# Abstract

Interaction of high power lasers with plasmas have become possible due to the recent advances in laser technology with the invention of chirped pulse amplification (CPA) [1, 2] and advanced femtosecond techniques. Electrons quiver with relativistic velocities under the influence of high laser fields and the electron motion becomes nonlinear [3, 4] which gives rise to a wide range of phenomena such as laser plasma based accelerators [5, 6], X-ray laser [7, 8], inertial confinement fusion [9–11], harmonic radiation generation [12–14] and relativistic soliton formation [15–17].

Particle acceleration from plasmas have gained a lot of importance in the field of laser-plasma interactions. Accelerating gradients of the order of 100 GV/m can be generated in plasmas which make them highly compact and inexpensive as compared to the large conventional accelerators [18]. Electrons can be accelerated by the large amplitude plasma waves or wakefields driven by a laser pulse propagating through plasma as in laser wakefield accelerator (LWFA) [5, 19]. Ions can be accelerated from solid and gaseous targets as well. A high-intensity laser on interaction with a solid target ionizes the front side and generates hot electrons which can penetrate through the target and reach the target rear side. These hot electrons then form a sheath which accelerates ions froward in the target normal direction and the process is termed as target normal sheath acceleration (TNSA) [20]. When the laser is highly intense and circularly polarized, the radiation pressure can effectively push the electrons forward forming a double layer structure with the ions at the target front side popularly termed as "laser piston". The piston moves ahead and accelerates the ions via radiation pressure acceleration (RPA) [21]. Ions can also be accelerated by electrostatic collisionless shocks formed at the target front surface in the collisionless shock acceleration (CSA) mechanism [22]. The shocks are assumed to be driven by the laser piston at the target front surface with velocity closer to the piston velocity. Ions can be accelerated to GeV energies from ultrathin targets via break-out afterburner acceleration (BOA) [23]. In this mechanism, the hot electrons make the target relativistically underdense via relativistically induced transparency. Thus, the laser reaches target rear side and generates a large localized longitudinal

electric field which accelerates the ions to high energies. Ions can also be accelerated effectively from near-critical and underdense plasmas such as cluster gas targets and foams. A strong magnetic vortex like structure can be formed at the rear side of such targets which enhances the accelerating electric field of the electrostatic sheath and accelerates ions to higher energies. This mechanism is known as magnetic vortex acceleration (MVA) [24]. In the present thesis, three dimensional (3D) particle-in-cell (PIC) simulations have been done to study the role of different laser and plasma parameters such as target thickness and laser polarization on acceleration of protons. Large amplitude magnetic fields can have significant effect on the hot electron dynamics due to cyclotron effects. We have also studied the effect of an axial magnetic field on proton acceleration from overdense plasmas. Moreover, the effect of such strong magnetic fields on the collimation of energetic proton beams has also been studied.

Generation of huge magnetic fields have been an interesting field of research in the field of laser-plasma interactions. Hot electrons generated during the interaction of intense lasers with overdense plasmas can make the plasma unstable leading to the formation of an instability termed as the Weibel instability [25, 26] which is mainly responsible for the generation of strong quasi-static magnetic fields. Magnetic fields can also be generated due to the presence of non-parallel temperature and density gradients. Such type of gradients can be established when the laser is irradiated on the target surface. The density gradient is pointed inward the solid-density surface and the temperature gradient is radially pointed inwards the laser axis. A toroidal magnetic field is thus generated having scale size comparable to the laser spot which falls to zero at the laser axis [27]. Magnetic field generation in general is observed when the laser is incident normally on the target. However, changing the angle of incidence can also have a considerable effect on the generation of magnetic field. In the present thesis 3D-PIC simulations have been done to study the generation of magnetic field by an obliquely incident laser and the formation of periodic density ripple like structures carrying strong magnetic fields on the front plasma surface is observed.

High-order harmonic generation (HHG) is one of the most active areas of research in the recent years due to its diverse applications in the study of material properties, biological samples etc. Harmonics can be generated effectively during the interaction of lasers with gaseous as well as solid targets. In case of gaseous targets and clusters, harmonics can be generated due to optical field ionization (OFI) [28] where the high amplitude laser electric field ionizes the atom by pulling out the electron away from the parent ion. Due to change in laser electric field polarity, the electron on accelerating back recombines with the parent ion and emits a photon which gives rise to the generation of harmonics as observed in experiments [29]. In case of solid targets, the laser ponderomotive force drives the plasma boundary into oscillatory motion. This oscillating boundary is termed as the "oscillating mirror" [30–32] which oscillates at the frequency of higher harmonics. The laser gets reflected from this oscillating boundary and gives rise to the generation of higher order harmonics. In the relativistic regime, the electrons can move in the periodic "figure-eight-motion" radiating photons which are harmonics of each other. The present thesis includes an analytical study on the generation of second harmonics by a obliquely incident laser in presence of magnetic field.

The simulation results presented in this thesis are obtained by using the code Picpsi-3D [33].

The **Chapter 1** of the thesis gives a general introduction about the basic aspects in interaction of intense lasers with plasmas. A brief description about the propagation of electromagnetic waves in plasmas including the relativistic effects is provided [34, 35]. Acceleration of electrons and ions via various standard acceleration mechanisms mentioned above has been discussed in detail. Generation of hot electrons in overdense plasmas via various laser absorption mechanisms such as resonance absorption [36], vacuum heating [37] and "$\vec{J} \times \vec{B}$" heating [38] have been discussed. Generation of magnetic fields via various mechanisms mentioned above and the effect of these strong quasistatic magnetic fields on the hot energetic electron flow have been discussed. Basic concepts regarding the generation of higher order harmonics in gaseous as well as in solid targets have been discussed. The methodology for understanding the underlying physics in the work presented in this thesis such as Particle-in-Cell (PIC) and the solution of Maxwell's equations via Finite-difference Time-domain (FDTD) has been discussed in detail.

In **Chapter 2**, the role played by the target thickness in generating high energetic protons by a circularly polarized laser from mass-limited targets (MLT) [39, 40] has been investigated. Three dimensional (3D) particle-in-cell (PIC) simulations have been done by varying the thickness of MLT. It has been observed that protons get accelerated both from the front side as well as from the rear side via RPA and TNSA respectively. It is observed that the synergy between these two processes can be controlled by adjusting the target thickness. Maximum proton energy as well as the collimation of the energetic proton beams is also effected by target thickness. A difference in the acceleration process is also observed on changing the laser polarization from circular to linear.

In **Chapter 3**, we have studied the effect of magnetic field on proton acceleration by an ultraintense short pulse circularly polarized laser from an overdense plasma target. 3D-PIC simulations have been done for right circular polarization (RCP) and left circular polarization (LCP) in presence of an axial magnetic field. The dielectric constant of the plasma gets changed due to cyclotron effects which causes a difference in the behaviour of ponderomotive force of RCP and LCP. Acceleration occurs both via RPA and TNSA and it is observed that due to cyclotron effects, a change in the laser polarization from RCP to LCP plays an important role in controlling the synergy between the two accelerating mechanisms. The optimum target thickness for maximum proton energy as well as the energetic proton beam collimation also gets effected due to combined effect of laser polarization and axial magnetic field.

In **Chapter 4**, the effect of magnetic field on collimation of energetic protons from near-critical plasmas has been investigated. 3D-PIC simulations have been done for linear polarization (LP), RCP and LCP in presence of an axial magnetic field. It is observed that the cyclotron effects causes an effective reduction in the transverse proton momentum which enhances the collimation. Since, the plasma is near-critical, cyclotron effects are carried deeper into the plasma which is responsible for the collimation of the energetic proton beams. Collimation achieved is observed to be different for LP, RCP and LCP as evident from the proton beam spot size.

In **Chapter 5**, the role played by the angle of incidence of a short pulse laser in the generation of magnetic field via Weibel instability from overdense plasmas is investigated with the help of 3D-PIC simulations. In case of normal incidence, self-focusing and strong current filamentation is observed which causes the generation of high amplitude magnetic fields across the filament. When the laser is obliquely incident, periodic density ripple like structures are observed at the plasma front surface which are formed due to emission of energetic electron jets by vacuum heating. These periodic structures carry strong magnetic fields. However, magnetic field generation is observed to be highest in case of normal incidence due to strong current flamentation.

In **Chapter 6**, second harmonic generation by an obliquely incident $s$-polarized laser from an underdense plasma has been investigated analytically. An expression for the relativistic factor in presence of magnetic field has been obtained. The efficiency of second harmonic radiation is calculated as a function of angle of incidence, electron plasma density, laser electric field amplitude and the magnetic field. It has been observed that the conversion efficiency gets affected by the magnetic field due to modified relativistic factor. The second harmonic conversion efficiency gets decreased on increasing the magnetic field.

Finally, summary of the results obtained in the present thesis and the future outlook is presented in **Chapter 7**.

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