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Enhancement of the maximum proton energy by funnel-geometry target in laser–plasma interactions

Peng Yang *, Dapeng Fan, Yuxiao Li

School of Physics and Engineering, Zhengzhou University, Zhengzhou 450001, China

HIGHLIGHTS

- Four targets with different shaped holes in the rear face are proposed.
- Particle-in-Cell method to simulate the interaction between laser and targets.
- Simulation results of four targets are compared.
- Transverse field generated by the sidewall of holes is calculated and compared.
- The maximum proton energy is improved with funnel-shaped hole target.

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ABSTRACT

Enhancement of the maximum proton energy using a funnel-geometry target is demonstrated through particle simulations of laser–plasma interactions. When an intense short-pulse laser illuminate a thin foil target, the foil electrons are pushed by the laser ponderomotive force, and then form an electron cloud at the target rear surface. The electron cloud generates a strong electrostatic field, which accelerates the protons to high energies. If there is a hole in the rear of target, the shape of the electron cloud and the distribution of the protons will be affected by the protuberant part of the hole. In this paper, a funnel-geometry target is proposed to improve the maximum proton energy. Using particle-in-cell 2-dimensional simulations, the transverse electric field generated by the side wall of four different holes are calculated, and protons inside holes are restricted to specific shapes by these field. In the funnel-geometry target, more protons are restricted near the center of the longitudinal accelerating electric field, thus protons experiencing longer accelerating time and distance in the sheath field compared with that in a traditional cylinder hole target. Accordingly, more and higher energy protons are produced from the funnel-geometry target. The maximum proton energy is improved by about 4 MeV compared with a traditional cylinder-shaped hole target. The funnel-geometry target serves as a new method to improve the maximum proton energy in laser–plasma interactions.

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1. Introduction

Proton beams generated from laser–foil interactions are expected to be widely useful for basic particle physics, medical therapy, compact particle accelerators, and controlled nuclear fusion, among other applications [1–4]. In recent experimental research, high energy protons have been observed by the development of laser technology [5–9]. However, because the

* Corresponding author.
E-mail address: 280363402@qq.com (P. Yang).

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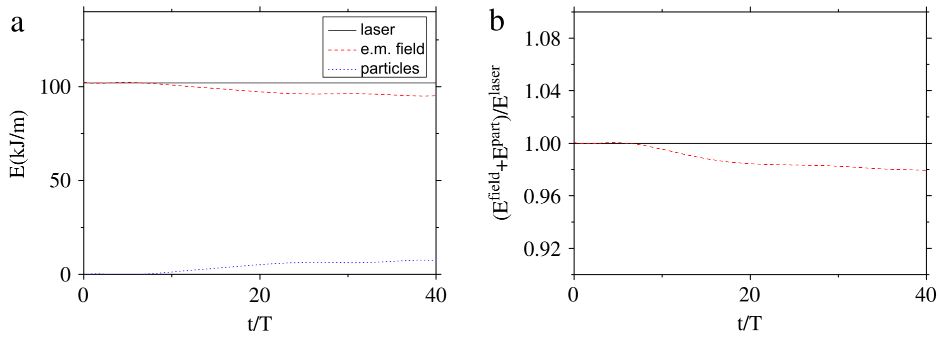

Fig. 1. (a) Energy balance terms for a double-layered slab target, plasma density $n_e = 100n_c$, and peak laser intensity. $I_0 = 1.0 \times 10^{20}$ W/cm^2. The laser FWHM is 20 fs. (b) The $f = (E^{field} + E^{part})/E^{laser}$ behavior demonstrates good energy balance conservation, as was seen in Petrov's simulation (Ref. [21]).

actual proton beams used in the experiments are not yet of sufficient energy for practical use, one of the most important factors in proton beam generation is improving the proton beam energy [10–12].

During the past decades, some excellent mechanisms for generation of high energy and well collimated proton bunch have been developed. For example, the target normal sheath acceleration (TNSA) [13,14], radiation pressure acceleration (RPA) [15], and the shock wave acceleration (SWA) [16], and so on. Among them, the TNSA is an important mechanism, which is easier to be realizable experimentally. In this mechanism, when an intense, short laser pulse illuminates a thin foil target, the foil electrons are pushed forward by the ponderomotive force, resulting in electric charge separation. The accelerated hot electrons form an electron cloud at the rear surface of the target. This electric charge separation generates a strong electric field that accelerates the protons [17]. In previous experimental and theoretical research, the energy distribution of the protons depends on the shape of the electron cloud. By comparing a flat target with a cylinder-shaped hole target, Sonobe et al. found that the divergence of the proton beam is suppressed by the target with a hole [18]. When there is a hole in the target at the opposite side of the laser illumination, the shape of the electron cloud is affected in the transverse direction by the hole. As a result, divergence of the transverse proton beam is suppressed [19,20].

In this paper, we focus on controlling the maximum proton energy by applying different hole shapes. The paper is organized as follows. Targets and simulation parameters are described in Section 2, results and discussion are presented in Section 3, and conclusion is given in Section 4.

2. Targets and simulation parameters

We perform particle-in-cell (PIC) [21–23] 2-dimensional simulations. The reliability of a simulation program can be judged by the energy balance conservation. Here we simulate a double-layered slab target, following work of Petrov (Ref. [21]). The result in Fig. 1 shows that the energy balance is conserved to within a few percent, as was seen in Petrov's simulation.

The simulation mode and the initial parameter values we use in this paper are assumed as follows. The laser peak intensity is 1.0×10^{20} W/cm^2, the laser wavelength is $\lambda = 1$ μm, the laser focal spot diameter is 3λ full width at half maximum. The laser has a Gaussian envelope, and the laser FWHM is 20 fs. The linearly polarized laser pulse of x direction enters the simulation box from the bottom boundary at $t = 0$, propagating along the $+y$ direction, and incident normally onto the target front surface, as shown in Fig. 2. The calculation area in both the longitudinal direction and the transverse direction are 20λ. The calculation mesh size is $\Delta x = \Delta y = 0.02\lambda$ and the integration time step is $\Delta t = 0.0125T$, where T is the laser period. In the transverse x direction, we applied periodic boundary conditions. In the longitudinal y direction, to prevent the particles and waves from being reflected at the boundary, we applied free boundary conditions [24].

In this research, the temperatures of the initial plasma electron and ion are both set at 1.0 keV. The plasma target consists of two layers of Al and H. As shown in Fig. 3, the structure of the target is designed such that there is a hole on the back surface of the Al layer and the H layer is located at the bottom of the hole. The thickness of the Al layer is 2λ, (and we assume there are four different shapes of holes). The depth of all the holes is 1λ. In Case 1 (Fig. 3(a)), the hole is cylindrical with a diameter of 3λ. The shape of the other three cases are all the frustum of a cone, and the diameters of the hole bottoms are all 3λ. For Case 2 (Fig. 3(b)), Case 3 (Fig. 3(c)), and Case 4 (Fig. 3(d)), the diameters of the hole exits are 2λ, 4λ, and 1λ, respectively. The four targets have the same H layers in the bottom of the holes. The thickness of the H layer is 0.3λ, while the diameter is 3λ. The ionization degree of the Al layer is 10, the density of ionized Al ions is $50n_c$, and the electron density of the Al layer is $500n_c$. Here $n_c = m_e\omega_0^2/4\pi e^2$ stands for the critical density. The plasma density of the H layer is $n_p = n_e = n_c$. The simulated particles mass ratio of protons and electrons is $m_p/m_e = 1836$, and $m_{Al}/m_p = 27$.

3. Results and discussion

According to the target normal sheath acceleration mechanism (TNSA), the foil electrons are pushed forward by the laser ponderomotive force, and form an electron cloud at the rear surface of the target. This electric charge separation indicates

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