IMPROVEMENT IN PROTON BEAM PROPERTIES DURING LASER ACCELERATION AND PROPAGATION*

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Abstract

In this paper, some approaches to improve the quality of proton beams are proposed during the both production and propagation of proton beams. We propose to use an umbrella-like target to accelerate, and collimate protons. We also propose a scheme to generate quasi-monoenergetic proton beam from the interactions of an ultra-intense laser pulse and a thin tailored hole target. In order to improve the beam quality during the propagation, plasma is proposed to use. All of them are proved applicable by particle simulations.

INTRODUCTION

Energetic ion beams produced from high-intensity laser-plasma interaction have been one of the most active research areas in high-field science in the past few years since they are relevant to particle physics, medical therapy, controlled thermonuclear fusion, and many other areas of science and engineering [1-3]. Ion energies of tens MeV or more have been observed in recent experiments and numerical simulations. Beam properties such as low energy spread and low beam divergence are crucial for many applications. Much effort has been made to improve them during the production of ion beam [2-4].

For most applications the target may be located far from the acceleration region. In such case space charge effects can deteriorate the beam emittance in the both longitudinal and transverse direction during its propagation. So it is important to keep and improve the beam properties during the propagation.

Here some approaches to improve the quality of proton beams are proposed during both the production and the propagation of proton beams. They are studied and proved applicable with the help of the 2D3V particle-in-cell (PIC) code PLASIM [5, 6].

COLLIMATED PROTON BEAM FROM AN UMBRELLA-LIKE TARGET

Firstly, we propose to use an umbrella-like target backside to accelerate, focus, and collimate protons [7]. It is shown that collimated MeV proton beams can be produced with such a target.

The proposed target with an umbrella-like cavity backside is sketched in Fig. 1. Without the central filament, the protons at the cone surface region will be accelerated by the sheath field into the cone-cavity and converge onto the axis along the laser direction and then immediately diverge. With the filament on the axis, the converging protons will be slowed down radially by its sheath electric field, preventing them from converging onto the axis (and then diverge). That is, the center filament effectively prevents the divergence of the accelerated protons by reducing their radial momenta. For target-normal sheath-acceleration (TNSA), the length of the focusing region is inversely related to the cone angle: the larger the angle, the shorter the focusing length. In general, the quality of the proton beam is determined by its maximum energy, charge number and density, divergence angle, etc. It is difficult to obtain a rigorous relation between the beam qualities and the laser and target properties since besides the nonlinear laser-plasma interaction and the complex geometry, the protons are also affected by the cavity plasma as well as the fields generated by the interaction. We shall thus investigate the problem using particle-in-cell (PIC) simulation.

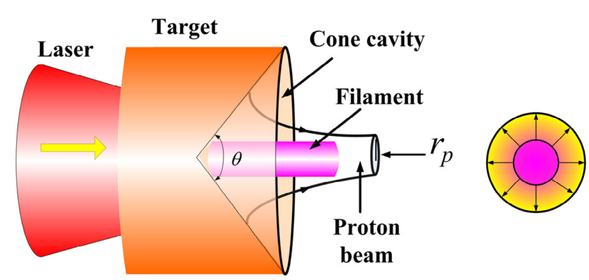

Figure 1: Schematic of the umbrella-like cone-cavity target for producing collimated proton beams.

In our simulations, we take an umbrella-like target with an open angle of 120° for the backside surface. For comparison, simulations are also conducted for a simple cone-cavity target, i.e., without the center filament, as shown in Figs. 2(a) and 2(c). The TNSA protons leaving the target backside are normal to the rear surface. They are then further accelerated and guided by the space-charge electrical field of the laser-expelled hot electrons.

*Work supported by NSFC—NSAF (No: 10976031), 973 Program of China (grants 2007CB815105 and 2008CB717806).
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In general, protons from opposite sides of the cone surface converge towards the axis [8], and diverge after the focus [9]. Typical proton trajectories from a 120°cone-cavity target and the corresponding umbrella-like target are shown in Figs. 2(a) and 2(b), respectively. One can clearly see that there are significant differences in the two cases. Figure 2(a) shows that, as expected, the protons from different locations on the cone surface are accelerated toward different locations (different focuses) on the axis. The closer the transverse distance of the cone surface location to the axis, the shorter the proton convergence distance along the longitudinal axis. The protons diverge after they cross the axis, forming a diverging proton beam or bunch with an angle of about 60° , which can also be seen in the proton density distribution in Fig. 2(c). This strong after-focus divergence also occurs for other cavity shapes such as parabolic [9] and semi-circular [8-9].

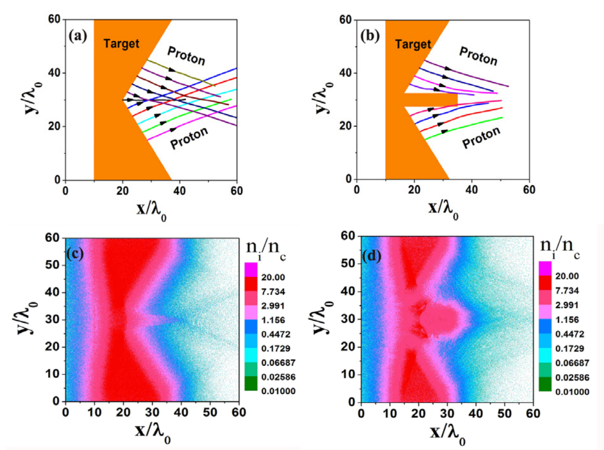

Figure 2: Typical proton trajectories from 2D simulations for (a) simple conic-cavity target, and (b) umbrella-like target. The corresponding proton density distributions at 208T for (c) the simple conic-cavity target and (d) the umbrella-like target.

Thus, high-quality collimated proton beams can be produced from the interaction of a relativistic laser pulse with an umbrella-like target. It is found that proton beams with much better quality can be produced from umbrella-like targets than from simple cone-cavity targets, i.e., much smaller beam divergence and larger proton numbers. The corresponding beam density is also much larger than that from a planar target.

COLLIMATED PROTON BEAM FROM AN UMBRELLA-LIKE TARGET

Secondly, we propose to use an micro hole target to generate quasi-monoenergetic proton beam [10]. In our scheme, we employ a special target with a hole backside. The hole diameter is of the order of the laser spot size so that a nearly uniform sheath filed can be generated in the hole. Using the PIC code PLASIM, we demonstrate that this special tailed target is a promising one to generate collimated as well as monoenergetic proton beams.

When the target has a small hole at the backside and the hole size is of the order of the spot size, the hot electrons are driven into such a narrow hole or channel. To simulate this scenario, we consider a target with a micro hole backside. The cylindrical hole at its backside has a depth of $\Delta = 1.0\lambda_0$ and a diameter of $D = 2.0\lambda_0$.

The particle simulation results show that a clear uniform longitudinal electric field is generated inside the hole and it acts on the protons. The transverse electric field (in the hole) generated by the radial charge separation is weaker compared to the longitudinal one. However, the field plays a very important role in proton focusing. This is because it not only delays the premature focusing of protons inside the hole but also suppresses the transverse divergence of the protons.

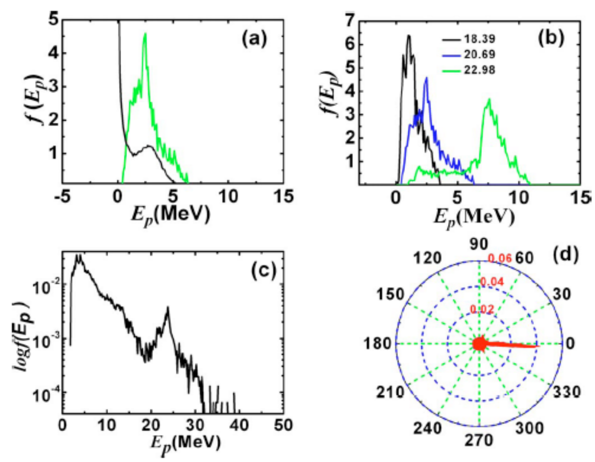

Figure 3: (a) Energy distribution of all the protons from the target (black/dark line) and the protons from the hole (green/gray line) at t=20.69T. (b) Proton energy spectra from the hole at t=18.39T, t=20.69T, and t=22.98T. (c) Energy spectra of all protons off the target backside at t=32.17T. (d) Angular distribution of the protons from the hole at t =22.98T.

A clear quasimonoenergetic peak with small energy spread can be observed in the proton energy spectrum. Figure 3(a) presents the energy spectra of the protons from the hole and whole target, respectively. In Fig. 3(a), both spectra show a narrow-band structure around the same peak energy of 2.5 MeV with a full width at half maximum (FWHM) of 0.5 MeV or 20%. It is indicated that the proton beams with a quasimonoenergetic feature are indeed from the tailored hole. Figure 3(b) plots the transient spectra of protons in the hole at three time points: t=18.39T, t=20.69T, and t=22.98T. We see that the quasimonoenergetic peak can be well maintained and the peak energy increases from 1.0 to 7.6 MeV. Figure 3(c) gives the spectrum of all protons off the target backside at t=32.17T. A clear peak with an energy of 22 MeV can be observed in this figure, which is formed by protons from the hole. The angular distribution of the protons in the hole is shown in Fig. 3(d). Obviously, the transverse divergence is well suppressed. In our scheme, the average divergence angle is about 2.5°, which is somewhat larger than that in Sonobe et al [11]. This can be attributed to the fact that we have used a simple hydrogen target.

In conclusion, we have proposed a scheme for the generation of collimated quasimonoenergetic proton beams from the interaction of a thin hole target with an ultraintense laser pulse. The optimal hole diameter is of the order of the laser spot size such that most of the TNSA protons in the hole experience a nearly uniform sheath field. In our model, PIC simulations show that the peak energy of the accelerated protons can be as high as 20.1 MeV with a cutoff energy of 47.2 MeV. The conversion efficiency from the laser to the quasimonoenergetic proton beam is estimated to be around 1.72%.

THE IMPROVEMENT OF BEAM PROPERTIES BY PROPAGATING IN PLASMA

Thirdly, it is proposed to improve the beam properties during the propagation by using plasma. After the acceleration, space charge effects can deteriorate the beam emittance in the both longitudinal and transverse direction during its propagation in the vacuum. Plasma can reduce the space charge effects during the propagation due to charge neutralization effect [12]. Here the propagation of a proton beam in vacuum, in a plasma slab and in bulk plasma is studied with the help of PIC code PLASIM. The beam densities at different place are shown in Figs. 4 when they propagate in vacuum (a), a plasma slab (b) and bulk background plasma (c), respectively. The plasma slab is located between two dashed lines in Fig. 4(b) and the bulk plasma is located between the dashed line and right boundary in Fig. 4(c). The beam emittance in transverse direction of the proton beam is poor because of space charge effects. Compared with the propagation in vacuum, the proton beam quality can be improved obviously by passing through a plasma slab. The simulations show that the plasma improves the emittance of the proton beam obviously. Compared to the plasma slab, the proton beam has a more stationary profile if it propagates long distance in the bulk plasma. We find that the plasma wave which excited by the beam can modulate the density of the proton beam, and our results confirm that a smooth proton beam profile can minimize the excitation of plasma waves. In conclusion, our simulations show that the properties of proton beam can be kept well during the propagation in the bulk plasma.

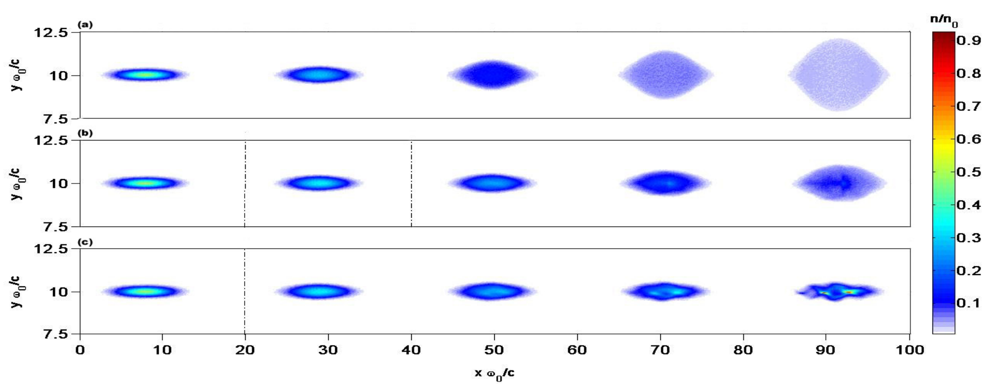

Figure 4: Distributions of normalized beam densities (n_b / n_0) at different place. Proton beam propagate in vacuum (a), plasma slab (b) and a bulk background plasma (c).

CONCLUSION

In this paper, some approaches to improve the quality of proton beam are proposed during the both production and propagation of proton beam. Collimated proton beams are produced from an umbrella-like target. Collimated quasi-monoenergetic proton beams from the interactions of an ultra-intense laser pulse and a tailored hole target are studied by particle simulations. During the propagation, it is found that bulk plasma is propitious to reduce the emittance of the proton beam.

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