Proton Acceleration in the Interaction of an Intense Laser Light with a Cone Plasma Target and Coated Proton Layer

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To increase the acceleration rate for producing highly energetic protons, a scheme using a cone-shaped target with a coated proton layer is proposed and demonstrated by 2D particle-in-cell (PIC) simulation. The simulation results show that because the laser light and electrons are guided along the cone wall, the energy and density of hot electrons are enhanced in the cone target. Thus, the amplitude of the sheath field on the target's rear surface is enhanced, since it is proportional to the hot electrons' temperature and the logarithm of their density. Therefore, protons are accelerated strongly by this sheath field.

Keywords: intense laser light, monoenergetic proton, acceleration, cone target, proton layer

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When an ultrashort intense laser light is incident on a planar plasma, hot electrons are generated mainly by ponderomotive force at the interaction surface. Hot electrons propagate through the target and produce a strong electrostatic field normal to the target rear surface due to charge separation, which results in the acceleration of ionized protons in a contaminant. This is termed the target normal sheath acceleration (TNSA) mechanism [1]. To accelerate ions effectively, a scheme that involves coating a proton layer on the rear surface of a planar substrate has been reported [2]. If the coated proton layer is small enough, quasi-monoenergetic MeV protons can be generated [3, 4]. Meanwhile, a target design of the re-entrant cone geometry [5] for fast ignition has attracted considerable interest. The cone target can focus the laser energy and guide high energy electrons to the cone tip, which results in higher energy coupling from the laser to electrons [6]. A cone target is also proposed to increase the generation of protons in simulation [7] and experiment [8], but their energy spreads are almost 100%.

To increase the energy of quasi-monoenergetic protons, we propose a new scheme in this rapid communication. In this scheme, a cone-shaped target of metal material is used to interact with an ultrashort intense laser light for improving the generation and confinement of hot electrons. The rear surface of this target is coated with an extra ultrathin proton layer with relatively low density to act as the source for the acceleration. Due to the TNSA mechanism [1], protons are accelerated by the sheath field produced by hot electrons on the boundary between the high-Z substrate and the proton layer. As a result, the higher energy and density of hot electrons in the cone target increase the proton energy.

Two-dimensional PIC simulations were performed to investigate the above process. The scales of the simulation box are $X \times Y = 60\lambda_0 \times 40\lambda_0$ with a cell size of $\Delta X = \Delta Y = 0.05\lambda_0$, where λ_0 is the wavelength of the incident laser light. A linearly polarized Gaussian laser beam with a focal spot of $6\lambda_0$ (FWHM) is incident to the simulation box along the X axis from left to right. The laser beam rises up in $5\tau_0$ with a sinusoidal profile, after which it maintains its peak intensity for $20\tau_0$, and then falls to zero in another $5\tau_0$, where τ_0 is the laser period. The peak normalized vector potential is $a_0 = eA/m_e\omega_0 c^2 = 5.0$, which corresponds to the incident intensity $I_0 = 3.5 \times 10^{19}\ \mathrm{W/cm^2}$.

The geometry of the cone-shaped substrate and coated proton layer is shown in Fig. 1. The width of the cone wall is $3\lambda_0$, the open hatch and the tip are $18\lambda_0$ and $2\lambda_0$ wide,

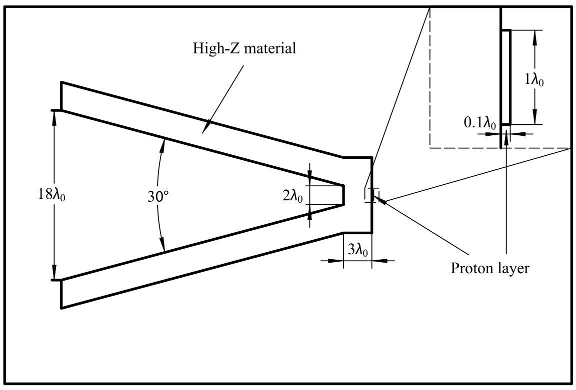

Fig. 1 Schematic of the cone-shaped substrate and the coated proton layer.

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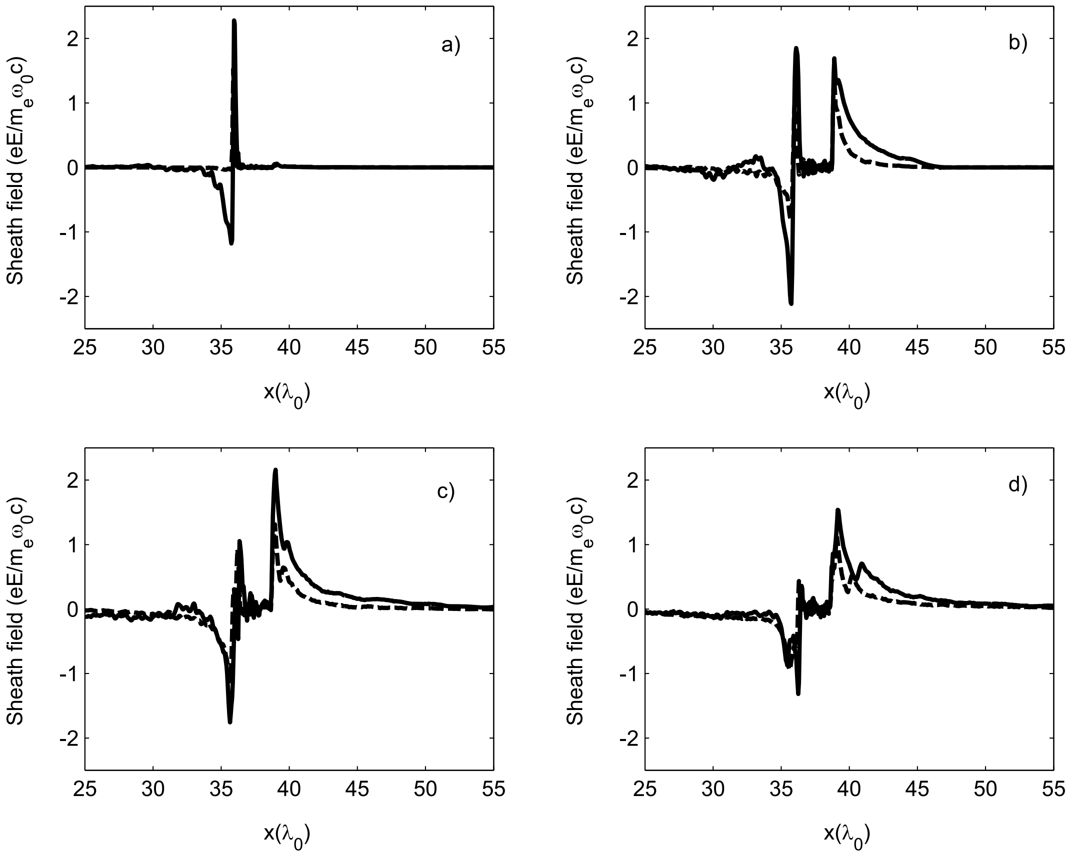

Fig. 2 Amplitudes of sheath fields for the cone target (solid line) and film target (dashed line) at a) $t = 40\tau_0$, b) $t = 50\tau_0$, c) $t = 60\tau_0$, and d) $t = 70\tau_0$.

respectively, and the open angle is 30°. The cone substrate consists of partially ionized plasma where the effective charge-to-mass ratio Z/A is assumed to be 1/10. The electron density of the target is 10 times the critical density (n_c), which is related to the frequency of the incident laser as $\omega_0^2 = 4\pi e^2 n_c/m_e$. The initial electron and ion temperatures are both 1.0 keV. At the rear surface of the cone substrate, there is a proton layer $1\lambda_0$ wide and $0.1\lambda_0$ thick, which is shown in the dashed square in Fig. 1. The electron density of the proton layer is $1.0n_c$. For comparison with the cone target, a film target is simulated. In the film target, the high-Z layer is $18\lambda_0$ wide and $3\lambda_0$ thick. The proton layer is $1\lambda_0$ wide and $0.1\lambda_0$ thick.

Because the protons on the target's rear surface are accelerated directly by the sheath field due to the TNSA mechanism, first we plot the evolution of the amplitudes of the electric fields along the laser axis for both targets in Fig. 2. We can see that at all times the amplitude of the electric field on the rear surface of the cone target (solid line) is much higher than that for the film target (dashed line), as expected. The electrostatic field's higher amplitude indicates higher acceleration for the cone target.

Enhancement of the sheath field is believed to result from the increase of hot electrons generated by the cone target. From the TNSA mechanism [1], the amplitude of the sheath field on the target's rear surface is determined by $E = T_h/e\max(L_n, \lambda_D)$, where T_h is the temperature of hot electrons (not thermal electrons), and L_n and λ_D are the scale length of the electron density and the Debye length. When an intense laser light interacts with the side wall of the cone target, electrons are confined on the surface to the tip by the self-induced surface magnetic field [6]. Meanwhile, the laser pulse is focused by the conical surface, and its intensity can be increased by a few tens of times. The temperature of hot electrons is $T_h = 0.511\times\left(\sqrt{I\lambda^2/1.38\times10^{18}} - 1\right)$ MeV due to the $\boldsymbol{J}\times\boldsymbol{B}$ mechanism dominant in this interaction. Thus, the focused laser light can increase the temperature of hot electrons significantly, and then the sheath field accelerating protons. The energy sepctra of hot electrons escaping from the target's rear surface are plotted in Fig. 3. The electron temperatures are 3.36 MeV and 1.14 MeV for the cone target and film target, respectively. The higher hot-electron temperature of the cone target accounts for the higher sheath field at the target's rear surface. The energy-transfer ratios from the laser to the hot electrons are 1.9% and 0.7% for the cone target and film target, respectively.

The above results demonstrate that the cone target can increase the temperature of hot electrons and then increase the sheath field, which can accelerate protons on the rear

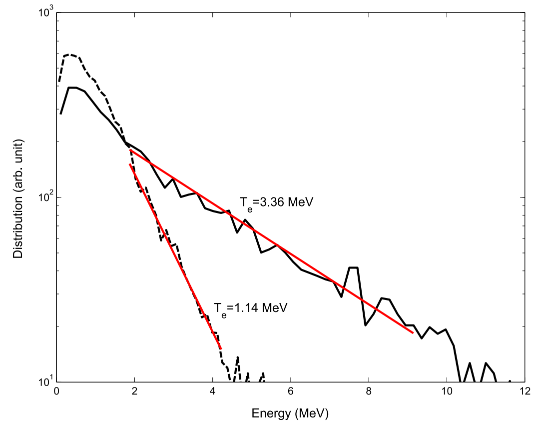

Fig. 3 Energy sepctra of electrons escaping from the rear surface of the cone target (solid line) and film target (dashed line).

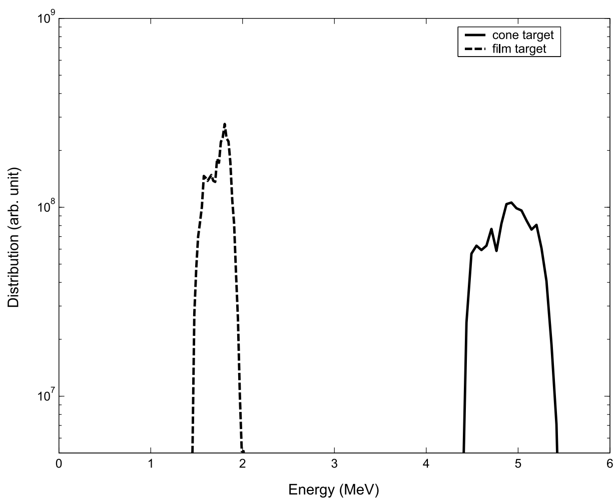

Fig. 4 Energy sepctra of protons at $t = 70\tau_0$ for the cone target (solid line) and film target (dashed line).

surface of the target. Figure 4 shows the energy sepctra of protons measured at $t = 70\tau_0$, just after the incident laser light interacts with plasma. For the film target (dashed line), the peak proton energy is $E_0 = 1.81$ MeV, and the energy spread is $\Delta E_{\mathrm{FWHM}}/E_0 = 9.4\%$. For the cone target (solid line), the peak proton energy is $E_0 = 4.93$ MeV, about three times that of the film target, and the energy spread is $\Delta E_{\mathrm{FWHM}}/E_0 = 10.5\%$. The total energy transported from the laser to protons for the cone target is also about three times that of the film target.

In this rapid communication, a new target design for a cone-shaped substrate, on the rear surface of which a proton layer is coated, is proposed and demonstrated by 2D PIC simulations. It is shown that this scheme can increase the energy of protons and the coupling from laser to protons by about three times while maintaining the protons' monochromaticity. This paper indicates that with this target scheme, a laser pulse of tens of Joules and hundreds of femtoseconds can produce quasi-monoenergetic protons about of 200 MeV, which can be applied in cancer therapy.

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