Free Electron Laser: current status and challenges ahead

The Free Electron Laser (FEL) is one of the historical activities of ENEA, where the relevant studies in the mid-seventies of the last century started. The Agency researchers contributed to its theoretical and experimental understanding and to the development of the associated technologies, which created significant advantages in different fields of research. FELs have nowadays merged with synchrotron radiation sources and are expected to provide coherent radiation with unprecedented characteristics. In this article the various aspects of this tool are reviewed

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Il Laser ad Elettroni Liberi: la situazione attuale e gli sviluppi futuri

Il Laser ad Elettroni Liberi (FEL, acrostico di Free Electron Laser) è una delle attività “storiche” dell’ENEA. L’Agenzia è impegnata nello studio di tale sorgente di radiazione dalla prima metà degli anni settanta del secolo scorso. Il contributo dato dai ricercatori dell’ENEA allo studio del FEL ha coperto praticamente tutti gli aspetti salienti: teorico, sperimentale e di sviluppo delle tecnologie associate, che hanno avuto ricadute importanti in altri campi di ricerca. Attualmente le sorgenti FEL stanno integrando e sostituendo le sorgenti di luce di sincrotrone convenzionale e si prevede che possano fornire radiazione in varie regioni spettrali e in particolare nei raggi X. In questo articolo si discutono i vari aspetti di tale sorgente coerente

Introduction

The Free Electron Laser has attracted a great deal of interest for the novelty of its operating principles and because [1] its developments have stimulated progress in various high-tech fields, such as high quality accelerators, permanent magnet technology and new materials. Most of these byproducts are highly innovative from the scientific and industrial points of view. More recently the pathway of FEL merged with that of Synchrotron Radiation sources [2], paving the way to the X-ray high brightness facilities [3]. In this article the different facets of FEL, including scientific, technological, geopolitical and applicative ones, are reviewed and possible developments in Italy are discussed.

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FEL fundamentals

Although sharing many common characteristics, FEL and conventional lasers have the main principal difference: the gain medium [1,4]. In conventional lasers, the amplification process is reached by the stimulated emission of electrons in an atomic or a molecular system (solid, liquid or gas), in which the population inversion has been achieved.

The laser performances in this case are limited by the discrete quantum states of a given atomic or molecular system. In FELs, the gain medium is a relativistic "free" electron beam passing through an undulator type magnetic system. By executing transverse oscillations, electrons spontaneously emit radiation, which can be stored in an optical cavity, reflected forth and back inside, interact with the electrons and amplified, according to the effect of induced stimulated emission. In that case, the restricting parameters are the energy of the electron beam and the magnetic field characteristics.

Therefore, albeit in very simplified terms, we have provided a description of a FEL device containing all the features which characterize a laser.

The power associated with the pump is that of the electron beam, which, in terms of beam energy and current, is written as:

$$P[MW]=I[A]E[MeV] \qquad (1),$$

where P is the power, expressed in Mega-Watt, I - the current in Ampère and E - the energy in Mega-electron-volt. The emission wavelength of the electrons radiating in a magnetic field is selected according to the mechanism illustrated in Fig. 1, based on two successive Doppler shifts. The electrons are transversally oscillating in the laboratory frame at a wavelength fixed by the undulator period. In the electron reference frame the period of oscillation is reduced by a factor γ. The oscillating electrons can be viewed as an oscillating electric dipole emitting radiation at the same frequency of oscillation, which is further Doppler shifted, when transformed back to the laboratory frame. The most significant consequence of such an effect is the following dependence of the wavelength on the electron beam energy:

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right),\ \gamma = \frac{E}{m_0c^2} \qquad (2),$$

$$K \cong \frac{B[kG]\lambda_u[cm]}{10.7}$$

where λ_u is the period of the undulator, B - its peak on axis magnetic field, and K is a parameter (called the undulator strength), measuring the amount of transverse motion, induced by the magnetic field on the initially longitudinal electron motion. We have denoted by γ the electron relativistic factor (m_0c^2=0.511 MeV is the rest electron mass)[1]. The wavelength (2) is called the resonant wavelength.

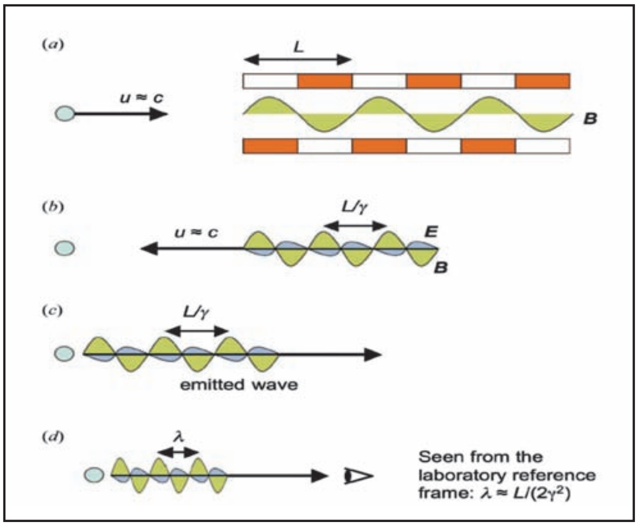

FIGURE 1 The undulator is viewed as an electromagnetic field with wave-length $2\lambda_u$, the emission process is a Compton backscattering so that

$$\lambda_R = \frac{1-\beta}{1+\beta}\lambda_u$$

Source: ENEA

The undulator is characterized by periods λ_u with a length of the order of few centimeters, by a peak on axis field not exceeding 10 KG and its length, fixed by the number of periods *N* as $L=N\lambda_u$, spans from a few meters (in the case of oscillators) to hundreds of meters (in the case of Self-amplified devices). The energy of the electron beam may be tens of MeV or a few GeV, the relativistic factor varies from 10^2 to 10^4 and the emitted wavelength - from FIR to X-rays.

The line-width of the emitted spectrum is fixed by the difference in flight time of electrons and photons inside the undulator. The relative width is simply given by the inverse of the number of undulator periods:

$$\frac{\Delta\omega}{\omega_R} \cong \frac{1}{N},\ \omega_R = \frac{2\pi c}{\lambda_R} \qquad (3)$$

Let us now figure out the light amplification mechanism, which is not dissimilar from what happens in the Klystron devices. With reference to Fig. 2, we note that when electrons enter the undulator, their initially random phases ensure that mostly incoherent radiation is emitted at the resonant radiation wavelength (nearly coincident with the wavelength of the spontaneously emitted radiation). Because the electrons interact collectively with the radiation they emit, small coherent fluctuations in the radiation field grow and simultaneously begin to bunch the electrons at the resonant wavelength. This collective process continues until the electrons are strongly bunched. When the process saturates the electrons begin to de-bunch. The mechanism we have described may occur in one passage in a long undulator or develop in many passes in oscillators.

Being the pump provided by the electron beam power, the FEL process can be effectively simplified by saying that a fraction of the electron beam power is transformed into coherent electromagnetic power at the wavelength given in eq. (2).

One can easily understand the amount of the fraction of power provided to the laser by the electron beam in terms of a heuristic argument. The coherent emission process lasts until the electrons are sufficiently "exhausted", i.e., till they lose enough energy, which brings them off the condition of resonance. This occurs when the energy lost by the electrons is

$$\frac{\Delta E}{E} = \frac{\Delta\omega}{\omega_R} \cong \frac{1}{N}$$

We have already remarked that the number of periods ranges from a few tens to thousands, there the power delivered to the laser may be a little percent or a fraction of percent of the electron beam power.

FEL Design and components

The mechanism described above holds if the FEL device operates in an oscillator or as a SASE (Self Amplified Spontaneous Emission) regime (see Fig. 2).

The field growth, inside the cavity or along the undulator, can be explained by using the same description for both devices. In Fig. 3 we have reported the laser energy evolution over time (represented by the cavity round trip periods or by the length of the undulator, according to the oscillator or SASE regimes, respectively). The shape of the curve is that of any process with exponential growth and saturation, and it is characterized by the following steps:

a) a lethargic phase, in which the electron beam undergoes an energy modulation;
b) a bunching process consequent to a), with an associated gain and exponential growth;
c) a de-bunching and a saturation mechanism.

The key parameters are the gain per cavity round trip, in oscillators, and the gain length (namely the gain per unity length) in the case of SASE devices. Furthermore, the saturated power is, in both cases, associated with a fraction of the laser power. In the oscillator configuration a further element, coming into play, is the mechanism chosen to extract the radiation from the cavity, which inevitably demands for mirrors with adequate losses, capable of supporting the storage of the radiation inside the optical cavity. The SASE solution, presenting significant disadvantages in terms of laser beam qualities, is an obliged step for FEL operating in the X-ray spectral region, where efficient mirrors confining the radiation do not exist.

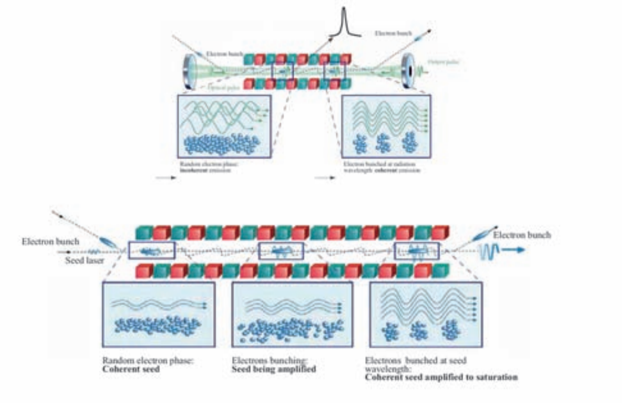

FIGURE 2 Bunching mechanism of the radiation growth inside the undulator:
a) FEL operating in the oscillator mode;
b) FEL operating in single pass Amplified mode. In the case of SASE, the laser seed should be replaced by the shot noise power of the electron beam
Source: ENEA

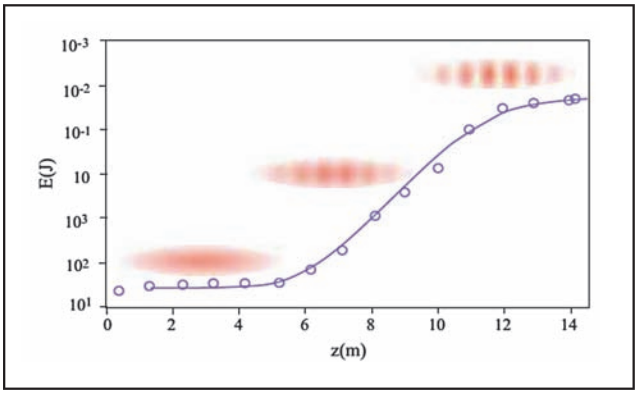

FIGURE 3 FEL intensity evolution, from noise to saturation
Source: ENEA

The engineering issues determined by the design of FEL devices are quite new, being they a mosaic of different technologies (magnetic materials for undulators, high quality electron beams, new accelerators, etc.). Design methods capable of merging these different aspects have been developed in the past and are still under validation. The accurate planning of a simulation strategy is, therefore, not a secondary issue, and ENEA has invested in the development of codes capable of satisfying two different requests, reliability and computational simplicity. This strategy has opened different scenarios, allowing the proposal of new and more advanced FEL conceptions. The development of FEL sources with these characteristics imposes the choice of devices operating in the oscillator configuration and demands for a breakthrough of the technology of mirror manufacturing, capable of confining radiation in the extreme UV-X ray region. It further demands for the development of high performance accelerators, designed to provide beams of excellent quality (high current, low angular dispersion and high energy resolution). In addition to this, the research on permanent magnets should be addressed towards the production of micro-undulators, and namely undulators with high on axis field and small period.

These challenging enterprises should be framed within an environment that provides for a strong participation of industry, which could be one of the major beneficiaries of the associated technological byproducts.

National geopolitical situation

The scenario of worldwide FEL sources is given in Fig. 4. In Italy two different facilities are under development, FERMI in Trieste and SPARC in the ROME-FRASCATI area. The latter is the result of a joint collaboration coordinated by ENEA (ENEA-INFN-CNR-University of Rome Tor Vergata), playing the role of a test facility. It has provided noticeable results regarding the new schemes of FEL operation, in particular, external seeding and harmonics generation.

On the other side, FERMI will provide a FEL source in the extreme UV-X ray region and is expected to have a significant impact for a large variety of applications, from biotechnology to the advanced magneto-dynamic materials.

The development strategy we have outlined at the end of the previous sections, could provide high standard research and the creation of qualified job positions for the next 20 years or so. In the meantime, a subsidiary strategy is necessary, for at least two reasons:

a) lack of a targeted preparation of industries within these specific issues,
b) need for requalification of the oscillator technology, which has been "abandoned" to invest in favor of SASE devices.

It is difficult to figure out a coordinated European strategy, but at the national level, we believe that the development of a further source complementary to the FERMI spectral range, that is THz-IR-UV FEL, can go in the direction of the previous points and at the same time provide important applications in biomedicine.

The reasons for this choice are clear: it will be possible to consider the two FELs as a "unique" Italian facility, and, furthermore, to maintain both competences alive in the oscillator and SASE technologies. Moreover, specific agreements with the local manufacturers will open the possibility for an industrial training and an effective cross fertilization between industries and research centers.

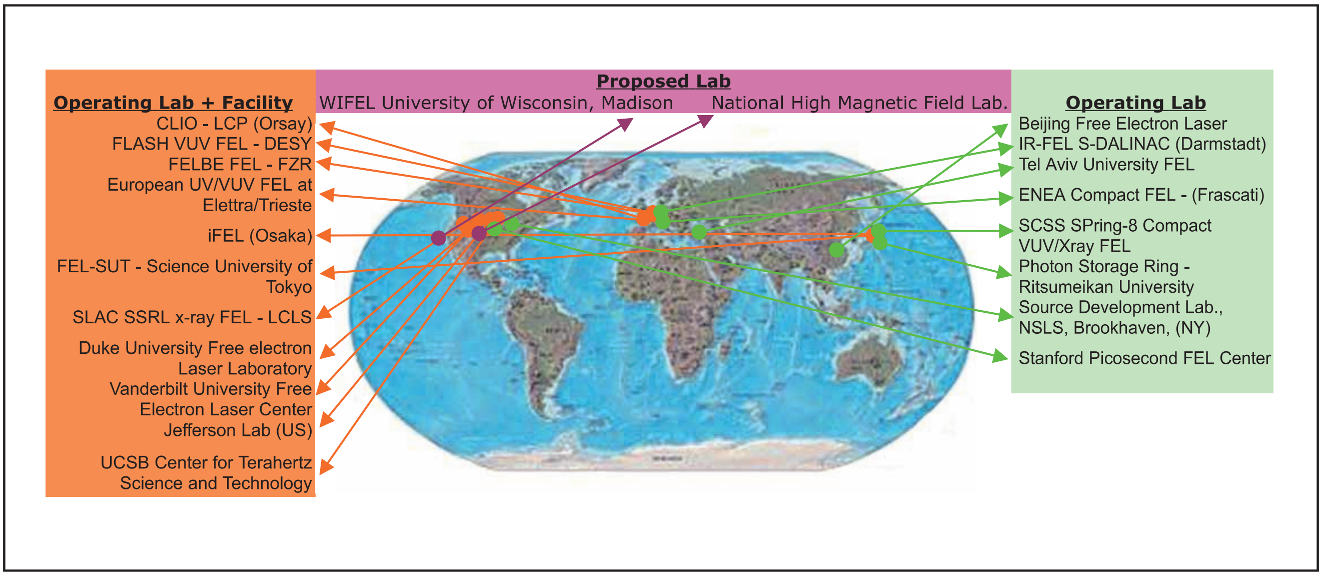

FIGURE 4 FEL worldwide scenario
Source: ENEA

FEL light sources and challenges in biomedicine

Nowadays, a rapidly growing interest in application of FEL beams is observed in many areas of biomedical science opening up new opportunities to study living forms on different levels, from biomolecules and subcellular structures up to the whole organisms. Here we give a brief overview of possible THz-IR-UV FEL applications in biomedicine.

The challenge of the research is to probe matter with substantially finer length, time and energy resolution, where biological systems can be observed on their femto- (atto-) second temporal, nanometers spatial and milli-electron-volts energetic scales. Dynamic studies will complement the investigation of static systems. To reach these goals, the next generation of light sources should have elevated transverse and temporal coherence, variable pulse length, pulse duration down to femtoseconds and possibly attoseconds, high brilliance and peak power, wide range and easy tuning of photon energy and polarization control. Free Electron Lasers are uniquely fitted to achieve these goals [5].

Recent technological applications of **THz-FEL** radiation in biology and biomedicine are based on the specific spectroscopic “fingerprints” related to the numerous vibrational-rotational modes of biomolecules in this spectral region, whereas still very little is known about its interaction with biological systems. Therefore, the study of the interaction of the THz-FEL radiation with biological systems of increasing complexity – from enzymes and protein biomolecules to DNA, cell membrane and nucleus, and finally, to biological tissues and organs, developing novel spectroscopic and microscopic THz-based techniques – is of great promise.

THz-FEL can be applied in biophysics to extract femtosecond-resolved dynamic information on different isomeric conformations of various biomolecules in their native water environment after photo-excitation. THz spectroscopy in liquids is very challenging and may allow to determine the tertiary structure of proteins (folding).

Among the possible future THz-FEL biomedical challenges is the early detection of alterations in the DNA chain sequence in patients’ blood with the scope of the earliest disease diagnosis, and detection of specific virus and bacteria “signatures” for rapid identification and control of epidemics. Recent advances in genetic diagnosis, which allowed to introduce biosensors (like, genome chip o DNA microarray), are worth to be mentioned [6].

THz-FEL medical imaging is of significant interest in various biomedical fields, being skin cancer detection at the earliest stages of the disease development one of them.

IR-FEL has great potentials for biomedical applications research, primarily in the field of laser-tissue interactions. FEL can be successfully applied in procedures like cutting tissues by the photo-thermal effect, ablating hard tissues by the photo-mechanical effect, and also modifying surface (surface functionalisation) by the photo-chemical effect. Such interactions can be precisely controlled by a suitable combination of FEL parameters, such as wavelength tunability, energy density, pulse duration and repetition rate, resulting in a non-invasive treatment, characterized by high efficiency and low collateral damage.

Recent achievements in the IR-FEL irradiation of hard and soft tissue indicate the great promise for the FEL-based protocols in surgery and medicine [7]. Successful studies on the FEL ablation of some hard tissues, like dentine and enamel of the tooth and the cortical bone, were carried out. The FEL radiation source was found to be excellent for probing the soft tissue as well. For example, the IR-FEL irradiation technology provides a potentially safe and minimally invasive treatment of atherosclerotic vascular diseases, enabling selective removal of cholesterol ester in atherosclerotic plaques accumulated on the arterial walls.

The ability to dissect through the fatty tissue surrounding many organs of the abdomen without transecting the blood vessels would be a major advance in laparoscopy. The unique spectral signatures of these fatty tissues in the IR range may enable controlled, selective irradiation of fatty tissue in the brain, blood vessels, abdomen and spinal cord.

IR-FELs are expected to give a substantial contribution in neurosurgery, for cranial nerves and deep brain areas, demonstrating a minimal o nearly absent collateral damage for surrounding tissues and high ablation yield. Good results were also obtained for the ophthalmic (cornea and neural) and dermal tissues. It should be stressed that laser assisted removal of biological tissue is a rapidly growing area, especially in oncology. The most frequent brain tumors often are spread in the vast areas, so that it is not possible to remove the whole tumor in conventional manner. FEL are expected to provide a breakthrough in understanding the damage/ablation mechanisms and to lead to new solutions in medical-related issues. As a consequence, new optimized techniques and devices can be developed.

Nanosurgery operates at the cutting edge of medicine [8]. Possible applications include gene therapy, nerve regeneration and cancer treatment involving the selective damage of tumoral cells. For cancer therapy, the targeted ablation results in the destruction of a single tumor cell, whilst neighboring cells remain intact. Precise nanosurgery ensures the complete damage of a targeted structure, becoming a formidable method for biomedical research, when laser systems are coupled with advanced imaging systems. Recent advances in ultrashort pulsed laser technology provide an attractive tool for cell and tissue manipulation. Indeed, femtosecond laser ablation, in addition to being a non-invasive and reliable technique, can be used to perform very accurate and selective surgery. For instance, a cell organelle can be dissected, while leaving the cell membrane intact. Thus, femtosecond irradiation ensures nanoscale precision, opening a new dimension in cellular and subcellular scale investigations. Laser subcellular surgery makes it possible to investigate morphogenesis (one of the three fundamental aspects of *developmental biology* along with control of *cell growth* and *cell differentiation*), to locally activate the gene expression, influencing the patterned growth of tissue and to investigate tissue dynamics *in vivo* [9]. The laser beam can be used to trigger tissues, cells and biomolecules, while monitoring the changes in real time by means of a high resolution imaging technique.

The IR FELs provide a way to substantially improve the Scanning Near-field Optical Microscopy technique, boosting its capabilities not only in static imaging (the possibility to get chemical information from cells and their internal structures), but also in providing the possibility to perform dynamic characterization of ultrafast biological processes.

The application of **UV-FEL** in biomedicine is at an early stage. Some surgery-oriented studies have been carried out in the Vacuum UV and Extreme UV regions. It should be mentioned, however, that studies in the short range of wavelength are at their beginning, since irradiation with short wavelength photons leads to a specific ablation mechanism with a substantial increase in ionization radiation damage and concerns about its potential mutagenic effects.

The UV-FEL would be invaluable in advancing the research of the mechanisms of UV radiation damage of biological systems, like DNA, proteins, membranes, etc. Short wavelength photons are strongly absorbed by water, hence cellular components can be damaged by an indirect mechanism involving the generation of reactive chemical species. The main problem in this case is a great number and complexity of occurring chemical reactions. The advantages of using UV radiation is that the energy-per-photon is adequate to produce a limited number of ionizations, that is the number of chemical reactions is much more limited than, for example, in the case of X-rays.

The state of time-resolved phosphorescence and fluorescence studies of biological systems could be advanced by exploiting FEL characteristics [10]. UV-FELs based on storage rings are particularly useful for the development of pump-and-probe two-color spectroscopic investigations of biophysical processes, being a powerful time-resolved technique in biomedicine and photochemistry. Future multi-photon excitation experiments and the upcoming tunable UV FELs will further stimulate this research field.

To conclude, the development of the versatile FEL technology in terms of its pulse format and wavelength tunability makes it a tool of great importance for the biomedical research field. These characteristics permit to select an appropriate wavelength and pulse structure for any given specific task, which will further lead to the development of reliable compact FEL devices and/or new conventional laser sources. FEL multidisciplinary research centers worldwide are at the base of the forefront spin-off technologies, which will have a significant impact in healthcare for years to come.

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Notes

[1] To reconcile the caption of fig. 1 with eq. (2), it should be kept in mind that the electron motion is relativistic

$$(\gamma >> 1\text{, therefore } \beta = c\sqrt{1-\frac{1}{\gamma^2}} \cong c\left(1-\frac{1}{2\gamma^2}\right))\,.$$

Furthermore, the motion consists of two contributions, namely the longitudinal and transverse parts, the latter being provided by the electron oscillations. Accordingly, after averaging on one undulator period, the relativistic factor should be replaced by

$$\gamma^* = \frac{\gamma}{\sqrt{1+\frac{K^2}{2}}}\,.$$