# Proposed Double-Layer Target for the Generation of High-Quality Laser-Accelerated Ion Beams

T. Zh. Esirkepov,[1] S. V. Bulanov,[2] K. Nishihara,[1] T. Tajima,[2] F. Pegoraro,[3] V. S. Khoroshkov,[4] K. Mima,[1]
H. Daido,[2] Y. Kato,[2] Y. Kitagawa,[1] K. Nagai,[1] and S. Sakabe[1]

[1]*Institute of Laser Engineering, Osaka University, Osaka 565-0871, Japan*
[2]*Advanced Photon Research Center, JAERI, Kyoto-fu 619-0215, Japan*
[3]*University of Pisa and INFM, Pisa 56100, Italy*
[4]*Institute of Theoretical and Experimental Physics, Moscow 117259, Russia*

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In order to achieve a high-quality, i.e., monoenergetic, intense ion beam, we propose the use of a double-layer target. The first layer, at the target front, consists of high-$Z$ atoms, while the second (rear) layer is a thin coating of low-$Z$ atoms. The generation of high-quality proton beams from the double-layer target, irradiated by an ultraintense laser pulse, is demonstrated with three-dimensional particle-in-cell simulations.

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The high efficiency of ion acceleration recently observed in the interaction of petawatt laser pulses [1] with solid targets [2] has led to important applications, such as the use of laser produced fast ion beam injection into conventional accelerators (see Ref. [3]), the fast ignition of thermonuclear targets discussed in Ref. [4], and hadron therapy in oncology [5]. Laser-accelerated protons have been used for proton imaging of small scale objects in laser produced plasmas with high time resolution [6]. The process of ion acceleration has been studied in detail with multidimensional particle-in-cell (PIC) simulations [7,8]. In the recent experimental results presented in Ref. [2], electron energy in the range of hundreds of MeV was observed, while the proton energy was in the range of tens of MeV, with the number of fast protons ranging from $10^{12}$ to $10^{13}$ per pulse, and with the transformation of 12% of the laser energy into fast ion energy. In Refs. [7,8] it was shown with PIC simulations that, by optimizing the laser-target parameters, it becomes possible to accelerate protons up to several hundreds MeV, with the number of fast ions approximately $10^{13}$ particles per pulse.

The typical energy spectrum of laser-accelerated particles observed both in the experiments and in the computer simulations can be approximated by a quasithermal distribution with a cutoff at a maximum energy $\mathcal{E}_{\max}$. The effective temperature $T$, that may be attributed to the fast ion beams, is much smaller than the maximum energy. On the other hand, almost all the applications mentioned above require high-quality proton beams, i.e., beams with a sufficiently small energy spread $\Delta\mathcal{E}/\mathcal{E}$. 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 saving neighboring healthy tissues [9]. In the concept of fast ignition with laser-accelerated ions presented in Ref. [4], the proton beam was assumed to be quasimonoenergetic. An analysis carried out in Ref. [10] has shown that fast ignition with a quasithermal beam of fast protons requires an energy several times larger than that which is required with a monoenergetic beam. Similarly, in the case of the injector (see Ref. [3]), a high-quality beam is needed in order to inject the charged particles into the optimal accelerating phase efficiently. Thus we see that the generation of high-quality beams is a key problem for many applications. However the energy spectra of the laser-accelerated ions at present are rather far from those required.

In this Letter we show with three-dimensional (3D) PIC simulations that such a required beam of laser-accelerated ions can be obtained using a double-layer target (see also Ref. [5]). Multilayer targets have been used for a long time in order to increase the conversion efficiency of the laser energy into plasma and fast particle kinetic energy (see references in [11]). In contrast to the configurations previously discussed, we propose to use a double-layer target in order to produce fast proton beams with controlled quality.

In the proposed scheme the target is made of two layers. The first layer consists of high-$Z$ atoms (atomic mass $m_i$), while the second layer is a very thin coating of low-$Z$ atoms (atomic mass $m_a$). Such a target can be a metal foil coated with a thin hydrogenous film. An ultraintense laser pulse is incident on the first layer, the target front, while the second layer is at the rear side of the target. We use the term "longitudinal" for the direction of propagation of the laser pulse and the term "transverse" for the perpendicular directions.

When an ultraintense laser pulse irradiates the target, the heavy atoms are partly ionized and the electrons are expelled from the foil. A quasistatic electric field is generated due to charge separation. The first layer of heavy ions (the foil) should be sufficiently thick to produce a large enough quasistatic electric field, and, at the

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same time, it should be sufficiently thin to produce a strong electric field at its rear side. Such an electric field has opposite signs on the two sides of the target and vanishes at some location inside the target and at some finite distance from it. The number of low-$Z$ ions in the second layer (the coating) should be sufficiently small not to produce any significant effect on the electric field. The quasistatic electric field accelerates both high-$Z$ ions (with average charge $eZ_i$) and low-$Z$ ions (with average charge $eZ_a$). If the ratio $m_i Z_a/(m_a Z_i)$ is sufficiently large, the light ions are accelerated much more efficiently than the heavy ions. The coated thin layer can be then accelerated forward. It detaches from the foil and moves as a whole in the longitudinal direction. The light ions within a small solid angle have a quasimonoenergetic energy spectrum: the thinner the coating, the narrower the energy spectrum of the light ions. An additional important requirement is that the transverse size of the coating must be smaller than the laser waist since an inhomogeneity in the laser pulse makes the accelerating electric field nonuniform and thus degrades the beam quality by increasing its energy spread, as seen in the experiments presented in Ref. [2] where the exposed targets had a thin proton layer on their surface.

In addition, the effect of the finite waist of the laser pulse leads 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 Refs. [8,12]. In a target, with transverse size much larger than the laser focal spot, the quasistatic electric field can be affected by background "cold" electrons from the periphery. Thus, in order to increase the quality and lifetime of the quasistatic electric field, we must use targets with a transverse size smaller than the laser waist.

In order to estimate the typical energy gain of the fast ions, we assume that most of the free electrons produced by ionization in the irradiated region of the foil are expelled. In this case the generated electric field near the positively charged layer is equal to $E_0 = 2\pi n_0 e Z_i l$. Here $n_0$ is the ion density and $eZ_i$ is the average ion electric charge in the foil, and $l$ is the foil thickness. The transverse size of the region of strong electric field is of the order of the diameter $2R_\perp$ of the focal spot. Thus the longitudinal size of the region where the electric field remains essentially one dimensional is of the order of $R_\perp$ and the typical energy of an ion with charge $eZ_a$, accelerated by this electric field, can be estimated as $\mathcal{E}_{\max} = 2\pi n_0 Z_a Z_i e^2 l R_\perp$. We have assumed that the electron energy in the laser field is well above the ion energy and larger than the energy required for the electrons to leave the irradiated region. The maximum electron energy in the electromagnetic wave is given by $\mathcal{E}_e = m_e a^2/2$, where $a = eE/(m_e c\omega)$ is the dimensionless amplitude of the laser pulse. From this condition we can find the required value of the laser pulse intensity and its power.

Let us consider a double-layer target with the shape of a prolate ellipsoid coated at its rear side with a very thin proton layer. We assume that the ellipsoid semiaxes are $R_\perp$ and $l/2$. We can estimate the energy spectrum of the protons, using the formulas for the electric field of an electrically charged prolate ellipsoid [13]. Let the $x$ axis be in the longitudinal direction, with its origin at the target center. On this axis the $x$ component of the electric field is given by $E_x(x) = (E_0/3)R_\perp^2/[R_\perp^2 - (l/2)^2 + x^2]$ and the distribution function of the fast protons $f(x, v, t)$ obeys the kinetic equation $\partial_t f + v\partial_x f + [eE(x)/m_p]\partial_v f = 0$, where we have assumed that the particle trajectories do not intersect the $x$ axis, as is the case for our ellipsoidal target. Then we have $f(x, v, t) = f_0(x_0, v_0)$, where $f_0(x_0, v_0)$ is the distribution function at the initial time $t = 0$.

The number of particles per unit volume $dxdv$ in phase space is equal to $dn = f dx dv = f v dv dt = f d\mathcal{E} dt/m_p$. We assume that at $t = 0$ all particles are at rest and that their spatial distribution is given by $n_0(x_0)$, which corresponds to the distribution function $f_0(x_0, v_0) = n_0(x_0)\delta(v_0)$, with $\delta(v_0)$ the Dirac delta function. For the applications discussed in this paper we are interested in the particle distribution function integrated over time. Time integration of the distribution $f v dv dt$ gives the energy spectrum of the beam $N(\mathcal{E})d\mathcal{E} = [n_0(x_0)/m_p] \times |dt/dv|_{v=v_0} d\mathcal{E}$. 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 dependence of the Lagrange coordinate on the energy $x_0 = x_0(\mathcal{E})$ is given implicitly by the integral of the particle motion: $\mathcal{E}(x, x_0) = \mathcal{E}_0 + e[\varphi(x) - \varphi(x_0)]$, where $\varphi(x)$ is 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 the inverse of the particle acceleration at $t = 0$, i.e., $|dt/dv|_{v=v_0} = 1/|eE_x(x_0)|$. On the other hand the function $|dt/dv|_{v=v_0}$ is equal to $|dx_0/d\mathcal{E}|$. Hence, we obtain the expression for the energy spectrum in the form

$$N(\mathcal{E})d\mathcal{E} = n_0(x_0)d\mathcal{E}/|d\mathcal{E}/dx_0|_{x_0=x_0(\mathcal{E})}. \tag{1}$$

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

In the vicinity of the target the electric field on the axis is homogeneous and equals to $E_x(l/2) = 2\pi n_0 Z_i e l/3$. Therefore, the form of the energy spectrum (1) is determined by the distribution of the proton density $n_0[x = \varphi^{-1}(\mathcal{E}/e)]$. We see that in general a highly monoenergetic proton beam can be obtained when the function $n_0(x_0)$ is strongly localized, i.e., when the thickness of the proton layer $\Delta x_0$ is sufficiently small, in which case $\Delta\mathcal{E}/\mathcal{E} \approx \Delta x_0/R_\perp$.

The longitudinal emittance of the beam is defined as the product of its energy spread $\Delta\mathcal{E}$ and time length $\Delta t$: $\epsilon_{||} = \Delta\mathcal{E}\Delta t$. Using the expressions obtained above we find for the longitudinal emittance of the accelerated proton beam $\epsilon_{\|} = (\Delta x_0/R_\perp)^2\sqrt{m_p\mathcal{E}R_\perp^2/2}$. For $\mathcal{E} = 100$ MeV, $R_\perp = 5\ \mu$m and $\Delta x_0/R_\perp = 6\times10^{-3}$ we obtain $\epsilon_{\|} \approx 1.3\times10^{-4}$ MeV ps, which is about 150 times smaller than the emittance observed in the experiments with nonoptimized targets in Ref. [14].

Near the axis, the radial component of the electric field depends linearly on the radius $r = \sqrt{y^2+z^2}$: $E_r(r) = (E_0 l/6R_\perp^2)r$. We find that the particle trajectory is described by $r = r_0\exp(\sqrt{kx})$, where $r_0$ is the initial radial coordinate of the particle and $k = l/R_\perp^2$. From this expression, for $l/R_\perp \ll 1$ we find the transverse emittance $\epsilon_\perp = \pi r_0\Delta\theta$ of the fast proton beam: $\epsilon_\perp = \pi r_0\sqrt{l/R_\perp}$. Here $r_0$ is the transverse size of the proton layer and $\Delta\theta = \exp(\sqrt{kR_\perp}) - 1$ is the angle of divergence of the beam. For $r_0 \approx 2.5\ \mu$m, $R_\perp = 5\ \mu$m, and $l \approx 0.5\ \mu$m, the transverse emittance is of the order of 2.5 mm mrad.

For hadron therapy the particle flux must be approximately $10^{10}$ to $5\times10^{10}$ protons per second [9]. If the laser pulse is focused onto a spot with diameter 10 $\mu$m, plastic (CH) layer with average density 1 g/cm$^3$ and thickness 0.03 $\mu$m provides $10^{11}$ fast protons per pulse.

In order to take into account the numerous nonlinear and kinetic effects, as well as to extend our considerations to a multidimensional geometry, we performed numerical simulations of the proton acceleration during the interaction of a short, high power laser pulse with a two-layer target. We used the three-dimensional massively parallel and fully vectorized code REMP (relativistic electromagnetic particle-mesh code) [15]. In these simulations the largest number of grid cells was $2560\times1024\times1024$ and the number of quasiparticles was up to $820\times10^6$. The boundary conditions for the particles and for the fields are periodic in the transverse directions and correspond to absorption at the end of the computation box along the $x$ axis. The simulations were performed on 64 processors of the vector supercomputer NEC SX-5 at CMC, Osaka University.

Here we present the results of these simulations. The size of the simulation box is $80\lambda\times32\lambda\times32\lambda$. A linearly polarized laser pulse with dimensionless amplitude $a = 30$ propagates along the $x$ axis. The pulse size is $15\lambda\times12\lambda\times12\lambda$. The pulse has a trapezoidal shape (growth-plateau-decrease), with $3\lambda - 2\lambda - 10\lambda$ in the $x$ direction, and $1\lambda - 10\lambda - 1\lambda$ in the $y$ and $z$ directions. The plasma consists of three species: electrons, protons with $m_p/m_e = 1836$, and heavy ions (gold with $Z_i = +2$) with $m_i/m_eZ_i = 195.4\times1836/2$.

The first layer (gold) is placed at $x = 5.5\lambda$. It has the form of a disk with diameter $10\lambda$ and thickness $0.5\lambda$. The second layer (protons) also has the form of a disk with diameter $5\lambda$ and thickness $0.03\lambda$, and is placed at the rear of the first layer, at $x = 6\lambda$. The electron density in the heavy ion layer corresponds to the ratio $\omega_{pe}/\omega = 3.0$ between the plasma and the laser frequencies, while in the proton layer it corresponds to $\omega_{pe}/\omega = 0.53$. The

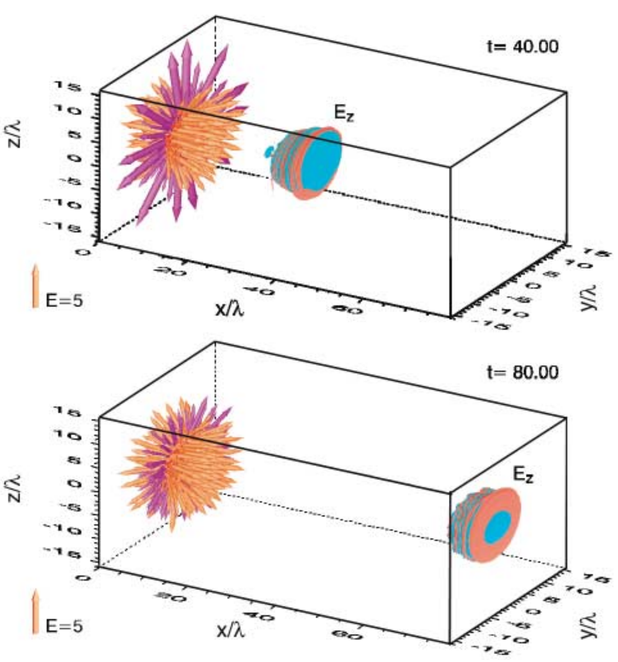


FIG. 1 (color). The electric field near the target is shown as a 3D vector field; the length of each vector corresponds to the magnitude of the electric field. Vectors with $|eE_x/(m_e\omega c)| \le 1$ are drawn in purple. The laser pulse is shown by the isosurfaces of the transverse component $E_z$ corresponding to the dimensionless values $\pm10$. The time unit is the laser period $2\pi/\omega$.

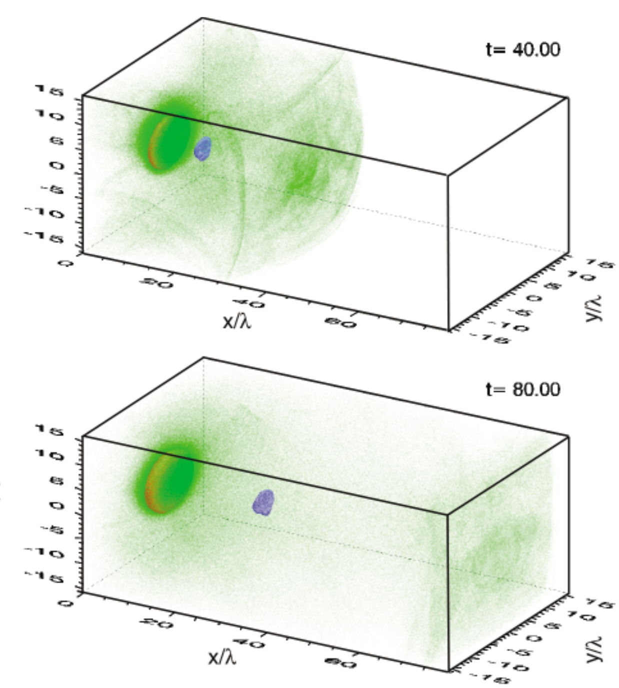


FIG. 2 (color). Plasma species. The shapes of the density distributions of the heavy ions (thick red disk) and of the light ions (thin blue plate) are shown. The electron density is shown as a "green gas" using a ray tracing technique.

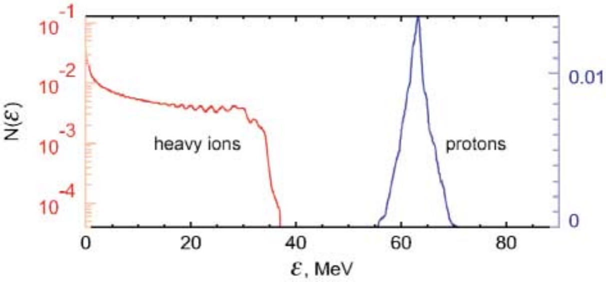


FIG. 3 (color). The proton (blue line) and heavy ion (red line) energy spectra at $t = 80 \times 2\pi/\omega$.

number of electrons in the first layer is approximately 2000 times larger than that in the proton layer.

The simulation results are shown in Figs. 1–3, where the coordinates are measured in wavelengths of the laser light and the time in laser periods. In Fig. 1 we present the electric field inside the computation box, in order to show the shape of the transmitted laser pulse and the longitudinal electric field that accelerates the protons. The electric field is shown as a three-dimensional vector field; it is localized in the vicinity of the first layer (the layer of heavy ions) of the target and can be described as the electrostatic field generated by a positively charged disk. The transmitted laser pulse is shown by the isosurfaces of the $z$ component of the electric field. In Fig. 2 we show the densities inside the computation box of the different plasma species. 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 its 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 adopted simulation parameters the electrons are not completely expelled from the region irradiated by the laser light. Even if only a portion of the electrons is accelerated and heated by the laser pulse, the induced quasistatic electric field appears to be strong enough to accelerate the protons up to 65 MeV, as seen in Fig. 3 which presents the energy spectra of the protons and heavy ions. The energy per nucleon acquired by the heavy ions is approximately 380 times smaller than that acquired by the protons. The heavy ions have a wide energy spectrum, while the protons form a quasimonoenergetic bunch with $\Delta\mathcal{E}/\mathcal{E} < 5\%$. We emphasize that the thinner the proton layer (or low-$Z$ coating) the better the beam quality. The proton beam remains localized in space for a long time because of the bunching effect due to the linearly decrease of the electric field in the direction of acceleration.

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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