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3.7 Theory and Computer Simulations of the Laser Accelerated Ions

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Numerous applications of protons and ions accelerated by laser radiation require charged particle beams of high quality (i.e., such that the ratio of the energy width of the beam to its mean energy is small). In order to produce beams with controlled quality, it is proposed to use two-layer targets in which the first layer consists of heavy multicharged ions and the second layer (thin and narrow in the transverse direction) consists of protons. The possibility of generating a high-quality proton beam in the interaction of ultraintense laser radiation with such a two-layer target is demonstrated by three-dimensional particle-in-cell computer simulations.

Keywords : High intensity laser pulse, Theory and PIC simulations, Fast ions, Double layer target, Hadron therapy

1. Introduction

Laser accelerators of ions are based on the high efficiency of converting laser energy into the energy of fast ions in the interaction of laser pulses with plasma. Beams of fast ions were recorded in experiments on the interaction of laser pulses with solid targets [1-4]. The ion acceleration processes are also investigated numerically [5-9] by means of two- and three-dimensional particle-in-cell (PIC) computer simulations. In the experiments mentioned above, electrons were accelerated to energies of about several hundred MeV while the proton energy was about tens of MeV, the number of fast protons ranged from 10^{12} to 10^{13} per pulse and with a 12% efficiency of transformation of the laser energy into fast ion energy. The generation of fast ions becomes highly effective when the laser radiation reaches the petawatt power limit as it was shown in Ref. [10].

The laser accelerated ions find important applications such as Fast Ignition for Inertial Confinement Fusion (ICF) [11], proton therapy [12-14], fast ion beam injection to conventional accelerators [15], and the proton imaging, [16].

The proton use in the radiotherapy in the oncology provides several advantages. First of all, the proton beam scattering on the atom electrons is weak and it results in low irradiation of healthy tissues aside the tumor. Second, the slowing down length for the proton with given energy is fixed, and it avoids irradiation of the healthy tissues at the rare side of the tumor. Third, the Bragg peak of the energy losses provides substantial energy deposition in the vicinity of the proton stopping point. By now, the proton beams with necessary parameters produced with classic accelerators of charged particles: synchrotron, cyclotron, and linear accelerator. The use of the laser accelerator is very attractive because its compactness and additional possibilities to control the proton beam parameters.

The typical energy spectrum of laser accelerated particles observed both in the experiments and in the computer simulations can be approximated by a quasi-thermal distribution with a cut-off at a maximum energy. The effective temperature that may be attributed to the fast ion beams is only within a factor several of the maximum value of the particle energy. On the other hand, almost all above mentioned applications require high quality proton beams, i.e. beams with sufficiently small energy spread $\Delta\mathcal{E} / \mathcal{E} \ll 1$. For example, for hadron therapy it is highly desirable to have a proton beam with $\Delta\mathcal{E} / \mathcal{E} \leq 2\%$ in order to provide the conditions for a high irradiation dose being delivered to the tumor while sparing neighboring tissues. In Refs. [13,14,17,18] it has been shown that such a required beam of laser accelerated ions can be obtained using a double layer target. Multi layer targets have been used for a long time in order to increase the efficiency of the laser energy conversion into plasma and fast particle kinetic energy. In contrast to the previously discussed configurations, it was proposed the usage double layer target to produce fast proton beams with controlled quality. In this scheme the target is made of two layers with ions of different electric charge and mass. The first (front) layer consists of heavy ions with electric charge eZ_i and mass m_i. This is followed by a second (rear) thin proton layer. The transverse size of the proton layer must be smaller than the size of the pulse waist since an inhomogeneity in the laser pulse causes the inhomogeneity of the accelerating electric field and thus a degradation of beam quality, as seen in experiments where the exposed targets to the laser light had a thin proton layer on their surface.

When an ultra short laser pulse irradiates the target, heavy atoms are partly ionized and the ionized electrons abandon the foil, generating an electric field due to charge separation. Because of the large value of the ratio μ / Z_i, where $\mu = m_i / m_p$, heavy ions remain at rest, while lighter protons are accelerated. In order to achieve 10^{10} fast protons per pulse from the two-layer target required for the applications, it is enough to have a proton layer approximately $0.02\mu m$ thick and a laser pulse focused onto a spot with diameter equal to two laser wavelengths. The first layer is made of heavy ions and the target is sufficiently thick so produce a large enough electric field due to charge separation. This electric field has opposite sign on the two different sides of the target, has a zero inside the target and vanishes at a finite distance from it. The number of protons is assumed to be sufficiently small not to produce any significant effect on the electric field. The most important requirement is that the transverse size of the proton layer be smaller than the pulse waist so as to decrease the influence of the laser pulse inhomogeneity in the direction perpendicular to its direction of propagation. The pulse inhomogeneity causes an inhomogeneity of the accelerating electric field, which results in an additional energy spread of the ion beam seen in experiments. The effect of the finite waist of the laser pulse leads also to an undesirable defocusing of the fast ion beam. In order to compensate for this effect and to focus the ion beam, we can use properly deformed targets, as suggested in Ref. [7].

2. Energy Spectrum of Accelerated Ions

In order to estimate the typical energy gain of fast ions, we assume that the main portion of the free electrons produced by ionization in the irradiated region of the foil is expelled. In this case the electric field near the positively charged layer is equal to $E_0 \approx 2\pi n_0 Z_i el$. Here l is the foil thickness. The region of strong electric field has a transverse size of the order of the diameter $2R_\perp$ of the focal spot. Thus the longitudinal size of this region where the electric field remains essentially one-dimensional is also of order $2R_\perp$ and the typical energy of the ions accelerated by the electric field due to charge separation can be estimated as $\Delta\mathcal{E}_{max} \approx 4\pi n_0 Z_a e^2 l R_\perp$.

The energy spectrum of protons can be found by taking the electric field in the vicinity of the target to be of the form of the electric field near an electrically charged prolate ellipsoid. On the axis the x component of the electric field is given by $E_x(x) = (4E_0 / 3)R_\perp{}^2 / (R_\perp{}^2 - l^2 + x^2)$. The distribution function of the fast protons $f(x,v,t)$ obeys the kinetic equation, which gives $f(x,v,t) = f_0(x_0, v_0)$, where $f_0(x_0, v_0)$ is the distribution function at the initial time *t=0*. The number of particles per unit volume in phase space $dxdv$ is equal to $dn = fdxdv = fvdvdt = fd\mathcal{E}dt / m_p$. We assume that at t=0 all particles are at rest, i.e. their spatial distribution is given by $f_0(x_0, v_0) = n_0(x_0)\delta(v_0)$, with $\delta(v_0)$ the Dirac delta function. Time integration of the distribution $fvdvdt$ gives the energy spectrum of the beam

$$N(\mathcal{E})d\mathcal{E} = \left(\frac{n_0(x_0)}{m_p}\right)\left|\frac{dt}{dv}\right|_{v=v_0} d\mathcal{E}. \tag{1}$$

Here the Lagrange coordinate of the particle x_0 and the Jacobian $|dt / dv|_{v=v_0}$ are functions of the particle energy $\mathcal{E}$. The Lagrange coordinate dependence on the energy $x_0(\mathcal{E})$ is given implicitly by the integral of the particle motion: $\mathcal{E}(x, x_0) = \mathcal{E}_0 + e[\varphi(x) - \varphi(x_0)]$, with $\varphi(x)$ the electrostatic potential. In the case under consideration, we have $\mathcal{E}_0 = 0$ and $x = \infty$. The Jacobian $|dt / dv|_{v=v_0}$ is equal to $|dx_0 / d\mathcal{E}|$. Hence, we obtain the expression for the energy spectrum in the form

$$N(\mathcal{E})d\mathcal{E} = \left[n_0(x_0)\left|\frac{dx_0}{d\mathcal{E}}\right|\right]_{x_0=x_0(\mathcal{E})} d\mathcal{E}. \tag{2}$$

We notice that the expression for the energy spectrum follows from the general condition of particle flux continuity in the phase space.

As we can see, in the vicinity of the target on the axis the electric field is homogeneous. Therefore, the form of the energy spectrum (2) is determined by the distribution of the proton density $n_0(\varphi^{-1}(\mathcal{E}) / e)$. We see that in general a highly monoenergetic proton beam can be obtained when the function $n_0(x_0)$ is a strongly localized function, i.e. when the thickness of the proton layer Δx_0 is sufficiently small.

3. The Results of the 3D PIC Simulations

In order to take into account the numerous nonlinear and kinetic effects as well as to extend our consideration to multidimensional geometry, in Refs. [17,18] it was performed numerical simulations with the code REMP [19] of the proton acceleration during the interaction of a short, high power laser pulse with the two-layer target. In Figs. 1-3 we present the results of these simulations for a linearly polarized laser pulse with dimensionless laser amplitude $a = 30$ interaction with a double layer target. The first layer of the target (gold) has the form of a disk with diameter 10λ and thickness 0.5λ. The second layer (proton) also has the form of a disk with diameter 5λ and thickness 0.03λ, and is placed at the rear of the first layer. The electron density in the heavy ion layer corresponds to the ratio $\omega_{pe} / \omega = 3$ between the plasma and the laser frequencies, for the proton layer it corresponds to $\omega_{pe} / \omega = 0.53$. The number of electrons in the first layer is 180 times larger than in the proton layer.

In Fig. 1 we present the spectra of the proton energy and the energy per nucleon of the heavy ions. In Fig. 2 we present the distributions of the electric field components inside the computation box, to show the shape of the transmitted laser pulse and the accelerating longitudinal electric field. The accelerating field is shown as a 3D vector field (a); it is localized in the vicinity of the first layer (the heavy ion layer) of the target and can be described as an electrostatic field from the charged disk. The transmitted laser pulse is presented by the isosurfaces of constant value of the z component of the electric field (b). In Fig. 3 we show the densities of plasma species inside the computation box.

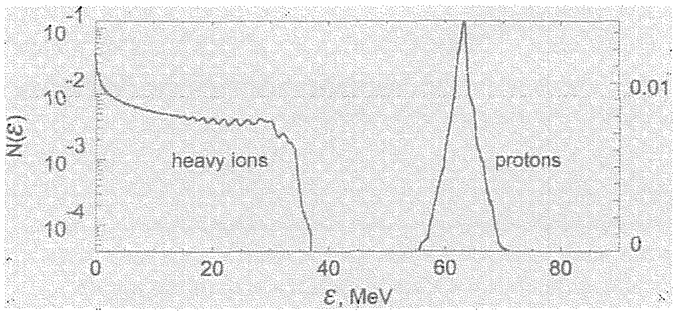

Fig. 1. The proton and the heavy ion energy spectrum at t=80.

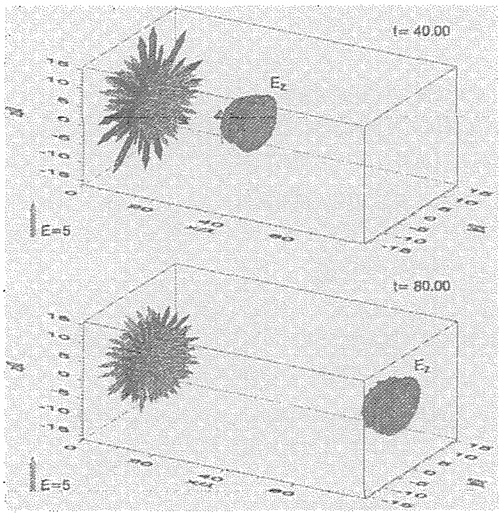

Fig. 2. Distribution of the electric field near the target (a) and in the region where the laser pulse is (b) at t=40, and at t=80.

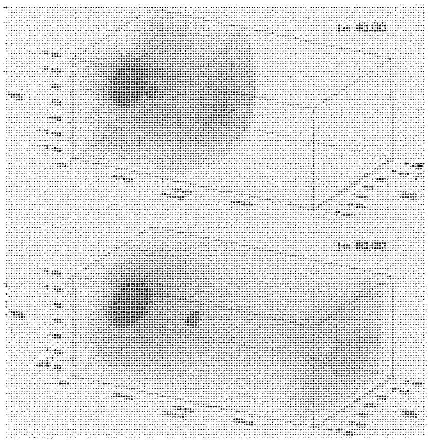

Fig. 3. Distribution of the electric charge inside the computation region at t=40 (a), and at t=80 (b).

We see that the proton layer moves along the x axis and that the distance between the two layers increases. The heavy ion layer expands due to Coulomb explosion and tends to become rounded. Part of the electrons is blown off by the laser pulse, while the rest forms a hot cloud around the target. We notice that for the simulation parameters the electrons do not abandon the region irradiated by the laser light completely. Even if only a portion of the electrons is accelerated and heated by the laser pulse, the induced quasi-static electric field appears to be strong enough to accelerate the protons up $65 MeV$. The energy per nucleon acquired by the heavy ions is approximately 100 times smaller than the proton energy. As seen in Fig. 1, the heavy ions have a wide energy spectrum while the protons form a quasi-mono-energetic bunch with $\Delta\mathcal{E} / \mathcal{E} < 3\%$. The proton beam remains localized in space for a long time due to the bunching effect of the decreasing dependence of the electric field on the coordinate in the acceleration direction.

3. Conclusions

In conclusion, the use of the multilayer targets with different shapes and compositions opens up new opportunities for controlling and optimizing the parameters of the fast proton (ion) beam, such as its energy spectrum, the number of particles per bunch, the beam focusing, and the size of the region where the beam deposits its energy.

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