FREE ELECTRON LASERS

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Abstract

The status and the perspectives of a quite new and promising laser source, the free electron laser (FEL), is presented. The accelerator performances required for FEL operation are discussed.

Introduction

One of the most interesting and *popular* laser sources developed in these last ten years is the so-called *Free Electron Laser* (FEL). The reason of this interest is related to the peculiar features of this device, like tunability and very high peak and average power output, in spite of the fact that a very small number of such lasers has been constructed and successfully operated. Moreover such device is *very famous* outside the FEL community too. This is probably due to its *non-conventional* working principle. Namely in a FEL the active medium is not made of atoms or molecules, but it is simply a beam of highly energetic *free electrons* traveling along a special magnet that forces the electrons to follow an oscillating trajectory (for this reason it is called *undulator magnet* (UM)). Due to this oscillation, electrons radiate electromagnetic energy, whose power and spectrum are related with the electron energy and the magnetic field characteristics. This kind of emission, which is analogous to the *spontaneous emission* from excited atoms or molecules, is nothing more than the *synchrotron radiation emission*. However, when a light beam of nearly the same frequency of that emitted spontaneously is running together the electrons along the UM, we have "stimulated emission" and, if enough feedback is provided and if the gain is larger than the losses, we can have lasing action.

A detailed description of the FEL working principle and of the main experimental configurations realized or suggested up to now can be found in many review articles and books (see, e.g., refs. [1], [2]).

In the following sections, after a short review of the main properties of FEL radiation, the status and the perspectives FEL devices will be outlined, together with a deeper insight in accelerator performances required for FEL operation.

The Free Electron Laser: main parameters

The typical layout of a FEL oscillator is depicted in fig. 1. The electron beam generated by the accelerator is injected into the undulator magnet and, after the interaction with the undulator and the laser beam trapped in the optical cavity, is sent to a beam dump. This is not the only FEL scheme utilized. In other schemes the electron beam is partially recovered, in order to enhance the efficiency of the device, or it

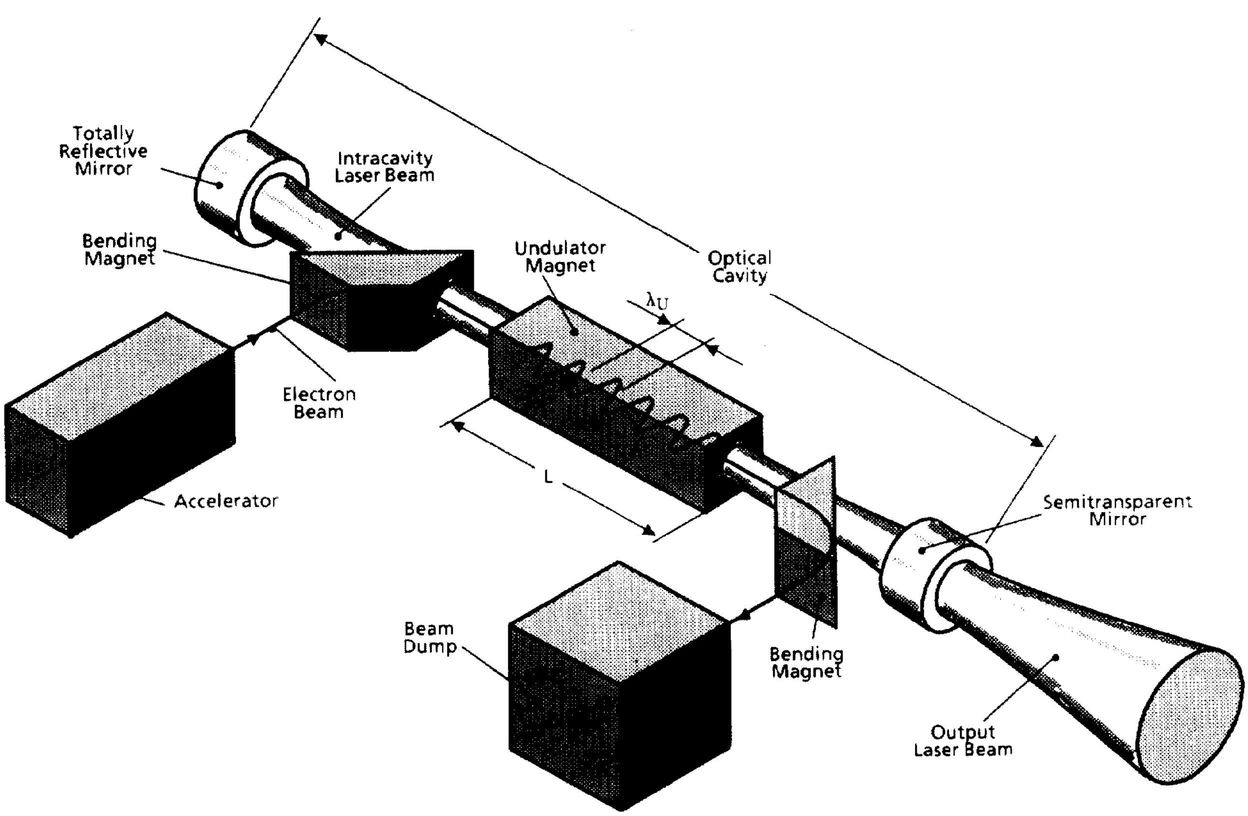

Fig. 1 - Typical FEL layout

is recirculated continuously (in this case the UM is placed in a straight section of a storage ring). Finally, in very high gain devices, MOPA (Master Oscillator Power Amplifier) configuration is utilized.

The most distinguishing FEL feature is its tunability. Namely the wavelength of the emitted radiation depends on to the electron energy E, the UM period λ_U and r.m.s. magnetic field B as it follows, (e, m = electron charge and mass, c = light velocity)

$$\lambda = \frac{\lambda_U}{2\gamma^2}(1+K^2),\ (\gamma = E/mc^2) \tag{1}$$

where we have defined the *K parameter*,

$$K = \frac{eB\lambda_U}{2\pi mc^2} \tag{2}$$

From eq.(1) we derive that it is possible to choose the operating wavelength by selecting correctly the FEL parameters. Moreover, for linearly polarized UM, there is on axis emission of all the odd harmonics of the fundamental (1) (for helical UM only the fundamental is present on axis). For example with 100 MeV electrons and a linear UM with 5 cm period and 3 kG r.m.s. field the fundamental lies in the near infrared (about 1 μm) and the third harmonics in the UV. We shall see in the following section that now FEL devices cover a very broad spectral region (from microwave to visible and UV radiation) and operation in the VUV and soft X rays is foreseen for not too late future.

In order to achieve oscillation or to obtain a large amplification in MOPA configuration, the FEL gain must be adequate. This parameter is strongly dependent on the electron beam characteristics. Namely high quality beams are required for FEL operation. We shall see in the following what current level, energy spread, emittance and pulse duration are needed. Let us stress, for the moment, that the main reason of the limited number of FELs up to now successfully operated is just related to the electron beam quality.

It is possible to derive an analytical description of small signal FEL gain in various regimes in terms of electron, UM and optical cavity parameters.

Namely in small gain regime (< 20-30%) within few % of accuracy, the gain for a linear UM reads [1] (we shall consider in the following only the more utilized linearly polarized UMs and we assume that the electron beam cross section is smaller than the laser one),

$$G = 0.85\,g\left|\left(1+\frac{\mu_c}{3}\right)(1+(n\mu_x)^2)(1+(n\mu_x)^2)(1+1.7(n\mu_\varepsilon)^2)\right|^{-1} \tag{3}$$

where n (odd) is the harmonic, g is a coefficient which depends on the number N of UM periods, on the electron peak current I, on the energy γ, on the K parameter (2) and on the harmonic n (J_m is the m-th Bessel function),

$$g = 2.2\times 10^{-3}\,(nN)^2\,\frac{K^2}{1+K^2}\,\frac{I[A]}{\gamma}\,(J_{(n-1)/2}(n\xi)-(J_{(n+1)/2}(n\xi))^2 \tag{4}$$

$$\left(\xi = \frac{1}{2}\,\frac{K^2}{1+K^2}\right)$$

and, finally, the parameters μ in eq.(3) describe the electron beam qualities,

$$\mu_c = N\lambda/\sigma_z \quad (\sigma_z = \text{r.m.s. bunch length}) \tag{5}$$

$$\mu_\varepsilon = 4N\sigma_\varepsilon \quad (\sigma_\varepsilon = \textit{r.m.s. energy spread}) \tag{6}$$

$$\mu_{x,y} = 2N\sqrt{2|h_{x,y}|}\,\frac{K}{1+K^2}\,(\gamma E_{x,y}/\lambda_U) \tag{7}$$

($E_{x,y}$ = r.m.s. (x,y) transverse emittance)

In eq.(7) $h_{x,y}$ are the UM sextupolar terms. In the usual case of wide flat poles we have (with the magnetic field parallel to the y axis),

$$h_x = -\delta,\ h_y = 2+\delta\quad (\delta \ll 1) \tag{8}$$

From eqs.(4-7) we derive that there is a strong reduction of the gain if the μ-parameters become larger than unity. Namely the bunch length must be larger than N times the laser wavelength (4), which is just the slippage between electrons and photons due to their different velocities (this condition guarantees the overlapping between the two beams); the energy spread (5) and the normalized emittances $\gamma E_{x,y}$ divided the UM period (6) must be smaller (apart some factors of the order of the unity) than the inverse of the number of UM periods (if this condition holds, all the electrons radiates practically at the same wavelength, i.e. no inhomogeneous broadening is present).

In high gain regime there is an exponential blow up of the laser wave along the UM. In this connection the integrated gain is an exponential function of the longitudinal coordinate z and, for a very long electron bunch (which is the typical operating regime for such a kind of FELs), it reads [3],

$$G(z) = (1/9)\exp[(8\pi\rho)\eta(z/\lambda_U)] \tag{9}$$

where ρ is given by ($I_0 = ec/r_0$, $r_0 = e^2/mc^2$),

$$\rho = \frac{1}{4\pi\gamma}\left(\frac{(2\pi\lambda_U K)^2}{\Sigma}\,\frac{1}{I_0}\right)^{1/3} \tag{10}$$

(Σ = laser beam cross section)

and η is a function of the electron beam qualities. Within an error less than 1%, η can be written as a function of electron energy spread and emittance as it follows [4]

$$\eta(\tilde{\mu}_\varepsilon,\tilde{\mu}_x,\tilde{\mu}_y) = \frac{\left(\eta(0,\tilde{\mu}_x,\tilde{\mu}_y)\, e^{-0.034\tilde{\mu}_\varepsilon^2}\right)}{\left(1+0.185\tilde{\mu}_\varepsilon^2\,\eta(0,\tilde{\mu}_x,\tilde{\mu}_y)\right)} \tag{11}$$

$$\eta(0,\tilde{\mu}_x,\tilde{\mu}_y) = 0.866\,\frac{1+\alpha(\tilde{\mu}_x^2+\mu_y^2)+\beta(\tilde{\mu}_x+\tilde{\mu}_y)}{(1+\tilde{\mu}_x^2)(1+\tilde{\mu}_y^2)}$$

$(\alpha = 0.636,\ \beta = -0.264)$

where the $\tilde{\mu}$ parameters are proportional to the μ previously defined in the low gain regime (eqs.(6,7)),

$$\tilde{\mu}_{\varepsilon,x,y} = \mu_{\varepsilon,x,y}/(2N\rho) \tag{12}$$

In this regime too energy spread and emittance affect heavily the gain. There are two main differences with respect to the previous case, namely $\tilde{\mu}_{\varepsilon,x,y}$ depend on current (through the ρ factor) and the dependence on the various $\tilde{\mu}$ factors is not with separate functions. As a consequence, for example, when $\tilde{\mu}_{x,y} \ll 1$ the condition for neglecting the energy spread effects is $\tilde{\mu}_\varepsilon < 1/4$, while for $\tilde{\mu}_{x,y} \approx 1$ it is enough to require $\tilde{\mu}_\varepsilon < 4$. This means that the analysis on the electron beam requirements is not so straightforward as in the low gain case, but it requires a more involved investigation.

Now a question is in order: do existing *standard* electron accelerators satisfy the previously outlined conditions? I.e. peak current, bunch length, emittance and energy spread may allow FEL operation (at least few % of gain for oscillators and many dB/meter for MOPA configuration)? As we shall see in the next section all kinds of accelerators have been utilized for FEL, this means that, depending on the spectral region and power level, the answer is yes. But we need to underline that a lot of work has been done in order to achieve the desired goal, moreover when the FEL operation failed, the main reason was due to the lack of suitable accelerator performances.

Status of FEL technology

A very brief history of FEL can be outlined as follows,

1950-1960 Pre-history: Invention of the undulator magnet (Motz [5]), Invention of the Ubitron, i.e. the non-relativistic FEL (Phillips [6]).

1971 Madey's proposal [7].

1976 Amplification experiment at Stanford [8].

1977 Oscillation experiment at Stanford [9].

1983 Storage ring FEL oscillator at Orsay [10].

1988 Less than ten above threshold operating FELs and one MOPA device.

We can see that the *FEL story* starts well before that of *standard lasers*, in particular the Ubitron (which is a sort of *non-relativistic* FEL) was developed just in the same years when the first Ruby laser was invented. The noticeable impact of atomic and molecular lasers stopped for many years the development of the sources of short wavelength coherent radiation based on free electrons. Namely we need to await the middle of the seventies for the first infrared FEL. Moreover, in spite of the big effort spent by many researchers after that successful FEL experiment, the second FEL oscillator was operated after six years. The reason of this delay, unusual in the laser field, is mainly related to the lack of accelerators with electron beam

Table I - FEL Scenario

Accelerator	Energy (MeV)	Peak current	Laboratory	Wavelength	Peak power	Applications
Electrostatic	6	1-2 A	UCSB (USA) (S. Barbara)	0.1-0.4 mm	10 kW	Solid state physics, biology, medicine
Induction LINAC	3.3	1 kA	LLNL (USA) (Livermore)	3-8 mm	1.5 GW	Very high gradient accelerators, plasma heating
RF LINAC (Superconduc.)	43.5	1 A	Stanford (USA)	3.3 μm	1 MW	First FEL source (1977)
	66	2.5 A	Stanford/TRW	1.6 μm	1.2 MW	Source development
	120	2.5 A	Stanford/TRW	IR-VIS	30 kW (vis) ≈ MW (IR)	Medicine, material Science
RF LINAC (Normal cond.)	40	10-20 A	Stanford	IR	5 MW	Medicine, material science
	22	50-300 A	LANL (USA) (Los Alamos)	10-30 μm	40 MW	Source development
	120	150 A	Spectra/Boeing (Seattle, USA)	Visible	30 kW	Source development
Microtron	20	3 A	ENEA (Italy) (Frascati)	10 μm	1 mW	Source development, photochemistry
Storage Ring	220	≈ 1 A	Orsay (France)	Visible	0.1 mW	Source development

parameters suitable for FEL operation. Namely, as we can derive from the previous section, peak currents of the order of many Amperes with pulse duration of many sec, energy spread better than 0.1-0.2% and emittance at least of the order of 10 mmxmrad are requested for infrared and visible operation (UV and VUV operation requires higher quality beams). It is not easy to obtain all these performances together in a single accelerator (e.g. in a r.f. linac it is possible to obtain the correct emittance but, generally, the energy spread is more than one order of magnitude larger, and viceversa for the microtrons).

Coming back to the FEL story, up to now about ten FEL devices have been operated successfully, as it is shown in the FEL scenario reported in Table I. In that Table, together with the main parameters of the FEL sources, the present and future applications are shown. Namely the problem of the utilization of such a kind of lasers is very urgent. In fact the technological and economical aspects connected with the realization and the operation of a FEL are noticeable and must be clearly justified by really useful applications.

Conclusions and outlooks

The scenario reported in Table I is not exhaustive. Namely in these years many experiments concerning various aspects of the FEL technology have been done. In particular in Europe low gain amplifier experiments clarified interesting aspects of the FEL working principle (in UK at Glasgow with a R.F. linac (amplification of intracavity injected signal) and in Italy at Frascati (INFN) with a storage ring (third harmonic amplification)). Many new FEL devices are now under design or construction around the world (in USA, USSR, Japan, China, India, Europe). In particular in Europe there are many laboratories that are now entering this field (in Holland, West Germany, UK, Sweden, Italy) and new devices are under construction in that laboratories already involved in these last ten years in FEL R&D (Orsay (France), ENEA (Frascati, Italy), INFN (Frascati, Italy)).

With all these new activities, in the near future we shall have a great deal of confidence in a large part of FEL physical and technological aspects and probably we will be able to say that FEL has left its infancy and it is ready to be utilized at the best, as it was foreseen about ten years ago [11] by the small group of first FEL investigators and potential users.

References

[1] U.Bizzarri, F.Ciocci, G.Dattoli, A.De Angelis, E.Fiorentino, G.P.Gallerano, T.Letardi, A.Marino, G.Messina, A.Renieri, E.Sabia and A.Vignati, *The Free Electron Laser: Status and Perspectives*, La Rivista del Nuovo Cimento, vol. 10, pp. 1-131, 1987.

[2] G.Dattoli and A.Renieri, *Experimental and Theoretical Aspects of the Free Electron Laser*, in Laser Handbook, vol. 4, edited by M.Stich and M.S.Bass (North-Holland, Amsterdam, 1985), p. 1.

[3] P.Sprangle, C.M.Tang and W.M.Manheimer, *Non Linear Theory of Free-Electron Lasers and Efficiency Enhancement*, Phys. Rev., vol. 21A, p. 302-318, Jan. 1980.

[4] G.Dattoli, A.Renieri, A.Torre and R.Caloi, *Inhomogeneous Broadening Effects in High Gain Free Electrons Laser Operation: a Simple Parametrization*, to be published.

[5] H.Motz, *Application of the Radiation from Fast Electron Beams*, J. Appl. Phys., vol. 22, p. 527-535, May 1951.

[6] R.M.Phillips, *The Ubitron, a Hihg-Power Traveling-Wave Tube Based on a Periodic Beam Interaction in Unloaded Waveguide*, IRE Trans. Electron. Devices, vol.ED-7, p. 231-241, Oct. 1960.

[7] J.M.J.Madey, *Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field*, J. Appl. Phys., vol. 42, p. 1906-1913, Apr. 1971.

[8] L.R.Elias, W.M.Fairbank, J.M.J.Madey, H.A. Schwettman and T.I.Smith, *Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field*, Phys. Rev. Lett., vol. 36, p. 717-720, March 1976.

[9] D.A.G.Deacon, L.R.Elias, J.M.J.Madey, G.J.Ramian, H.A.Schwettman and T.I.Smith, *First Operation of a Free-Electron Laser*, Phys. Rev. Lett., vol. 38, p. 892-894, Apr. 1977.

[10] M.Billardon, P.Elleaume, J.M.Ortega, C.Bazin, M.Bergher, M.Velghe, Y.Petroff, D.A.G.Deacon, K.E.Robinson and J.M.J.Madey, *First Operation of a Storage-ring Free-Electron Laser*, Phys. Rev. Lett., vol. 51, p. 1652-1655, Oct. 1983.

[11] S.Scoles ed.,*The possible inpact of Free-electron lasers in spectroscopy and chemistry*" (IRST, Riva del Garda (Italy), 1979)