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Effects of Plasma Foil Target Geometry on Achievable Energy of Fast Ions Generated by an Intense Ultra-Short Laser Pulse

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Abstract

Particle-in-cell (PIC) simulations of fast particles produced by a short laser pulse of duration of 40 fs and intensity of 10^{20} W/cm^2 interacting with a foil target are performed. Dependence of the generated fast ion energy on the target geometry is examined. The absorbed laser energy is transferred to fast electron, which interact with the foil and are partially ejected from the foil surfaces. These electrons produce an electric field that causes an ion beam to be emitted from the foil rear surface. Mechanism of fast (multi-MeV) ion acceleration in the foil plasma and the influence of the front density gradient and other laser and plasma parameters on ion acceleration are analyzed.

Keywords:

intense ultra-short laser pulse, fast electron generation, fast ion generation

1. Introduction

Fast particles generated by laser-plasma interactions can be used in many applications, from manufacturing to medicine and even for the initiation of tabletop nuclear reactions. Fast ion generation by the interaction of an ultra-short high intensity laser pulse with a plasma has been demonstrated in recent theoretical [1] and experimental [2] papers, with maximum ion energies of up to 0.5 GeV having been observed. Different methods of fast ion generation have been proposed for both gas [3] and solid [4] targets. It has been shown that the energy of a laser pulse can be efficiently converted into fast ion energy using foil targets. Simulation [5] has shown that the mechanisms for generating ion acceleration are the ambipolar field and the Coulomb explosion. It has also been shown that fast electrons ejected from the foil by the laser field create a strong ambipolar field, which is the main source of acceleration of ions ejected from the back of the foil. Thus a collimated ion beam can be produced by focusing an intense laser onto the surface of a solid film [4]. Fast ions are accelerated normally to the foil surface [6]. Most experimental high power lasers produce a pre-pulse, which generates a plasma layer with a smooth density gradient on the surface of the foil. In this paper, we attempt to develop a simulation model to analyze the mechanism of ion acceleration in plasma layers with smooth density gradients. We select a very short (40 fs) laser pulse and thin foil (2 μm).

2. PIC simulation

In solid target experiments with focused intensities exceeding 10^{20} W/cm^2, high-energy electron generation and energetic protons have been observed on the backside of the target [7]. We apply a PIC method to simulate the interaction of a plasma layer with an intense ultra-short laser pulse. The method is based on the electromagnetic PIC and is appropriate for analysis of the dynamics of over dense plasmas created by arbitrarily polarized, obliquely incident laser pulses. The two dimensional (using a Cartesian coordinate system) relativistic, electromagnetic code [6] is used to calculate the interaction of an intense laser pulse with an over-dense plasma. Calculations with ion mobility allowed were carried out for a plasma with the initial density profile shown in Fig. 1. Simulations were performed for laser wave length of 1 μm

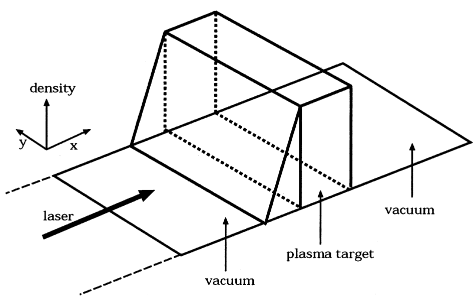

Fig. 1 Target density profile.

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and laser intensity of 10^{20} W/cm^2. The time step is chosen to be $0.03c/\omega$ where ω is the laser frequency, and the mesh size is chosen to be $0.03c/\omega$, where c is the velocity of light. The number of x-axis grid points is 10^4 and the maximum electron density is $4n_c$, where n_c is the critical density. The plasma density gradient varied $155 \leq \omega x/c \leq 183$ and the constant plasma density was at $183 \leq \omega x/c \leq 239$ (see Fig. 1). We have demonstrated fast ion production and focusing from the rear surface of the foil. We consider three kinds of target here, which are slab target, target with triangle cavity and target with circle cavity. Figure 2 shows the geometry of the targets with the triangle and circle cavities.

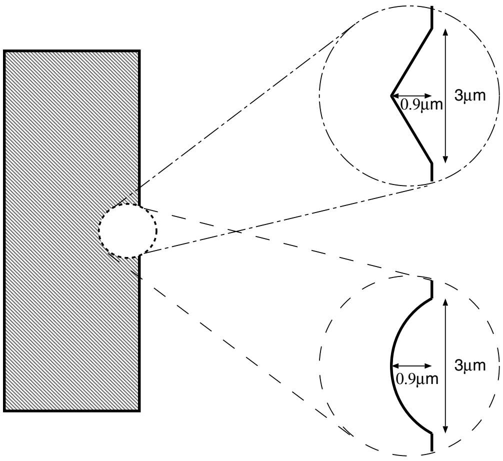

Fig. 2 Geometry of a target containing a cavity with geometrical sizes.

3. Fast ion production from the rear surface of the foil

The absorbed laser energy is transferred to fast electrons, which interact with the foil and are partially ejected from the foil surfaces. These electrons produce an ambipolar field that causes an ion beam to be emitted from the foil rear surface. Fast ions accelerate normally to the foil surface because this is the direction of the ambipolar field. We note that ions are ejected from both sides of the target: but fewer fast electrons, and hence fewer ions, are ejected from the front side. Thus, we only consider the rear side of the target. In Figs. 3, 4 and 5, spatial distributions of ion density at different times are shown for the slab target, the target with triangle cavity and

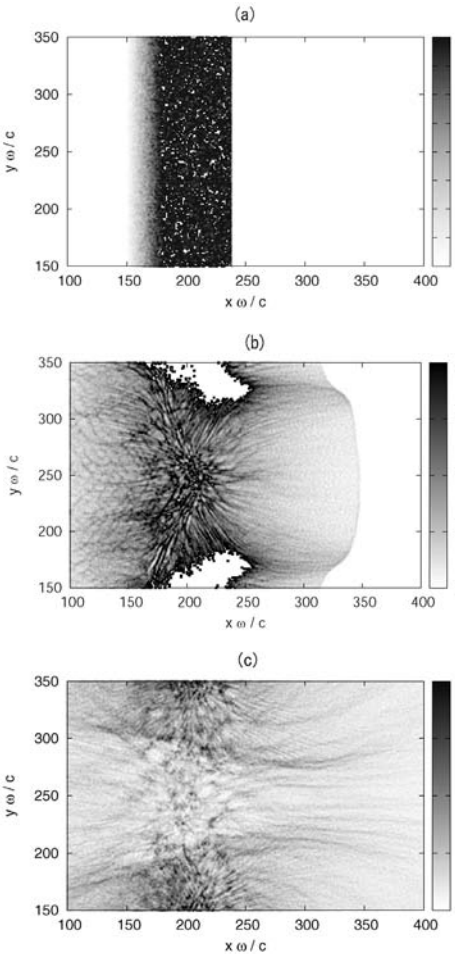

Fig. 3 Spatial distribution of ion density from the slab target at (a) $\omega t = 0$, (b) $\omega t = 400$ and (c) $\omega t = 800$. The density scales are limited to (a) $4n_e$, (b) $2n_e$ and (c) $2n_e$.

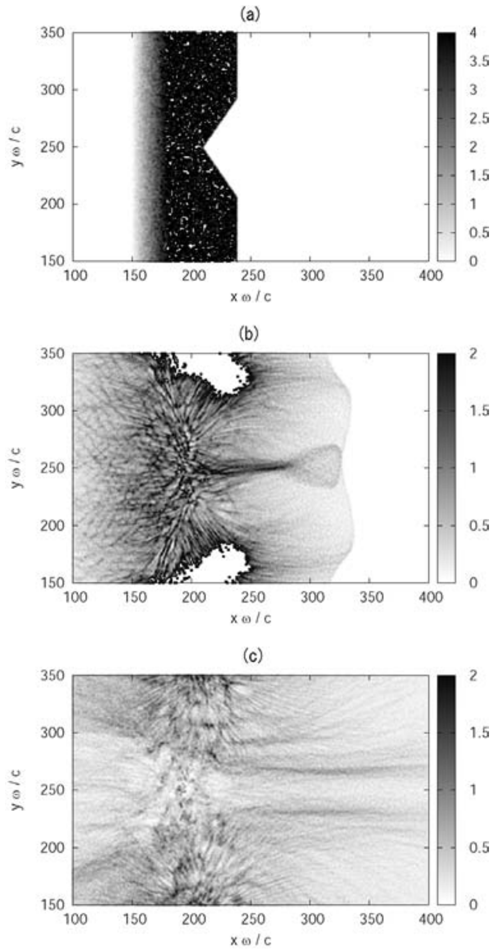

Fig. 4 Spatial distribution of ion density from the target with triangle cavity at (a) $\omega t = 0$, (b) $\omega t = 400$ and (c) $\omega t = 800$. The density scales are limited to (a) $4n_e$, (b) $2n_e$ and (c) $2n_e$.

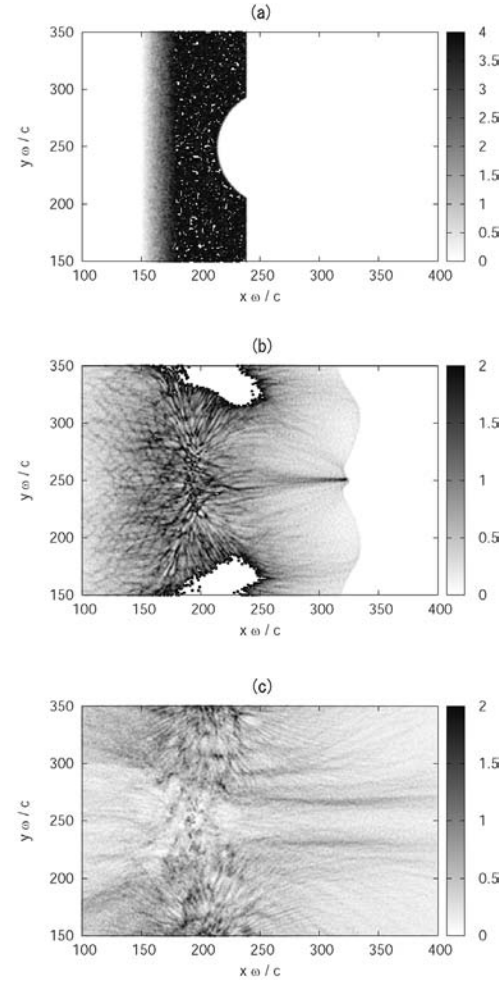

Fig. 5 Spatial distribution of ion density from the target with circle cavity at (a) ωt = 0, (b) ωt = 400 and (c) ωt = 800. The density scales are limited to (a) $4n_e$, (b) $2n_e$ and (c) $2n_e$.

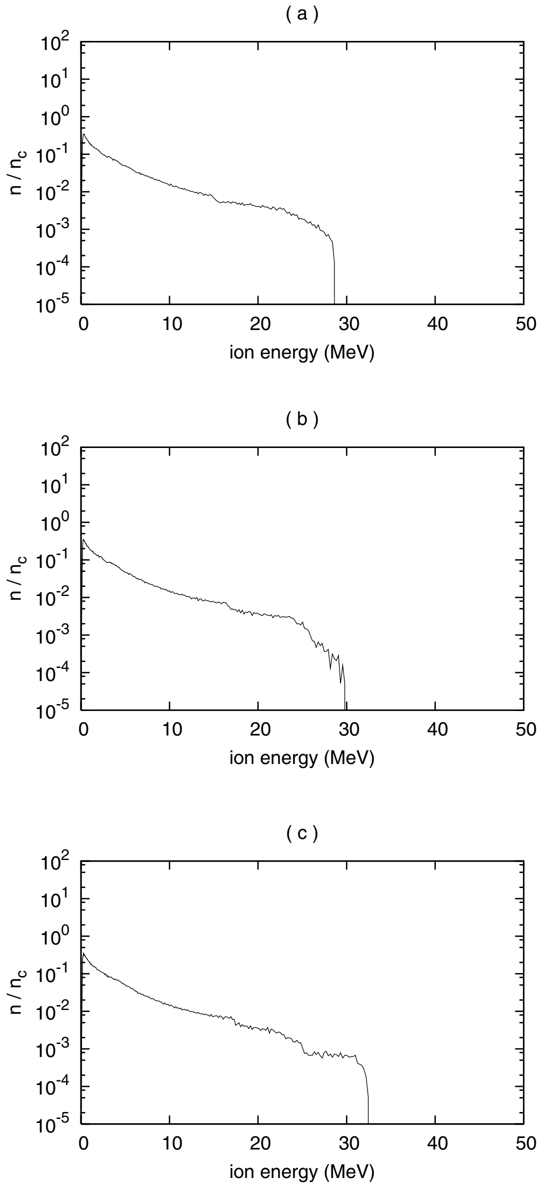

Fig. 6 Ion energy distributions at $\omega y/c$ = 250 for ωt = 800 with (a) the slab target, (b) the target with triangle cavity and (c) the target with circle cavity.

the target with circle cavity, respectively. In Fig. 6, ion energy distributions at $\omega y/c$ = 250 for ωt = 800 are shown in the three cases of the target. It is clear that these ions could be focused by a target with circle cavity in a small volume.

4. Conclusion

We have shown numerically that a laser pulse of intensity 10^{20} W/cm^2 and a duration of 40 fs will generate an intense ion bunch that propagates directly from the rear surface of the foil. Finally, we get a maximum ion energy of 32.4 MeV at ωt = 800 from the target with circle cavity, a maximum ion energy of 29.8 MeV at ωt = 800 from the target with triangle cavity and a maximum ion energy of 28.6 MeV at ωt = 800 from the slab target. We can conclude that the target with circle cavity is the most useful target to generate an intense ion bunch in these different targets.

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