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Two-dimensional particle-in-cell simulation of energetic proton generation by an intense ultrashort laser pulse

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Abstract. Two-dimensional particle-in-cell (PIC) simulations of fast particles produced by a short laser pulse with a duration of 40 fs and an intensity of 10^{20} W cm^{-2} interacting with a foil target are performed. The dependence of the energy of the generated fast protons on the target geometry is examined. 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 electric field that causes a proton beam to be emitted from the rear surface of the foil. Various kinds of target are considered. The optimum target plasma conditions for the maximum proton acceleration are determined.

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 proton generation by the interaction of an ultrashort high-intensity laser pulse with a plasma has been demonstrated in recent theoretical [1] and experimental [2] papers. Different methods of fast proton 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 proton energy using foil targets. Simulations [5–7] have shown that the mechanisms for generating proton 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 protons ejected from the back of the foil. Thus, a collimated proton beam can be produced by focusing an intense laser onto the surface of a solid film [4]. It was shown that the peak proton energy was reduced as the target thickness was increased [8]. Fast protons are accelerated normally to the foil surface. 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 [5, 9]. In this paper, we attempt to develop a simulation model to analyze the mechanism of proton acceleration in plasma layers with

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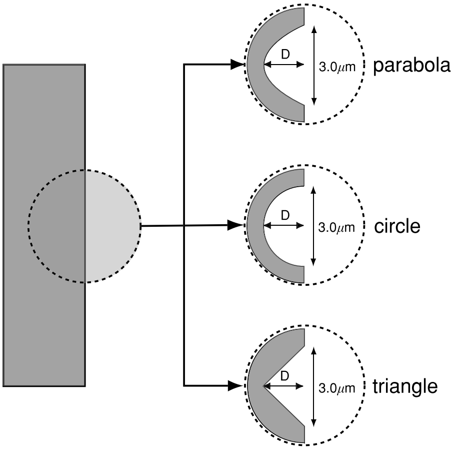

Figure 1. Target profile.

smooth density gradients. We select a very short (40 fs) laser pulse and thin foil (3 μm). We consider various kinds of target. The depth D of the cavity of the target is changed from ϕ to λ. Optimum target conditions with cavity for the peak proton energy are found.

2. Fast proton generation from the rear surface of the foil

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 [10]. We apply a particle-in-cell (PIC) method to simulate the interaction of a plasma layer with an intense ultrashort 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 is used to calculate the interaction of an intense laser pulse with an over-dense plasma. Simulations were performed for a laser wavelength λ of 1 μm and laser intensity 10^{20} W cm^{-2}. The time step is chosen to be $0.03/\omega_{\mathrm{L}}$ where ω_{L} is the laser frequency, and the mesh size is chosen to be $0.03c/\omega_{\mathrm{L}}$. The number of x-axis grid points is 10^4 and the maximum electron density is $4n_{\mathrm{c}}$, where n_{c} is the critical density. We have demonstrated fast proton production and focusing from the rear surface of the foil [6]. We consider various kinds of target. The depth D of the cavity of the target is changed from ϕ to λ.

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 a proton beam to be emitted from the foil rear surface. Fast protons accelerate normally to the foil surface because this is the direction of the ambipolar field. It is clear that these protons could be focused by a curve of some sort in the foil surface. 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 proton bunch that propagates directly from the rear surface of the foil. Figures 1–5 show

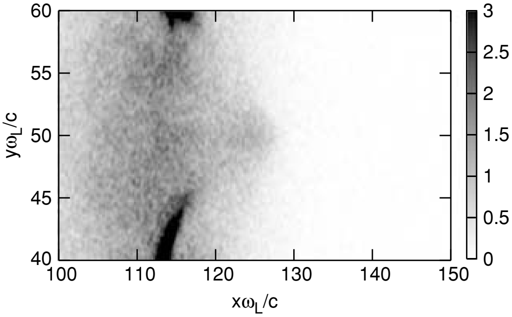

Figure 2. Electron density in the target with parabolic cavity at $\omega_{\mathrm{L}}t = 350$.

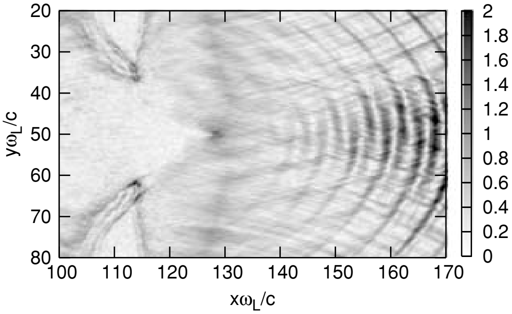

Figure 3. Electric field in the target with parabolic cavity at $\omega_{\mathrm{L}}t = 350$.

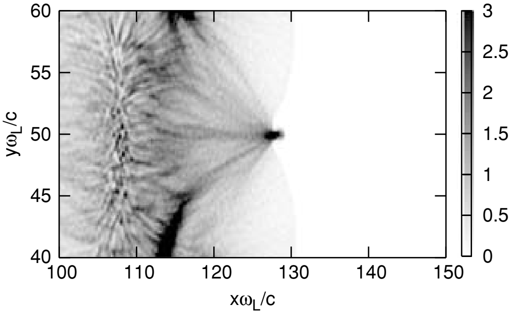

Figure 4. Proton density in the target with parabolic cavity at $\omega_{\mathrm{L}}t = 350$.

the target profile, electron density in the target with parabolic cavity, electric field in the target with parabolic cavity, proton density in the target with parabolic cavity and peak proton energy, respectively. In Figs 2–4, the initial position of the rear surface is $x\omega_{\mathrm{L}}/c = 118$. In Fig. 5, we can conclude that there is a maximum peak proton energy for the depth of the cavity.

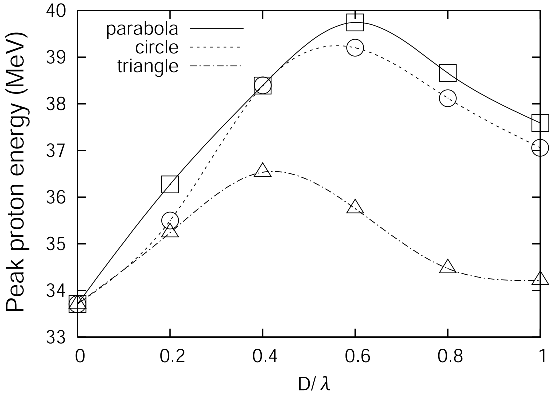

Figure 5. Peak proton energy versus cavity depth D.

3. Conclusions

We have investigated the peak proton energy for targets with triangular, circular and parabolic cavities by two-dimensional PIC simulation. An optimum target condition with parabolic cavity for the maximum peak proton energy has been found.

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