Free Electron Lasers

The free-electron laser was invented by John Madey in 1971 at Stanford University.

In a free-electron laser (FEL) the lasing medium consists of very-high-speed electrons moving freely through an undulatory magnetic field. The greatest advantage of free-electron laser is that it is tunable and has a wide frequency range among all laser types, ranging (in wavelength) from microwaves, through terahertz radiation to infrared, to the visible spectrum, ultraviolet, and X-ray. In a FEL, a beam of electrons is accelerated to nearly the speed of light. The beam passes through a periodic arrangement of magnets with alternating poles across the beam path providing a transverse magnetic field. This array of magnets is called an undulator or a wiggler. This arrangement of magnetic field applies the Lorentz force and the electrons wiggle transversely along a sinusoidal path.

An electron beam moving on a straight line cannot transfer energy to a light wave. The electric field is perpendicular to the direction of motion, and the force between electron and light wave is orthogonal to the electron velocity. This implies that no work is done on the electron. In order to facilitate energy exchange, the electrons must be given a velocity component in the transverse direction. This is what is done by the undulator. The transverse component of the electron velocity and the electric vector of the light wave point in the same direction to get an energy transfer from the electron to the light wave. A problem is encountered as the light wave, traveling with the speed of light, slips forward with respect to the electrons due to two reasons; firstly, since the electrons are particles with mass and thus move slower than light, and secondly, they travel on a slalom (move or race in a winding path, avoiding obstacles) orbit which is longer than the straight path of the photons. If this be the case it is not possible at all to achieve a steady energy transfer from the electron beam to the light wave along the entire undulator. However, as a matter of fact, the light wave slips by a certain wavelength only. The transverse velocity and the electromagnetic field of the light wave remain parallel if the light wave slips by one optical wavelength in a one period of the electron trajectory.

The calculation shows that the proper light wavelength is identical with the wavelength of undulator radiation in the forward direction. This equality is the physical basis of the self-amplified spontaneous emission mechanism: Spontaneous undulator radiation serves as seed radiation for a high-gain FEL. Thus, FEL displays one of the great advantages; in contrast to conventional lasers as the wavelength of an FEL can be tuned at will, simply by changing the electron energy.

The electron bunch is far longer than the light wavelength. Generally the electrons will be distributed uniformly along the bunch axis, and although there are many electrons fulfilling the condition that their transverse velocity is almost parallel to the pulsating electromagnetic field and which thus transfer energy to the light wave, there will be equally many anti-parallel electrons and they will withdraw energy from the light wave. How should one then achieve an overall amplification of the light wave? The net energy exchange between electron bunch and light wave is in fact zero if the electron energy is equal to the resonance energy, where the electrons emit undulator radiation of exactly the incident wavelength. However, there will be light amplification if the electron energy is above the resonance energy, but light attenuation of the energy is below that value.

The essential advantage of FEL radiation as compared to undulator radiation is its much higher intensity because a large number of electrons radiate coherently. If it were possible to concentrate all electrons of a bunch into a region far smaller than the light wavelength, then all these particles would radiate like a “point macroparticle”. The problem is, however, that the concentration of some 109 electrons into such a tiny volume is totally unfeasible, even the shortest particle bunches are much longer than the wavelength of an X-ray FEL.

The way out of this dilemma is given by the process of microbunching, which is based on the following principle: Electrons losing energy to the light wave travel on a wave like trajectory of larger amplitude than electrons gaining energy from the light wave. The result is a modulation of the longitudinal velocity which eventually leads to a concentration of the electrons in slices that are shorter than the wavelength. These microbunches are close to the positions where maximum energy transfer to the light wave can happen, and the particles within a microbunch radiate like a single particle of high charge. This increase in the radiation field enhances the microbunching even further and leads to an exponential growth of the energy of the radiation pulse as a function of the length of the undulator.

The transverse acceleration of the electrons across this path results in the release of photons (synchrotron radiation), which are monochromatic but still incoherent, because the electromagnetic waves from randomly distributed electrons interfere constructively and destructively in time. The resulting radiation power scales linearly with the number of electrons. Mirrors at each end of the undulator create an optical cavity, causing the radiation to form standing waves, or alternately an external excitation laser is provided. The synchrotron radiation becomes sufficiently strong that the transverse electric field of the radiation beam interacts with the transverse electron current created by the sinusoidal wiggling motion, causing some electrons to gain and others to lose energy to the optical field via the ponderomotive force.

This energy modulation evolves into electron density (current) modulations with a period of one optical wavelength. The electrons are thus longitudinally clumped into microbunches, separated by one optical wavelength along the axis. Whereas an undulator alone would cause the electrons to radiate independently (incoherently), the radiation emitted by the bunched electrons is in phase, and the fields add together coherently.

The radiation intensity grows, causing additional microbunching of the electrons, which continue to radiate in phase with each other. This process continues until the electrons are completely microbunched and the radiation reaches a saturated power several orders of magnitude higher than that of the undulator radiation.

The wavelength of the radiation emitted can be readily tuned by adjusting the energy of the electron beam or the magnetic-field strength of the undulators.

FELs are relativistic instruments. The wavelength of the emitted radiation, λ_r , is given by[

$$\lambda_r = \lambda_u \, (1+K^2)/2\gamma^2$$

or when the wiggler strength parameter K is small

$$\lambda_r = \lambda_u/2\gamma^2$$

here λ_u is the undulator wavelength (the spatial period of the magnetic field), γ is the relativistic Lorentz factor and the proportionality constant depends on the undulator geometry and is of the order of 1.

Wiggler strength parameter K

K, a dimensionless parameter, tells the wiggler strength as the relationship between the length of a period and the radius of bend,

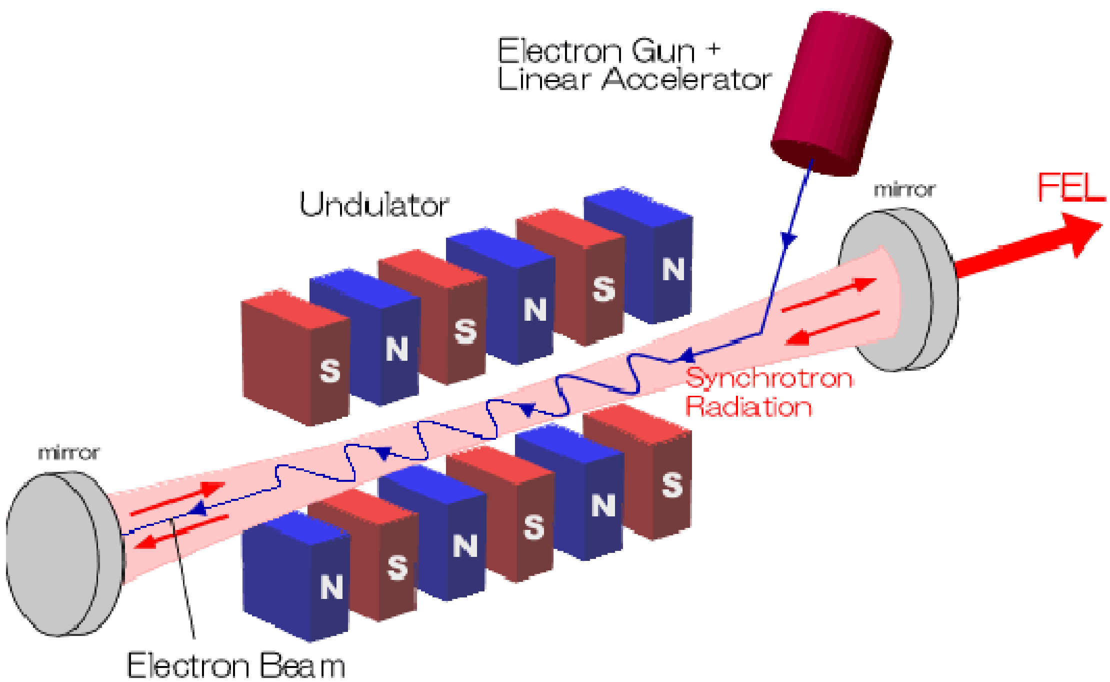
$$K = \gamma\lambda_u/2\lambda\rho = (eB_o\lambda_u)/2\pi m_e c$$

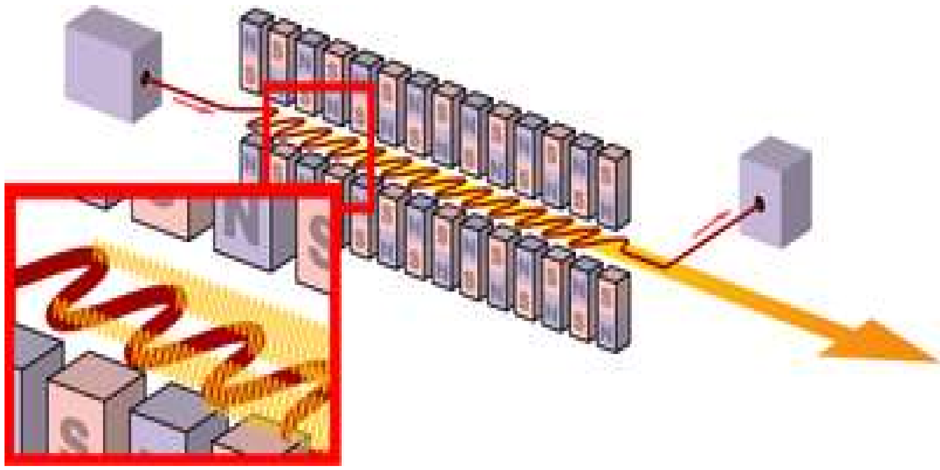
where ρ is the bending radius, B_o is the applied magnetic field, m_e is the electron mass, and e is the elementary charge.

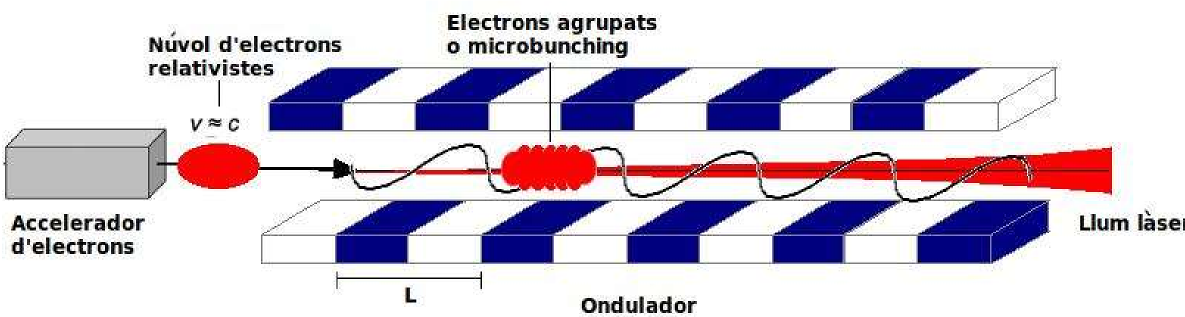
Expressed in practical units, the dimensionless undulator parameter is

$$K = 0.934\ B_o(T)\ \lambda_u(nm)$$

Free-electron laser (FEL) achieves laser amplification and saturation within a single pass of the electron bunch through a long undulator section. The lasing process is initiated by spontaneous undulator radiation. The FEL works in the so-called Self-Amplified Spontaneous Emission (SASE) mode without needing an external input signal.







Some Schematic representations of an undulator