Collimated Ion Beam by a Tailored Target Illuminated by an Intense Short Pulse Laser

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Abstract. In a laser-foil interaction for an ion beam generation, suppression of a transverse proton beam divergence is realized by a tailored thin foil target, which has holes at the rear side of the target. The electron and proton clouds are limited in transverse by the plasma at the protuberant part. In this paper, we investigate the robustness of the hole target for the high quality proton beam generation in the laser-plasma interaction. The transverse edge effects of the ion cloud and the electron cloud deform the potential shape, which defines the proton extraction direction. Consequently the proton beam divergence is induced by the deformed potential shape. The protuberant part of the hole target shields the edge fields of the ion and electron clouds. The present work demonstrate that the hole target is robust against the additional contaminated proton source layers. The multiple-hole target is also robust against the laser alignment error and the target positioning error. The multiple-hole target may serve a robust target to produce a collimated proton beam in realistic experiments and uses.

1. Introduction

Acceleration of ions to high energies (>MeV) has been demonstrated in an interaction between an intense laser pulse and a thin foil target [1-9]. The ion beams are useful for basic particle physics, medical therapy, controlled nuclear fusion, high-energy sources, and so on [10-19]. One of the important issues of ion beam parameters is a quality of the ion beam. When an intense laser illuminates a thin foil, electrons obtain energies from the laser pulse and create an electric charge separation. The electrons, accelerated by the laser, form an electron cloud, and ions are accelerated by the strong electric field, which is produced by the electric charge separation. The quality of an ion beam is one of the critical issues in the ion beam generation. Mono-energetic ion beams are also generated in recent studies [20]. On the other hand, a reduction of the transverse ion beam divergence is also important. In our previous work [19], we proposed a thin foil target with a hole at the opposite side of the laser illumination, in order to eliminate the transverse edge fields of the ion cloud and the electron cloud. The accelerated electrons propagate in the laser longitudinal direction and also expand in the transverse direction (see Fig. 1(a)) [21, 22]. The transverse edge effects of the ion and electron clouds contribute to the ion beam divergence in transverse. In the case of the target with the hole, the transverse edges of the ion cloud and the electron cloud are limited and shielded by the protuberant plasma of the target hole. For the hole target in Fig. 1(b), the transverse edge field $E_y$ is shielded by the high density protuberant part. This is the hole shielding effect on the suppression of the ion beam divergence. When a thin-foil target has no hole (see Fig. 1(a)) or a shallow hole, this $E_y$ shield is not expected and $E_y$ remains. If a target has the hole and the hole depth is sufficiently deep, a collimated
ion beam is produced. In this paper, we focus on the robustness of the hole target against a contaminated surface layer and the laser alignment error. 2.5-dimensional PIC (particle-in-cell) simulations demonstrate the robustness of the hole target against a contaminated proton source layer. The simulation results also present that a multiple-hole target is robust against the laser alignment error and the target positioning error.

2. Robust hole target

2.1. Contaminated layer effect on proton beam generation

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. We investigate the influence of the additional contaminated ion source layers to the generation of the proton beam from the “Base” proton layer at the hole bottom in Fig. 2. The hole depth is 2.3\( \lambda \), and the H thickness is 0.3\( \lambda \). The laser peak intensity is \( 1.0 \times 10^{20} \) W/cm\(^2\), the laser spot diameter is 4\( \lambda \), and the laser pulse length is 20 fs. Figures 3 show the spatial distributions, the proton kinetic energy distributions and the velocity distributions for the “Base”, “Side” and “Surface” protons at \( t=800 \) fs in the case of the hole depth of 2.3\( \lambda \). In the case shown in Figs. 3 the “Base” proton divergence is suppressed and the “Base” protons are accelerated well in the longitudinal direction. The divergence angle of the “Base” protons is \( \theta_{div}=0.37 \) degree. 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. The “Surface” protons are not well collimated, and are accelerated in both the longitudinal direction and the transverse direction. The maximum value of the longitudinal electric field reaches \( \sim3.12 \) MV/\( \mu \)m at the “Surface” proton layer and \( \sim5.16 \) MV/\( \mu \)m at the “Base” proton layer. The maximum kinetic energies of the “Surface” and “Base” protons are 1.5 MeV and 2.8 MeV, respectively, in the cases shown in Figs. 3 (a), (b) and (c). The result presents that protons originated from the additional contaminant layers do not disturb the “Base” proton acceleration, and that the “Base” proton beam is well separated in space and in their energies from the other protons originated from the contaminated layers.

Figure 1. Thin-foil targets (a) without a hole and (b) with a hole. In the hole target the proton cloud is limited by the hole width in transverse. The hole protuberant part plays a role of a plasma source and shields the transverse edge field generated by the ion and electron clouds, so that a collimated proton beam is produced by the hole target.

Figure 2. The hole target with additional contaminant hydrogen layers.
2.2. Effect of errors of laser alignment and target positioning on proton beam generation

In actual uses and realistic experiments it may be difficult to make the laser axis coincide with the target hole center line. In this Subsection we propose a robust target with multiple holes shown in Fig. 4. Figure 4 also shows the laser illumination pattern (the patterns A and B). In the pattern A, the laser axis coincides with one of the target hole center lines, and in the pattern B the laser illuminates the center of the protuberant part, that is, the partition boundary wall wing. The Al layer thickness is 2.0 $\lambda$, the hole depth is 1.3 $\lambda$, and the wing width is 0.15 $\lambda$. The laser intensity is $2.5 \times 10^{19}$ W/cm$^2$, the laser spot diameter is 8 $\lambda$, and the laser pulse length is 20 fs. Figures 5 show the proton spatial distributions at 700 fs. The divergence angle distributions and the energy spectra are almost identical in both the patterns. In the patterns of A and B, the maximum kinetic energies are 1.24 MeV and 1.14 MeV, the divergence angles are $\theta_{div}=0.25$ degree and $\theta_{div}=0.26$ degree, and the maximum values of the proton beam intensities are $2.34 \times 10^{16}$ W/cm$^2$ and $1.96 \times 10^{16}$ W/cm$^2$, respectively. The simulation results demonstrate that the multiple-hole target is robust against the laser alignment error and the target positioning error, as far as the wing width is small compared with the laser spot size.

3. Conclusions

In this paper, we investigated the robustness of the hole target for the high quality proton beam generation in the laser-plasma interaction. The transverse edge effects of the ion cloud and the electron cloud deform the potential shape, which defines the proton extraction direction. Consequently the proton beam divergence is induced by the deformed potential shape. The protuberant part of the target hole shields the edge fields of the ion and electron clouds, and consequently the proton beam divergence is suppressed. The present work demonstrated that the hole target is robust against the additional contaminated proton source layers. The multiple-hole target is robust against the laser alignment error and the target positioning error. The multiple-hole target may serve a robust target to produce a collimated proton beam in realistic experiments and uses.
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