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Control of the charge and energy of the proton beams from a laser-driven double-layer target

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ABSTRACT

Control of the proton beam charge and energy in a laser-driven double-layer target was numerically investigated. Generally the proton beam charge is determined by the areal density $\sigma = nl$ of the second layer, while the accelerating field is governed by the substrate thickness L. From a series of one-dimensional particle-in-cell simulations over a broad range of σ and L, it was confirmed that those two control parameters do not interfere significantly, indicating the beam charge and energy can be separately controlled. We suggest self-assembly monolayers technique be used for the fabrication of the areal density of the second layer.

1. Introduction

Ion acceleration from an ultraintense laser pulse and a thin target has attracted much interest as a potential ion beam source with compactness and low cost compared to conventional technologies. Depending on the power regime of the driving laser pulse, numerous scenarios of ion acceleration have been suggested and tested by theory, simulations, and experiments [1]. Among them the target normal sheath acceleration (TNSA) [2–5] has a relatively long history, and is still gaining much interest, since it can be realized even with a moderate laser power.

Though the TNSA has an intrinsic disadvantage in the broad energy spectrum of the accelerated heavy ions, the acceleration of light ions like protons still has some benefits from the TNSA mechanism by employing a double-layer target [6–16]. In this scheme a thin proton layer coated on the main target is accelerated as a single body by the sheath field, yielding a quasi-monoenergetic proton beam. Due to its natural abundance in the form of a contamination layer [2], some attentions have been paid to the double-layer scheme. For instance, Esirkepov et al. [13] studied the scaling of proton energy by varying the laser intensity for the different areal densities of the target. Yu et al. [14,15] investigated the effects of the layer thickness, where they found that the maximum proton energy increased as the layer thickness increased up to a certain level. Somewhat differently, Robinson et al. [16] analytically studied the influence of the areal density of the proton-ion composite (mixture) target on the proton energy spectrum. However, the combined effects of the substrate thickness and the areal density of the proton layer have not been systematically studied previously.

Recently the technique of the self-assembly monolayers (SAMs) [18] has become available, enabling a separate control of both the layer density and thickness. On the other hand, it is well known that the sheath field from the main target increases as the target thickness is reduced down to roughly the skin depth [13,17]. Motivated by these, we naturally suggest a separate control of the proton beam charge by the layer's areal density as well as the beam energy by the main target (called a substrate from here on) thickness. We studied this idea for the first time by a series of one-dimensional particle-in-cell (PIC) simulations to eventually find that those two control parameters, i.e. the areal density $\sigma = nl$ of the proton layer and the substrate thickness L, do not interfere strongly. This conclusion indicates that σ and L can be utilized as design parameters of the beam charge and energy in the double layer

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scheme.

This paper is organized as follows. In Section 2, the simulation conditions are described. In Section 3, the effects of the areal density of the layer are briefly reviewed along with our own simulation results. The effects of the substrate thickness can be found in Section 4, followed by a summary.

2. Simulation set up

For the simulations, we used a one-dimensional particle-in-cell (PIC) code, where a numerical-dispersion-free field solver in a propagation direction was employed [19], and the third order current calculation and the field interpolation were used to reduce the numerical noise for the high density plasmas.

The physical parameters were set as realistically as possible: for the substrate, we assumed a fully ionized C^{6+} and electron plasma with the density $600n_c$. A thin proton layer, whose thickness and density were 2 nm and $2n_c$, respectively, was put on the front side of the target, corresponding to a contamination layer. On the back side, an artificial proton layer was assumed to be coated with variable thicknesses from 10 to 80 nm, and densities from 2 to $20n_c$. The target configuration is presented in Fig. 1. The driving laser pulse was linearly polarized and longitudinally Gaussian with the normalized vector potential $a_0 = 10$, where $a_0 = eE/mc\omega$, e and m are the charge and mass of an electron, respectively, E and ω are the electric field and angular frequency of the laser pulse, respectively, and c is the speed of light. The wavelength and the pulse duration were 1 μm and 27 fs in FWHM, respectively. The length of the simulation domain was 20 μm with the mesh size 0.5 nm, which was sufficiently small enough to resolve the initial proton layer thickness and the Debye length. The number of macro particles per species per cell was 1000. The initial electron temperatures of the front side proton layer, main target, and the back side proton layer were set as 100 eV, 10 keV, and 500 eV, respectively, to start the simulation with the Debye length resolved by the mesh. The different initial temperature of each layer used in our simulations does not influence significantly the calculation, since the target temperature increases very rapidly up to MeV as soon as the laser pulse irradiates the target. Pre-plasmas were not considered assuming a high contrast ratio of the driving pulse.

Usually in one-dimensional simulations, the accelerating field tends to be sustained permanently in the TNSA regime, since the sheath field expansion in the radial direction on the back side cannot be properly counted. In order to avoid the overestimation of the proton energy by such an artefact, the simulation should be stopped at a certain point. Among various criteria for the simulation stop, a formula by Fuchs et al. [20], where the sheath expansion is taken into account, is known to be consistent with numerous simulations and experiments for a short driving laser pulse, as in our work. The formula is described by $t_{acc} = \alpha(\tau_L + t_{min})$, where t_{acc} is the acceleration time in the rear-surface, t_{min} an empirical constant defined by 60 fs, τ_L is the laser pulse duration, and α is another empirical constant, whose value is 1.3 for a laser intensity higher than 3×10^{19} W/cm^2. Then the corresponding acceleration time is $t_{acc} = 134$ fs for our simulation condition. Considering the time taken by the pulse to arrive at the front side, we stopped the simulations after 153–156 fs, depending on the target thickness.

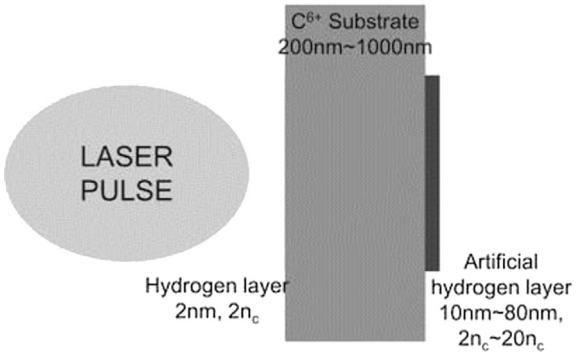

Fig. 1. The target configuration. We varied the thickness and density of the artificial hydrogen layer on the backside from 10 nm to 80 nm, and from $4n_c$ to $20n_c$, respectively. The substrate was varied from 200 nm to 1000 nm in thickness with a fixed density $600n_c$. Another hydrogen layer with 2 nm in thickness and $2n_c$ density was on the front side of the substrate, assuming hydrogen contamination.

3. Effects of the areal density of the proton layer

The average and maximum energy of the proton beams from the layer are known to be dependent on the initial areal density σ [9,13,14], which is the product of layer density n and the thickness l. We verified by a series of simulations that such a previous conclusion is valid for quite a broad range of the layer parameters, including the case where the thickness or the density is comparable to those of the sheath.

We conducted a series of simulations for quite a broad range of the layer parameters, including the case where the thickness or the density is comparable to those of the sheath.

This point is immediately noticed from the left column of Fig. 2. For different substrate thicknesses, the colored strips, which correspond to constant-energy contours, coincide well with the line of constant areal densities, decreasing overall as σ increases. Here, the simulations were carried out for the layer thicknesses ranging from 10 nm to 80 nm, and the densities from $2n_c$ to $20n_c$. Note that the average length and the electron density of the sheath were measured to be a few tens of nano-meters and several tens of the critical density, which were comparable to the maxim density and thickness of the layer.

Opposite to the average energy, the maximum energy of the protons increases as σ increases due to the influence of the Coulomb repulsion between the protons. In this case also, the maximum proton energy is dominantly determined by the areal density as in the right column of Fig. 2. This result can be explained by considering the maximum electric field at the proton beam edge, represented by [14,15].

$$E_{max}\left(\frac{l}{2}, t\right) = E_s \pm \frac{2\pi enl}{1 + 2\pi ne^2 t^2/m_p} \quad (1)$$

where l is the proton beam thickness, E_s the sheath field, and m_p the proton mass, respectively. Note that the maximum field described by the above equation depends on the product of n and l, i.e. σ. Since the maximally energetic protons come from the layer edge, whose part is most strongly accelerated by this maximum field, consequently the maximum proton energy should be determined by the areal density.

4. Effects of the substrate thickness

The virtue of manipulating the areal density of the proton layer is that the proton beam charge can be put under control; the total beam charge is the same as the initial proton charge in the layer, since the detached proton layer is accelerated as a whole. However the beam charge increment comes at the cost of the decreased average beam energy. Though the maximum proton energy usually increases for a higher areal density by the Coulomb repulsion, in this case, the energy spectrum becomes wider.