A Technical Tutorial on Free Electron Lasers and short Review of their Recent Novel Applications

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Abstract
The field of Free Electron Lasers (FELs) is evolving at a very brisk pace, and the researchers are exploring the newer applications of these lasers. This paper gives the technical analysis of the concepts, mathematical modeling, and applications of FELs, besides presenting a short review of the recent novel applications of FELs, depicting the fast evolution of the field. It is felt that the paper should be useful for the new entrants in the field, and also the researchers engaged in exploring the newer applications of FELs.

Keywords: Free Electron Lasers, X Ray Free Electron Lasers, Undulators.

Resumen
El campo de los láseres de electrones libres (FEL) está evolucionando a un ritmo muy rápido, y los investigadores están explorando las aplicaciones más nuevas de estos láseres. Este documento proporciona el análisis técnico de los conceptos, el modelado matemático y las aplicaciones de los FEL, además de presentar una breve reseña de las recientes aplicaciones noveles de los FEL, que describen la rápida evolución del campo. Se considera que el documento debería ser útil para los nuevos participantes en el campo, y también para los investigadores que se dedican a explorar las nuevas aplicaciones de los FEL.

Palabras clave: Láseres de electrones libres, láseres de electrones libres de rayos X, onduladores.

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I. INTRODUCTION

Free electron laser (FEL), is a laser, which a powerful combination of particle-accelerator and laser physics. The light coming out of this laser is ~a billion times stronger than the ordinary synchrotron light. FEL is a relativistic electron tube based on the use of the open optical resonator, and has the same optical properties as the conventional lasers like – the emission of a beam of coherent electromagnetic radiation, capable of reaching high power, but uses the entirely different operating principles for the beam formation. Unlike the gas, liquid, or solid state lasers, these are based on the bound atomic or molecular states. They work with relativistic electron beam as the lasing medium, which is precisely the reason that they are called FELs. Being relativistic in nature, FELs have the widest frequency range amongst the various types of lasers, and mostly are widely tunable, having the wavelength range from microwaves, to the terahertz radiation, and infrared, to the visible spectrum, to ultraviolet, and to the soft X-rays. The FEL is made from a beam of electrons, accelerated to relativistic speeds, which on passing through a periodic, transverse magnetic field, produced by arranging magnets with alternating poles along the beam path, called an undulator (Fig.1), forces the electrons in the beam to follow a sinusoidal path. It is obvious that the electron motion is in phase with the already emitted field of the light, and this leads to the fields being added together coherently. Though in the case of the conventional undulators, the electrons radiate independently, the instabilities in the electron beam due to the interactions of the oscillations of electrons in the undulators, and the radiation emitted by them result in a bunching of the electrons, and hence the emitted radiations remain in phase with each other. The wavelength of the light emitted can be readily tuned by adjusting the energy of the electron beam or the magnetic field strength of the undulators. The acceleration of the electrons along this path is responsible for the release of a photon. The schematic for the fabrication of the FEL is given in the Fig. 2.

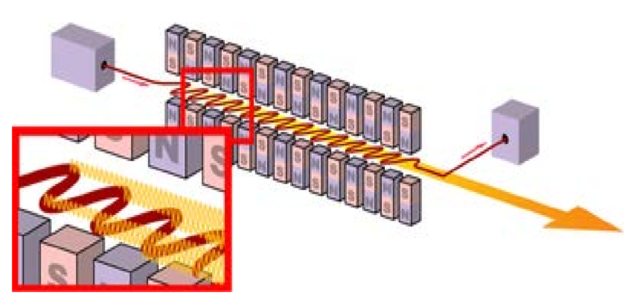

FIGURE 1. Schematic of an undulator at the core of a free electron laser.

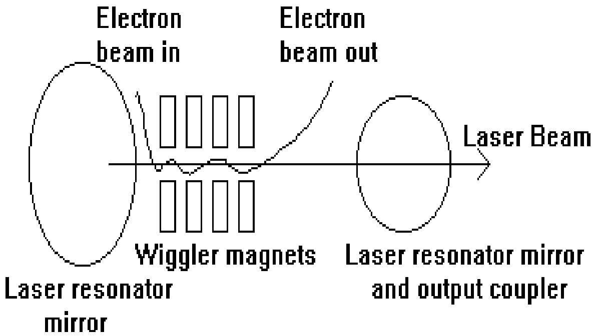

FIGURE 2. Schematic of a free electron laser. **FIGURE** courtesy M/s. Google.

As we view the relativistic electron in the rest field, the magnetic field can considered as if it were a virtual photon, and hence their collision results in the release of an actual photon., due to the Compton scattering. These photons are captured by the mirrors, resulting in the generation of the resonant gain. The tuning of the lasing wavelength can be done easily over a long range by adjusting the beam energy or the field strength, which is the main characteristic that separates the FEL from the conventional lasers. A simpler explanation is that the undulator forces the electrons in the sinus path, which then switch in a rest frame moving along the undulator. It is important to know that here the electrons are only oscillating, but not moving in the general sense, and thus emit dipole radiation, and subsequently switch back into the rest frame of the undulator, to transform this radiation into a forward emitted radiation of shorter wavelength. As mentioned above, the emitted photons can be influenced by the electron beam and magnetic field strength, which makes the FEL easily tunable, for controlling the lasing wavelength.

Laser light is coherent in nature, i.e. the light waves in this case are in phase. In case of the FEL, any radiation moving along the undulator, at the speed of light, passes over the electrons, and leads to their synchronization; and thus the light either tries to accelerate or decelerate these electrons; and hence gains or loses kinetic energy, i.e. moves faster or slower along the undulator, resulting in causing the electrons to form bunches, which are synchronized, and in turn emit synchronized i.e. coherent radiation.

II. X-RAY FREE ELECTRON LASER

It is well known that for the laser sources in the visible and IR regions, dielectric coated laser mirrors [1] are required for the optimum performance. Because of the limitation of the non availability of the laser mirrors suitable for the extreme UV and the x ray wavelengths, it is not possible to perform the operation of the FEL oscillator, which has led to the efforts for finding a suitable amplification over a single pass of the electron beam through the undulator. Therefore, the long undulators are used for making the useful X-ray FELs. The intense pulses from the X ray laser are produced by the self amplified stimulated emission (SASE), which results in the microbunching of the electrons. Initially, there is an even distribution of electrons, which emit only the incoherent spontaneous radiation. This radiation interacts with the electrons' oscillations, and drifts into microbunches separated by a distance equal to one radiation wavelength. As a result of this interaction, the electrons begin emitting coherent radiation in phase i.e. all emitted radiation can reinforce itself perfectly, and the wave crests and wave troughs are superimposed on one another in the best possible way, which results in an exponential increase of emitted radiation power, leading to high beam intensities and laser like properties.

The FEL process can be started when at least one of these initial conditions is satisfied: (i) Radiation field (FEL amplifier); (ii) Density modulation (Self-amplified spontaneous emission FEL - SASE FEL); and (iii) Energy modulation. It is observed that due to the finite number of electrons and their discreet nature, an intrinsic fluctuation in the density is always present, which can drive a SASE FEL. It should be seen that to operate as an FEL amplifier, the seeding power level must be higher than the equivalent power level from the SASE startup i.e. the shot noise power.

The free electron laser emitting X-rays with a wavelength ~ 1 Å has been fabricated based on the self organization of the electrons in a relativistic beam, termed as the free electron laser collective instability, which converts an electron beam with a random electron position distribution into a distribution of regularly spaced electrons at ~ the x-ray wavelength, and hence produces 1-D electron crystal, the radiation from which has the new and exciting properties. It is worthwhile to note that the high peak brightness of the new x-ray light sources is good for the HEDS needs, because of the characteristics: (i) The sources are based on the synchrotron radiation; (ii) The number of photons per bunch is quite low; and (iii) The bunch duration is quite long ~ 60 ps. However, the stringent requirements for the HEDS studies are: (i) high intensity X ray sources, which are able to probe dense matter at finite temperature; and (ii) ultrashort pulses for studying the highly transient behavior, and also able to remove the hydrodynamic changes. The FEL sources provide solution for these requirements, because they have short bunch duration ~100 fs, and high number of photons per bunch, besides being tunable.

The lasers have various applications: (i) Medical, (ii) Defence, (iii) Industry, (iv) Communication, and (v) Scientific.

(i) MEDICAL APPLICATIONS: It has been reported that at the IR wavelengths, the water in tissue is observed to be heated by the laser, but at the wavelengths = 915nm, 1210nm, and 1720 nm, the subsurface lipids are differentially heated more strongly than water, and this observation can be applied for the selective destruction of sebum lipids for treating the acne, and some other lipids for the treatment of cellulite and atherosclerosis. Also, it has been observed that the soft tissues like skin, cornea, and brain tissue can be cut, or ablated, using IR FEL wavelengths ~ 6.45 mm with minimum collateral damage to adjacent tissues, which makes it extremely useful in various surgical applications. The successful research efforts have been reported on the medical application of the FEL in melting the fats without harming the overlying skin. Chopra [2, 3] has discussed in detail the uses of lasers in surgery and biomedical field. It is widely known that the conventional lasers have been found useful in some forms of surgery for more than the last three decades, but their use in neurosurgery has been limited because of the likelihood that they can damage areas surrounding the diseased tissue. However, the advantage in case of the FEL is that it creates laser light in an entirely new manner, giving the FEL beam special characteristics, which make it able to cut a variety of tissues with exceptional cleanliness. Whereas the conventional lasers generate light in either a solid or a gas, the FEL, works by passing a stream of electrons traveling at nearly the speed of light through a wiggler, a device for producing the alternating magnetic fields, causing the electrons to vibrate at a specific frequency, which leads to their emission of a beam of laser light. By varying the energy in the electron beam, the FEL can be tuned to a wide range of frequencies. The design is also capable of generating extremely powerful beams of coherent infrared light.

(ii) DEFENCE APPLICATIONS: The FEL is now accepted as a strong candidate for the anti missile directed energy weapon, because of the great progress made in increasing the FEL power levels (> 10 kW), and also the success achieved in building the compact multi megawatt class FEL lasers for defence purposes.

(iii) INDUSTRY APPLICATIONS: The FEL has many applications in industry e.g. Drilling, Cutting, Marking, Welding, Heat Treatment, and Cladding. The laser drilling is done by using either single or multiple pulses for the production of holes, the technique being called as laser percussion hole drilling, in which the work piece is placed near the focal point of the laser beam. The process of laser cutting is based on using the concentrated light from the laser with a high velocity gas jet to vaporize the nonmetals or to melt the metals for the fast removal of the material. The laser marking is done by a pulsed laser with high peak power density along with computer controlled beam scanning system. The welding (both spot welding and seam welding) can be performed either by pulsed lasers or continuous wave lasers. The heat treatment is done by lasers for surface hardening of steels with carbon percentage > 0.3 up to 2 mm depth, by defocusing a laser beam to produce a power density of 150 W/cm2 to 1500 W/cm2, which causes the heating of the part surface. The cladding is done by melting the alloys, and then selectively depositing them onto the part surface, the melting being carried out by the defocused laser beam and a local shield gas. It should be noted that this technique is particularly useful for the deposition of wear resisting layers on the components like rock drills, and turbine blades.

(iv) COMMUNICATION APPLICATIONS: Lasers are very attractive for communication purposes because of the reasons: (i) extreme directionality, and (ii) the information carrying potential, the amount of information that can be sent being proportional to the bandwidth of the wave. These are particularly useful for the space communications, in which case, the distances are enormous, and the atmospheric interference is not a problem.

(v) SCIENTIFIC APPLICATIONS: The FELs have many important properties like: (i) Ångstrom wavelength range, which allows Spatial resolution to resolve individual atoms in molecules, clusters and lattices; (ii) Tens to hundreds of femtosecond pulse duration, which allows high Temporal resolution, useful for the most dynamic process (change in the molecular structures or transition; (iii) High Brightness, which helps to focus the radiation beam down to a small spot size and thus increasing the photon flux on a small target; (iv) High Photon Flux (1012 photons per pulse), which helps to increase the number of scattered photons even at small targets; and (v) Transverse Coherence, which helps to allow the diffraction experiments, and to reconstruct 3D model of target sample. In addition, the high charge densities produce strong electromagnetic fields generated by the electron bunches. Electrons within the bunch experience these fields: (i) Coherent Synchrotron Radiation; (ii) Space Charge fields; and (iii) Wake fields. All these useful characteristics make them very useful in the scientific research.

The development of the femtosecond lasers has led to revolutionizing many areas of science from solid state physics to biology, which is based on the availability of a novel source for the generation of femtosecond pulses with the help of ultra fast VUV and X-ray science. Recently, the seeding limitation for x-ray wavelengths has been overcome by self-seeding the laser with its own beam after being filtered through a diamond monochromator, which provides the unprecedented intensity and monochromaticity of the beam, allowing the new experiments to be conducted involving manipulation of atoms and imaging of molecules.

Lasers are used in the technique of recording of the complete information of an object i.e. its amplitude and phase, called Holography, which produces three dimensional images, and has many useful applications in various fields including the identification and data storage.

III. PRINCIPLE AND MATHEMATICS OF THE PARTICLE MOTION IN UNDULATOR

If a weak entering radiation is incident on the undulator, its output is a high power radiation. However, it is really interesting to note that for a sufficient length of the undulator, even the entering radiation is not required, since the resonant harmonics of density fluctuations become large, and consequently the bunch can radiate a powerful wave. Another case to be understood is the one in which the gain per unit path through the undulator is small, and hence the undulator has to be installed in the cavity having mirrors (as is the case with the conventional lasers), where the radiation is stored.

The equations governing the particle motion in the undulator are based on simple mathematics. The electrons pass through the undulator, in which the magnetic field has a periodicity in a period λ_u, given by the following equation:

$$B(z) = B(z + \lambda_u). \tag{1}$$

The periodic magnetic field produces a transverse oscillation of an electron moving along the axis of the undulator.

$$\beta_x = \frac{K}{\gamma}\sin(k_u z)\ , \tag{2}$$

with

$$K = \frac{e}{2\pi mc}B_0\lambda_u\ ,$$

where K is the net deflection strength of the Lorenz force of a single undulator pole, and is proportional to the peak field B_0 and pole length (undulator period λ_u). As the total energy is preserved, the transverse oscillation affects the longitudinal motion. The average longitudinal velocity in an undulator is given by:

$$\beta_z \approx 1 - \frac{1}{2\gamma^2} - \frac{1}{2}\beta_x^2 = 1 - \frac{1+K^2/2}{2\gamma^2}\ . \tag{3}$$

The Tunability of the emitting wavelength is given by:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right). \tag{4}$$

where $K = (e/2\pi mc)B_0\lambda_u$, is the undulator parameter, and γ is the electron energy.

The undulator induces the transverse velocity components in the electron motion, resulting in the coupling of electrons with a copropagating radiation field.

$$\frac{d}{dz}\gamma = \frac{e}{mc^2}\vec{E}\cdot\vec{\beta} = k\frac{K_r K}{\gamma}\sin(k_u z)\cos(kz - \omega t + \phi). \tag{5}$$

For bunch length shorter than the undulator period, the electron bunch oscillates collectively, which leads to the sinusoidal change in energy with the periodicity of the radiation field. It has to be appreciated that the radiation field propagates faster than electron beam, and the energy change is not constant along the undulator. However, it has to be understood that for a certain longitudinal velocity, a net gain energy change can be accumulated.

IV. PARTICLE ACCELERATION BY EM WAVE IN UNDULATOR

The method of particle acceleration is based on the autophasing technique, routinely employed in the theory of accelerators. The autophasing, is similar to Hamiltonian describing synchrotron oscillation in accelerators, and is given by the effective Hamiltonian:

$$H = \frac{P^2}{2\mu} + U_S[\{\Psi - \Psi_S\}\cos\Psi_S - \sin\Psi], \tag{6}$$

where $P = (E - E_s)$, is energy deviation of equilibrium particle energy, describing the amplitude of the effective potential, which is proportional to the transverse component of velocity and wave field; and Ψ and Ψ_s are the corresponding wave functions, and U_s is the energy corresponding to Ψ_s.

At linear increase of a field undulator, we have the particle acceleration with constant rate, and hence E_s, and $\cos\Psi_s$ are given by:

$$E_S = mQ(\omega/2a\varepsilon_0)^{\frac{1}{2}},$$
$$\cos\Psi_s = \{m\omega Q/2eEa\varepsilon_0\}, \tag{7}$$

where Q is the undulator parameter, given by:

$$Q = \{\frac{eB}{a\varepsilon_0 m}\}. \tag{8}$$

Just to have an idea about the parameters of the FEL, these are given below:

E = 0.5GeV; Ne = 10^{12}, λ_u = 2cm, H_0 = 5kG, $\lambda = 2\times10^{-6}$ cm; Δ^{-1} = 60cm; $L_{\text{modulator}}$ = 6m; L_{bunch} = 2cm, $\varepsilon = 10^{-3}$ rad.cm; $W_{\text{peak}} \sim 10^{10}$ W; and W_{avg} = 10kW. Thus, it is clear from these parameters that for E = 0.5 GeV, we can extract very high values of average W and Peak W.

V. RECENT STUDIES IN FREE ELECTRON LASER AND CONCLUSIONS

Castelvecchi [4] has discussed in detail the utility of the FELs for the old applications. Great interest has recently been shown in some of the novel applications of the FELs. Bucksbaum *et al.* [5] have provided the Special Issue on Frontiers of Free Electron Laser Science, which highlights the recent advances in x-ray free electron laser research carried by the new generation of FELs in Europe, Japan and the USA. The central area of interest for this issue is a broad energy range from a few 10 eV to several tens keV, besides the x-ray lasers pumped by FELs, the physics of the x-ray FEL developments in beam conditioning including seeding, echo and selective emittance spoiling, which have led to the femtosecond x-ray matter studies by the FELs. Vlahos [6] has described that the Navy has set a new world record, by doing a test blast, using a novel type of laser capable of shooting cruise missiles from the sky in seconds with a deadly accuracy.

Emma *et al.* [7] have described the operation and performance of this new fourth generation light source, which produces coherent soft and hard x-rays with peak brightness nearly ten orders of magnitude beyond conventional synchrotron sources, and a range of pulse durations from 500 to <10 fs (10^{-15} s), thereby making it capable of imaging the structure and dynamics of matter at atomic size and timescales. Seggebrock *et al.* [8] have discussed in detail the use of chicane as a bunch stretcher instead of a bunch compressor to allow the operation of a laser wakefield accelerator driven FEL using the currently available electrons, instead of the FEL operation in the vacuum ultraviolet range based on an optimized undulator, and bunch decompression using electron bunches from a laser-plasma accelerator. This has been done by deriving a scaling characterizing the impact of bunch decompression on the gain length and testing numerically the feasibility of the concept in a demanding scenario.

Recently, SPIE Conference [9] was held on the Advances in X-ray Free-Electron Lasers II: Instrumentation, which had six sessions – (i) Status of Operational and Planned FEL Facilities and Source Developments; (ii) Scientific Applications and Their Instrumentation Requirements; (iii) Optics, Beam Transport Performance, Spatial and Coherence Properties; (iv) Diagnostics of FEL Radiation I: Electron Beam Diagnostics; (v) Diagnostics of FEL Radiation II: X-ray Beam Diagnostics in the Time Domain; and (vi) FEL Instrumentation and Sample Related Issues.

Hara *et al*. [10] have proposed a novel method to deliver bunch-to-bunch energy changed electron beams at the end of the accelerator. Since all the components are operated in steady state, this method provides the quasi simultaneous operation of multi-beam-line in the same undulator hall without degrading the stability and performance of the electron beam. Kumar et al [11] have reviewed several schemes of soft X-ray and hard X-ray free electron lasers (XFEL) and their progress, by including the discussions on the Self-amplified spontaneous emission (SASE) schemes, the high gain harmonic generation (HGHG) scheme and various enhancement schemes through seeding and beam manipulations, with a view of the generation of attosecond X-ray pulses. Laser, chicane and electron beam parameters have been optimized to generate an isolated attosecond hard X-ray pulse at 0.1 nm (12.4 keV), and simulations have been done to show that the manipulation of electron energy beam profile may lead to the generation of an isolated attosecond hard X-ray of 150 attosecond pulse at 0.1 nm. Saldin et al [12] have studied the statistical and coherence properties of radiation from X-ray free-electron laser. Caleman *et al.* [13] have reported the feasibility of nanocrystal imaging using intense and ultrashort X-ray pulses. Caleman et al [14] done the simulations of radiation damage in biomolecular nanocrystals induced by femtosecond X-ray pulses.

Margaritondo and Ribic [15] have shown that an elementary semi quantitative approach explains the essential features of the X-ray free-electron laser mechanism, especially the gain and saturation lengths. Based on the mathematical methods and derivations, the treatment has revealed the basic physics dominating the mechanism, and provided the explanation of the difficulty in realizing the free electron lasers for short wavelengths. Huang *et al.* [16] have published a very interesting idea for a compact XFEL facility that uses an ultra-short pulse laser instead of an ordinary linear accelerator. Based on the calculations, it has been shown that such a transverse gradient undulator along with a properly dispersed beam can substantially reduce the effects of electron energy spread and jitter on the performance of XFEL generation. Grguraš *et al.* [17] have discussed in detail the ultrafast X ray pulse characterization at free-electron lasers. By using the single-cycle terahertz pulses from an optical laser, they have extended the streaking techniques of attosecond metrology for the measurement of the temporal profile of individual FEL pulses with 5 fs full-width at half-maximum accuracy, as well as their arrival on a time base synchronized to the external laser to within 6 fs r.m.s.

Yu *et al.* [18] have proposed a method to generate low emittance electron bunches from two colour laser pulses in a laser-plasma accelerator. A two region gas structure has been used containing a short region of a high Z gas like – krypton for the ionization injection, followed by a longer region of a low-Z gas for the post-acceleration. A long-laser-wavelength (e.g., 5 μm) pump pulse is made to excite the plasma wake without triggering the inner-shell electron ionization of the high-Z gas due to low electric fields. Barty *et al.* [19] have discussed that the opening of hard X-ray free-electron laser facilities, such as the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory in the USA, has provided a new era in structural determination., because the X-ray pulse durations ~ 10 fs, and of ~ 10^{13} transversely coherent photons per pulse in a narrow spectral bandwidth, the focused irradiances of 10^{18} to 10^{21} W cm^{-2} can be produced at X-ray energies in the range 500 eV to 10 keV.

Edwards *et al.* [20] have displayed the Electron paramagnetic resonance (EPR) powered by a free electron laser (FEL) to dramatically expand the capabilities of EPR at frequencies above 100 GHz, for which other high-power sources are not available, and have presented the phase cycling of two pulses in an FEL-EPR spectrometer operating at 240 GHz. It has been emphasized that their techniques have many advantages of arbitrary phase control, and allowing the application of phase cycling for enhancing the signal quality in pulsed EPR experiments utilizing the high power sources, which cannot be phase-locked. An International Free Electron Laser Conference [21] has recently been held in New York, USA; which included invited lectures and contributed papers in many sessions - FEL Theory, Beam Physics for FEL, Short Wavelength FELs, Long Wavelength FELs, Seeding and Harmonics, FEL Technology I: Guns, Injectors, Accelerators, FEL Technology II: Timing, Stability, Optics, FEL Technology III: Undulators, Beamlines, Beam Diagnostics, Novel concepts, and Applications of FELs.

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