an angular aperture of order $1/\gamma$ [13]. The radiation spectrum is a superposition of the synchrotron radiation emitted when the electron trajectory is bent in the undulator field, a narrow line introduced by the periodic nature of the motion in the same field, and its harmonics. The wavelength of the fundamental line is of the order of $\lambda_0/2\gamma^2$, which can be interpreted as the undulator period λ_0 doubly Doppler shifted by the electron motion.

The aperture $1/\gamma$ of the synchrotron radiation cone can be compared with the angle between the electron trajectory and the undulator axis, a_w/γ. If a_w is smaller than 1, the emitted radiation is contained within the synchrotron radiation cone, and the emission is predominantly in a single line. If a_w is larger than 1, the synchrotron radiation cone sweeps an angle larger than its aperture. In this case, the spectrum is rich in harmonics and approaches the synchrotron radiation spectrum when a_w is very large. When $a_w \gg 1$, the magnet is usually referred to as a wiggler, reserving the name undulator for the case a_w less than or on the order of one. In this article, we use the generic term "undulator" to describe a magnet with a periodic transverse field described by Eq. 4.

The fundamental wavelength seen by an observer looking at an angle θ to the undulator axis is $\lambda = (\lambda_0/2\gamma^2)(1 + a_w^2 + \gamma^2\theta^2)$, and is the wavelength at which there is positive interference between the radiation emitted in two undulator periods. This is also, when $\theta = 0$, the wavelength corresponding to the "synchronism condition" Eq. 1.

In a planar undulator, the magnetic field has only one component, say along y. Then the velocity has components in the x and z directions. The wavelength of the spontaneous radiation is the same as that for a helical undulator if the vector potential a_w is replaced by its rms value, $a_w/\sqrt{2}$.

In a helical undulator, the radiation on axis contains only the fundamental harmonic given by Eq. 1. In a planar undulator, the longitudinal velocity is modulated twice at the undulator period. This leads to a richer spectrum: all the odd harmonics of Eq. 1 appear on axis. For both type of undulators, even and odd harmonics appear off axis.

The linewidth of the radiation is determined by the number N_w of undulator periods; the total length of the pulse emitted by one electron is that of a wave train with a number of periods equal to N_w, the number of undulator periods. The corresponding linewidth of the fundamental is

$$\frac{\Delta\omega}{\omega} = \frac{1}{2N_w}. \tag{6}$$

When more than one electron is producing the radiation, the pulse length and angular distribution can be affected by the electron-beam characteristic. The pulse length is increased by the electron bunch length when this is larger than $N_w\lambda$. The radiation linewidth is increased if the beam energy spread is larger than $1/2N_w$, the single electron width. Similarly, the effective source radius and angular distribution can be increased by the electron beam. This effect can reduce the FEL gain, as we will discuss in the next section.

2.2 The FEL Amplification

Undulators are widely used in storage rings as brilliant sources of synchrotron radiation. In this case, the superposition of spontaneous radiation of many electrons has no phase correlation, so that the total intensity is proportional to the electron number N_e. In an FEL, as in an atomic laser, there is a phase correlation between emitting electrons. This correlation is obtained by modulating the longitudinal beam density on the scale of the radiation wavelength, a process called *bunching*. When electrons are bunched together in •a distance that is short compared to the Q3 wavelength of the radiation, they emit in phase, thus increasing the intensity in the emitted line and simultaneously reducing its width.

The formation of bunching is caused by the interaction between the electrons and the radiation field. It can be summarized by three actions, fundamental to any FEL process:

1. the modulation of the electron energy due to the interaction with the radiation field,
2. the change in the longitudinal position of the electrons owing to the path length difference of the trajectories within the undulator of electrons with different energies,
3. the emission of radiation by the electrons and, thus, growth in the radiation field amplitude.

Each point will be explained in detail below. The FEL amplification couples these basic processes and exploits the inherent instability of this system. A stronger modulation in the electron density increases the emission level of the radiation, which, in return, enhances the energy modulation within the electron bunch. With stronger energy modulation, the formation of the bunching (modulation in the electron positions) becomes even faster. The FEL amplification is stopped, when the electron density modulation has reached a maximum. At this point, all electrons have the same phase of emission and the radiation is fully coherent. The free-electron laser has reached saturation.

The FEL process is either initiated by a seeding radiation field or by the inherent fluctuation in the electron position at the undulator entrance. The first classifies the free-electron laser as an FEL amplifier, while the latter is called a *self-amplifying spontaneous radiation* (SASE) FEL, where the initial radiation level is produced by the spontaneous radiation, as described in
Q4 Sect. 2.1•.

In the following, we describe the basic FEL process. We start with a simplified model, where transverse effects such as the diffraction of the radiation field due to its finite size is ignored. The discussion of these three-dimensional effects is postponed till Sect. 2.5. Let

$$\vec{E} = E_0 \left[\vec{e}_x \cos\left(2\pi \frac{z}{\lambda} - \omega t + \Psi\right) + \vec{e}_y \sin\left(2\pi \frac{z}{\lambda} - \omega t + \Psi\right) \right] \quad (7)$$

be the electric field of a plane wave propagating along the undulator axis. The initial phase of the radiation field at t, $z = 0$ is Ψ. This field is transverse to the undulator axis, and thus has components parallel to the transverse electron velocity, as given by Eq. 5. An energy transfer between the EM field and the electron beam can take place. Using Eqs. 5 and 7, one finds

$$mc^2 \frac{\mathrm{d}\gamma}{\mathrm{d}t} = eE_0 \frac{a_w}{\gamma} \sin(\Phi + \Psi), \quad (8)$$

where the phase Φ is

$$\Phi = 2\pi \left(\frac{1}{\lambda} + \frac{1}{\lambda_0}\right) z - \omega t + \Phi_0. \quad (9)$$

This quantity is called the *ponderomotive force phase* [14] and plays a key role in FEL physics. The ponderomotive force phase has terms changing at the "fast" EM field frequency and terms changing with the "slow" undulator period. The time-average value of the electron energy change (8), averaged over a few radiation periods, is 0 unless we satisfy a "synchronism condition" $\mathrm{d}\Phi/\mathrm{d}t = 0$. This condition can be written as $\lambda = \lambda_0(1 - \hat{\beta}_z)/\hat{\beta}_z$ with $\hat{\beta}_z$ as the "resonant" velocity for a given undulator period and radiation field wavelength. In the case of relativistic particles, using the relationship $\hat{\beta}_z = (1 - 1/\gamma^2 - \beta_x^2 - \beta_y^2)^{1/2}$, and assuming $\gamma \gg 1$, $\beta_z, \beta_y \ll 1$, this condition can be approximately written as $\lambda = \lambda_0(1 + a_w^2)/2\gamma^2$. These are Eqs. 1 and 2, given in the introduction. If the synchronism condition is satisfied, the ponderomotive force phase is constant, and the electron beam, oscillating at the slow undulator frequency, can exchange energy with the fast oscillating EM wave.

If the longitudinal velocity β_z differs from the resonant velocity $\hat{\beta}_z$, the electron slips in the ponderomotive force phase as

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{2\pi c}{\lambda} \left(\frac{\beta_z}{\hat{\beta}_z} - 1\right). \quad (10)$$

If the electron moves with the resonant velocity, its ponderomotive force phase is constant according to the synchronism condition. Particles with higher energy move forward with respect to the initial phase Φ_0, while particles with lower energy fall back.

The distribution of the initial position of the electrons within the bunch is determined by the electron source and the acceleration process. If the electron beam is produced by an accelerator using RF cavities to accelerate the beam, the distribution is characterized by two scale lengths. One is the RF wavelength; the other is the radiation wavelength. In an FEL, the first is much larger than the second. The wavelengths used in RF cavities vary from a minimum of about 10 cm for an RF linear accelerator to infinity for an electrostatic accelerator. At the scale length defined by the RF system, the electrons are distributed longitudinally into bunches separated by one RF wavelength. The length of these bunches is a fraction of the wavelength of the accelerating RF and varies from about 1 mm for the case of a 3-GHz ($\lambda_{\mathrm{rf}} = 10$ cm) RF linear accelerator to a continuous beam for the electrostatic case.

At the scale length of the radiation wavelength, the electron distribution is in good approximation uniform; there is no correlation between the longitudinal electron positions at the scale of the radiation wavelength λ except for a residual, but small bunching owing to the finite number of electrons per radiation wavelength. It represents the spontaneous radiation level at the given wavelength λ, which is amplified in an SASE FEL. Section 2.6 discusses in detail the properties of this device.

If the electrons have the resonant velocity or are close to it, the interaction with the radiation field results in a sinusoidal modulation of the electron energy (Eq. 9). Electrons, lying within the phase interval $[\Psi,\ \Psi + \pi]$, gain energy and become faster $(\mathrm{d}\Phi/\mathrm{d}t > 0)$, while electrons in the interval $[\Psi + \pi,\ \Psi + 2\pi]$ are slowed down $(\mathrm{d}\Phi/\mathrm{d}t < 0)$. As a result, all electrons tend to drift toward the phase $\Psi + \pi$ and become bunched with the periodicity of the radiation field. The electrons emit in phase and the radiation is coherent.

The radiation emitted by the electrons adds up to the interacting EM wave. The amplitude E_0 and the phase Ψ of the EM field change with the ongoing interaction between radiation field and electron beam. This is apparent because the electrons tend to bunch at a phase different to the radiation field. The radiation phase is slowly adapting to the new phase defined by the bunching phase of the electrons. For a self-consistent description of the FEL interaction, the Maxwell equation for the EM wave has to be solved as well. If the fast oscillation of the EM wave $\exp[i(2\pi/\lambda)z - i\omega t]$ is split from the amplitude and phase information, the complex amplitude $E \equiv E_0 \exp[i\Psi]$ changes slower than the "slow", transverse oscillation of the electrons (Eq. 5). The change is given by [15]:

$$\left(\frac{\partial}{c\partial t} + \frac{\partial}{\partial z}\right) E = i\frac{\mu_0}{2} a_w \sum_j \frac{\mathrm{e}^{-i\Phi_j}}{\gamma_j} \quad (11)$$

with μ_0 as the magnetic permeability and the sum over all electrons. Equations 8, 10, and 11 are the mathematical representation of the three basic processes, listed at the beginning of this chapter. Note that the right-hand side of Eq. 11 is determined by the degree of bunching in the electron density and is at maximum when all electron phases Φ_j are identical. It is also clear from the same equation that if more electrons are contributing to the FEL process, the growth in the radiation field is stronger.

The strength of this coupling scales with the FEL parameter [16]

$$\rho = \left(\frac{a_w}{4\gamma}\frac{\omega_p}{\omega_0}\right)^{\frac{2}{3}}, \qquad (12)$$

where $\omega_p = (4\pi r_e c^2 n_0/\gamma)^{1/2}$ is the beam plasma frequency, n_0 is the electron-beam density, and $\omega_0 = 2\pi c/\lambda_0$. Typical values of ρ vary from 10^{-2} for a millimeter FEL to 10^{-3} or less for a visible or UV FEL.

The solutions for Eqs. 9, 10, and 11 are of type $E \propto \exp[i\Lambda 2\omega_0 \rho t]$, where the growth rate Λ depends on the electron distribution in energy and the deviation of the mean energy from the resonance energy $\gamma_R = \sqrt{(\lambda_0/2\lambda)\cdot(1 + a_w^2)}$. For the simplest case of a mono-energetic beam with $<\gamma> = \gamma_R$, Λ is the solution of the dispersion equation $\Lambda^3 = -1$ [17]. Although energy deviation or finite energy spread adds additional terms, the resulting dispersion equation is always cubic for this one-dimensional model.

Of particular interest for the FEL process is the solution of the dispersion equation, which has a negative imaginary part. It corresponds to an exponentially growing mode. The maximum growth rate in this one-dimensional model is $-\Re e(i\Lambda) =$
Q28 $\sqrt{3}/2$. Inserted into the •ansatz for the radiation field amplitude E, the e-folding length of the amplification is

$$L_g = \frac{\lambda_0}{2\pi\sqrt{3}\rho}, \qquad (13)$$

which is also referred to as the gain length [18]. Besides the exponentially growing mode, the other modes are either oscillating or decaying. In the beginning of the free-electron laser, all modes are of the same magnitude and it requires a few gain lengths before the exponentially growing mode dominates. This retardation in the amplification of the seeding field is called *lethargy regime* [16].

The growth in the radiation field amplitude stops at saturation, when the modulation in the electron distribution has reached a maximum. At this point, the bunch is broken up into multiple microbunches. The spacing of the microbunches is the radiation wavelength. Because the wavelength is tunable with the electron beam energy, the free-electron laser is also a device to modulate the current of a long pulse with free control on the periodicity. This property is useful for some experiments on plasma-beam interaction [19].

2.3
The Small-signal Gain Regime

The first FEL experiments had an enhancement of a few percent of the seeding radiation field. In this low-gain regime, the undulator length is shorter than the gain length. All modes – growing, decaying, and oscillating – have approximately the same amplitude and the radiation power at the end of undulator as a result of the interference of these modes. If the wavelength of the seeding radiation field fulfills the synchronism condition, the interference is completely destructive and the gain – the relative change in the radiation field intensity – is zero. The growth rate of each mode depends differently on the deviation from the synchronism condition (Eq. 1) and a slight deviation $\Delta\omega$ results in an enhancement of the EM field.

The small-signal gain was first evaluated by Madey [1]. Although his original theoretical discussion of the FEL used a quantum-mechanical description, it was soon realized that under most conditions, a classical description is sufficient to describe the system, since the most relevant quantities, such as gain, Eq. 14, are independent of the Planck constant.

When the initial EM field amplitude is small – and the relative change in the intensity is also small – the gain is called the *small-signal gain*. For an initially monoenergetic electron beam, the small-signal gain, calculated by Madey, is

$$G_s = 4\sqrt{2}\pi \frac{\sqrt{\lambda\lambda_0}}{w_0^2} \frac{a_w^2}{\sqrt{(1+a_w^2)^3}} \frac{I_p}{I_A} N_w^3 \times \frac{d}{d(x/2)} \frac{\sin^2(x/2)}{(x/2)^2}, \quad (14)$$

where $x = 2\pi N_w \Delta\omega/\omega$, N_w is the number of undulator periods, I_p is the beam current, $I_A = ec/r_e$ is the Alfvén current (about 17 kA), r_e is the classical electron radius ($r_e \approx 2.8 \times 10^{-15}$ m), and πw_0^2 is the transverse cross section of the EM wave (assumed to be larger than that of the electron beam).

The gain curve in Eq. 14 is proportional to the derivative of the spectrum of the spontaneous radiation. The gain is zero for $x = 0$, at synchronism, and is maximum for $x \simeq 2.6$. The linewidth is on the order of $1/N_w$, the inverse of the number of periods in the undulator.

Since the EM radiation frequency and the electron energy are related by the synchronism condition, Eq. 2, we can also redefine x, for a fixed frequency, as $x = 4\pi N_w \Delta\gamma/\gamma$. The gain linewidth then corresponds to an energy change $\Delta\gamma/\gamma$ on the order of $1/2N_w$. When the radiation field increases, the beam kinetic energy decreases; and when the change is about $1/2N_w$, the gain becomes 0. Hence the maximum FEL efficiency, defined as ratio of the laser intensity to the initial beam kinetic energy, is on the order of $1/2N_w$.

2.4 High-gain Regime and Electron Beam Requirement

The FEL saturates when the electron bunch has achieved maximum modulation and all electrons radiate coherently. Early free-electron lasers could not reach saturation with a single pass through an undulator. The gain can be accumulated when the undulator is enclosed by an optical cavity and the radiation field is reflected back to seed the FEL for succeeding electron bunches. On the other hand, optical cavities restrict the FEL to radiation wavelength where the losses of the cavity are smaller than the gain per single pass. To avoid this restriction, the undulator length has to be several gain lengths long to obtain a large gain and to reach saturation [18].

To reduce the overall undulator length, the gain length (Eq. 13) must be made as short as possible. The undulator period length is typically limited to a few centimeters and found by optimization of the gain length. Shorter values would reduce the undulator parameter and, thus, the coupling of the electron beam to the radiation field, while longer values would increase the resonant wavelength (Eq. 2). The energy has to be increased to keep the radiation wavelength constant, which reduces the ρ-parameter.

The gain length depends on the electron beam parameters as well. The gain length is reduced for a higher electron density, although there are limits on this, given by the transverse velocity spread in the electron beam. We discuss this and other three-dimensional effects in the next section.

The gain length of Eq. 13 is based on a beam with no energy spread. Energy spread prevents bunching of all electrons at the same ponderomotive force phase, because the electrons have different longitudinal velocities and the bunching is smeared out. The bandwidth in energy, which contributes to the FEL performance, is given by the ρ-parameter. A larger value means that the energy exchange between radiation field and electron beam is stronger. The undulator length, over which the synchronism condition must be fulfilled, is shorter. This allows a larger tolerance in the spread of the longitudinal velocity and thus, in energy. To keep the increase in the gain length reasonable, the initial rms energy spread σ_γ must be

$$\frac{\sigma_\gamma}{\gamma_R} \ll \rho. \tag{15}$$

Following the same argument, the deviation of the mean energy from the resonant energy is limited to

$$\left|\frac{<\gamma> - \gamma_R}{\gamma_R}\right| \ll \rho. \tag{16}$$

Note that in the high-gain regime, the gain is the largest if the beam energy is on resonance, as shown in Fig. 3. This is opposite to the small-signal gain regime with no gain at $<\gamma> = \gamma_R$.

Only electrons that lie within the energy acceptance bandwidth of the FEL around γ_R contribute to the FEL interaction. The relative width is approximately ρ. During the FEL amplification, energy is transferred from the electron beam to the radiation field. The amplification stops when most of the electrons are dropped out of the bandwidth. After that the interaction with the radiation field is negligible because the synchronism condition is no longer satisfied. Thus, the efficiency of the FEL, which is the relative amount of energy transferred from the electron beam to the radiation field, is ρ. The saturation power of the radiation field [20] is given by

$$P_{sat} = \rho P_b, \tag{17}$$

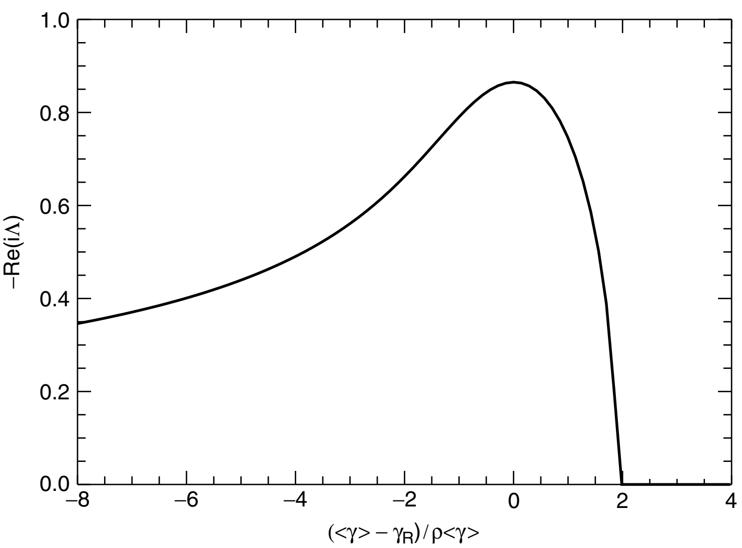

Fig. 3 Growth rate of the FEL amplification as a function of the detuning–the deviation of the mean energy of the electron beam from the resonant energy

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where $P_b = <\gamma> I_p mc^2/e$ is the electron beam power and I_p is the peak current. Because of this scaling, it is of interest to maximize the ρ-parameter not only for reducing the needed undulator length for saturation but also for increasing the output power level of the FEL.

Because the FEL amplification is an exponential process, the major change in the electron energy occurs close to saturation, when the electrons are pushed out of the FEL bandwidth. Although the FEL amplification stops at saturation, further energy can be extracted from the electron beam. For this, the synchronism condition has to be extended beyond saturation. The radiation wavelength is fixed, so the undulator field or period has to be reduced to compensate for the beam energy, which has been lost due to the FEL interaction. This process to gradually reduce the undulator field or period is called *tapering*. Although the energy transfer during tapering is slow compared to the exponential regime of the FEL, the process has no fundamental limits beside the given length of the undulator. Experiments have shown that a tapered system can enhance the efficiency up to 40% [21].

2.5 Three-dimensional Effects

The basic FEL process, as described in Sect. 2.2, remains the same when three-dimensional effects are included in the discussion, although the one-dimensional FEL parameter ρ (Eq. 12) might not be valid anymore. However, an effective three-dimensional FEL parameter can be found, which satisfies Eqs. 13, and 15 to 17.

Two major effects contribute to the extended, three-dimensional model of the FEL process, which are

1. the spread in the transverse velocity of the electron beam and
2. the diffraction of the radiation field.

A measure for the transverse spread in the electron beam is the normalized emittance ε_n [22], which is the area covered by the electron beam distribution in transverse phase space. It is an invariant in linear beam optics. If the beam is more focused, the spread in the transverse momenta is increased. Focusing along the undulator is necessary to prevent the growth of the transverse electron beam size, reducing the electron density and decreasing the gain. Electrons that drift away from the axis are deflected back to the undulator axis. As a result, electrons perform an additional oscillation even slower than the "slow" oscillation due to the periodic magnetic field of the undulator (Eq. 5). Because part of the electron energy goes into this so-called betatron oscillation, the electron is slower in the longitudinal direction than an electron without a betatron oscillation. The spread in the betatron oscillation, which scales with the normalized emittance, has a similar impact as an energy spread. Thus, the requirement for the transverse emittance is

$$\varepsilon_n \ll \frac{4\lambda\beta <\gamma>}{\lambda_0}\rho, \qquad (18)$$

where the beta-function β [22] is a measure for the beam size of the electron beam. Stronger focusing would increase the electron density (β becomes smaller) and consequently, the ρ parameter. But at the same time, the impact of the emittance effect is enhanced, reducing the amount of electrons that can stay in phase with the radiation field. It requires the optimization of the focusing strength to obtain the shortest possible gain length. A rough estimate for the optimum β-function is $\beta \approx L_g \approx \lambda_0/4\pi\rho$. Inserting this into Eq. 18 shows that the beam emittance $\varepsilon = \varepsilon_n/\gamma$ has to be smaller than the photon beam "emittance" $\lambda/4\pi$. If this condition is fulfilled, the electron beam does not diverge faster than the radiation field and all electrons stay within the radiation field.

The diffraction of the radiation field transports the phase information of the radiation field and the bunching of the electron beam in the transverse direction. This is essential to achieve transverse coherence of the radiation field, in particular, if the FEL starts from the spontaneous radiation (SASE FEL). SASE FELs do not guarantee the transverse coherence as a seeding laser signal of an FEL amplifier would do. The betatron oscillation, which yields a change in the transverse position of the electron, contributes to the growth of transverse coherence as well.

As a degrading effect, the radiation field escapes from the electron beam in the transverse direction. The field intensity at the location of the electron beam is reduced and the FEL amplification is inhibited. The compensation for field losses due to diffraction is the FEL amplification itself. After the lethargy regime, the FEL achieves equilibrium between diffraction and amplification. The transverse radiation profile becomes constant and the amplitude grows exponentially. This "quasi-focusing" of the radiation beam is called *gain guiding* [23] and the constant profile of the radiation field is an eigenmode of the FEL amplification.

Similar to the eigenmodes of the free-space propagation of a radiation field (e.g., Gauss–Hermite modes), there are an infinite number of FEL eigenmodes [24]. Each couples differently to the electron beam and thus has a different growth rate or gain length. That mode, which has the largest growth rate, dominates after several gain lengths and the radiation field becomes transversely coherent.

At saturation •gain, guiding vanishes Q5 and the electron beams radiate into multiple modes. Typically, the fundamental FEL-eigenmode is similar to that of free-space propagation and the resulting reduction in transverse coherence at saturation is negligible.

The characteristic measures for diffraction and FEL amplification are the Rayleigh length z_R and gain length L_g. To calculate z_R, we approximate the radiation size at its waist by the transverse electron beam size Σ as the effective size of the radiation source, resulting in $z_R = k\Sigma/2$. For $z_R \ll L_g$, the FEL amplification is diffraction-limited with a gain length significantly larger than that in the one-dimensional model (Eq. 13). In the opposite limit ($z_R \gg L_g$), the one-dimensional model becomes valid.

2.6
Longitudinal Effects, Starting from Noise

The radiation field propagates faster than the electron beam and advances one radiation wavelength per undulator period. Thus, information cannot propagate further than the slippage length $N_w\lambda$, where N_w is the total number of undulator periods. If the bunch is longer than the slippage length, parts of the bunch amplify the radiation independently. While an FEL amplifier is seeded by a longitudinal coherent signal, this is not the case for an FEL, starting from the spontaneous emission (SASE FEL). SASE FELs with electron bunches longer than the slippage length generate longitudinally incoherent signals. Further processing, succeeding the FEL, is required for fully longitudinal coherence

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(e.g., it can be achieved with a monochromator with a bandwidth smaller than the Fourier limit of the electron bunch length).

An FEL amplifier has a coherent seeding signal and the electron beam can be more or less in resonance with it. The output power level depends on the deviation of the mean energy of the electron beam from the resonant energy γ_R. An SASE FEL, on the other hand, uses the broadband signal of the spontaneous emission to start the FEL amplification. Independent of •the beam energy, the resonance condition is always fulfilled, but the SASE FEL amplifies all frequency components within the acceptance bandwidth of the FEL as well. The relative width is $\Delta\omega/\omega = \rho$ and is typically much larger than the observed width of an FEL amplifier.

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The initial emission level of the spontaneous radiation depends on the fluctuation in the electron density. Because there are only a finite number of electrons per radiation wavelength and the initial ponderomotive force phase is random, electrons can cluster together at random. The radiation from parts of the bunch with a larger clustering will have larger intensity than that of other parts. The variation in these clusters and, thus, the fluctuation in the beam current, depend on the total number of electrons. Because of the random nature of the electron positions, more electrons result in a smoother distribution. The chances for large clusters are reduced.

The effective power level, emitted because of spontaneous radiation and then further amplified by the FEL interaction, is called the *shot noise power* [25]. An FEL amplifier, seeded with a power signal smaller than the shot noise power level does not operate as an FEL amplifier but as an SASE FEL instead. Typical values are a few watts for free-electron lasers in the IR regime to a few kilowatts for FELs in the VUV and X-ray regime.

When the electron bunch length is longer than the slippage length, the radiation profile contains many spikes. The spikes are also present in the frequency spectrum. The origin is the random fluctuation in the beam density. The shot-to-shot fluctuation in the radiation pulse energy follows a Gamma distribution [26]. The only free parameter of this distribution, M, can be interpreted as the number of the spikes in the radiation pulse. The relative width of the distribution is $1/\sqrt{M}$. The length of the spikes is approximately $(\lambda/\lambda_0)L_g$ [27]. A shorter pulse would result in a larger fluctuation of the radiation energy. The fluctuation of the instantaneous power is given by a negative exponential distribution.

From the optical point of view, the electron beam acts as a dielectric, dispersive medium for the radiation field. The field amplitude E evolves as $\exp[i\Lambda 2\omega_0 \rho t]$. The imaginary part of Λ results in the growth of the radiation field and thus, gain guiding, while the real part adds a phase advance to the fast oscillating wave $\exp[ikz - i\omega t]$. The effective phase velocity differs from c, the speed of light. The electron beam is dielectric and the radiation field is focused due to the same principle of fiber optic cables. In addition, Λ depends on the deviation of the radiation frequency from the frequency that fulfills the synchronism condition in Eq. 1. This dispersion reduces the group velocity below the speed of light [28] and spikes advance less than one radiation wavelength per undulator period. Amplification stops at saturation and the "dielectric" electron beam becomes nondispersive.

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2.7 Storage Ring–based FEL Oscillators

Free-electron lasers are mainly based upon linear accelerator and storage rings. Electron beams, provided by linear accelerators, have the beam quality needed to reach saturation in a single pass. Because this setup exhibits a strong amplification, the single-pass FEL has properties that are a disadvantage in comparison to quantum lasers or storage ring–based FEL oscillators. Radiation of a single-pass FEL suffers from the inherent fluctuation of the beam parameters such as energy and position jitter. In addition, an SASE FEL does not necessarily provide longitudinal coherence and has a spectral bandwidth, which is large compared to standard lasers. The average power is limited by the repetition rate of a linear accelerator, small compared to that of a storage ring. The single-pass high-gain FEL is the only solution for a high-brightness radiation source for wavelength regions, where an FEL oscillator system will not work owing to the losses in the optical cavity.

The limitations for storage ring–based FEL are given by the instabilities that occur in a storage ring. These instabilities yield an upper limit on the electron beam current of typically a few hundred amperes [29]. In addition, the energy spread and normalized emittance are large compared to those in a linear accelerator [30].

The FEL oscillator accumulates the single-pass gain of typically a few percent. As long as the amplitude of the EM field is small, the gain per pass is constant (small-signal gain) and the field grows exponentially with the number of passes. The oscillator reaches saturation when the FEL interaction is strong enough to induce complete bunching within a single pass. Because the electron emission is fully coherent at saturation, the field cannot be further amplified. The oscillator reaches an equilibrium between the losses of the optical cavity and the reduced gain is closed to saturation.

When the FEL oscillator has reached saturation, the power level within the optical cavity is small compared to that of a single-pass FEL because the effective ρ parameter and beam power are lower (Eq. 17). In addition, only a fraction can be coupled out of the cavity for succeeding experiment because the out-coupling contributes to the net loss of the optical cavity. Higher, out-coupled radiation power requires a higher gain to compensate for the losses. In the equilibrium state, the FEL oscillator's temporal and frequency stability, longitudinal coherence, and repetition rate are better than those of a linear accelerator–based FEL. However, the official quality of linear accelerator–based FELs can be improved using optical instruments, like monochromators.

The radiation of an FEL oscillator is typically longitudinal coherent, because the phase information of the radiation field is distributed over the entire electron bunch mainly due to two reasons. The first reason is the same as for a single-pass FEL, because the radiation field propagates faster than the electron beam. The second reason depends on the design of the optical cavity. If the cavity is "detuned", the time of the radiation pulse to pass the cavity is different from the arrival time of the next electron bunch. The radiation field has a longitudinal offset with respect to the electron bunch. This offset allows a faster buildup of coherence.

The FEL oscillator can start from the spontaneous radiation. If the gain is larger than a few percent and the detuning is small, the random nature of the

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spontaneous emission phase can manifest in the occurrence of superradiant spikes [31]. The peak power can be considerably larger than the power level of the fully coherent signal, while the spike length is shorter than the electron bunch length. The nature of these superradiant spikes is the same as those occurring in the temporal radiation profile of an SASE FEL.

3 Present Status

The current status of the FEL research program around the world can be classified into two groups with different objectives. The single-pass free-electron laser is aiming toward shorter wavelength, while storage ring–based FELs are developed to overcome the limitation of the losses of the optical cavities. Free-electron lasers, which have finished their research program, are often converted to user facilities, where researchers can use the unique properties of the FEL radiation for research in their field.

3.1 Single-pass Free-electron Lasers

Single-pass free-electron lasers are frequently based on linear accelerators. Because the FEL does not rely on any optical cavity to accumulate the gain, there is no restriction on the wavelength. A beam energy of about 10 MeV corresponds to a resonant wavelength of about 10 microns, while a 10- to 25-GeV beam can drive an FEL in the VUV and X-ray region. The energy of the electron beam is determined by the length of the linear accelerator.

The requirements on the beam quality (Sect. 2.4 & 2.5) are more stringent for FELs operating at shorter wavelength, and the first single-pass FELs started at wavelengths in the millimeter or infrared regime [32]. The major motivation of the ongoing FEL research is to shorten the wavelength down to the angstrom level, where no alternative radiation sources with the same radiation properties exist. The total number of single-pass FEL is numerous and Table 2 lists a selection, namely, those with the shortest wavelength. The record for the shortest wavelength so far lies at around 80 nm [33]. The majority of future

Tab. 2 Linear accelerator–based free-electron lasers

FEL	*UCLA*	*VISA*	*LEUTL*	*TTF-FEL I*
Energy [MeV]	18	71	217/255	250
Energy spread [%]	0.25	0.1	0.4/0.1	0.06
Norm. emittance [mm·mrad]	5.3	2.3	8.5/7.1	6
Peak current [A]	170	250	630/180	1300
Wavelength [nm]	12 000	840	530/385	95
Peak power [MW]	0.0001	15	500	1000
Pulse length [ps, RMS]	5.5	0.3	0.2/0.7	0.02
Gain length [cm]	25	18.7	97/76	67

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FELs will operate at shorter wavelengths (Sect. 4).

The FEL performance is limited by the electron beam quality, the transverse emittance, the energy spread, and the beam current. The linear accelerators of all the latest single-pass free-electron lasers are based on RF photoelectron guns [34]. A conventional laser in the visible or UV illuminates a cathode, embedded into an RF cavity. The photo effect generates the electrons and the RF field accelerates them to minimize the beam ''blowup'' due to the electric field of each electron (space charge field). The value of the transverse emittance arises mainly from this space charge field at the cathode region [35]. At higher energy, the electron beam is relativistic and is less sensitive to space charge effects.

Because a more intense pulse of the photo gun laser produces a higher electron density, the space charge field is stronger. As a consequence, there is a limit on the achievable emittance and current from the RF photoelectron gun [36]. Increasing the current would increase the emittance as well. Typical values are an emittance of around 2 mm·mrad at a current of about 50 A. The total charge of the electron bunch is on the order of 1 nC. Single-pass free-electron lasers typically require beam currents of 100 A and above to keep the saturation length within reasonable limits. This is achieved by including bunch compressors in the beam line of the linear accelerator.

A bunch compressor consists of bending magnets, which deflect the beam off the axis of the linear accelerator and then bend it back to the axis. Because the bend angle depends on the electron energy, electrons with a lower energy have a stronger distortion and, thus, a longer path length. The electron bunch is given a correlated energy variation along its length by the RF structure, so that electrons at the head of the bunch have lower energy than those in the tail. The path-length difference in the bunch compressor reduces the bunch length and increases the beam current. The beam energy correlation is obtained when the RF field is still building up (''off-crest'' injection). Electrons entering first see a lower accelerating gradient than those entering later. At the cavity exit, the bunch has an energy correlation along bunch, needed to compress the bunch in the bunch compressor.

3.2 Free-electron Laser Oscillators

Storage rings impose a limit on the achievable electron beam quality. Because bending magnets are required to transport the electron bunches back to the undulator entrance, electrons emit spontaneous radiation. When an electron looses energy owing to the spontaneous radiation, its orbit shifts with respect to the design orbit. The energy losses are not the same for every electron due to quantum fluctuations of the emitted photons. This results in a limitation of the achievable transverse emittance [37]. To increase the performance of a storage ring–based FEL oscillator, this limit has to be reduced, which often requires a special lattice of bending and focusing magnets. Bends with more, but shorter, bending magnets alternating with quadrupole magnets, perform better than those with less magnets. This approach is not only used for storage ring–based FEL but also for most third-generation light sources [38].

Since electron bunches are kept in a storage ring for minutes or hours, even small effects can be accumulated and can degrade the beam quality. One effect is intrabeam scattering, in which, due to Coulomb collision electrons are gradually kicked out of the orbit and lost in the storage ring aperture [39]. Another effect is the "communication" between bunches by means of wakefields [40]. Each storage ring has RF cavities to compensate energy losses, which occur because of spontaneous radiation and the FEL interaction. The modes of the cavities are excited whenever an electron bunch passes the cavities. These higher modes are not damped quickly enough, Q7 so that• the next bunch interacts with them. The resulting energy modulation is not constant over the entire bunch and dispersion – energy dependence of the orbit – tears the bunch apart, spoiling the beam quality or even dumping part of the beam in the vacuum chamber wall.

Besides an advanced lattice design of the storage ring to minimize the effects described above, storage ring limitation can be diminished by improving the optical cavity of the FEL oscillator. The current research on oscillators is focused to improve the reflecting mirrors in two areas such as

1. the extension of the wavelength range in the VUV range by novel coating or material,
2. increasing average power by improved power handling.

The shortest wavelength an FEL oscillator is operating is around 100 nm [41] with significant power emitted at higher harmonics as well. The FEL oscillator at Jefferson Lab achieved an average power in the IR region above 2 kW [42]. In slight contrast to the single-pass FEL, which are mostly FEL experiments to extend the wavelength range, storage ring–based FELs mostly serve as a user facility, where the radiation wavelength and power is tuned to the needs of experiments from all fields of science.

The limitations in beam current and bunch length can be overcome in an Energy Recovery Linear accelerator (ERL) [43], where the electron bunches are only kept for a few turns in the storage ring. The beam energy is extracted back to the accelerating field prior to the ejection and dumping of the bunch. Since the peak current in an ERL is higher than that in storage ring, the brightness and the saturation power is increased.

Q8 **Tab. 3** Free•-electron laser oscillators

FEL	*Duke*[a]	*Elletra*[a]	*Clio*[b]	*Felix*[c]	*Jefferson Lab*[d]
Energy [MeV]	200–1200	1000	15–50	15–50	48
Avg. current [mA]	115	25	2–40	2.5–100	4.8
Bunch length [ps]	<50	6.3	0.5–6	0.8	0.4
Rep. rate [MHz]	13.95	4.63	62	25/1000	74.8
Wavelength [μm]	0.19–0.4	0.19–0.20	3–90	4.5–250	3–6.2
Avg. power [W]	0.025	0.01	3	25–5000	2000

[a] Storage ring.
[b] 10 μs electron bunch train from thermionic gun at 25 Hz.
[c] 10 μs electron bunch train from thermionic gun at 10 Hz.
[d] Energy recovery linear accelerator.

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4 Future Development

All recent single-pass free-electron laser experiments have not shown any fundamental limits that would prevent a resonant wavelength at the angstrom level. The typical beam energy would be around 10 to 25 GeV. The required undulator length would be around 100 m. Several projects have been proposed or are under construction to have single-pass FELs operating in the wavelength regime between 1 and 1000 Å [5–7]. Table 4 lists a selection of them. All these FELs are planned to be user facilities. Most of them have several beam lines and undulators to serve multiple users simultaneously. To reduce the limitation on the average brightness, most of the linear accelerators are based on superconducting technology. It allows to lengthen the RF pulse and fill the beam line with multiple bunches per RF pulse, while operating on a lower power level of the RF system.

A combination of a storage ring with a linear accelerator is the Energy Recovery Linear accelerator (ERL) [43]. After the electron bunch is accelerated and passes the undulator, it is transported back to the beginning of the beam line. It propagates to the accelerating cavities a second time, but with a 180° difference in the RF phase. The residual kinetic energy of the bunch is transferred back to the RF field, and thus is available for succeeding bunches. It requires superconducting cavities; otherwise the stored energy will be lost by thermal losses before the next bunch enters the beam line. Using this setup, the repetition rate of the electron bunches are not limited by the RF system and FELs can be operated in cw mode, similar to storage ring but with the advantage that there are no limitations on the beam current or emittance.

Tab. 4 VUV & X-ray free-electron lasers, planned or under construction (∗)

FEL	*Wavelength [Å]*	*Location*
TESLA*	1–50	Germany
SCSS	1–10	Japan
LCLS*	1.5–15	USA
MIT Bates FEL	5–1000	USA
FERMI	12–100/400	Italy
BESSY	12–1500	Germany
SPARX	15–140	Italy
TTF-FEL II*	60–1200	Germany
4GLS	120–4000	UK
NSLS DUV-FEL	200–2000	USA

The research in FEL physics is shifting from the proof of principle toward enhancement of the radiation properties, in particular, in the X-ray regime. SASE FELs have an intrinsic instability in the output energy of a few percent up to 100%. In addition, the operation of a linear accelerator is not as stable as that of a storage ring. The system fluctuation adds up to the intrinsic fluctuation of the SASE pulse. Another disadvantage is the reduced longitudinal coherence. Because of the short cooperation length of FELs in the VUV and X-ray regime, part of the bunch amplifies the spontaneous radiation independently. The longitudinal coherence can be achieved by a pulse stretcher, namely, monochromator, with a bandwidth slightly smaller than the Fourier limit of the electron bunch length. All spikes are stretched to the bunch length and add up coherently. Each spike in the SASE pulse has 100% fluctuation, so has the resulting coherent pulse after the monochromator. Stability of the output power is achieved if the monochromator is not placed after the SASE FEL but between, splitting the undulator in two parts [44]. The second undulator is seeded by the output signal of the monochromator and operates as an FEL amplifier instead of an SASE FEL. Because the saturation power of an FEL amplifier does not depend on the input signal, the output power level in the deep saturation regime is stable despite the 100% fluctuation of the input signal.

Another focus is on short radiation pulses. Standard methods are pulse compression and slicing, similar to conventional lasers. It requires an energy correlation along the electron bunch ("chirp"), driving an SASE FEL. Because of the square dependence of the resonant wavelength on the energy (Eq. 1), the radiation frequency chirp is twice as large. A monochromator selects only that part of the pulse in which frequency components fall within the bandwidth. The monochromator bandwidth has to be optimized in order to avoid a pulse stretching for a too-small bandwidth or large chirps for a too-wide bandwidth. For X-ray FELs, a monochromator bandwidth of 10^{-4}, which is roughly a tenth of the intrinsic FEL bandwidth, and a frequency chirp of around 1%, results in a 10-fs slice [45].

An alternative method for short bunches is to condition the driving electron bunch. A stronger compression spoils the emittance and energy spread by wakefields and coherent synchrotron radiation in the linear accelerator and bunch compressor, so that the electron pulse length is limited to roughly 200 fs FWHM for the shortest gain length. On top of that, the beam can be conditioned by various methods (RF cavities, wakefields, external laser pulses) to keep the beam quality good over only a short subsection of the bunch. Although the entire bunch emits spontaneous radiation, only the preserved part of the bunch amplifies it and reaches saturation [46].

A free-electron laser in the X-ray regime requires about 100 m of undulator and a linear accelerator of about 1 km, using the present technology. It is desirable to reduce the size of the FEL facility or make it even portable and robust. The FEL can benefit from results of other branches in the accelerator physics. Acceleration based on plasmas are promising higher acceleration gradient and lower emittances [47], thus shortening both the undulator and the linear accelerator. The FEL physics is unchanged, when the undulator is replaced by a device that also enforces a transverse oscillation of the electron bunch. A possible solution would be a •high-intensity Q9 optical laser pulse [48]. Because the period length is several orders of magnitude smaller than that for an undulator, the FEL interaction requires less energy to obtain the same wavelength. Other proposals are based on plasma columns [49], transverse wakefields [50] or crystal lattices [51].

Glossary

3rd Generation Light Sources: Spontaneous emission from dipoles and undulator with radiation pulse lengths in the picosecond regime and recirculating electrons with an energy between 3 and 10 GeV.

Bending Magnet: see *dipole magnet*.

β-function: Characteristic function of the focusing property of a given beam line. Depending on the initial values of the β-function and its derivative, it describes the evolution of the beam size along the beam line.

Bunch Compressor: A series of dipole magnets to deflect the electron beam from the orbit and then back onto the orbit. The resulting orbit and thus the path length of this orbit bump depends on the electron energy. With a correlation between longitudinal position and energy within an electron bunch, the path-length difference yields a reduction in the bunch length and an increase in the beam current.

Bunching: Density modulation of the electron beam on a scale shorter than the bunch length. Also called *microbunching*.

Coherent Synchrotron Radiation: Strong enhancement of the synchrotron radiation for wavelength longer than the bunch length. The radiation can interact back with the electron bunch and because of its large amplitude alter the electron energy and, thus, the orbit of the electron bunch.

Dipole Magnet: Magnet with a constant, transverse magnet field to deflect electron and thus, cause a bend in the orbit of the electron bunch.

Emittance: Phase space area, covered by the electron bunch distribution.

Energy Recovery Linear Accelerator: Circular accelerator with continuous injection of electron bunches. After acceleration, each electron bunch passes each RF cavity again but with a 180° phase difference. The deceleration transfers back the kinetic energy of the electron bunch to the RF field, which can be used to accelerate the succeeding bunch.

Microbunching: See *bunching*.

Photoelectron Gun: RF cavity with an embedded photo cathode. A UV laser pulse illuminates the cathode and generates free electrons due to the photo effect. The RF field accelerates these electrons to relativistic energies within the length of the RF gun.

Plasma Frequency: Measure for the strength of the beam size growth due to the repulsive electrostatic field between each electron.

Ponderomotive Phase: Phase of the electron–radiation interaction due to the beat wave of the transverse oscillation of the electrons and the oscillation of the EM wave.

Quadrupole Magnet: Magnet with a linear growing transverse magnetic field with respect to the orbit of the electron bunch. The field configuration yields a focusing in one transverse plane but a defocusing in the perpendicular transverse plane. A net focusing in both planes is achieved by a series of quadrupoles with alternating polarity.

Linac: linear **ac**celerator, where the electron passes the beam line only once. In contrast to the storage ring, the linear accelerator consists mainly of accelerating structures, such as RF cavities. Quadrupole magnets keep the transverse beam size within the acceptable limits.

Radiofrequency Cavity: Cavity, which resonantly holds an oscillating EM field at well-defined frequencies. The fundamental mode has a longitudinal electric field component, which is used to accelerate an electron beam, passing the cavity.

Shot noise Power: Power of the spontaneous radiation, which falls within the bandwidth of the free-electron laser and which is amplified in the SASE FEL configuration.

Storage Ring: Circular accelerator to keep injected electron bunches on a closed orbit for many turns. RF cavities compensate the energy loss due to the spontaneous radiation within the dipole magnets and other transverse deflecting magnets (e.g., undulators)

Superconducting Magnet: Electromagnet, based solely on superconducting windings to overcome saturation effects of any yoke material.

Undulator: Device with transverse, alternating magnetic field on the main axis in planar and helical configuration. In a planar undulator, the transverse magnetic field is oscillating within only one transverse plane, while the magnetic field is constant but rotates along the longitudinal axis for a helical undulator.

Undulator Parameter: Normalized amplitude of the vector potential of the undulator field. It is proportional to the product of peak undulator field and undulator period and can be regarded as the total deflection strength of the undulator field per half period.

Undulator Taper: Variation of the undulator field and/or period along the longitudinal axis of the undulator.

Wakefield: Radiation, caused by the interaction of the electric static field of an electron with the vacuum chamber. The radiation can interact with succeeding electrons, changing the electron energy or transverse momentum.

Wiggler: See *undulator*.

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Further Reading

A complete description of the FEL theory is given in the books *Thy Physics of Free Electron Lasers* by E. L. Saldin, E. A. Schneidmilller, M. V. Yurkov (Springer, Berlin, 2000) or *Free-Electron Lasers* by C.A. Brau (Academic Press, Boston, 1990). A brief overview on the high gain FEL can be found in the paper ''Introduction to the Physics of the FEL'' by J.B. Murphy and C. Pellegrini (Proc. of the South Padre Island Conference, Springer (1986) 163).

The book *An Introduction to the Physics of High Energy Accelerators* by D.A. Edwards and M.J. Syphers (John Wiley and Sons, New York, 1993) covers the physics, needed to generate and accelerate an electron beam, driving the free-electron laser. A review of undulator design is given by J. Spencer and H. Winick in *Synchrotron Radiation Research* (eds. H. Winick and S. Doniach, Plenum Press, New York, ch. 21, 1980).

The radiation process of relativistic particles are covered in great detail by J.D. Jackson's *Classical Electrodynamics* (John Wiley and Sons, New York, 1975) while the description of the random nature of the SASE FEL follows the treatment of *Statistical Optics* by J. Goodman (Wiley and Sons, New York, 1985).