CHAPTER-1

INTRODUCTION AND OVERVIEW

1.1 INTRODUCTION

The development in particle accelerators during the past few decades is playing a major role in exploring the properties of subatomic particles. Particle accelerator is a unique device that accelerates charged particles to very high speeds using electric and/or magnetic fields. The single electron passes through a potential difference of $1.5V$, thus gaining $1.5eV$ of energy considered to be act like accelerator. A simple form of accelerator is a cathode ray picture tube used in television set.

In 1931, E.O. Lawrence made the first modern particle accelerator -the cyclotron. This cyclotron was only 4 inches in diameter, and contained two magnets with D-shape, having a small gap in between magnets. An alternating voltage creates an electric field across the small gap, which accelerate the particles as they went around the accelerator. In 1942, the first successful attempt for electron acceleration was made by Donald-Kerst by using magnetic induction. His first betatron reached upto $2.3MeV$ of energy, while the improved versions of betatron have achieved $300MeV$ of energy. In 1947, the synchrotron radiation was found with $70MeV$ electron-synchrotrons at General Electric. Such radiations were due to the magnetic field influenced acceleration of electrons in vacuum that can move close to the velocity of light. DC based accelerator or voltage multipliers are capable of accelerating the charged particles to a speeds which is enough high to induce nuclear reactions and are called Cockcroft-Walton generators. Such generators can convert AC to a high potential DC. The other type is Van de Graaff generators based on carrying static electricity with the use of belts.

Modern accelerators are categories as- Linear and Circular. In linear accelerators, the charged particles can be accelerated in a straight path, and directed towards a target to create a collision. Circular accelerators use high power electromagnets to propel the charged particles in a circular till the particles attain appropriate speeds/energies. Particles can be accelerated in a clockwise pattern through accelerator, while antiparticles can be accelerated in anticlockwise direction. ADONE began to operate in 1968 which was the first high-energy particle collider with the beam energy of about $1.5 GeV$. This device accelerates electrons as well as positrons in reverse directions and effectively double the energy of their collision as compared to collision with a static target using an electron.

The Large Electron-Positron (LEP) collider, achieved collision energies of $209 GeV$, was in operation from 1989 to 2000. LEP was a circular electron-positron collider, built at Cern, Geneva. The ring design ($c = 27km$) meant that the accelerating structures are seen many times by the circulating beams of particles. The ring had 4 experimental sites - ALEPH, DELPHI, L3 and OPAL. The large hadron collider (LHC) uses the same tunnel as LEP, at Cern in Geneva. The machine is a $14 TeV$ proton-proton collider, so each stored beam will have energy of $7 TeV$.

In linear accelerator (LINAC), a microwave is passed through a cylindrical waveguide loaded with periodic rings to slow down the velocity of phase of the wave slightly below the velocity of light in vacuum. LINAC yield electron energies up to several tens of MeV. The dimensions of the device are, however huge and the acceleration process is quite slow. This is also true for storage rings and other accelerators. Machines like LHC and ILC are pushing the limits of technology and cost. Till that time the making of magnets with $\geq 10 Tesla$ fields was not feasible.

Acceleration of charged particle by waves has been an interesting field of study for last few decades. A wave accelerates co-propagating particles when: (a) it exerts a longitudinal force on them, (b) its phase velocity is close to velocity of accelerating particles so that the wave field appears quasi-static to the particle and efficient energy transfer to them from the wave could take place.

The intense short pulse laser opens up the possibility to miniaturize the acceleration region and to accelerate electrons at much faster rate. A significant development in this field was demonstrated by Leeman *et al.* in year 2006. They proposed the generation of a GeV electron beams with the use of a centimetre scale accelerator. The acceleration gradient of such capillary guided accelerator is in the range of GeV/m.

1.2 ELECTRON ACCELERATION BY LASER

Traditional methods for the acceleration of charged particles require huge size and big space to accelerate a particle in vacuum upto ultra high energies. The development of effective and relatively efficient methods of accelerating the charged particles would reduce both cost and size. In recent years the study of laser influenced acceleration of electron in vacuum has renewed the interest of researchers and scientist with the possibilities of higher energy gain. It is due to the development advanced techniques and availability of ultrahigh power ($\geq 10TW$), short pulse table-top lasers loaded with chirped pulse amplification (CPA) technique. During last few decades a progressive development of high intense short pulse lasers has been seen to be more focused on CPA technique. Consequently, many new application and development areas have emerged, among them the vital are laser based particle acceleration in vacuum and plasmas.

The researches on laser induced acceleration of electron in plasma are based on techniques like plasma beat wave acceleration and the laser wake field acceleration (LWFA). As plasma-based acceleration schemes are capable of achieving ultrahigh acceleration gradient ($\geq 10GV/m$) and also present the feasibility of guiding the laser pulse. Laser induced electron acceleration in vacuum is capable of eliminating the problems connected with the plasma. The laser acceleration of relativistic electrons has been exhaustively studied theoretically and some models have been proposed for the experimental verifications.

The intense short pulse laser opens up the possibility to miniaturize, the acceleration region and to accelerate electrons at much faster rate. Tajima and Dawson was the first who presented the idea of plasma wave excitation for electron acceleration by using high power laser in year 1979. In the laser wake field acceleration schemes, the wake plasma wave is promoted by the laser's ponderomotive force when its pulse duration τL is nearly equal to half of plasma wave period. This is same as the electron acceleration in vacuum by electromagnetic laser field. There are two routes to it

A) Via the excitation of a plasma wave

B) Direct laser acceleration

In the excitation of plasma wave, the large phase velocity of the wave is excited by the laser. Laser beat wave accelerator (LBWA) and LWFA follow this route.

In LBWA two collinear lasers with nearby frequencies ω_1 and ω_2 are propagated through an under dense plasma with frequency $\omega_p \approx \omega_1 - \omega_2$. The laser exerts a ponderomotive force on the plasma electrons which drives the plasma wave resonantly, having phase velocity matches the group velocity of the laser. In LWFA a single laser pulse of short duration, is employed that drives a plasma wave in the wake of the laser pulse, where $\omega_p = 4\pi ne^2 / m$ is the frequency of plasma, n, e, m are the density, charge and mass of the electron respectively. The electrostatic potential of the plasma wave is comparable to the ponderomotive potential. The modulated laser exerts a ponderomotive force on the electrons, enhancing the amplitude of the plasma wave.

The route of the direct laser acceleration exploits the presence of strong self generated magnetic field in the plasma. The electrons make betatron oscillations in the azimuthal magnetic field produced by a stream of accelerating electrons. A resonance occurs, when the frequency of betatron oscillations equal to the Doppler shifted laser frequency. This leads to an effective transfer of energy from the laser to the electrons. The process requires power sufficiently higher than that of critical power for the process of self focusing. The generation of multi-MeV electrons was observed by direct laser acceleration in the high density plasma channels. Laser induced electron acceleration in vacuum can be realized by using the ponderomotive forces associated with the interaction of laser with electron.

The Lawson-Woodward (LW) theorem, conclude that the electron is travelling with the velocity of light and its velocity remains unaltered by the laser fields. It's the ponderomotive forces due to the laser field which influences the electron trajectory. For a laser beams propagating parallel to z axis and interacting with relativistic electron travelling along z-axis, the vacuum acceleration scheme is connected with the term $v_z E_z$, where $v_z \approx c$, so that the gain in energy is determined by the integral $\int E_z dz$. For a finite transverse electric field $E_{x,y}$ of the laser, a transverse velocity $v_{x,y}$ will gets introduced. For a finite energy gain with laser field in vacuum, a few of the assumptions in the LW theorem must be contradicted. Such as, a finite interaction region can be considered. However, this may be difficult to obtain in actual due to high-intensity requirement of the laser field and the damage threshold limitations of optical materials. Alternatively, the nonlinear forces such as ponderomotive force, can produce the desired acceleration. This leads to significant energy gains even in the limit of infinite interaction region.

One approach for the acceleration of electron is to make use of laser beam in the limit of far field i.e. in the region that is far from boundaries. Far field limit suffers the difficulties for acceleration of electron by laser. Many acceleration techniques in vacuum and plasmas have been proposed based on the laser ponderomotive forces, inverse processes, tightly focused laser etc.

Hora *et al.* was the first to consider the nonlinear mechanism involved in vacuum acceleration of charged particle in year 2000. The major problem in laser-induced acceleration of electron in vacuum is that the phase velocity of accelerated electron is greater than the speed of light. However, the theoretical study shows that the electron can be accelerated when the phase slip is within the range of accelerating phase. The energy gained by the electron during vacuum acceleration is mainly depends on the intensity of laser because the longitudinal electron momentum is proportional to square of the amplitude.

1.3 POLARIZATION CHARACTERISTICS OF LASER PULSE

The polarization characteristics of a laser pulse determine the energy gain by electron during laser electron interaction. Our study is focused on the following polarized laser pulses:

(a) Linearly polarized (LP) laser pulse

(b) Circularly polarized (CP) laser pulse

(c) Radially polarized (RP) laser pulse

For a LP laser pulse, the parametric limitations of the laser interaction with the electron depend upon the direction of the polarization, whereas the parameters gets time averaged in circular polarization which increases the interaction of laser pulse and the electron. Thus, a LP laser pulse is more efficient for single electron acceleration whereas

CP laser pulse is more efficient for electron bunch acceleration. A CP laser pulse provides a wider platform for laser particle interaction. Hence, CP laser pulse is capable for higher acceleration of charged particle.

RP laser pulses have inherent property of cylindrical symmetry which enforces better trapping of electrons with narrow divergence and narrow spread than that with LP and CP laser pulses. An electron while interacting with RP laser pulse experiences a force due to longitudinal component of lasers electric field. As a result electron is accelerated around the direction parallel to propagation of the laser with high energy gain. The rest electron is accelerated to sufficiently high energy by using a RP laser pulse in vacuum.

1.4 CHIRPED LASER PULSE

Chirped-pulse amplification (CPA) presents a revolutionary development in generation of high peak powers from lasers. This is by amplification of very short (femtosecond) laser pulses to pulse energies where are previously possible only with long-pulse lasers. The CPA technique ensures the effective energy extraction from very compact amplifier systems.

The characteristic variation of frequency of laser pulse increases the time duration of interaction of electron with laser pulse and hence ensures the resonance for longer duration. We employ the following chirps to study the electron dynamics under interaction with laser pulse:

(a) Linear chirp

(b) Non-linear chirp

A nonlinear chirp can further be categorized as quadratic and periodic chirps. The most common chirped form is the linear chirp in which the instantaneous frequency changes linearly during the chirped pulse. In periodic chirp the frequency variations can be expressed in terms of harmonic dependence of functions. We analyse the frequency variations with sin and tan functions for periodic frequency chirp. The positive and negative chirp specifies the frequency increase and frequency fall during chirped pulse respectively. We investigate the chirp variations in term of the polarization characteristics of laser pulse.

1.5 MAGNETIC FIELD ASSISTED ELECTRON ACCELERATION

An accelerated electron is capable of gaining a significant amount of energy and retaining the same with a magnetic field of suitable strength and appropriate period. The magnetic field strengthens the cyclotron oscillations due to $\vec{v} \times \vec{B}$ force. Hence, contributes towards the forward drift and the rate of gain of electron energy. We study the electron energy gain under influence of following magnetic fields:

(a) Axial magnetic field

(b) Azimuthal magnetic field

(c) Wiggler magnetic field

The axial magnetic field improves the strength of $\vec{v} \times \vec{B}$ force which supports the retaining of betatron resonance for longer duration. Hence restrict deceleration of electron and support in retaining of gained energy for longer duration. The azimuthal magnetic field having pinching effect which keeps the motion of electron parallel to the direction of propagation for larger distances. Hence, the electron not only gains much higher energy at resonance with optimized magnetic field but also retains the high energy for larger distance even after passing of the laser pulse. Electron is capable of gaining a sufficient amount of energy and retaining the same with a wiggler magnetic field of suitable magnitude and appropriate period. The presence of external wiggler magnetic field encircles the trajectory of accelerated electron which improves the strength of $\vec{v} \times \vec{B}$ force and enforces the retaining of betatron resonance for longer duration. It restricts the deceleration of electron and supports the retaining of gained energy for longer duration.

1.6 ELECTRON INJECTION FOR ENHANCED ENERGY GAIN

A pre-energetic electron is capable of gaining a high energy and also retains it till saturation. In addition the angle at which an electron is injected with respect to direction parallel to propagation of laser pulse determines the enhanced energy gain. Two possible injects exist: axial injection and sideway injection. For a set of laser parameters there exist an optimized value of injection angle at which electron meets the phase of laser field for a high energy gain.

1.7 INFLUENCE OF LASER BEAM WIDTH PARAMETER

Laser beam width parameter determines the electron energy gain from laser field. Laser beam width is determined by the initial values of laser spot size. The dependence relates the Rayleigh length. Smaller the beam width stronger the laser field and vice versa. Hence, high acceleration is observed with a small beam width parameter. Thus it is the laser beam width parameter which is controlling the electron acceleration distance. The electron is accelerated where laser field is high in the vicinity of sharp focus and decelerates where field is weak. This makes an effective acceleration of electron in plasma.

1.8 LASER-CLUSTER INTERACTIONS

Laser excites the charged particles of cluster plasma. An electrostatic field appears. This persisted Coulomb field during laser-cluster interaction enforces the electron to be in phase with laser pulse. Thus, ensures an efficient energy gain by the electron from laser fields. At a certain distance the impact of cluster field decreases, the electron energy gain increases. A single Xe cluster with $10^4 - 10^6$ atoms when interact with a short pulse laser of high intensity in the range of $10^{17} - 10^{19} W/cm^2$ is a suitable cluster for a significant removal of electrons. The inner free electrons get accelerated out of the cluster due to laser field to energy values of higher MeV.