Proton Acceleration by Laser-plasma Interaction

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Abstract. The target shape influence on the accelerated proton energy is discussed in this paper by 1D Particle in Cell (PIC) code. With laser beam energy of 1.23*1022W/cm2, the outgoing proton energy could reach 232.31 MeV with a special target setup.

Keywords: laser plasma interaction, PIC simulation, proton acceleration.

1. Introduction

With the rapid growth in energy demands, finding new clean energy has become an essential problem which limits the progress of new technologies. Laser-plasma confinement fusion is one of the most important research direction [1-2], detailed theoretical and experimental study have revealed that the electrons or the ions in the plasma could be accelerated to very high energy by a short energetic laser pulse. The high quality ion (electron) beam is highly demanded in medical science, biological science, material science and frontier research in the fundamental physics, e.g., proton (neutron) beam has proved to be very efficient tool for cancer treatment in the medical science (to get an optimized treatment effect, the proton beam energy should be in range of 150 MeV to 250 MeV) [3-4], and very high energy particle beam is the key to explore the new physics on earth. However, the traditional proton beams is produced by the large electromagnetic accelerators which have very large size (e.g., the Large Hadron Collider (LHC) at CERN has a circumference of 27 Km), and the cost of these acceleration facilities are very huge that most of the countries could not afford it by themselves, this restricts the development and the application of high-energy proton beam. So iron accelerating devices with low cost and small form factor are highly demanded. Along with the modern laser technology development, especially the invention of the chirped pulse amplification technology, the energy and intensity of the laser pulses have been significantly improved [5], which have ensured the laser plasma acceleration mechanism.

Recently, with the rapid development of the ultrashort laser beam, the proton acceleration by the laser-plasma interaction has attracted the interest of many researchers. There are a variety of different acceleration mechanisms researchers have proposed, but the underlying reaction mechanisms are still not fully understood in the proton acceleration process, *e.g.*, Target Normal Sheath Acceleration (TNSA), Radition Pressure Acceleration (RPA)[6], Break Out Afterburner (BOA)[7], Collision less Shock Acceleration(CSA)[8] and etc.. However, due to the mechanism of laser-plasma interaction is still imperfect; to achieve more than 100 MeV proton beam of monoenergetic experimentally is still a challenge. With the rapid development of computer-based numerical simulation technology, which allows us using numerical simulation to study the laser plasma acceleration mechanism, and optimize the experimental settings to achieve the best results. The intensity, duration and polarization of the laser, and the shape and density of the target all have a unique impact on the outgoing proton energy spectrum. In this paper, the impact of the target shape on the accelerated proton beam is studied by 1-Dimensional PIC code MLPIC++ [9].

2. Simulation settings

A series of 1D PIC simulations are performed with the MLPIC++ code to investigate the impact of the target to final accelerated proton energies. In the simulation, the laser wavelength $\lambda_0 = 1\ \mu m$, the simulation box is set to be 10 λ0 with 1000 cells per wave length. The target is located between 4.0 λ0 and 6.5 λ0 with densities as a function of the position. The target density is set based on the plasma critical density nc, typical maxium density used in the simulation is 8.0 nc. The right-circularly polarized laser with the maxium amplitude of 1.23*1022W/cm2 enters into the simulation box from left side which has a sin2 shape and duration of 4 laser periods, the laser would reach the front of the target after 4 laser periods. The laser shape and target are shown in figure 1. The laser amplitude $a_0 = eE_0/m_e\omega c = 95$,where e, m_e are the charge and mass of electron, E_0 and ω are the electric field strenth and the frequency of the electromagnetic wave, and c is the speed of light in vacuum.

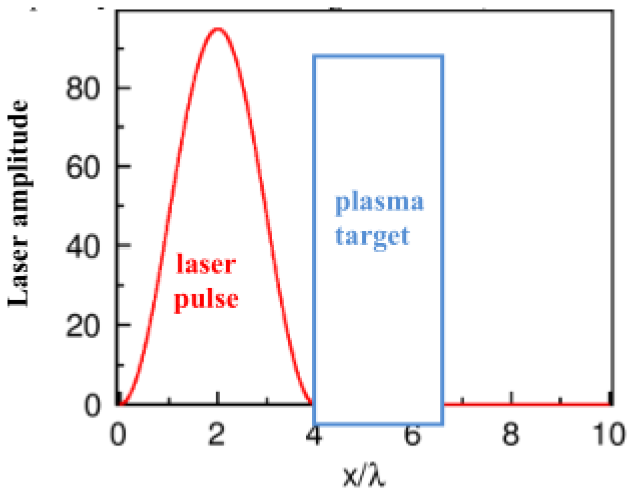


Fig.1 (color online) the simulation setup. The red line presents the laser shape after 4 laser periods after the laser entering the box; the blue box shows where the target locates.

3. Simulation Results and Discussion

3.1 Flat Target.

With the laser parameters fixed, we performed a simulation with flat target density distribution, the density of the target is set to be 8.0 n_c. The proton velocity distribution after 11 laser periods is shown in figure 2.

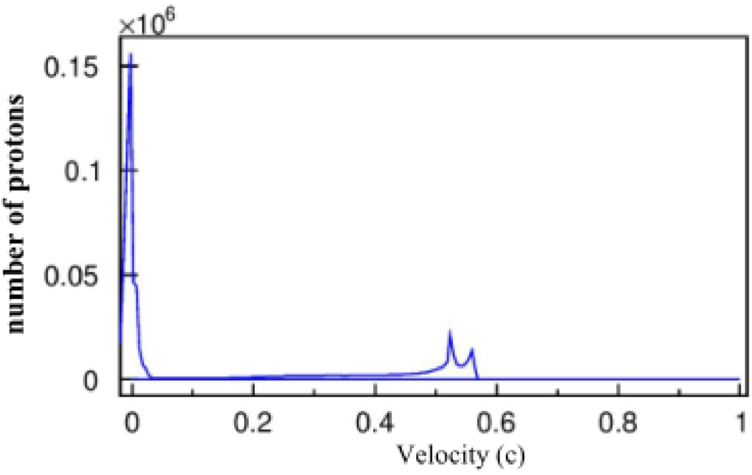


Fig.2 (color online) proton velocity distribution at T= 11T_0.

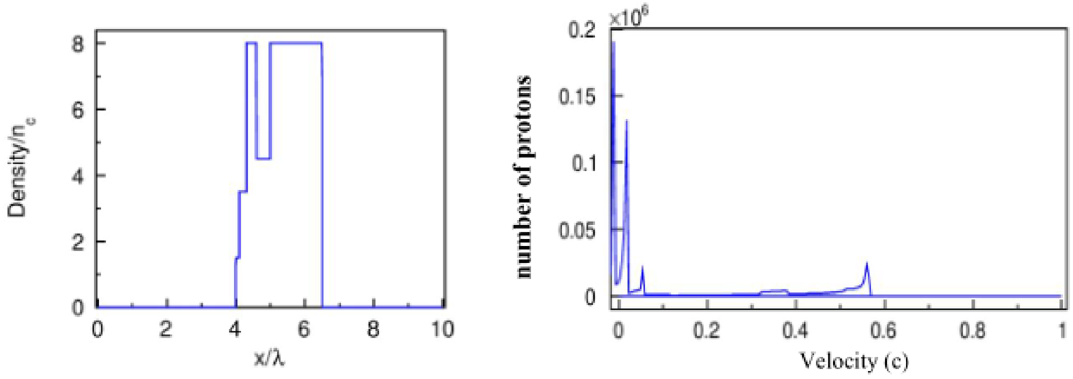
The x axis is the velocity of the protons in unit of the speed of light in vacumm, and the y axis is the number of protons. In the spectrum, parts of the protons are clearly accelerated to a high speed which corresponding to the two peaks near 0.55 c. With relativity theory, the kinetic energy E_k is defined by:

$$E_k = (\gamma - 1) m_p c^2 \tag{1}$$

Where $\gamma = \sqrt{1 - \frac{1}{\beta^2}}$ $\beta = \frac{v}{c}$, and m_p is the mass of proton in its rest frame. In the Natural Unit System, the protons energy corresponding to about 185.13 MeV. This energy is in the cancer therapy window, but there are two secondary peaks near the 0.55 c which means the energy is spirited and this is not an optimized beam for application.

3.2 Hollow Target.

With all the other parameters fixed, the target density is changed to a distribution as shown in figure 2 (a). The target density ramp up from 0 to 8 n_c in 3 steps and then drop to 4.5 n_c at 4.6 λ_0 , then changed baxk to 8 n_c afterwards. This target density distribution is similar to what is happening in real laser plasma interation where the target is heated by the prepluse of the laser and part of the target is peared off the target before the mainpluse is coming in. The velocity distribution is shown in figure 2 (b), it is clear that the secondary peak near 0.55 c vanished. This suggesets that such a target distribution would depress the secondary peak in the proton velocity spectrum, but the kinetic energy of the proton is not improved by this target setup. The mean proton energy in this peak is close to 192.34 MeV.

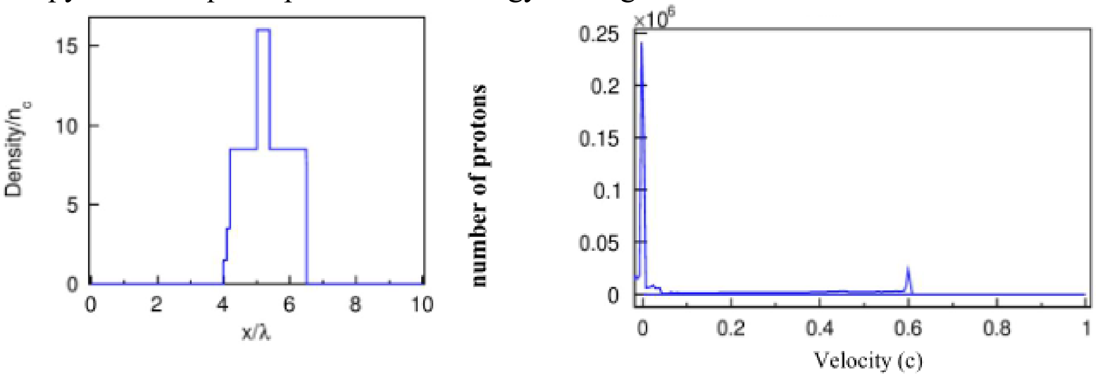


(a) (b)

Fig.3 (color online). (a) target density distribution; (b) velocity distribution of the proton at T=11 T_0

3.3 Convex Target.

The target shape is modified to a convex type, which the density ramps up to 8.5 n_c in 3 steps and then remains as a constant for 0.8 λ_0 . The main differences comparing to case B is the target density increases to 16.0 n_c in 0.4 λ_0 and then drop back to 8.5 n_c to the end of the target, the setup is shown in figure 4 (a). With the same laser parameters and such a target setup, the proton velocity is ploted in figuer 4 (b),. In the spectrum, it is clear that the velocity of the proton has better monochromaticity which would be good for the beam to be applied. Moreover, the mean beam energy also is increased that reached 0.598 c, which corresponding to 232.31 MeV. This energy would also be very useful for caner therapy which requires proton beam energy in range of 150 MeV to 250 MeV.



(a) (b)

Fig. 4 (color online). (a) target density distribution; (b) velocity distribution of the proton at T=11 T_0.

4. Conclusion

In this paper, 3 type of targets are tested with same laser pulse. It is shown that the flat target not the best option for proton acceleration. The convex type target would give the best beam both in energy and monochromaticity in 1D PIC simulation, which might shine a light into the practical applications of laser plasma proton (ion) acceleration.

Acknowledgments

This work was supported in part by the oversea sponsored research programs of Department of Education in Heilongjiang Province No. 1253HQ014, the Returned Overseas Scholars Science Foundation of Heilongjiang Province No. LC2013C02.

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