Ion acceleration using intense laser interaction on a spherical plasma target

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Ankita Bhagawati
Registration No.TZ155499 of 2015

Department of Physics
School of Sciences
Tezpur University
Napaam, Tezpur-784028
Assam, India

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Chapter 6

Summary and Future Prospects

In the present thesis, the motion of energetic protons from a spherical plasma target is studied after it is irradiated with an intense short laser pulse. The spherical shape of the target is found to facilitate the generation of stronger proton beams, compared to a flat target. The development of shocks are also observed at the core of the spherical plasma. The spherical geometry of the target may thus be quite helpful in studies related to acceleration of ions to high energies. The 3D PIC simulations in the present thesis are performed using the Picpsi-3D code. The plasma density in the near-critical regime ensures a stronger laser energy absorption inside the plasma, and thus leads to the generation of faster protons from the plasma target. These fast protons can be cultivated for several prospective applications.

6.1 Chapter-wise Summary

In **Chapter 2**, a micron-sized plasmasphere impinged by an ultrashort intense pulse having transverse dimensions comparable to the laser focal area is simulated. The plasma density is varied in the near-critical regime and it is found that the final proton energies are highest for the relativistically critical target. The transverse-limited dimension of the target is found to assist an effective confinement of hot electrons in a smaller region which drives shockwaves in the laser propagation direction. The generation of these collisionless shock structures can accelerate the upstream protons by reflecting them elastically to higher velocities. Moreover, the spherical shape of the target is found to have a positive impact on the proton beam quality in terms of energy as well as collimation. A variation of the target densities and size suggests a relativistically critical target having dimensions less than the laser focal area to produce an optimal proton beam with maximum energies ($\sim 40 MeV$) using a circularly polarized laser of peak intensity $\sim 10^{20} W cm^{-2}$. It is also found that an increased hot electron generation at the transverse direction suppresses the final proton energies to some extent. Therefore, the transverse confinement of the electrons ensured by a smaller sphere is essential to obtain a high energetic proton bunch.

In **Chapter 3**, a pre-exploded target is used with the initial expansion considered to be caused by the interaction with a pre-pulse of lower intensity. The spherical shape of the target leads to an almost radially isotropic expansion, before the main pulse hits the target. This inevitably lowers the target density with the creation of density gradients inside the spherically expanding target. The effect of the pre-pulse intensity is analysed by comparing with a uniform density target. It is seen that the use of a pre-exploded target increases the energies of the protons. As a first approximation, the density inhomogeneity before the interaction with the main pulse is taken to be linearly decreasing radially outward from a peak value at the centre. This density variation at the front side of the target results in an enhancement in the laser energy absorption. The shock created at the decreasing density gradient region due to the non-uniform velocities of the expanding protons helps in achieving a high value in the final energy spectra of the protons. The shock accelerated protons experience an added boost due to the strong sheath field produced at the target rear. This additional effect leads to the broadening of the proton energy spectra. In addition, a Gaussian shaped density variation with a peaked centre is also implemented in this chapter. It is found that, the rear-side sheath field is comparatively weaker in this case compared to a linear density case. The suppression of the sheath effect helps in retaining the near-uniform velocities of the bulk-accelerated protons. This makes a Gaussian shaped density profile favourable in generating quasi mono-energetic peaks in the proton spectra, motivating the studies in the next chapters of this thesis.

Using a Gaussian-shaped target density profile, the target expansion is studied in **Chapter 4**. The central peak density is kept around the relativistically critical value so that most of the exploded target is transparent to the incoming laser pulse. Thus, a strong target expansion is prevalent in this target density domain. With a micron-sized plasma-sphere, it was found that the interaction with the laser pulse of peak intensity $\sim 10^{20} W cm^{-2}$ resulted in a favourable direction of expansion along the laser direction. The laser ponderomotive effect causes this anisotrpicity in the plasma expansion. The presence of a high number of electrons in the vicinity of the protons suggests the expansion to be ambipolar. The target size governs this expansion phenomena and is found to transit to a Coulombic explosion regime upon reducing the target diameter. The incomplete removal of the electrons from the core of the target leading to an ambipolar expansion of the target is found to yield protons of higher energies. This observation, along with the favoured anisotropy of the plasma expansion suggests spheres of a few-μms diameter to be preferable over smaller targets.

The density gradients in a Gaussian shaped distribution are explored in **Chapter 5**. Similar to the previous chapter, a radially decreasing plasma density profile (following a Gaussian distribution) is considered with its value peaked at the centre. In this chapter, the density gradients are tuned by varying the central peak density and keeping the inhomogeneity scale-length (the full-width at half maxima) constant throughout. Thus, a higher peak density at the target centre translates to a higher density gradient and vice versa. In Chapter 4, it was found that with the peak densities around the relativistically critical value, the expansion of the target becomes the dominant process of ion motion. In this Chapter, it is found that upon increasing the peak density, and thereby increasing the density gradient, electrostatic shocks are formed along with the ambient expansion mechanism. For high values of the density gradients ($n_{peak} > 2.5\gamma n_c$), the steep plasma gradient faced by the incoming laser pulse induces a hole-boring effect initially. Upon further expansion of the target, the density drops and a collisionless shock is generated at the target bulk that helps set the upstream protons into high velocities. The sharp plasma-vacuum interface at the rear surface supports a TNSA field which pulls the shock-reflected protons to non-uniform velocities. Now, in terms of the proton dynamics, an interesting and fertile density domain is discovered for moderate plasma density gradients ($1.5\gamma n_c < n_{peak} < 2.5\gamma n_c$). In this regime, the velocity difference between the inner and the outer proton populations of the expanding sphere constitutes a wave-breaking shock at the overtaking region. This shock reflects the upstream protons which is further aided by the overall expansion of the target. As a result, the accelerated protons are emitted from the rear side with a limited spread in their energies. A collimated bunch of protons is obtained having a narrow energy distribution with mean energy exceeding 100 MeVs using such a density-modified target with a laser having peak intensity $\sim 10^{20} W cm^{-2}$.

6.2 Future Outlook and Prospects

The present thesis is dedicated to study the various processes of proton acceleration using an intense laser irradiated on a micron-sized plasma sphere. With the incorporation of modifications in the target density distribution, it has been found that the energies of the resultant protons are getting enhanced. A linear and a Gaussian variation in the density is studied in great detail in the present thesis. Further modifications on the target density profiles could be made with an aim to enhance the laser energy absorption to generate stronger shocks for ion acceleration. Moreover, other target geometries can also be explored adding suitable density modifications in them. The beam collimation may be improved upon by using advanced target geometries (such as modified cones) which can support a proper guiding of the fast ions.

In this thesis, a hydrogen plasma target is considered that comprises of just protons and electrons. In the future, these parametric studies could be extended to heavier ions using combination targets of protons and massive ions. Such studies could help develop new insights on the dynamics of the heavy ions and could be helpful in replacing the hydrogen target with a plastic or a metallic target.

It has been found that the use of a low-density plasma target can lead to an increase in the final ion-energies by virtue of stronger laser absorption. In this thesis, pre-exploded targets has been explored to generate the required density regime for efficient generation of fast ions. However, there are other ways of developing such near-critical density targets, for example, by using foam targets or by introducing structures on the solid targets. Such targets have a reduced effective density and can efficiently absorb the laser and generate hot electrons. The present study can be extended using such micro-structured or nano-structured targets and will be interesting to analyse their role on the ion dynamics.