PROTON BEAM QUALITY IMPROVEMENT BY A TAILORED TARGET ILLUMINATED BY AN INTENSE SHORT-PULSE LASER *

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Abstract

Suppression effect of proton beam divergence is numerically demonstrated in a tailored thin foil target with a hole at the opposite side of laser illumination. When an intense short pulse laser illuminates the thin foil target with the hole, edge effects of an accelerated electron cloud and an ion source cloud are eliminated by a protuberant part of the hole: the edge effects of the electron and ion-source clouds induce the proton beam divergence. Therefore the transverse proton beam divergence was suppressed well. In this study, we present the robustness of the hole target against laser parameter changes in a laser spot size and a laser pulse length, against a contaminated proton source layers, the laser alignment error, and the target positioning error by using particle-in-cell simulations.

INTRODUCTION

Recent researches have demonstrated acceleration of ions to high energies (>MeV) in an interaction between an intense laser pulse and a thin foil target [1-13]. These ion beams are expected to be useful for medical therapies, nuclear physics, controlled nuclear fusion, and so on [14-25]. One of the important parameters is a quality of the generated ion beams.

When an intense laser illuminates a thin foil, electrons obtain energies from the laser pulse and cause an electric charge separation. These electrons accelerated by the laser from an electron cloud, and ions are accelerated by the strong electric field, which is produced by the electric charge separation. Ion energies of a few MeV have been already observed in recent. The quality of an ion beam is one of the key issues in the beam generation. Mono-energetic ion beams are also generated in recent studies [26, 27]. On the other hand, a suppression of the transverse ion beam is also important. In our previous work, a thin foil target with a hole at the opposite side of the laser illumination was proposed in order to eliminate the edge field of the ion and electron clouds, which induces the ion beam transverse divergence. The electrons accelerated propagate in the laser longitudinal direction and also expand in the transverse direction. The edge effect of the ion and electron clouds contributes to the ion beam divergence in transverse direction. Using the target with the hole, the transverse edges of the ion and electron clouds are limited and shielded by the protuberant plasma.

In this paper, we focus on the robustness of the hole target against a contaminated surface layers. It may be also difficult to make the laser axis coincide with the target hole center line in realistic experiments, when the target has only one hole. In this 2.5D particle-in-cell (PIC) simulations demonstrate the robustness of the hole target against a contaminated proton source layer. The simulation results also present that the multiple-hoe target is robust against the laser alignment error and the target positioning error.

NUMERICAL MODEL FOR PROTON ACCELERATION ILLUMINATED BY AN INTENSE SHORT PULSE LASER

We perform 2.5-dimensional PIC simulations in our study. Figure 1 shows a conceptual diagram of aluminium (Al) target with a hole at the opposite side of laser illumination. The Al target has a linear density gradient in 0.5λ at the laser illumination surface. The laser wavelength λ is 1.053μm. The mesh size for the calculation is $\Delta x=\Delta y=0.02\lambda$ and the integration time step is $0.04\Delta x/c$, where c is speed of light.

In this research, we employ a two-layered target, which consists of Al and hydrogen (H). The heavy material Al layer prevents the target deformation and supplies more electrons compared with the H layer. The initial target peak density is the solid one, i.e., 42 times the critical density.

The hole protuberant part shields the transverse edge field by the ion and electron clouds. As a result, the transverse electric field generated is well suppressed. Consequently, the proton beam divergence can be suppressed. It is important to produce a high quality ion beam for various applications, and the target must be also robust against changes in laser parameters and contaminated additional layers.

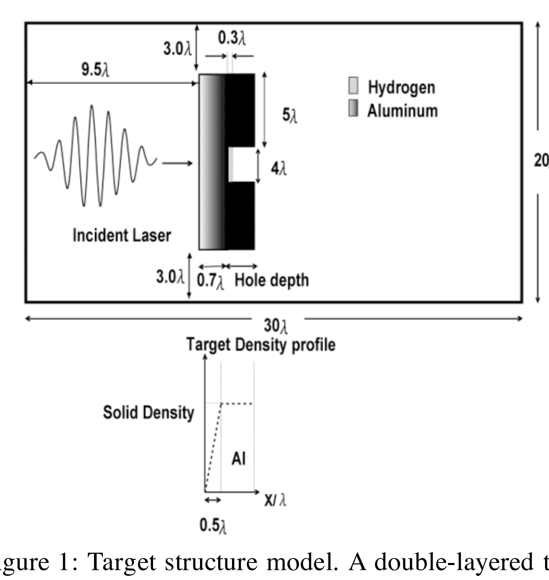

Figure 1: Target structure model. A double-layered target consists of Al and H.

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CALCULATION RESULTS FOR ROBUST TARGET WITH HOLE

In real experiments, the target may be contaminated by additional proton source layers, for example, at the hole side wall or so, as shown in Fig.2. Therefore we investigate the influence of the additional contaminated ion source layers to the proton beam generation from the proton source layer ("Base" proton layer in Fig.2) at the bottom. The hole depth is 2.3λ or 4.3λ, the H layer is placed at the opposite side of the laser illumination and the H thickness is 0.3λ. The laser peak intensity is 10^{20}W/cm^2, the laser spot diameter is 4λ and the laser pulse length is 20fs. Figure 3 shows the spatial distributions for the "Base", "Side" and "Surface" protons and the proton kinetic energy distributions at t=700fs. In both cases, the "Base" proton divergence is suppressed and the "Base" protons are accelerated well in the longitudinal direction.

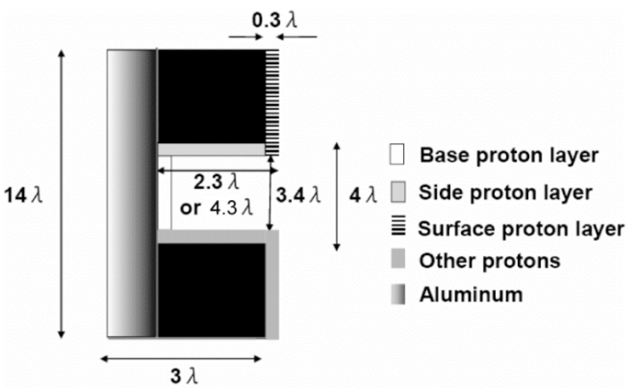

Figure 2: Hole target model with additional contaminant hydrogen layers.

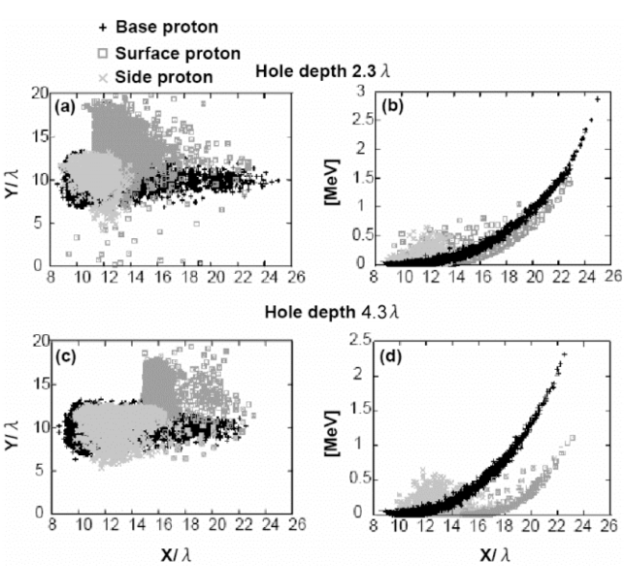

Figure 3: Spatial distributions of the protons and the kinetic energies at t=700fs.

The divergence angle θ_{div} of protons is calculated by

$$\theta_{div} = \sqrt{\frac{\sum_{i=1}^{N}\left(\Delta\theta_i\right)^2}{N}} \tag{1}$$

where is N is the total number of protons and the divergence angle at each proton i is

$$\Delta\theta = \arctan\frac{V_y}{V_x} \tag{2}$$

where V_x and V_y are the proton velocities in the transverse and in the longitudinal directions, respectively.

The divergence angle of the "Base" protons is 0.37. The "Side" protons are accelerated mostly in the transverse direction (normal to the hole side wall surface) and their kinetic energy is small compared with the "Base" proton energy, especially in the case of the deeper hole. The "Surface" protons are not well collimated, and accelerated in both the longitudinal and the transverse directions. The maximum value of the longitudinal electric field reaches 3.12MV/μm at the "Surface" proton layer and 5.16MV/μm at the hole bottom of the "Base" proton layer. Consequently, the maximum kinetic energies of the "Surface" and "Base" protons reach 1.5MeV and 2.8MeV, in the cases shown in Fig.3. Figure 3 shows the proton distributions and the kinetic energies in the case of the hole depth of 4.3λ. These results present that protons originated from the additional contaminated layers do not disturb the "Base" proton acceleration, and the "Base" proton beam is well separated spatially and in their energies from the other protons generated from the contaminants.

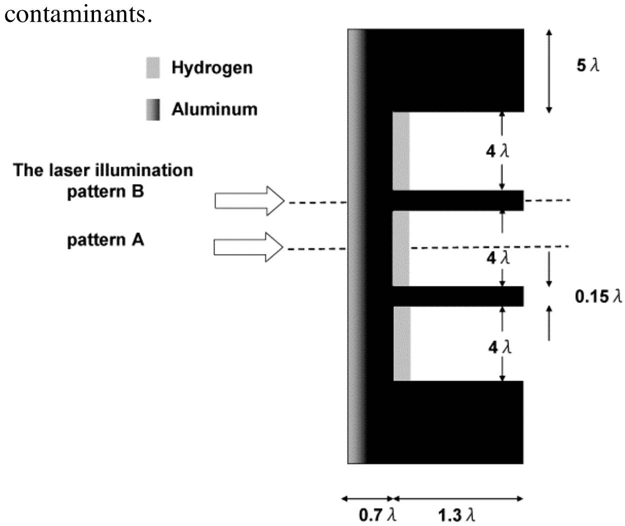

Figure 4: Multiple hole target and laser illumination patterns.

In actual uses, it may be difficult to make the laser axis coincide with the target hole center line. Therefore we propose a new robust target with multiple holes shown in Fig.4. Figure 4 shows the laser illumination patterns. In the pattern A, the laser axis coincides with one of the target hole center lines. On the other hand, in the pattern

B, the laser illuminates the center of the protuberant part, i.e., the partition boundary wall. The laser intensity is $2.5x10^{19}W/cm^2$, the laser spot diameter is 8λ and the laser pulse duration is 20fs.

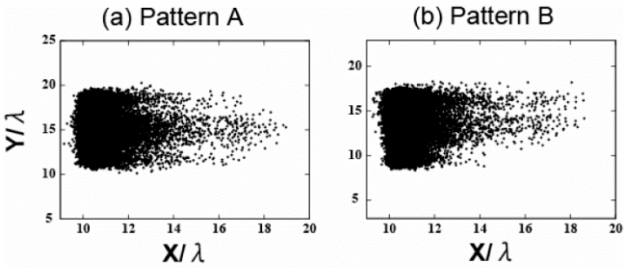

Figure 5: Spatial distributions of the generated proton beams in the patterns of A and B at t=700fs.

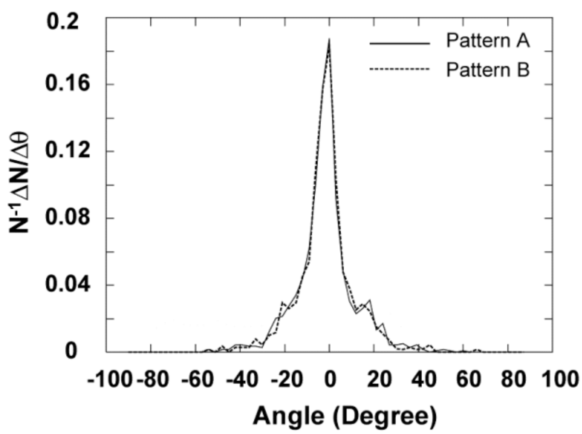

Figure 6: Angular distributions of the protons for the patterns A and B (>150keV). The solid line shows case in the pattern A and the dotted curve indicates case in the pattern B.

Figure 5 show the proton spatial distributions at t=700fs. Figure 6 presents the angular spectra for both patterns of A and B. In the patterns of A and B, the maximum kinetic energies are 1.24MeV and 1.14MeV, the divergence angles are 0.25 and 0.26, respectively. These results demonstrate that the multiple-hole target is robust against the laser alignment error and the target positioning error.

CONCLUSIONS

We investigated the robustness of the hole target for the high quality proton beam generation in the laser-plasma interaction. The edge effects of the ion and electron clouds deform the potential shape, which defines the proton extraction direction. Consequently, the proton beam divergence is induced by the deformed potential shape especially at the ion cloud transverse edge. The hole target can shields the edge field of the ion and electron clouds at the ion cloud transverse edge, and the proton beam divergence is suppressed successfully.

The present work demonstrated that the hole target is robust against the laser parameter changes in the laser spot size and the pulse length, and against the additional protons emitted from the contaminants. The multiple-hole target is also robust against the laser alignment error and the target positioning error. The hole target may serve a robust target to produce a collimated proton beam in realistic experiments and uses.

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