Abstract

The advent of high power lasers over the years and the ability of plasma to sustain large electric fields has led to the concept of a novel category of particle accelerators known as the laser-plasma accelerators. The theoretical idea of utilising the high electromagnetic fields of the laser to accelerate high energetic electrons was proposed by Tajima and Dawson [1] in 1979. The laser field drives a plasma wakefield as it propagates through the plasma and the electrons are trapped in them to get accelerated to high energies. With the presently available laser systems, it has been possible to drive the electrons directly to relativistic motion. On the other hand, the acceleration mechanisms of ions due to their heavier masses rely on the motion of the electrons. Usually, the ions get accelerated as a result of the charge separation field that is formed due to the displacement of the electrons. A number of ion acceleration schemes have been identified both experimentally and through simulations and the production of a controllable high energetic ion bunch of high beam flux has been an active research area. Ion bunches of low transverse and longitudinal emittance have the potential viability as sources for several essential applications like tumour hadron therapy, fast ignition of the fusion fuel in thermonuclear reactors, etc.

The present thesis work is aimed to explore advanced target regimes which has the capability to generate fast ions beyond the sheath acceleration mechanism using spherical targets. Previous works [2, 3, 4, 5, 6] have reported the generation of a focused ion beam of higher energies using a spherical target compared to an extended flat foil target. An isolated spherical target can be suspended in the laser path with the help of a Paul trap, enabling studies using an isolated micrometre-sized sphere [7, 8]. Motivated by these works on spherical plasma targets, the present thesis work deals with the PIC simulation study of the ion dynamics when an ultrashort intense laser pulse gets impinged on a micron-sized spherical plasma target. The parametric optimization

allows identification of numerous ion acceleration processes along with the production of MeV-ranged proton bunches. With a laser pulse of peak intensity $\sim 10^{20} W cm^{-2}$, the plasma electrons attain relativistic velocities inducing the plasma transparency due to the relativistic effects. Therefore, the use of a relativistically near-critical plasma resulted in a strong laser energy absorption inside the plasma. This effect created the conditions favourable for the excitation of a shock wave leading to the reflection of the protons upstream of the shock-front. This collisionless shock acceleration (CSA) mechanism is supplemented by the sheath acceleration of the upstream protons, which causes them to attain high velocities. The transverse beam spread is also suppressed due to the front-surface curvature of the sphere target compared to a planar one.

The laser energy absorption into the plasma is crucially responsible for the formation of the strong shocks inside the plasma. The laser transfers a part of its energy to the plasma electrons which are thus termed as the 'hot-electrons'. For an enhanced plasma heating, usually a near-critical density target is irradiated with the plasma. However, such targets are challenging from the fabrication perspective. Solid targets have densities nearly 100-times higher than those required to create critical density targets. As a result, engineered targets like structured [9, 10, 11], foam [12, 13, 14] or pre-exploded targets [15, 16, 17, 18] are used to increase the laser absorption. These modified targets have a reduced average density which has been observed to be beneficial in enhancing the hot electron production. For the pre-explosion of the target, the target is first impinged by the laser pre-pulse of lower intensity. The resultant plasma creation and expansion leads to an eventual low-density target with the inevitable presence of a density gradient inside the plasma. In case of a spherical target of dimension of the order of the laser spot-size, the target expansion occurs nearly isotropically. This leads to a radial inhomogeneity in the target density profile. Utilizing such variations of the target density profile in the study of the ion acceleration processes is important. This motivation led to the next part of the present thesis where a pre-exploded plasma target is simulated to explore the underlying proton dynamics. A structural layout of the presented thesis is demonstrated in the following paragraphs.

In **Chapter 1**, the theoretical background of laser interaction with plasma and the motivation behind undertaking this thesis is presented. A brief account is also made on the possible applications of laser-plasma accelerated ions. Different laser-to-electron energy absorption mechanisms are demonstrated, followed by a discussion on the various ion acceleration mechanisms. The PIC simulation technique is also demonstrated in brief in the methodology section.

Chapter 2 is dedicated to the generation of MeV-range protons from a spherical micrometre sized plasma by impinging it with a circularly polarized laser pulse. The initial plasma density is found to play an important role in governing the acceleration of the protons. The relativistically critical plasma target supports enhanced plasma heating to sustain shock structures that help in the production of high energetic protons.

In **Chapter 3**, an exploded target is interacted with an intense laser pulse. Such targets undergo a pre-expansion due to the presence of a low-intense pre-pulse. The expanded spherical target thus has a radially dropping density peaking at the target centre. A linear and a Gaussian-shaped density non-uniformity are analysed and compared on the basis of the ion dynamics. A shock front is generated due to a relative drift between the inner and the outer ions. The Gaussian density profile suppresses the formation of the sheath electric fields, thus creating spectral peaks in the final proton energies.

The Gaussian density profile is further explored in **Chapter 4**, where the central peak density is kept around the relativistically critical density. An anisotropic expansion of the target is observed due to the momentum boost due to the light pressure along the laser direction. The expansion type has been identified to be ambipolar, which could be transitioned to Coulomb explosion by decreasing the target size. The asymmetry in the proton expansion and the high values of energy favours a micron-sized target.

In **Chapter 5**, the study is further extended to higher densities in the central peak of the spherical target having a radially Gaussian density profile. A moderate peak density along with the downward density ramp at the target rear supports the formation of a strong shock with suppressed sheath field contribution. This resulted in a proton bunch having energy excess of 100 MeV with narrow spectral peak ($< 6\%$) with strong collimation. Further increasing the peak density results in a transition to the standard CSA regime with plateau shaped energy spectra.

Finally, in **Chapter 6**, the summary of the results presented in the thesis are provided in brief. An outlook on the prospective avenues created by this thesis work is also discussed.

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