Improving proton acceleration with circularly polarized intense laser pulse by radial confinement with heavy ions

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Energetic proton acceleration from interaction of intense short circularly polarized laser pulse with a sandwich target is investigated using two-dimensional particle-in-cell simulation. The sandwich target consists of a hydrogen-plasma layer surrounded by carbon-plasma layers. It is found that the transverse electric fields generated at the plasma layer interfaces efficiently confine the longitudinally accelerated protons to within the hydrogen-plasma layer such that they are collimated and have smaller energy spread compared with a pure proton layer target. The proton energy spectrum can be controlled by adjusting the target parameters, in particular the width of the hydrogen-plasma layer and the density of the carbon-plasma layer. © *2010 American Institute of Physics*. [doi:10.1063/1.3302536]

I. INTRODUCTION

With rapid development of the chirped pulse amplification technique, ultraintense ultrashort laser pulses with peak intensity as high as 10^{22} W/cm^2 have become available,[1–5] and have opened a new regime for ion acceleration from intense laser-plasma interactions.[6–15] In particular, generation of monoenergetic ion beams has attracted much attention because of its potential applications in proton diagnosis, cancer therapy, fast ignition in inertial confinement fusion, etc.[16–19] Hegelich *et al.*[20] have obtained quasimonoenergetic laser-driven C^{5+} ions with energy spread of 17% and Schwoerer *et al.*[21] have obtained similar proton beams by laser irradiation of a microstructured solid target. In these experiments, the laser pulse is linearly polarized (LP). Recently, radiation pressure acceleration by circularly polarized (CP) laser pulses has been modeled for monoenergetic ion beam generation.[22–25] Without the oscillating component of the ponderomotive force, the target electrons are less heated than that from of a LP laser and are thus accelerated forward and compressed by the CP laser light pressure. The intense electrostatic space-charge field thus formed can effectively accelerate the target ions. One-dimensional simulations have shown that monoenergetic ions can be generated. For example, Ji *et al.*[24] have obtained nearly monoenergetic heavy ions by using a target consisting of a thin heavy-ion layer sandwiched by two light-ion layers. In reality, multidimensional effects such as hole boring and other instabilities can reduce the quality of the generated ion beams.[26–29] Chen *et al.*[22] proposed to use intense CP laser pulses with a super-Hermite and Gaussian profile instead of the usual Gaussian profile to avoid the multidimensional effects.

Here we propose to use a sandwich target consisting of a hydrogen layer surrounded by two heavy-atom layers. Proton acceleration by a CP laser pulse irradiating the layered side of the sandwich target, as shown in Fig. 1, is studied using two-dimensional (2D) particle-in-cell (PIC) simulation. Our results indicate that, comparing with that from a simple proton target, energetic protons with smaller energy spread can be obtained. This result can be attributed to the formation of transverse space-charge electric fields at the two proton-heavy-ion interfaces. The fields suppress the transverse motion of the protons in the sandwich target, such that the protons are accelerated longitudinally forward with smaller energy spread.

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II. SIMULATION PARAMETERS

In our 2D PIC simulation, the simulation box is $60\lambda_L \times 40\lambda_L$, where $\lambda_L = 1$ μm is the laser wavelength, and contains 2400×1600 cells. A CP Gaussian laser pulse with beam waist radius $\omega_0 = 10\lambda_L$ is normally incident from the left side. The dimensionless laser amplitude $a = eE/m_e\omega c$, where E, ω, and c are the laser electric field, frequency, and speed, respectively, and m_e and e are the electron mass and

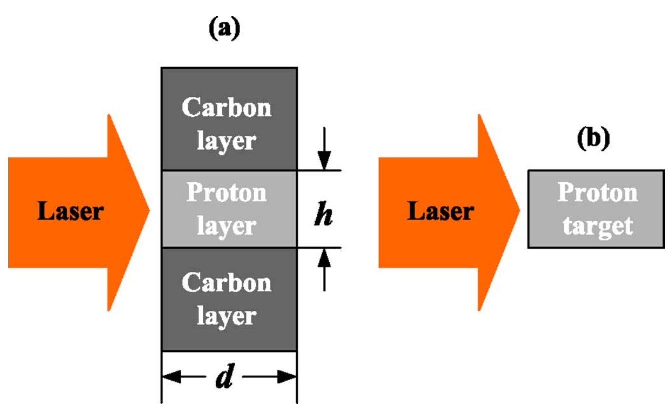

FIG. 1. (Color online) (a) Structure of the sandwich target. Here, h and d are the width and thickness of the proton layer, respectively. (b) Structure of the reference proton target.

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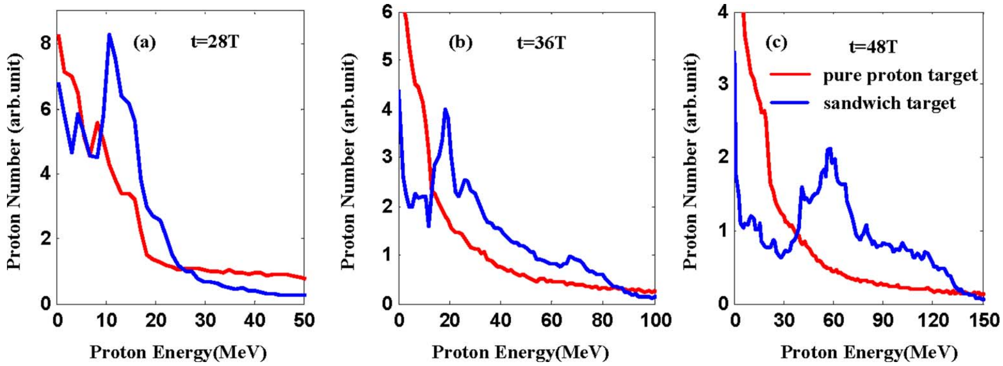

FIG. 2. (Color online) Proton energy spectra for the sandwich and reference target at (a) $t=28T$, (b) $t=36T$, and (c) $t=48T$. Here, $h=2$ μm, and $d=1$ μm, and the initial plasma densities in the proton and carbon layers are $10n_c$ and $30n_c$, respectively.

charge, rises from 0 to 30 (corresponding to a laser intensity of $I_L=2.48\times10^{21}$ W cm^{-2}) in $2T$, where T is the laser period. It remains constant at $a=30$ for $20T$ and then vanishes. The hydrogen plasma is bounded on the two sides by carbon (C^{6+}) plasmas. The front of the 32×1 μm^2 sandwich target, shown in Fig. 1(a), is located at $x_0=20$ μm. The initial temperature of the electrons, protons, and carbon ions is 1 keV. The width h of the proton layer is 2 μm and that of the two C^{6+} layers is 15 μm. The electron densities of the proton and C^{6+} layers are $10n_c$ and $30n_c$, respectively, where $n_c=\omega^2 m_e/4\pi e^2$ is the critical density. As reference, we also simulate proton acceleration in a simple hydrogen target with initial density $n_0=10n_c$, shown in Fig. 1(b).

III. SIMULATION RESULTS

Figure 2 shows the proton energy spectra obtained for the reference and sandwich targets. Figures 2(a)–2(c) correspond to the times $t=28T$, $t=36T$, and $t=48T$, respectively. One sees that at the early time $t=28T$ the proton energy spectrum from the reference target has a small peak around 10 MeV. For the sandwich target, the spectrum shows a larger peak at the higher energy 12 MeV. At $t=36T$, the energy spectrum from the reference target is much broadened and the peak vanishes. In contrast, for the sandwich target the energy peak survives for a much longer time, even up to $48T$, when it reaches 60 MeV. That is, a proton beam of significantly better quality can be achieved by using the sandwich target.

Figure 3 shows the distributions of the cycle-averaged transverse electric field E_y and the transverse momentum M_y of the accelerated protons for the sandwich and reference targets. In the reference target, the transverse electric field in 20 μm$<x<21$ μm is positive in the upper part and negative in the lower part of the target, as shown in Fig. 3(a). This field accelerates the protons outward, i.e., the accelerated protons expand into the surrounding vacuum. In contrast, in the sandwich target the transverse electric field is negative at the upper proton-carbon interface and positive at the lower interface, as shown in Fig. 3(b). These electric fields thus tend to confine the protons in the proton layer, preventing them from migrating into the carbon layers. The confinement and collimation of the accelerated protons in the sandwich target can also be seen in the distribution of the transverse proton momentum M_y, shown in Fig. 3(d). The confinement and collimation lead to prolonged proton acceleration and suppression of higher dimensional effects. The accelerated protons can thus retain a peak at increasing energy, as shown in Fig. 2. As long as they are still inside the sandwich target, the transverse electric field confines and collimates them. However, once they leave the rear target surface they will expand transversely, similar to that of the reference case.

IV. EFFECT OF THE TARGET PARAMETERS ON PROTON ACCELERATION

Figure 4 shows the proton energy spectra for the sandwich target with different mass-to-charge ratio A/Z of carbon ions (i.e., C^{6+}, and C^{3+} ions). It is seen that the proton energy spectra are nearly identical for C^{6+} ions and C^{3+} ions, indicating that the parameter A/Z is not a crucial parameter to affect the proton acceleration. This is contrary to the previous results where either double-layer (i.e., front heavy ion layer and rear proton layer) targets or one-layer (i.e., mixture of heavy ions and protons) targets were simulated.[30–33] In

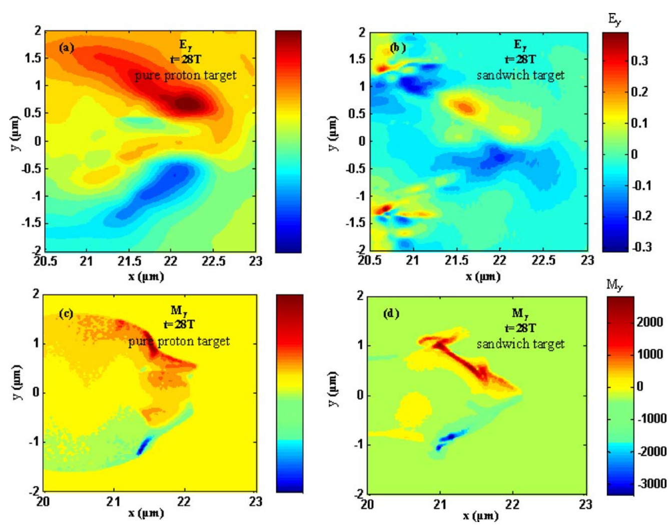

FIG. 3. (Color online) [(a) and (b)] are cycle-averaged transverse electric field E_y. [(c) and (d)] are the distributions of the transverse proton momentum M_y at $t=28T$ for the reference and sandwich targets, respectively. The electric field is normalized by the laser electric field E_0. The front of the target is at $x=20$ μm, and the laser and target parameters are the same as those for Fig. 2.

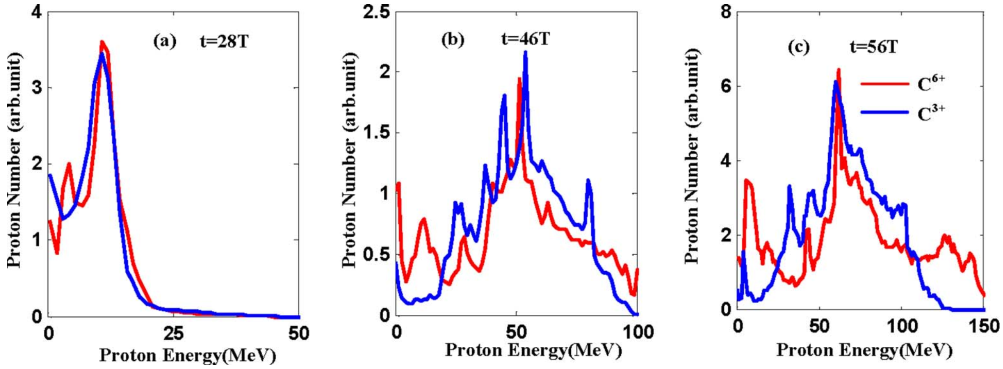

FIG. 4. (Color online) Proton energy spectra for the sandwich target for different carbon ion charge states at (a) $t=28T$, (b) $t=46T$, and (c) $t=56T$. The other simulation parameters are the same as those for Fig. 2 except $h=1$ μm.

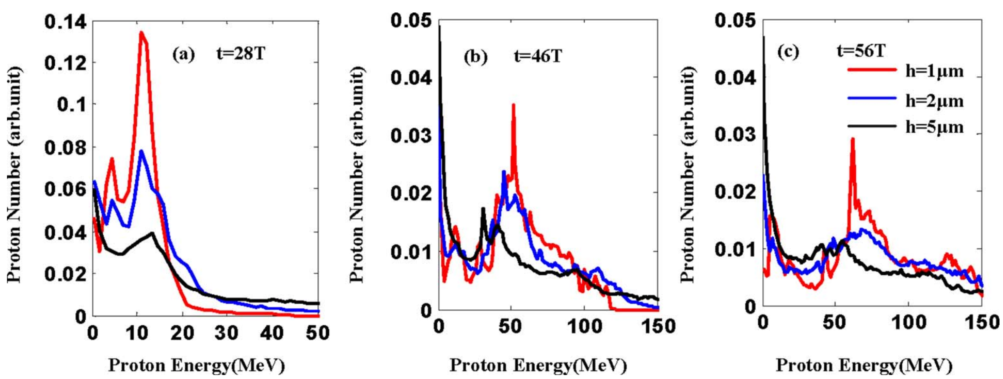

FIG. 5. (Color online) Proton energy spectra for the sandwich target for different width h of the proton layer at (a) $t=28T$, (b) $t=46T$, and (c) $t=56T$. The other simulation parameters are the same as those for Fig. 2.

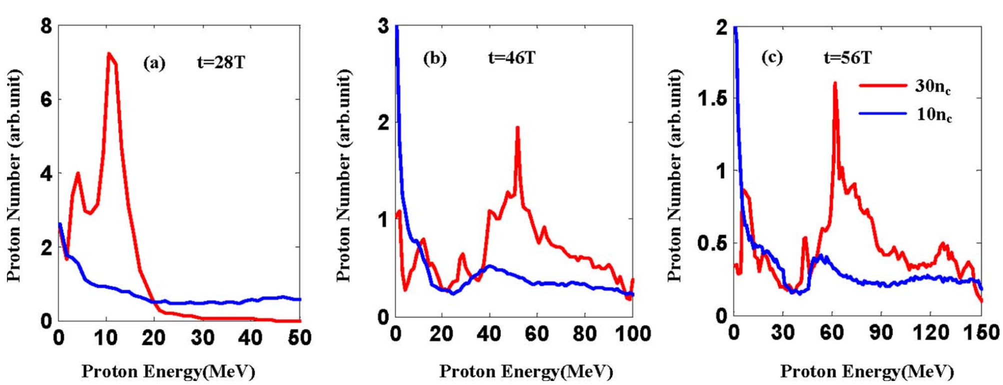

FIG. 6. (Color online) Proton energy spectra for the sandwich target for different carbon-ion densities at (a) $t=28T$, (b) $t=46T$, and (c) $t=56T$. The other simulation parameters are the same as those for Fig. 2, except that the width of proton layer is $h=1$ μm.

these simulations, heavy ions with different A/Z values can strongly affect the longitudinal ponderomotive acceleration field of the protons and thus result in the large difference in the proton energy spectra. However, in the present study, the heavy ions do not affect the longitudinal acceleration field but act to radially confine the protons so as to prolong the longitudinal acceleration of the protons.

Figure 5 shows the dependence of the proton energy spectra on the width of the proton layer. The peak energies in all the three cases shown are almost the same. However, the peak can be narrowed by decreasing the width h of the proton layer. The narrowest energy spread and highest proton yield is for the $h=1$ μm case. This behavior can be attributed to the fact that collimation of the accelerated protons is due to the confining effect of the transverse interface electric fields. As h increases the strength and thus the effect of the latter decreases, so that the lateral motion of the accelerated protons cannot be efficiently suppressed and the proton energy peak broadens.

Figure 6 shows the proton energy spectra for two different initial carbon densities. When the density of the carbon layer is $10n_c$, there is no obvious peak in the energy spectrum since the transverse electric fields at the interfaces are too small to bunch the protons effectively. A fairly sharp peak in the proton energy spectrum appears when the density of carbon layer is increased to $30n_c$.

V. CONCLUSION

In conclusion, proton acceleration using a sandwich target consisting of a hydrogen-plasma layer surrounded by carbon-plasma layers has been investigated by 2D PIC simulation. When an ultraintense CP laser pulse irradiates a sandwich target, the transverse space-charge electric field around the proton-carbon interfaces prevents the protons from moving radially into the surrounding carbon layers and thus suppresses the deformation of the proton layer. The protons can thus be longitudinally accelerated with smaller energy spread compared to the simple proton target. It is found that the width of the proton layer and the density of carbon layer can affect the proton energy spectrum. The peak in the proton energy spectrum can be narrowed by decreasing the width of the proton layer and/or increasing the density of the carbon layer. In real experiments the sandwich target can be replaced by a concentric cylindrical target with the hydrogen plasma at the center.

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