CHAPTER-2

REVIEW OF LITERATURE

2.1 LITERATURE REVIEW

The electron acceleration by laser is a fascinating and an advancing area of research during past few decades. Researchers and scientists vision its wide application with high impact on society.

Tajima and Dawson was the first to explain the nonlinear mechanism behind the laser-electron acceleration, more than three decade ago [1]. They presented the trapping and accelerating the electrons while propagation of an intense electromagnetic pulse through plasma.

Cicchitelli *et al.* [2] studied the propagation of electromagnetic beam through vacuum and analysed the polarization effects of the fields on particle acceleration. They demonstrated the role of longitudinal and transverse field components on acceleration of electron in vacuum. They proposed a paraxial approximation to obtain the exact solution for a Gaussian beam using Maxwell equations.

Steinhauer and Kimura [3] proposed a scheme for particle acceleration by laser in vacuum. They targeted the critical issue of particle slippage with respect to laser beam phase during laser particle interaction in vacuum. Due to which the particle passes through successive accelerations and decelerations and loses energy. The proposed scheme overcome such difficulties and was based on following three features: (i) an axisymmetric characterised radially polarized laser beam, (ii) an axicon focus which aligned with the path of particle beam, and (iii) the approximate phase matching of laser beam and charged particle. They predicted an acceleration gradient of about $1 GeV/m$ over a distance of a few cm using a laser with peak intensity $10^{13} W/cm^2$ at $10.6 pm$.

Goreslavskii *et al.* [4] presented a method to calculate the relativistic motion of a free electron under the influence of strong field due to a focused laser pulse. They observed the variations in ponderomotive scattering with short and long pulses and applied the effects of ponderomotive scattering to analyse the angular distribution of radiation due to a relativistic electron. They revealed the importance of optical periods per pulse ($\omega\tau$) and wavelengths per focal waist radius in characterizing the spatiotemporal structure of the fields.

Erikson and Singh [5] analysed the polarization characteristics of laser field to describe the propagation of fundamental and higher order laser beams. A laser beam with a polarization dominant in transverse x-direction has a small longitudinal component in z-direction and a small polarization component in y-direction. The longitudinal component contributes for focussing whereas the small polarization component contributes for polarization property of laser pulse. The work was experimentally supported to represent the polarization structure for a Gaussian laser beam.

Haaland [7] presented a scheme of superposed linearly-polarized Gaussian laser pulses focused and phased in a pattern to cancel their transverse field components in vacuum. The longitudinal components accelerate the suitably-phased relativistic electrons. High gradient of the order of GeV/m was observed.

Ivanov *et al.* [9] investigated the generation of electrons during laser plasma interactions. They used laser of intensity of the order of $10^{13} W/cm^2$ with pulse duration $3ns$ to generate electrons upto $380 KeV$ of energy.

Sprangle *et al.* [10] discussed the laser induced acceleration of electron in vacuum, gas and plasmas. They proposed that a net energy gain by electron can be attained by limiting the interaction distance within the range of laser focus in vacuum. High order Gaussian beam with radial polarization was employed. Further the choice of electron injection point determines the net acceleration attained by electron. The electron diffraction effect limits of accelerating distance, which can be enhanced by using self-generating field due to laser beam with an Inverse Cherenkov Accelerator in a gas. Plasma beat wave accelerator (PBWA) and laser wake field accelerators (LWFA) were highlighted as electron acceleration configuration in plasma driven by laser. The simulation results of self-modulated LWFA indicated the electron energy gain of the order of $100 MeV$ with high acceleration gradient.

Zeng [16] used a circularly polarized laser pulse to obtain the cyclotron resonance of relativistic electrons under induced axial magnetic field in plasma. The limit of electron energy gain was analysed to be focused on electron dephasing and cyclotron radius. It was observed that the energy of electrons increase with induced magnetic field. Thus the electron dynamics can be controlled either by adjusting the laser field or by varying the induced magnetic field. The induced magnetic field of the order of $7.65MG$ was presented with the laser frequency of about $3\times10^{14} rad/s$.

Hora *et al.* [19] presented the nonlinear theory for vacuum electron acceleration by lasers. They explained that the nonlinear nature of electromagnetic forces of the laser fields permits the energy transfer to electrons.

Sprangle *et al.* [21] demonstrated the importance of group velocity dispersion (GVD) and wakefield acceleration for achieving the multi-GeV electron energies. They derived the laser pulse propagation related 3D envelop equation in plasma channels. This equation includes relativistic effects on wakefields, pulse length of finite value, and GVD. The electron energy enhancement was proposed by tapering the plasma channel which reduces the electron de-phasing.

Hu and Starace [33] applied Monte Carlo simulations to investigate the interactions of ultra-intense laser with charged particles. They considered a linearly polarized laser beam with transverse electric field $\vec{E}$ in x-axis and propagating along z-direction. The lasers magnetic field $\vec{B}$ is directed along y-axis. The electron is accelerated by $\vec{E}$ along x-axis and by $\vec{v}\times\vec{B}$ force along z-axis whereas the z-component of this force reduces the effective acceleration along x-axis which keeps electron to remain in focusing area.

Krainov and Roshchupkin [34] calculated the Xe clusters irradiated by using an intense ultra-short laser pulse. They considered a cluster with 1000 atoms under interaction with a laser pulse of peak intensity of $10^{16} W/cm^2$ and pulse duration of $100fs$. Under interaction with laser pulse the polarizability of free electrons inside the cluster decreases due to which it reduces the outer ionization. The electron moves to the side of cluster opposite to the laser field. The electrons get ejected out of cluster only if their energy is higher than the effective potential barrier.

Tanimoto *et al.* [39] proposed a direct electron acceleration scheme focused on stochastic phase disturbance of laser field in plasma. The energy as well as the momentum of accelerated electron was derived under the impact of self generated magnetic field. The enhanced energy gain by electron was observed under the influence of magnetic field. High energy electron appeared with phase jump. On increasing the phase jumps, the more energetic electrons were realized under influence of magnetic field. The electron energy gain further enhanced with increased magnetic field.

Umstadter [40] reviewed laser-driven particle acceleration concepts in plasma. Highly relativistic plasmas under interaction with a petawatt laser of intensity of about 10^{21}W/cm^2 were studied. The force exerted by the laser pulses accelerates the electron beam. The achieved acceleration gradient was many times higher than that can be attained with RF accelerators.

Bingham *et al.* [47] studied the charged particle acceleration by plasma waves. Such plasma waves are promoted by particle beams and intense laser pulse. The plasma electrons tends to neutralize the charge of relativistic electron beam when enters in a plasma. The axial current flows in reverse to electron beam in the plasma if the skin depth is greater than the beam radius. This makes the beam current lagged from neutralization with generation of an azimuthal magnetic field. This self-generated magnetic field pinches the beam in the radial direction. Hence contributes to a high acceleration gradient. The field of the order of $1GVcm^{-1}$ was observed with particles accelerated to $200MeV$ of energy over a small distance of millimetre.

Xu *et al.* [52] proposed a scheme for electron acceleration in an under dense plasma induced by a tightly focused laser pulse. This scheme is based on wave breaking of wakefield by a self-injection of electrons. The tightly focused geometry of the laser pulse and the transverse wave breaking of the wakefield play a vital role to place the electrons in accelerating phase of wakefield. With a 2D3V PIC simulation, average energy upto 8MeV was observed for the electron ensemble with density twice that of the plasma background density.

Gupta and Suk [62] investigated the role played by the frequency variation of laser pulse and applied magnetic field on electron acceleration in vacuum. They considered a plane polarized laser pulse with frequency variations due to a linear chip. The electron trajectory, momentum and energy was analysed under the influence of axial magnetic field. The electron oscillates in the direction parallel to the propagation of the laser after experiencing a ponderomotive force. Frequency chirps significantly affect the dynamics of electron. Thus due to the mutual contribution of the chirp and the magnetic field the electron accelerate more effectively in the direction parallel to the propagation of the laser pulse.

Bochkarev and Bychenkov [67] studied the vacuum acceleration of a test electron with a tightly focused light beam. They obtained exact solution of the Helmholtz equation for electron dynamics, and presented a comparison with results due to paraxial approximation. The acceleration of the electron was analysed under the laser field keeping in view of the initial position in interacting region and the phase of the laser field. The electron acceleration, energy gain and ejection were explained on the basis of longitudinal and transverse components of forces due to laser. They proposed that the energy gained by electron is much higher than the energy of electron while escaping far from the fields.

York *et al.* [71] presented a model for direct electron acceleration in a waveguide of corrugated plasma. They used a Nd:YAG laser beam modulated radially. In direct acceleration the fields has been limited by phase matching, diffraction and the threshold control for material damage. The simulation results show an acceleration gradient of the order of 80MV/cm with a laser pulse power of $1.9TW$.

Singh *et al.* [74] studied the effect of initial phase and pulse parameters on laser driven electron acceleration in vacuum. They used linearly polarized laser pulse and observed that the electrons with initial phase $\pi/2$ and close to pulse peak experiences lowest scattering and highest energy gains. The initial phase remains ineffective for the electrons close to the trailing edge of pulse. The electron energy gain further depends upon the initial energy of electron as well as intensity of laser pulse. The study also presented estimation for laser spot size.

Esarey *et al.* [79] presented the developments of theoretical and experimental models for electron acceleration based on laser-plasma interactions. They reviewed the concepts leading to generation of high energy gradients of the order $100GV/m$. They discussed the plasma based techniques for electron acceleration such as LWFA, PBWA, self-modulated LWFA, plasma waves driven by multiple laser pulses, and highly nonlinear regimes. They discussed the linear and nonlinear properties of plasma waves with respect to the acceleration of electron in plasma waves. They also presented the related instabilities due to intense short-pulse laser-plasma interactions.

Sharma and Tripathi [80] investigated the acceleration of electron by a Gaussian laser pulse in magnetized plasma. With a fixed refractive index they analysed the role of laser frequency, electron cyclotron frequency, amplitude of the laser pulse and plasma density in the acceleration of electron. They observed that the plasma frequency influences the electron acceleration. A small decrease in plasma frequency can enhance the energy gain significantly. They proposed that with a circularly polarized laser pulse of peak intensity about $10^{19} W/cm^2$, the electrons with $0.1 MeV$ of initial energy injected into the magnetized plasma can be accelerated to energy of about $100 MeV$.

Li *et al.* [81] investigated the electron resonance acceleration with an inhomogeneous magnetic field and an intense laser pulse. The electron cyclotron resonance plays a vital role in increasing the energy of accelerated electron. The duration of resonance increases by appropriate variation in magnetic field. Due to which the electron gets attracted towards the cyclotron-resonance and trapped by laser pulse with enhanced energy gain.

Sohbatzadeh *et al.* [87] derived the laser beam parameters such as radius of curvature, spot size, and Rayleigh length for a chirped laser pulse in paraxial approximations. A slight change in parameters varies the results significantly. It is observed that with the change in frequency of laser pulse, the laser beam waist as well as Rayleigh length changes.

Mirzanejhad *et al.* [88] analysed the generation of electron bunch with energy of the order of GeV with a wake-field of chirped laser pulse. The linear chirped parameters were optimized to increase the wake field and hence energy gradient. They observed that the electrons with initial energy of about $100 KeV$ get accelerated to $1 GeV$ of energy by laser wake-field in a small distance of $1.88 mm$. It was observed that with a pre-accelerated electrons beam, 98% gets accelerated efficiently and 2% de-phased. The observed energy spread is also very low.

Li *et al.* [89] studied the vacuum electron acceleration induced by tightly focused chirped laser pulse. With a tightly focused linearly polarized laser pulse it is possible to focus the laser beam to the order of wavelength with inclusion of third order in diffraction angle. Additionally the chirp parameter contributes in electron energy enhancements. Further the phase slippage between the energetic electrons and laser pulse remains small and such electrons retain energy for longer duration.

Dai *et al.* [95] analysed the vacuum electron acceleration induced by a tightly focused radially polarized laser pulse. They employed Weniger transformation field (WTF) to avoid the electron divergence due to Lax Series field (LSF) which affect the electron dynamics significantly. They have also analysed the roles of position, injection, and initial energy of electron and phase of laser field on electron acceleration.

Yuan *et al.* [98] analysed the two instantaneous frequency forms of linearly chirped laser pulse. They compared the results of frequency variations with and without retarded coordinates with a linearly polarized laser pulse. They proposed that the chirped frequency form with retarded coordinates is more significant than that with non retarded coordinate.

Marceau *et al.* [100] used the ultra-short and non-paraxial radially polarized laser pulses for the direct acceleration of electrons in vacuum. They demonstrated that the threshold power for acceleration can be reduced by using a tightly focused laser pulse. Using tightly focused conditions a high energy gain of the order of MeV can be attained with a non-paraxial radially polarized laser pulse of peak powers of a few GW. The value of this peak power is about 10^3 times lower than that with a paraxial approximation to obtain the same energy gain.

Salamin [101] demonstrated that the chirping of frequency enables a net energy gain while interaction of a plane polarized laser pulse with electron. Due to chirping the laser field gets distorted in a sensitive way to enforce the electron for more interaction with laser pulse. Thus a significant electron energy gain appeared.

Zhu *et al.* [107] investigated the acceleration of electron by a phase modulated circularly polarized laser pulse. Such wave influences the electron dynamics during interaction. The electron gets trapped and accelerated with suitable phase for longer duration and hence gain high energy. They reported that the energy spectrum with linearly polarized (LP) and circularly polarized (CP) laser pulse is alike. However the electron trap with CP laser pulse is higher than that with a LP laser pulse.

Jha *et al.* [109] presented a 2D PIC simulation for acceleration of electron by an intense super-Gaussian laser pulse through wake field generation in plasma. The electron trapping, dynamics and energy gain was analysed for an injected electron accelerated by wake field. With a super-Gaussian pulse the generated wake field appeared to be 23% higher than that with a Gaussian laser pulse. Thus the electron energy gain with a super-Gaussian laser pulse is higher than that with a Gaussian laser pulse.

Hooker [111] described the operational concepts of laser-driven plasma accelerators in present scenario, and reviewed their progressive development. Accordingly, the laser-driven plasma accelerators provide acceleration gradients of three orders of magnitude greater than conventional machines. The potential applications of plasma accelerators are described and the challenges which must be overcome before they can become a practical tool were discussed.

Afhami and Eslami [116] analysed the electron acceleration under influence of a nonlinear chirped Gaussian laser pulse. They defined the polynomial and periodic chirp forms and proposed that the maximum energy of electron with a nonlinear chirped laser pulse is about three times greater than that with a linear chirped laser pulse. The field of the nonlinear chirped pulse enforces the electron for a much smaller divergence than that with a linear chirped pulse.