CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

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1.1. Introduction

The Free electron lasers (FELs) are a relatively new branch of engineering physics and technology. The science of the free electron lasers is highly desirable in many streams of applied physics, medical and classical mathematics. Typically, not all, the science of the free electron lasers studied in many areas as classical physics, engineering physics, applied mathematics, material science, biology, medicine, life science, nuclear physics, electrical, electronics & mechanical engineering besides many other curriculums, which begin studies of the free electron laser physics [Liu and Tripathi (1994), Jia (2011), Pae and Hahn (2002), Shea and Fruend (2001)]. The distinguishing feature of tunability for higher frequency ranges, their properties are determined by the relativistic electron beam or a short pulse laser. FELs are an extremely adaptable light source of radiation across very wide ranges of electromagnetic spectrum from microwaves to X-rays. It is based on radiation from “free” electrons or unbound electrons rather than electrons bound in atomic and molecular systems [Pellegrini (1990), Pellegrini and Reiche (2004)]. The HUMAN BODY is the best example of FEL that produces radiated energy after gyrated foods (seed signals) into the human body chamber interact with water as e-beams and finally dumps it through depressed collector [Gopal and Jain (2018)]. FEL devices can be operated at multiple wavelengths and allow tuning of the wavelength continuously within some range. However, the major advantage of this device is that, it does not require a metallic structure for the beam-wave interaction to take place. Consequently, it has the potential to either radiation very high power with metallic walls or generation at sub millimetre wavelengths, infrared, terahertz radiation, visible, UV, XUV or X-ray, where there are no other sources achieved [Jia (2011), Chen and Joshi (1980), Liu and Tripathi (1994), Pellegrini (1990), Oerle and Mathias (1997), Pelka *et al.* (2010), Baxevanis *et al.* (2013)].

The conventional sources of radiation offer very little in terahertz range. The microwave sources, for instance, operate below $60GHz$, while lasers operate above $30THz$ and gyrotrons are limited to $30-200GHz$ range. Free electron lasers can offer an alternative to fill the frequency gap. However, conventional magnetic wiggler with wiggler period $\geq 1cm$ requires electron beams of energy $\geq 3MeV$, which escalates the size and cost considerably. Using accelerator facilities with intense bunched of electron beams via transition radiation or synchrotron, the higher pulse energies could be generated [Sharma and Tripathi (1996)]. Recently, the range of energies, such as $10-100\mu J$ per pulse intense THz frequency has been generated via transition radiation using accelerated electron beam passing through plasma to vacuum. Hence, there have been efforts to produce THz radiation by alternate methods [Tripathi and Liu (1989), Pellegrini (1990)]. Since FELs are an extremely adaptable light sources and a fascinating devices that produce tunable coherent radiation over a wide frequency range from sub millimeter wavelengths to visible region with high efficiency and high power levels using energetic electron beams. It comprises a high voltage $(>1MV)$ power supply (accelerator) and an electron gun, an interaction region with a strong wiggler magnetic field, beam pump, radiation coupler (mirror) and diagnostics, the device is tunable by changes the voltage. The FEL has a magnetic field perpendicular to the beam velocity, i.e., the main components, hence, the electrons have an oscillatory motion in transverse direction, which is suitable for interaction with either TE mode or TEM mode (Travelling Wave Tube (TWT) is always interacting with the TM mode whereas in gyrotron always dominantly interact with the TE mode). As fast-wave device, gyrotron interacts with an electromagnetic wave (uniform or periodic magnetic field) with phase velocity equal or slightly larger to the light velocity, c. In the case of FEL, the electron oscillations are in transverse direction while its bunching process is in longitudinal direction similar to the TWT. Hence, the free electron lasers offer an alternative radiation source in the sub millimetre and above wavelengths.

In 1930s, Kapitza and Dirac reported first analysis of electron motions in the wiggler which showed the possibility of stimulated scattered radiation through an electromagnetic wave. To prove this stimulated radiation, authors injected low beam energy of electrons into a standing wave region and observed the number of scattered electron bunches [Schachter (2011)]. In early 1950s, Hans Motz at Stanford University built Undulator and performed initial experiments for generating coherent millimeter-wave radiation by taking advantage of the up-shift of the radiation from undulating electron oscillator moving at relativistic velocities and also they examined the amplification of waves in a long waveguide with his coworkers in 1953, whereas, in late 1950s, the same experiment was emanated by R.M. Phillips at General Electric Microwave Laboratory, Palo Alto [Motz (1951), Motz (1953), Phillips (1960)]. They have built a similar device named UBITRON, using a permanent magnet undulator and pencil electron beam with voltages between 110kV and170kV and current of the order of 70A for an oscillator and amplifier both. In 1971, J.M.J. Madey built a relativistic electron tube used with optical resonator called as FELs [Madey (1971)]. In 1976 at Stanford University, Madey developed FEL amplifier using $5m$ long wiggler with $43MeV$ beam of electrons to signal amplification at $10\mu m$ wavelength and measured gain successfully. This experiment was also performed for the same FEL configured oscillator at $3\mu m$ wavelength in 1977, which led to the large interest for researchers [Madey (1971)]. Tunability and design flexibility, the two important aspects were observed by using the FELs at different wavelengths by Madey [Madey (1971)].

The experiments that led to the present day FELs evolved along two separate paths, as the type of accelerator and the regime of operations. Experimentally in occurrence of FELs, two types of scattering processes are used as one is Compton (wave-particle) scattering and others Raman (wave-wave) scattering [Pourkey and Toepfer (1974)]. If the Debye wavelength is much greater than pumped wavelengths, the wave-particle process dominates and is called Compton scattering (i.e., off single "shielded" particles), whereas, if the Debye wavelength is much smaller than pumped wavelengths, then wave-wave process dominates and Raman scattering occurs [Darke *et al.* (1974), Manheimer and Ott (1974)]. Experimentally, Elias demonstrated the FELs and observed their amplification gain by 7% per pass of a $10.6\mu m$ laser beam with $70mA$ beam current which is paved the way for high power tunable FELs [Elias *et al*. (1976)]. Another experiment at Stanford University demonstrated wave-particle stimulated scattering above $3.4\mu m$ threshold wavelengths in infrared region is built the oscillator using high electron beams energy with low current linear accelerator [Deacon *et al.* (1977)]. Though the demonstrated efficiencies were less than 0.01% and attempts to improve efficiency were focused on the use of storage rings to continuously recirculate the beam through the wave generation region. The first stimulated scattering experiments in the Raman regime using relativistic electrons beam was performed by Granatstein in 1976 [Granatstein *et al.* (1976), Granatstein *et al.* (1977)]. Through utilization of intense REBs generators, the super radiant FEL oscillators were demonstrated by producing megawatt power levels in short interaction regions $\sim 30cm$ at wavelengths ranging from $2mm$ to $400\mu m$ and with efficiencies as high as 0.1%. More recently, McDermott reported a collective Raman FEL for the first time. The experiment was designed so as to permit several passes of feedback by employing a quasioptical cavity. A laser output of $1MW$ was observed at $400\mu m$ and narrow line with of $\Delta\omega/\omega \approx 2\%$ compared to $\Delta\omega/\omega \approx 10\%$ for the earlier super radiant oscillator studies [McDermott (1978), Marshall and Schlesinger (1978)]. Tapered wiggler and axial fields is another alternative which drastically changed the scenario leading to improved efficiency of the device.

The properties of the FELs are defined by its relativistic electron beam or a short pulse laser having wiggler magnetic field. The wiggler couples the fast radiation mode to negative energy beam space charge mode and both get amplified as the interaction takes place. The important aspect of the FELs is the possibilities of “free” electron that emit radiation without violating the energy and momentum conservation principle. It is noticed that each and every time a “free” electron emits radiation interacting with an external field that follows energy and momentum conservation principles. Some such types of field examples are given bellow,

i. ***Synchrotron radiation of emission*:** It allows the conservation of the magnetic fields through the bending magnets to the radiation.

ii. ***Bremsstrahlung*:** The Coulombs field of the atomic nuclei act as external field to the radiation.

iii. ***Compton scattering*:** The conservation allows through incident EM field wave to the radiation.

iv. ***Smith-Purcell radiation*:** The conservation is allowed through the charge passing close to a metal grid surface resulting into the radiation emission.

v. ***Cherenkov radiation*:** If the charge moving with velocity greater than the light velocity in the given medium, the asymmetric polarization is induced in the dielectric which causes the emission of radiation.

The disadvantage of FEL is the cost and complexity. Since the particle accelerators have more complexity as well as higher cost associated with the FELs are mainly used for the following [Pellegrini and Reiche (2004)]:

i. It is used for EM spectrum as the soft and hard X-ray or far infrared (FIR) region.

ii. It is used where atomic or molecular lasers are not available due to the tenability limited power.

iii. It is used for high-efficiency and large average power.

A comparison of the magnitude of the peak brightness for a free electron lasers and other radiated EM sources is given Fig. 1.1. FEL is highly efficient device for the soft to hard X-ray spectrum [Pellegrini and Reiche (2004)]. In recent years, as with Vacuum Tube Devices (VTDs), gyroklystron, gyratron, gyro-TWT or gyro-twystron, FELs and Cerenkov free electron lasers (CFELs) have become very attractive devices at sub-millimeter to infrared wave lengths and are capable for radiation emission of very shorter wavelengths, up to x-rays [Chen and Joshi (1980), Liu and Tripathi (2013)].

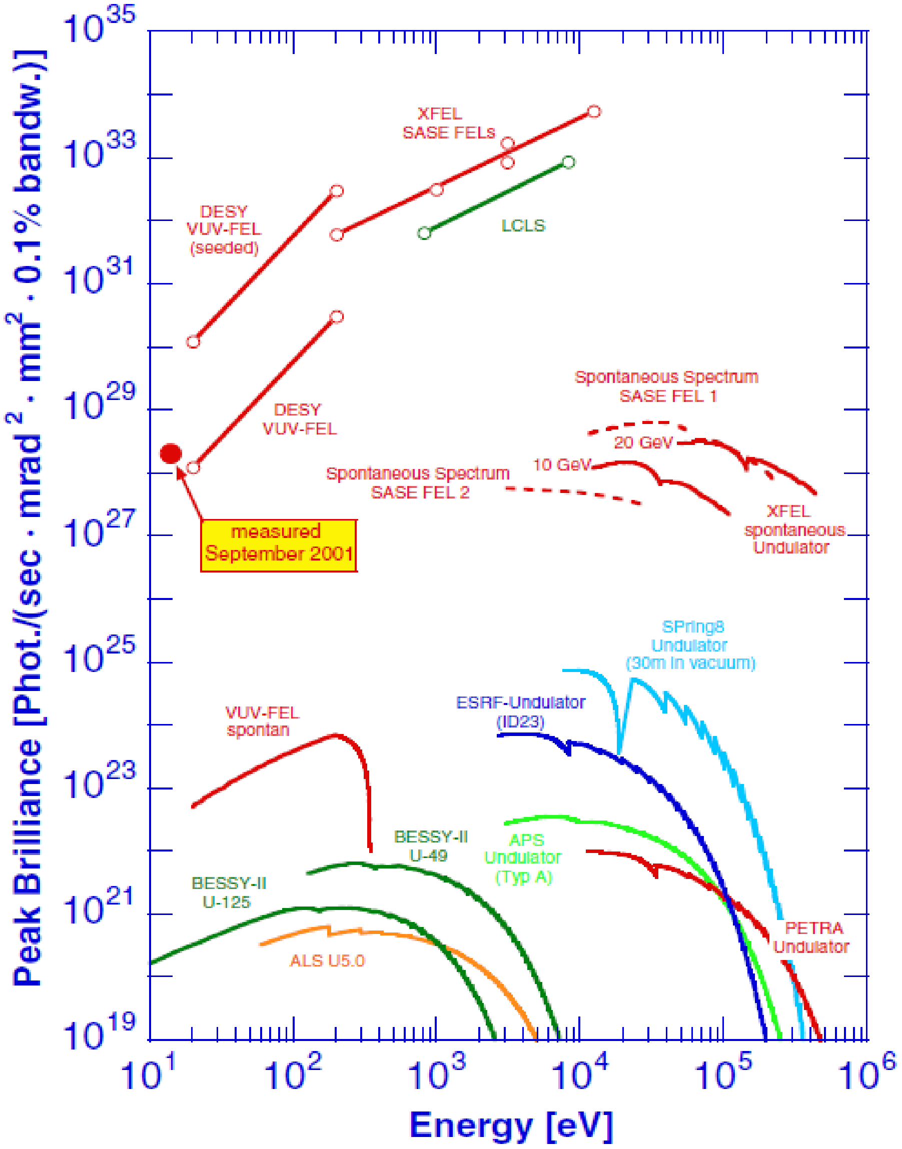
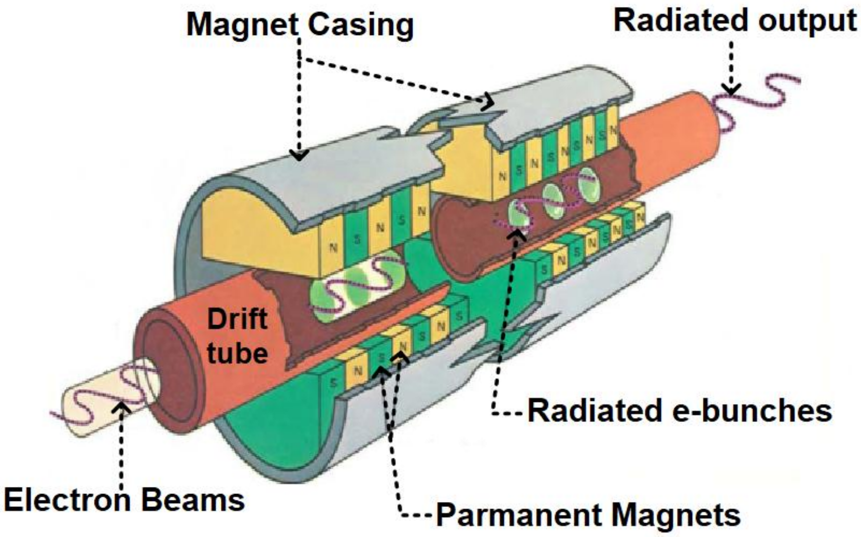


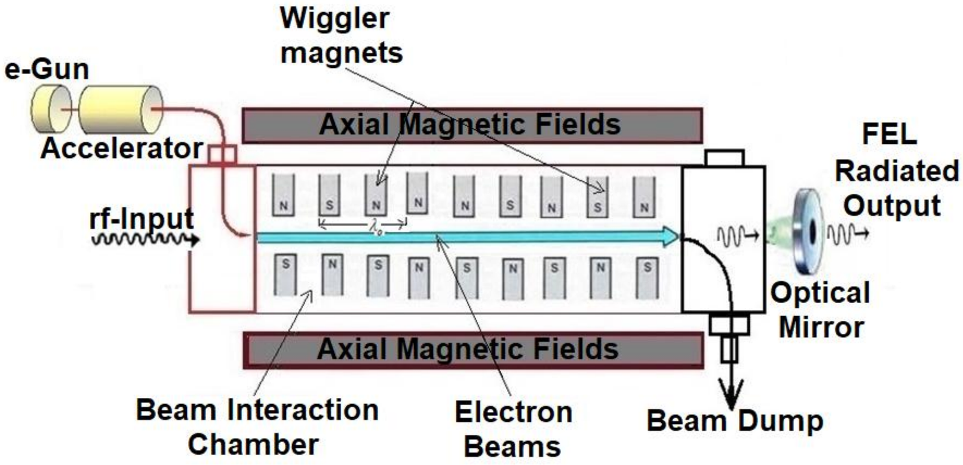
Figure 1.1: Peak brightness of free-electron lasers in the VUV and X-ray regime compared to 3rd generation light sources [Pellegrini and Reiche (2004)].

1.2. Geometrical structure of FEL and its components

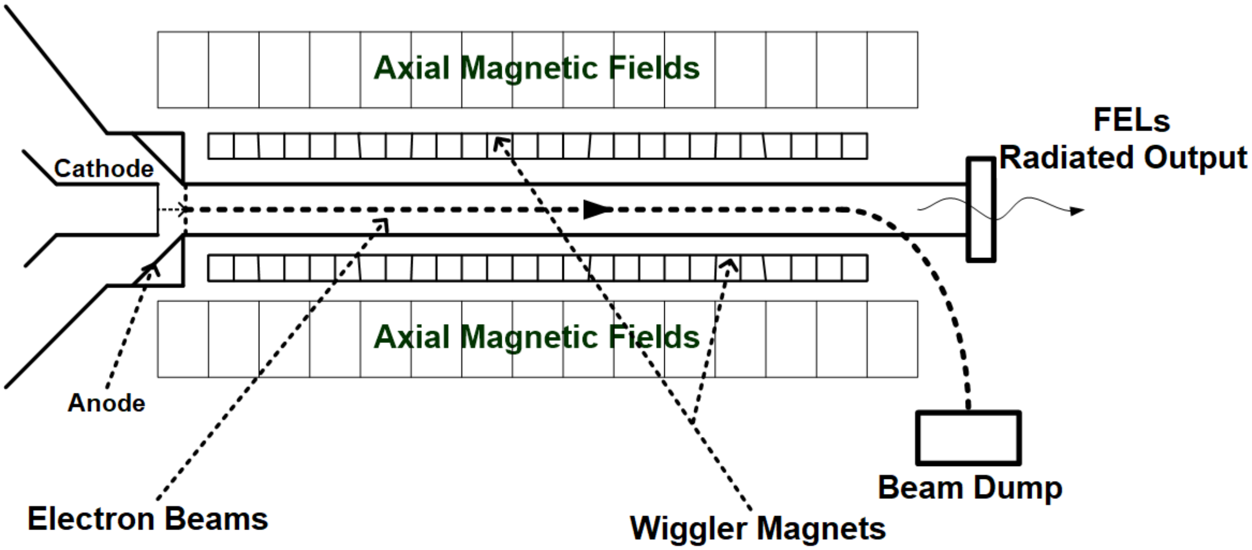
The graphical representation and typical layout sketch of the free electron laser (FEL) is shown in Fig. (1.2 (a), (b), (c)) [Prosnitz and Swingle (1982), Gopal and Jain (2018), Liu and Tripathi (1994)].



(a)



(b)



(c)

Figure 1.2: Free Electron Lasers (FELs) (a) Typical layout [Prosnitz and Swingle (1982)] (b) Geometrical configuration [Gopal and Jain (2018)] (c) Schematics sketch [Liu and Tripathi (1994)].

Figure 1.2 shows the schematic of typical FELs where its subassembly has an electron gun/electron accelerator, cathode, anode, wiggler/undulator, axial field magnets, pumping port for RF-input, interaction chamber, drift tubes, optical mirror and depressed collector/beam dump. The roles of these components in the FELs operation are briefly described below.

1.2.1. Electron gun

In FELs, the first and most important component is an electron gun/ accelerator which produces higher beam voltage $>500kV$ and beam current $(>1A\,up\,to\,100kA)$ but its beam current limitation is $17kA$ due to the space charge effects in vacuum, whereas, plasma is an alternative medium channel to propagate and to generate of high beam current that provides charge neutralization with $\leq 100 n\sec$ pulse life time (In some other experiments, the consideration of pulse length is approximate $\approx 1n\sec$) [Marshall (1985), Liu and Tripathi (1994)]. Usually, the electrons are accelerated through the structure of diode (with cold or hot cathode) together with a guiding magnetic field and /or focusing elements. Here, the beam spread energy have been taken very small as the frequency of the FELs depends on relativistic gamma factor (γ_0) and the typical value of beam radius is $1cm$ with $\approx 1-2mm$ thickness of the beams, respectively. An electron gun/accelerator is used to controls the beam current, beam voltage, pulse repetition rate, pulse duration, beams energy and quality of beam. It also determines the electron beam size and if not designed properly, beam quality deterioration is affected the electron optics or focusing fields [Liu and Tripathi (1994)].

1.2.2. RF interaction region

In FELs, the interaction region is the one, where undulated electron beam interacts with the RF wave. During these interactions, when the electrons are in the accelerating zone, it is experienced a Ponderomotive force and quickly moved out from the accelerating zone to the retarding zone. In the retarding zones electrons become slowed down by the negative Ponderomotive force and spent some more time over there. As a result, more electrons cross the accelerating zones to the retarding zones. So, there is a net bunching of electrons, in the retarding zones. Hence there is a net retardation of charge particles or electrons and net transfer of energy from the electron to RF wave. In this region, the Ponderomotive force can resonantly interact with the particles and the amplitude of this quantity is proportional to the amplitude of the regular field. It is also proportional to the amplitude of the field of the RF wave; obviously, in the device electrons amplitude evolves as the electrons travels. Now the examination of the energy and gain is estimated by FELs due to the force and the force amplitude also goes up. These two points have been taken into consideration simultaneously, self consistently. Mainly the interaction region is called drift space which is consists of sequence of an isolated RF cavity which acts as cut off to operating mode.

1.2.3. Wiggler

The transportation of the beam from the source to the interaction region is also a big issue which is resolved with the help of the wiggler. There are two kinds of wiggler, one is a permanent magnetic wiggler which have essentially an arrangement of magnets is called a linear wiggler (permanent magnets) and second is a circularly polarized wiggler (produced by a coil or solenoid). Typically, the values of the wiggler strengths is $\approx 1kG$ and the wiggler period $\approx 3cm$ [Liu and Tripathi (1994)]. The simple or linear wiggler have constant B_o and k_o along the interaction region lengths. An alternative is the tapered wiggler with amplitude B_o and period $2\pi / k_o$ whose drastically change the scenario and the latter leads to adiabatic slowing down of the ponderomotive wave, hence, the tapered wiggler leading to efficiency improvement of the device. The important issue that the electron which was moving with a DC velocity, it has acquired some sort of a velocity which is a function of time or distance and accelerated electrons with radiations. Thus, launching of millions electrons and radiation emitted by this is called undulator radiation. There is another term for wiggler, called undulator and this radiation is called undulator radiation [Tripathi

(1994)]. The more interesting thing is the coherent radiation that they generated by the electron beam, not the spontaneous radiation or not the radiation by different electrons and acceleration, then, the kinetics process of the radiation by examining the response of electrons to wiggler and the radiation signal, called FEL signal [Marshall (1985), Liu and Tripathi (1994), Walsh (1980)]. If the shorter wiggler period, then the radiation frequency is become shorter and reduce the wave length of generated radiation by increasing the energy of the electron beam also. In the term of total γ_o can be written as $\lambda_L = \frac{\lambda_w}{\beta_b(1+\beta_b)\gamma_o^2} = (\frac{\lambda_w}{2\gamma_o^2})(1+\frac{a_w^2}{2})$ at $\beta_\mathrm{b} = \mathrm{v_b}/\mathrm{c}$, where $a_w = eB_w\lambda_w/2\pi mc^2 = eB_w/k_w mc^2$ is called wiggler constant or wiggler parameter [Roberson (1989), Pellegrini (1990)].

1.2.4. Axial Magnetic Field

In FELs, the DC axial field may be affects the strengths of the FEL amplifiers through coupling with the pondermotive potential. It is observed that, energy transfer efficiency gets enhanced while reduction along the interaction region of about with the variation of the axial fields. The electron trajectories are strongly modified, particularly when the wiggler-induced motion near resonance with the cyclotron motion due to the axial field. Hence the axial field has affected the strengths of the FELs through coupling with the pondermotive potential and the axial field makes possible an additional instability which can play an important role in these devices.

1.2.5. Depressed Collector

In FELs, role of depressed collector is to collect the dissipated beam (acts as a trash for the spent beams) after beam-wave interaction at a reduced potential. The spent beam is collected in the axial direction after interaction with wiggler field. Depressed collector is also used controls the spreading of beam velocity during beam-wave interaction into the interaction chamber, hence the depressed collector is became used for performance improvement and called an energy recovery system of the device [Piosczyk *et al*. (1999), Walsh (1980)].

1.2.6. Output window

In FELs, role of RF output window is to pass the radiated signals at the output end. It is accomplished by using an optical mirror. An oscillation of FEL oscillator has been estimated by two reflecting mirror with broad band high reflectance, here ignoring boundary effects to the growth of the FEL radiation in the interaction region [Marshall (1985), Liu and Tripathi (1994)].

1.2.7. Applications

Physics of free electron lasers are desirable in many streams of applied physics, medicals and classical mathematics. Typically, not all, the science of the free electron lasers studied in many areas as classical physics, engineering physics, applied mathematics, material science, biology, medicine, life science, nuclear physics and engineering, electrical engineering, electronics engineering, mechanical engineering and other curriculums, which begin studies of the free electron laser physics [Liu and Tripathi (1994), Pellegrini (1990), Workie (2001), Shea and Freund (2001), Pae and Hahn (2002), Jia (2011)]. FELs are used very important potential application for the sum-millimeter to UV, XUV or X-rays wavelengths. In addition, it is also used for the materials Characterization (Spectroscopy of solids and liquids), clean up toxic waste and nanotubes synthesis [Wenlong (2000), Pelka *et* *al.* (2010)]. Furthermore, the FELs sub millimeter wave has been used for the technological applications for the varieties of diagnosis and others also. It is demonstrated for extremely high power, continuous tunable radiation and moderated efficiency of the source in millimeter wave to sub millimeter ranges and the potential application in the field of communication system, nuclear fusion, radio astronomy, military applications, atmospheric studies, chemical and isotope separation, inertial confinement fusion, remote sensing and security identification, plasma accelerator diagnostics, medicine and molecular spectroscopy, biological imaging (general test, measurement and diagnosis), room temperature THz imaging, materials characterization (spectroscopy of solids and liquids), build computer chips and to clean up toxic waste, electronic material processing, nanotubes synthesis and many other curriculums [Pourkey and Toepfer (1974), Darke *et al.* (1974), Manheimer and Ott (1974), Elias *et al.* (1976), Deacon *et al.* (1977), Granatstein *et al.* (1976), Granatstein *et al. (*1977), McDermott, Pellegrini and Reiche, Chen and Joshi (1980), Marshall (1985), Roberson and Sprangle (1989), Walsh (1980), Dattoli and Renieri (1993), Saldin *et al.* (1999)].

1.3. Types of Free Electron Lasers

The underlying physics of the devices is simple and exciting. The FELs has operated in four different modes:

1.3.1. Amplifiers

In FEL amplifiers, there is no need of optical resonator at both ends of the interaction chamber. The seed signal (send by optical pulses) interacts with electron beams and is synchronized in the interaction region. Hence, there is no need of feedback from output to input of the amplifier to amplify an external EM sources.

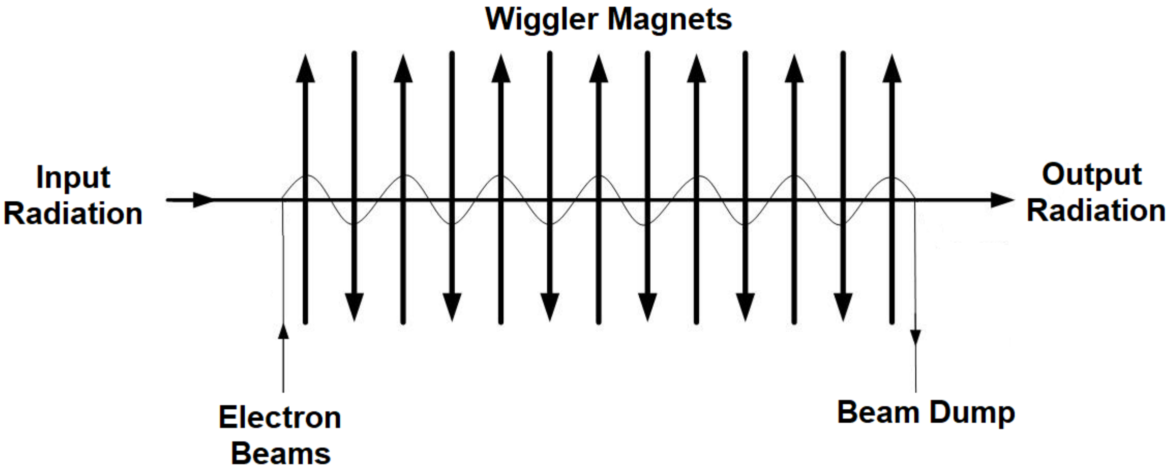


Figure 1.3: Free electron laser amplifiers configuration [Saldin *et al.* (1999)].

The external coherent signal is amplified by the FEL, known as direct seeding. The output power preserves the properties of the input signal (coherence, wavelength), however, the tunability range is limited by the availability of coherent sources as Fig. 1.3, [Saldin *et al.* (1999)].

1.3.2. Oscillators

In FEL oscillators, the optical pulses are bouncing with feedback between the optical resonator mirror cavities and free-space optical communication (FSOC)**.** It is also designated by FEL amplifiers with feedback. The radiation in FEL oscillators grows from fluctuations of the electron beam density. In FEL oscillators, the optical wavelength range for the feedback is carried out by means of an optical resonator which also defines the radiation modes, excited in the resonator, Fig. 1.4 [Saldin *et al.* (1999)].

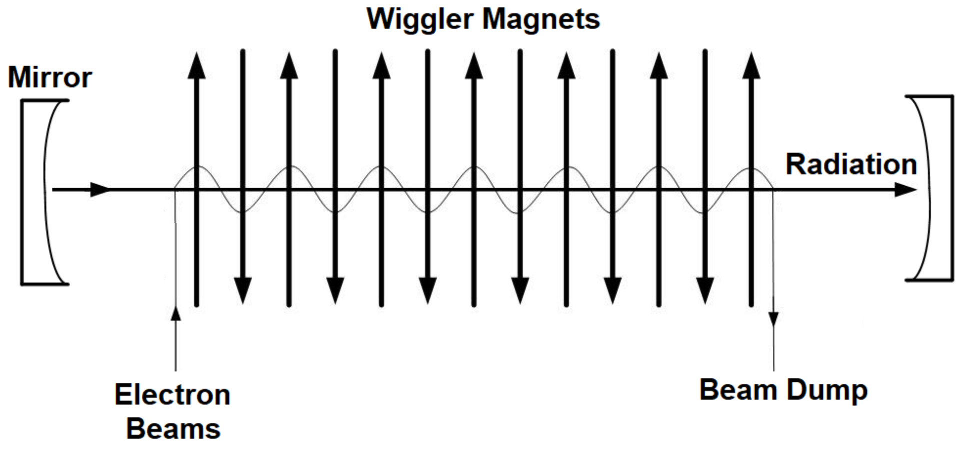


Figure 1.4: Free electron laser oscillators configuration [Saldin *et al.* (1999)].

1.3.3. Self-amplified spontaneous emission (SASE) FELs

The process is initiated by shot noise and both temporal and spectral properties are affected and do not required mirror or seed pulse as oscillators or others FELs. The system is completely tunable the radiation wavelength and it is possible to reach very high peak power. They are allowed generate a high intensity, short pulse radiation in the spectral region from deep ultraviolet down to hard X-ray wavelengths. Single pass FELs are being considered as the next generation light sources (Fig. 1.5).

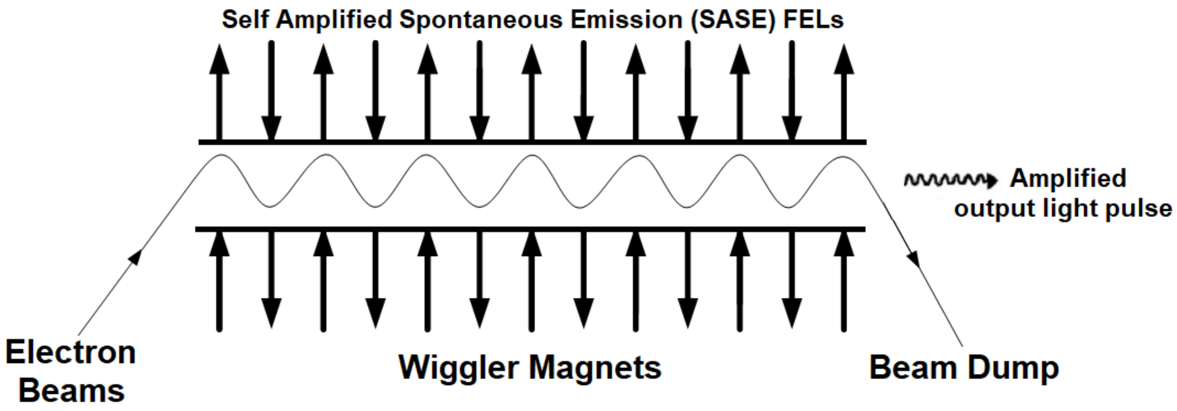


Figure 1.5: Self-amplified spontaneous emission (SASE) FELs [Saldin *et al.* (1999)].

1.3.4. Storage ring FELs (SR-FELs)

Storage rings are also drive as FEL oscillators using circulating electron beams. In the storage ring FEL (SR-FELs), the circulating electron bunches produces synchrotron radiation when passing through FELs undulator. The emitted radiation is stored inside the optical cavity and amplified during many successive interactions with the electron beam until the lasing is fully established. FEL oscillators have been developed to operate from IR to VUV with employed a suitable high reflectivity mirrors for the cavity. Typically, storage ring FELs (SR-FELs), use dielectric multilayer mirrors with a high reflectivity and a narrow bandwidth [Jia (2011)].

1.4. Free Electron Laser Amplifiers - Literature Review and Challenges

The conventional sources of radiation offer very little in terahertz range. The microwave sources operate below $60GHz$, while lasers operate above $30THz$ and gyrotrons are limited to $(30-200GHz)$ range [Liu and Tripathi (1994)]. Free electron laser offers an alternative as $(30GHz-30THz)$ ranges. However, conventional magnetic wiggler with wiggler period $\geq 1cm$ requires electron beams of energy $\geq 3MeV$, which escalates the size and cost considerably. Using accelerator facilities with intense bunched of electron beams via transition radiation or synchrotron, the higher pulse energies has been generated [Sharma and Tripathi (1996)]. Recently, the range of energies as $10-100\mu J$ per pulse intense THz frequency has been generated via transition radiation using accelerated electron beam passing through plasma to vacuum. Hence therefore it has been efforts to produce THz radiation by alternate methods [Tripathi and Liu (1989), Pellegrini (1990)]. Since FELs are an extremely adaptable light source and a fascinating device that produces tunable coherent radiation over a wide frequency range from sub millimeter wavelengths to visible region with high efficiency and power levels using energetic electron beams. It comprises a high voltage $(>1MV)$ power supply (accelerator) and an electron gun. An interaction region with a strong wiggler magnetic field, beam pump, radiation coupler (mirror) and diagnostics, the device is tunable by tuning the beam voltage.

In order to enhance the FEL amplifiers efficiency and performance improvement, there are some techniques used as- (i) Axial magnetic field tapering: The axial field is affected the strengths of the FEL amplifiers through coupling with the pondermotive potential. The axial field makes possible an additional instability which is play an important role in these devices. The linear tapering (negative and positive tapering) of the DC magnetic field is enhanced the efficiency of the net transfer energy of the wave. It is DC fields and an efficiency of the transfer energy is became changed with the variation of the axial magnetic fields, (ii) Wiggler magnetic field tapering: Gradually decreases the amplitude of the wiggler field due to decreasing the electron wiggler velocity, and hence improved the device efficiency. It is also enhanced by decrease the phase velocity of the pondermotive wave after the electrons are trapped by the spatially decreasing the wiggler wavelength, (iii) Depressed Collector Techniques: The efficiency of the FELs operation is quite sensitive to spreads in the electron beams velocity. Therefore, spreads in the energy is obviously remove some of the electrons from the resonance stage and improved the device efficiency [Ganguly and Freund (1988), Freund and Ganguly (1992), Chung *et al.* (1993), Roberson and Sprangle (1989), Khodyachykh (2004), Tripathi and Liu (1989), Pellegrini (1990), Dattoli and Renieri (1993), Pant and Tripathi (1994), Gold *et al.* (1984), Gold *et al.* (1984), Gold *et. al* (1987), Liu and Tripathi (1994), Oerle and Mathias (1997), Saldin *et el.*

(1999). Hence, the basic challenges of existing technique are the feasibility of the whistler-pumped with axial field tapering in FEL amplifiers. Generally, the whistler wave does not exist as suitable wiggler for FEL amplifiers operation due to requirements of extremely high pump power density (10-15 Tesla for operating frequencies scaled upto 200-250 *GHz*) for reasonable growth rate, hence including the effect of finite space charge mode, Raman Regime operation plays an important role in whistler-pumped FEL amplifiers only [Pant and Tripathi (1994), Sharma and Tripathi (1996)].

Experimentally, Elias demonstrated the amplification of a $10.6\mu m$ laser beam and the gain has been observed by 7% per pass at an electron beam current of $70mA$. The experiments indicate the possibility of a new class of tunable high-power free electron lasers [Elias *et. al*. (1976)]. FELs oscillator and amplifiers have been operated above threshold at a wavelength of $3.4\mu m$, experiments demonstrating wave-particle stimulated scattering with an output in the infrared have been performed at Stanford University using a low current, high energy electron beam from a linear accelerator [Deacon *et al.* (1977)], observed efficiencies were less than 0.01% and attempts to improve the efficiency have focused on the use of storage rings to continuously recirculate the beam through the wave generation region.

The first relativistic beam experiments demonstrating stimulated scattering in the Raman regime were performed by Granatstein in 1976 [Granatstein *et al.* (1976), Granatstein *et al. (*1977)]. Utilizing intense relativistic electron beam generators, super radiant FEL oscillators were demonstrated by producing megawatt power levels in short interaction regions $\sim 30cm$ at wavelengths ranging from $2mm$ to $400\mu m$ and with efficiencies as high as 0.1%. More recently, McDermott reported the realization of a collective Raman

FEL for the first time and observed output of $1MW$ at $400\mu m$ and line narrowing to $\Delta\omega/\omega \approx 2\%$ were observed, compared to $\Delta\omega/\omega \approx 10\%$ for the earlier super radiant oscillator studies [McDermott (1978), Marshall and Schlesinger (1978), Walsh (1980), Roberson and Sprangle (1989), Pellegrini (1990), Dattoli and Renieri (1993), Saldin *et el.* (1999), Shea and Freund (2001), Workie (2001)]. FELs radiation is produced as stimulated Compton back scattering of wiggler electromagnetic wave (laser) by the relativistic electron beam [Scharlemann (1986), Sprangle *et al.* (1979)]. The process can be viewed as a nonlinear coupling between the FELs radiation and negative energy beam mode. The wiggler provides phase synchronism for the process and stimulates it.

Freund and Ganguly have introduced a Nonlinear Simulation of a High-Power, using a uniform wiggler while tapered wiggler experiment achieved 35% efficiency for same frequency using an $3.5MeV/850A$ electron beam in conjunction with a planar wiggler with tapered amplitude and explain the high-efficiency operation of FEL amplifiers [Ganguly and Freund (1988), Freund and Ganguly (1992)]. In 1993, Chung proposed the simulation technique of tapered FEL amplifiers in millimetre and infrared regions [Chung *et al.* (1993)]. Sharma and Tripathi is examined the feasibility of the device in the low-current Compton regime, practically, in the Compton regime, the whistler wave does not appear to be a suitable wiggler for FELs operation due to requirements of extremely high pump power density for reasonable growth rate [Sharma and Tripathi (1993)], hence including the effect of finite space charged mode, Raman Regime operation plays an important role in whistler-pumped FELs only [Pant and Tripathi (1994)]. In 2004, Khodyachykh *et al.* investigated the influence of a tapered undulator on the main parameters of FELs and the experiments were carried out at the Darmstadt at electron beam energy of $31MeV$ with $7\mu m$ wavelengths. Chung has developed one dimensional nonlinear theory and numerical simulation of the FEL amplifiers with the tapered wiggler and the axial guide magnetic field. They have also investigated the possibility of a tunable IR-FEL with a test linac of energy $20-60MeV$ of PAL with effects of energy spread and space charge with the current density of the test linac, the feasible to amplify a $14kW$ signal of $10.6\mu m$ radiation to a $2GW$ level [Chung *et al*. (1993)]. Orzechowski examined the operation of FEL amplifiers at $35GHz$ with a peak output power of $180MW$ and powered by $3.6MeV/850A$ of electron beams and find out an extraction efficiency of 6% with operating bandwidth of approximately 10%, while the amplifier saturates at a $1.4m$ wiggler lengths [Orzechowski *et al*. (1986)]. Gardelle and Parker emphasized the effects of electron beam quality and space charge on FELs efficiency, a very good agreement has been found between experimental results and simulations. The collective FELs laser interaction has been studied at millimeter wavelengths and the Measurements in a super radiant amplifier configuration indicate the production of $35MW$ at $4mm$ with an efficiency of 2.5% [Parker *et al*. (1982), Gardelle *et al*. (1994)]. Lefevre and their groups are also examined the measurements of microwave power and frequency in a pulsed-FEL amplifiers (P-FELA) [Lefevre *et al.* (1997)].

In 1984, Gold *et al*. experimentally demonstrated a high power FEL amplifier using relativistic electron beams (REBs) at $35GHz$ for $1.2dB/cm$ growth rates and experimental efficiency $>3\%$ with $50dB$ gain. They have also examined an effect of strong axial magnetic field tapering on both ends of the device to enhancement of the efficiency and power for the generation of $>75MW$ at $75GHz$ with 6% experimental efficiency to the device [Gold *et al.* (1984), Gold *et al.* (1984), Gold *et. al* (1987)]. Orzechowski *et al.* [Orzechowski *et al.*

(1986), Orzechowski *et al.* (1986)] examined the operation of a FEL amplifier at $35GHz$ with $180MW$ peak output power and electron beams energy governed by $3.6MeV\ /850A$ and find out an extraction efficiency of 6% with operating bandwidth of approximately 10% to $1.4m$ wiggler lengths. An efficiency of FEL amplifiers was 35% for $8mm$ wavelength with tapered wiggler [Freund (2013)] and it is about 1% at $800nm$ wavelengths [Wang (2009)].

In addition, many advances have been reported in the theory of FEL amplifiers, such as the optimization of efficiency, space charge effect, the effects of the detune parameter, tapering of the axial guide and wiggler magnetic fields, the theory of multi-beam stagger tuned and frequency cascading in FEL amplifiers [Elias *et al*. (1976), Deacon *et al.* (1977), Granatstein *et al.* (1976), Granatstein *et al.* (1977), McDermott (1978), Marshall and Schlesinger (1978), Pellegrini and Reiche, Roberson and Sprangle (1989), Dattoli and Renieri (1993), Dattoli *et al.* (2013), Saldin *et al.* (1999)].

1.5. Objective of the Research Work

Ongoing through the literature survey, the microwave sources (such as relativistic klystron, magnetron, MILO and vircator etc.) operate below 60GHz, while lasers operate above 30THz and gyrotrons are limited to 30-200GHz range. FEL is offered an alternative which overcomes many of the drawbacks of the other HPM sources. Time to time, many techniques has been explored to improve the performance of the device. The linear tapering of the DC magnetic field is play an important role to makes the possibilities of the performance improvement of whistle-pumped FEL amplifiers. An analytical formalism of whistler-pumped FEL amplifiers with negative tapering is developed. The nonlinear theory is proposed for collective Raman regime operation in whistler mode. The dispersion relation of the FEL amplifiers is sensitive to the linear tapered strong axial magnetic fields, electron cyclotron frequency and plasma frequency of electrons. For the synchronism of the pumped frequency, it is closed to electron cyclotron frequency which is resonantly enhanced the wiggler wave number that produces the amplifier radiation for higher frequency from sub millimeter wave to optical ranges. FELs Device Design methodology to be developed based on the device fundamental theory. Simulation study of the FEL amplifiers is needed to examine the RF field excitation signal growth and start oscillation under various device operative regions. The emission process in the FEL amplifiers into the interaction chamber is simulated through the commercially 3-D PIC simulation codes "CST Particle Studio". Increases the RF energy, radiation frequency, growth rate and efficiency of the FEL amplifiers are the main goals of this work towards the research.

1.6. Plan and Scope

FEL amplifiers is an attractive device and offers an alternative which overcomes many of the drawbacks of the other microwave sources for enhancing the gain, efficiency, operating regime and finding out for the major applications. Experimentally demonstrated a high power FEL amplifier using intense relativistic electron beams (REBs) at 75GHz for 1.2dB/cm growth rates, experimental efficiency >6% with 50dB gain and output power is >75MW. In the present work, a detailed insight of the analysis, design and simulation of the FEL amplifiers are presented. Finally, the work embodied in the present thesis is organized into six chapters, as follows.

In Chapter 1, the geometrical structure of FELs and its components as electron gun, RF interactions, wiggler/undulator, depressed collector, output window and applications are studies. Types of FELs as amplifier, oscillator, self-amplified spontaneous emission (SASE), storage ring FELs (SR-FELs) are also explained. A brief review of the FEL amplifiers, problem definition, plan and scope are discussed. The state of the art of the FEL amplifiers is presented with their scope and limitations.

In Chapter 2, we study the fundamental analysis of FEL amplifiers and their behavior into the interaction region. The working principal of FEL amplifiers, frequency operations, mechanism of radiation, phase coherence and bunching, Madey's theorem for gain, stimulated emission by Madey's theorem, principles of energy conservation by Madey's theorem are discussed here. The Raman regime operation, nonlinear state of Raman regime and gain estimate of Raman regime in FEL amplifier has been presented to investigate the beam-wave interaction behavior in an interaction chamber of the FEL amplifier. The studies of the FEL amplifiers are further used in the subsequent chapters for their design analysis and performance improvements.

In Chapter 3, the device has been explored the magnetic field tapering for gain and efficiency in collective Raman regime mode. The dispersion relation of the FEL amplifiers is sensitive to the linear tapered strong axial magnetic fields, electron cyclotron frequency and plasma frequency of electrons. For the synchronism of the pumped frequency, it is closed to electron cyclotron frequency which is resonantly enhanced the wiggler wave number that produces the amplifier radiation for higher frequency from sub millimeter wave to optical ranges. The guiding of radiation signal into the waveguide and charge neutralization phenomenon, the beam density is greater than the background plasma density with tapered strong axial magnetic field. It is quite considerable that radiation signal slowed down at much higher background plasma density comparable to the density of beams and enhanced the instability growth rate also. In Raman Regime operation, the growth rate decreases as increases with operation frequency of the amplifier, however, the growth rate is larger in this regime. It is noted that as increases with background plasma density, the beat wave frequency of the Ponderomotive waves is increases thus the mechanism of background plasma density can serve for tenability of the higher frequencies. It is observed that, an efficiency of the transfer energy enhanced with the variation of tapered magnetic fields to the amplifiers.

In Chapter 4, a detailed design procedure, methodology and simulation study of the FEL amplifiers has been presented to the 231GHz operating frequency. The operating behavior and optimization in the TM_{01} mode of FEL amplifiers has been discussed using the Eigen mode analysis and the simulation techniques and their results has been also analyzed with 3-D particle-in-cell (PIC) code CST particle studio. The detail description of FEL amplifiers has been explained using 3-D PIC simulation approach which is commercially available in "CST Studio Suite". The emission process in the FEL amplifiers interaction chamber is simulated through the commercially 3-D PIC simulation codes “CST Particle Studio”. To find out the excitation of electromagnetic modes, frequencies and EM field patterns inside the interaction region of an amplifier is carried out through the Eigen mode simulation (i.e., cold simulation or beams absent simulations). To observed the overall performance of an FEL amplifiers, such as frequency of operations, gain, power, efficiency, RF output and the beams present PIC simulation is carried out. To understand the performance analysis and sensitivity of the FEL amplifiers using an intense relativistic electron beams (REBs) on various parameter effects such as power, gain, efficiency, beam current, beam voltage and operating frequencies has been explained. The reading of the measurement values has been showed for the large radiation growth rate 2dB/cm approximately with 231 GHz instantaneous band width. The good agreement of the simulation results has been found as reported experimental values with predicted theory of operation in the Collective Raman Regime (CRR). Additionally, the result to extraction of the kinetic energy from the electron beams to beat-wave has been observed the power and efficiency largely increases experimentally with the linear tapering of the strong axial magnetic field that produces 20% experimental efficiency in the FEL amplifiers.

Finally, in Chapter 5, the works embodied in the present thesis are summarized. The conclusions of the work are drawn and highlighting the major findings with their significance. In addition to this, the limitations of the present study are also discussed and outlined the scope for future work.

1.7. Conclusion

The geometrical structure of the FELs and their components (i.e., Electron Gun, RF Interaction region, Wiggler, Axial magnetic field, Depressed collector, Output window) has been explained with neat and clean diagram. In the present chapter, Amplifiers, Oscillators, Self-Amplified Spontaneous Emission (SASE) FELs, Storage ring FELs (SR-FELs) and their Applications are also explained briefly. Objective of the research work, plan and scope and are studied of the FELs to use in the subsequent chapters for their analytical study, design, simulation and performance improvements.