# Generating Monoenergetic Heavy-Ion Bunches with Laser-Induced Electrostatic Shocks

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A method for efficient laser acceleration of heavy ions by electrostatic shock is investigated using particle-in-cell (PIC) simulation and analytical modeling. When a small number of heavy ions are mixed with light ions, the heavy ions can be accelerated to the same velocity as the light ions so that they gain much higher energy because of their large mass. Accordingly, a sandwich target design with a thin compound ion layer between two light-ion layers and a micro-structured target design are proposed for obtaining monoenergetic heavy-ion beams.

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Generation of monoenergetic proton or ion bunches is of much recent research interest because it plays an important role in fast ignition of inertial confinement fusion, cancer therapy, and other applications [1]. A number of novel methods have been proposed for accelerating protons or heavier ions to high energies using the recently available high-intensity short-pulse lasers. With target-normal sheath acceleration [2,3], protons up to 58 MeV have been obtained with $3 \times 10^{20}\ \mathrm{W\,cm^{-2}}$ lasers [4,5]. With micro-structured targets, quasi-monoenergetic proton or ion bunches with energy spread of about 20% have been produced [6,7]. Other promising schemes include shock acceleration at the front of the foil [8], direct laser-pressure acceleration [9,10], and acceleration by plasma wake [11]. However, generation of high-energy heavy ions by laser-plasma interaction is still difficult [12] because of certain physical limits. Heavy ions cannot be accelerated as efficiently as protons since the electric force per unit mass on them (with lower charge-to-mass ratio) is smaller. Accordingly, the target should be free of protons which would be preferentially accelerated [13].

Here, we propose a method for accelerating heavy ions as efficiently as protons by making use of the electrostatic shock driven by an intense circularly polarized laser pulse irradiating a compound target. With a circularly polarized laser pulse, whose ponderomotive force does not have an oscillating component, the target electrons are less heated than that for other polarizations. They are instead mainly pushed forward and compressed by the light pressure, so that an intense self-consistent space-charge field that can accelerate the ions is formed [14]. When the laser pulse is flat-topped, the perturbed system can propagate as an electrostatic shock. In the latter, the ions are mostly trapped and reflected forward at a nearly constant velocity, leading to the formation of a quasi monoenergetic ion beam and a flat-top structure in the ion phase space [15]. According to the scaling law obtained in Refs. [14,15], one can reduce the target density to obtain ion bunches with higher energy. However, the target density must be above the critical plasma density or even higher, so that the target remains opaque to the laser and the resulting space-charge field sufficiently high to trap and accelerate the ions [16].

We propose to mix the light- and heavy-ion species in the target. It is shown by particle-in-cell (PIC) simulation that both the heavy and light ions will be trapped and accelerated to the same velocity, which is higher than when the target consists of only heavy ions when the other parameters remain the same. That is, with the present scheme, the heavy ions can be accelerated to much higher energies than that from the existing laser-driven schemes.

Compound targets or multi layer targets have been used earlier for proton and ion acceleration [6,7,11,17–19]. But the heavy ions were mainly used as a heavy background to increase the gradient of the space-charge field for proton acceleration. The corresponding laser pulse is also usually linearly polarized and has a Gaussian rather than flat-topped profile. The resulting heavy ions from existing compound targets are not monoenergetic. Accordingly, to improve the quality of the accelerated heavy ions, here we employ a circularly polarized laser pulse and a sandwich target design. The latter consists of a thin compound ion layer between two light-ion layers. In 3D, the target is micro-structured to yield heavy-ion beams of good quality. Our results show that at a laser intensity of $5 \times 10^{19}\ \mathrm{W\,cm^{-2}}$, heavy-ion beams with energy divergence about 5% at the longitudinal kinetic energy of $E_x \sim 58$ MeV with a total carbon ion number of about $3.36 \times 10^8$ (that is a total charge of $3.23 \times 10^{-10}$ C) is obtained.

When a circularly polarized laser pulse irradiates a compound target, no higher harmonics are generated, and the plasma is not much heated. An electrostatic shock can appear (as in the single-ion target case). Our simulation (see below) shows that both the heavy and light ions are mostly trapped and accelerated to the same velocity.

 

Assuming that all the ions are accelerated, from momentum and energy conservation, we obtain

$$\frac{I}{c} = -\eta\frac{I}{c} + \left(n_{e1}\frac{A_1}{Z_1} + n_{e2}\frac{A_2}{Z_2}\right)m_p v_i v_a, \tag{1}$$

$$I = \eta I + \left(n_{e1}\frac{A_1}{Z_1} + n_{e2}\frac{A_2}{Z_2}\right)\frac{m_p v_i^2}{2} v_a, \tag{2}$$

where $I$ and $\eta$ are the intensity and reflectivity of the laser pulse, $m_p$ is proton mass, $v_i$ and $v_a$ are the velocities of the reflected ions and the shock, respectively, $Z$ and $A$ are ion charge and mass number, and $n_{e1} \equiv Z_1 n_{i1}$, $n_{i1}$ and $n_{e2} \equiv Z_2 n_{i2}$, $n_{i2}$ are the corresponding electron and ion densities of each species, respectively. The subscripts 1 and 2 denote the light- and heavy-ion species. Since the ions are reflected by the shock, we have $v_i \approx 2v_a$, and Eqs. (1) and (2) give

$$\frac{v_i}{c} \approx 2\sqrt{\frac{n_c}{n_{e1}A_1/Z_1 + n_{e2}A_2/Z_2}}\sqrt{\frac{m_e}{m_p}}a_L, \tag{3}$$

where $n_c$ is the critical plasma density, $m_e$ the electron mass, $c$ the light speed, $a_L = eE_L/m_e\omega_L c$ the dimensionless laser electric field, $e$ the elementary charge, and $E_L$ and $\omega_L$ are the electric field amplitude and frequency of the laser. For a single-ion target, Eq. (3) reduces to that given in Refs. [14,15].

As an example, in the following 1D simulation using VORPAL [20], we set the light-ion species as hydrogen with $Z_1 = A_1 = 1$ and the heavy one as carbon with $Z_2 = 6$ and $A_2 = 12$. A circularly polarized laser pulse with the wavelength $\lambda_0 = 1\ \mu$m irradiates the target from the left. The laser amplitude rises from zero to $a_L = 2$ in $6T_0$, where $T_0$ is the laser period, and then it remains constant for $200T_0$. The simulation box is $101\lambda_0$ long in the $x$ direction, and the cold target initially occupies the region between $x = 80.5\lambda_0$ and $x = 82.5\lambda_0$. The total electron density of the target is $n_e = 5n_c$, and the densities of the two-ion species are given by $n_{e1} = n_{e2} = 0.5n_e$.

Figure 1(a) shows the phase space of the light and heavy ions, together with the electric field distribution. The presence of the collisionless electrostatic shock structure can be clearly seen. Most of both types of ions are trapped (reflected) by the electrostatic field created by the laser-compressed electrons, and there are only a small number of untrapped (passing ions). It also shows that all the reflected ions move forward together when they leave the high-field region. The light and heavy ions do not have different final velocities because they and the accelerating electric field belong to the same self-consistent electrostatic shock system, whose speed is self-consistently determined by the laser and plasma parameters, including the charge and mass of both ion species. Thus, a monoenergetic heavy-ion bunch is formed. Since the carbon mass is 6 times that of hydrogen, the energy per accelerated carbon ion is about 6 times that of the hydrogen ion, as can clearly be seen in Fig. 1(b). From Eq. (3), we also see that the ion velocity is higher than that from a simple target with only the heavy ions. Thus, here we have a simple method to raise the energy of heavy ions.

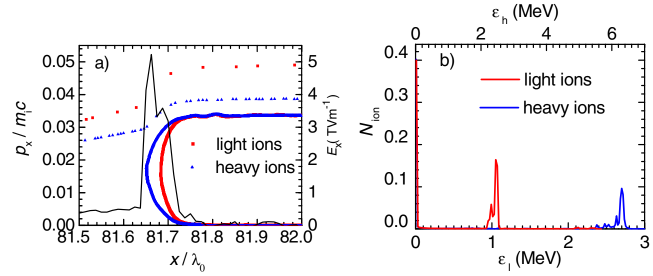


FIG. 1 (color online). (a) Phase space of the light and heavy ions and the electric field distribution of the collisionless electrostatic shock at $t = 150T_0$ for $a_L = 2$, $n_e = 5n_c$, and $d = 2\lambda_0$. (b) The energy spectrum of the light and heavy ions. Here, $\varepsilon_l$ and $\varepsilon_h$ are the longitudinal kinetic energies of the light and heavy ions, and $N_{\rm ion}$ is the species ion number normalized by the total ion number.

We can write Eq. (3) in terms of the ratios $\alpha = n_{e1}/n_{e2}$ and $\beta = (Z_1/A_1)/(Z_2/A_2)$ as

$$v_i/c \approx 2\sqrt{1 + \frac{\alpha(\beta - 1)}{\alpha + \beta}}\sqrt{\frac{Z_2}{A_2}\frac{m_e}{m_p}\frac{n_c}{n_e}}a_L, \tag{4}$$

so that the effect of these rations on the acceleration efficiency are more transparent. For comparison, we carried out simulations for various combinations of $\alpha$ and $\beta$ values. The other conditions are the same as in Fig. 1. The results are shown in Fig. 2. We see that there is excellent agreement between the simulation and Eq. (4), and that shock acceleration of this kind exists for a very wide parameter range. Figure 2(a) shows that in order to raise the energy of the heavy ions efficiently, its concentration must be much lower than that of the light ions. On the other hand, since the ion velocity first increases quickly with the density ratio and then slowly saturates to the maximum, the concentration of the heavy ions does not need to be reduced very much in order to obtain significant energy increase. This point is important since the number of energetic heavy ions per bunch should not be too small. For example, for $n_{e1}/n_{e2} = 9$, or a carbon ion density of $10^{20}$ cm$^{-3}$, the velocity is $0.039c$, which is an increase of 34.5% with respect to the single heavy-ion target case, or

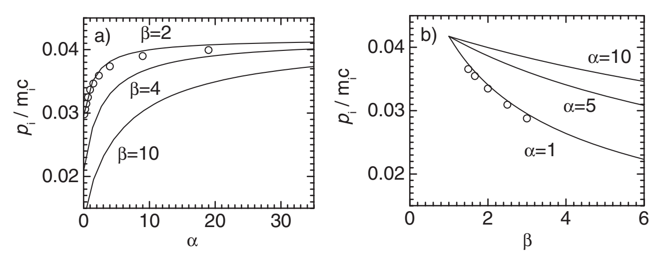


FIG. 2. Reflected heavy-ion momentum vs (a) $\alpha$ and (b) $\beta$ from simulations (circles) and Eq. (4) (solid line) at $t = 150T_0$. The other parameters are the same as in Fig. (1).

81% of the total kinetic energy increase. This value is close to the maximum of 41.5% predicted by Eq. (4), which is based on steady-state conservation arguments. We also note that the rate of velocity increase of heavy ions does not depend on the other laser and target parameters as long as the shock-acceleration mechanism operates.

The results here are due to a self-consistent velocity-space phase-mixing effect in the collisionless electrostatic shock. The local ions (electrons) are reflected, or accelerated, forward (backward) by the electrostatic space-charge field set up by the laser field. The light ions (with larger charge-mass ratio) tend to move faster and the heavy ions slower. The faster (slower) ions will be pulled back (pushed forward) by resulting space-charge-field redistribution. Finally, the entire system moves together at a common speed, so heavy ions are drawn by light ions indirectly, which explains why the light ions are slightly ahead of the heavy ions and the electrostatic field distribution presents a tiny valley between the two reflected ion front in Fig. 1(a). The circularly polarized laser pulse maintains the accelerating electrostatic field, whereas the response of the electrons and ions is another key to this interesting phenomenon. It should be mentioned that the higher is the shock speed, the longer is the time for picking up all heavy ions. Thus, with the present compound target, heavy ions can be accelerated efficiently. We also found by PIC simulations that more complex multispecies targets (such as that with three types of ions) exhibit similar phenomenon.

In the above consideration, the laser pulse is flat-topped and the accelerated ions are monoenergetic. In most practical cases, the laser is roughly Gaussian, so that according to our model, used in Eq. (3), the accelerated ions may not be monoenergetic. Based on the analyses above, we proposed a simple but effective method for overcoming this problem. We employ a sandwich target with a thin compound layer between two light-ion layers, as seen in Fig. 3(a). By this target structure, the beginning of the laser pulse would interact with the front light-ion layer, then the following part with much smaller duration irradiates the thin compound layer, leaving the rest to the back light-ion layer. As the inside compound layer is very thin, its interacting time with partial laser pulse is short enough that laser intensity keeps almost constant, which would lead to a more monoenergetic heavy-ion bunch.

Here, position and thickness of the thin layer have great influence on the quality of heavy-ion bunches. As for Gaussian pulse laser intensity peaks in the center, it is better to place compound layer in the right position of the target to make it interact with only the central part of the laser pulse, and thus ions would gain peak energy. Moreover, one can control the interacting time of the thin compound layer and laser by changing its thickness according to FWHM of the Gaussian pulse to gain heavy-ion bunches as monoenergetic as you want. In a word, main parameters of heavy ions' energy spectrum can be regulated. A single thin compound foil cannot work like this because it might be destroyed by prepulse of the laser. Otherwise, it is more convenient to produce this sandwich target than a single thin compound foil. The outside two layers being made up of light ions is to make it comfortable to separate these two species through their different charge-mass ratio in succeeding treatment.

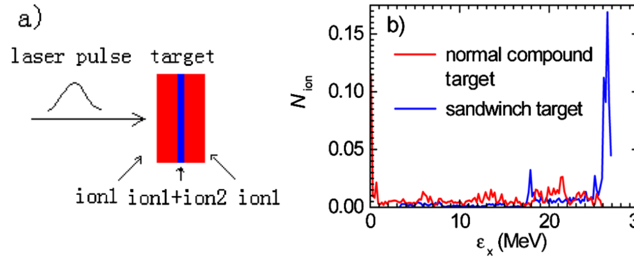


FIG. 3 (color online). Sandwich target scheme (a) and energy spectrum of normal compound target (red solid) and sandwich target (blue solid) (b) at $t = 240T_0$ for a Gaussian laser pulse with peak amplitude $a_L = 4$ and FWHM of $22T_0$.

For 1D simulations, the cold sandwich target electron density is $5n_c$, and the target is from $x = 80.5\lambda_0$ to $x = 82.5\lambda_0$, while the simulation box length is $101\lambda_0$. The central thin layer is a mixture of hydrogen and carbon ($\beta = 2$) with their electron density ratio $\alpha = 1$. Its thickness is $0.2\lambda_0$, and both the front and back hydrogen layers are $0.9\lambda_0$. The Gaussian laser pulse is of duration $220T_0$, peak amplitude $a_L = 4$, and FWHM $22T_0$. Comparison of ion kinetic energy spectrum with normal compound target is shown in Fig. 3(b). All figures are taken at $t = 240\,T_0$ when the interaction between laser and target is just over. An obvious improvement is seen in the sandwich target way, by which carbon ions are almost around peak energy 26 MeV while the other is nearly averagely distributed. Parameters we chose here are to guarantee that the compound layer interacts only with the center part of Gaussian pulse in a short time; therefore, heavy ions are well monoenergetic in peak energy. We notice that the heavy-ion peak energy 26 MeV is perfectly 4 times as in Fig. 1(b) according to the scaling law of Eq. (3), indicating that the bunch generation mechanism operates exactly.

However, one may doubt the efficiency of this monoenergetic heavy-ion bunch generating method in practice because so far we have not counted in 2D or 3D effects. It has been confirmed by 2D PIC simulations in Ref. [14] that 2D effects do not have qualitatively influence on ion bunch formation, but they do affect energy and beam divergence of ion bunches. Following the sandwich target way, we can just reduce transverse dimension of the inside thin compound layer to weaken these negative effects. Thus, the target is micro-structured with a compound microdot in it. We carry out 3D PIC simulations by VORPAL here. Subscripts "1" and "2" are still hydrogen and carbon. The simulation box is $25\lambda_0 \times 120\lambda_0 \times 120\lambda_0$. The micro-structured target occupies a region of $15\lambda_0$–$17\lambda_0$ (2 $\mu$m) in $x$ (longitudinal) and $-54\lambda_0$–$54\lambda_0$

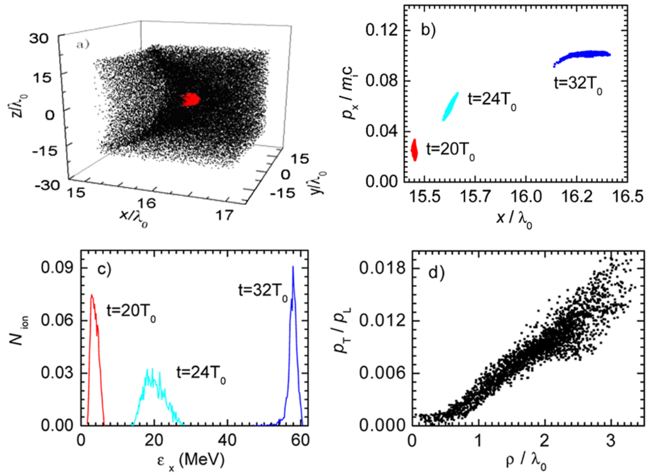

FIG. 4 (color online). Space distribution of hydrogen (black dots) and carbon ions (red dots) at $t = 30T_0$ (a), phase space of heavy ions at different time (b), energy spectrum of heavy ions at different time (c) and transverse distribution of $p_L/p_T$ (d), where $p_L = \gamma m_i v_{ix}$ and $p_T = \gamma m_i (v_{iy}^2 + v_{iz}^2)^{1/2}$ are heavy ions' longitudinal and transverse momentum and $\rho = (y^2 + z^2)^{1/2}$ is the distance from the target center.

(108 $\mu$m) in both $y$ and $z$ (transverse) with total electron density of $5n_c$. The inside microdot is mixed with hydrogen and carbon by $\alpha = 1$, occupying a region of $15.4\lambda_0$–$15.435\lambda_0$ (35 nm) in longitudinal and $-2.4\lambda_0 \sim 2.4\lambda_0$ (4.8 $\mu$m) in transverse. The rest of the target is made up of light ions. The Gaussian laser pulse with beam waist radius $\omega_0 = 17\lambda_0$, peak amplitude $a_L = 6$ and a duration of $40T_0$ propagates from the left. Figure 4(a) shows the proton and carbon ion distribution at $t = 30T_0$ where ions in outer part of target are eliminated to display the inside structure. A proton front of gausslike shape is formed due to the Gaussian intensity profile in transverse of laser front, and all carbon ions have been reflected, leading to a compact beam with very small dimension. From phase space and longitudinal kinetic energy spectrum at different time in Figs. 4(b) and 4(c), we see clearly the following process: the compound microdot is initially irradiated by laser front; carbon ions are being accelerated by electrostatic field; carbon ions are all trapped and reflected and finally propagating stably, gradually from $t = 20$ to $t = 32\,T_0$ or longer, which describes exactly the movement of heavy ions in a electrostatic field as shown in Fig. 1(a). A quasi-mono-energetic carbon ion bunch with energy divergence about 5% at the longitudinal kinetic energy of $E_x \sim 58$ MeV with a total carbon ion number of about $3.36 \times 10^8$ (that is a total charge of $3.23 \times 10^{-10}$ C) is obtained. Collimation of the obtained carbon ion bunch is pretty good as seen in Fig. 4(d), with the maximum angle of divergence $\Delta\theta_{\max} \sim 6 \times 10^{-3}\pi$ rad at the transverse rim of the mixed microdot.

From description about Fig. 4(c) and noticing again that the peak energy is about 9 times as in Fig. 1(b) which verifies the scaling law, we conclude that 3D effect does not qualitatively impact ion bunch generation either, and our proposed method turns out to be very effective. The transverse dimension of the microdot can be changed to control the energy divergence.

In summary, a target with two ion species irradiated by a circularly polarized laser pulse is examined by PIC simulations. It is found that the two ion species are accelerated to the same velocity which is higher than in the case of the pure heavy-ion target. A simple model based on momentum and energy conservation is proposed and it describes the found effect very well. When the laser pulse is not uniform in space and time, we propose a sandwich microstructured target with a compound microdot in it. Using 3D PIC simulations, we find that a quasi-mono-energetic heavy-ion bunch can be generated. This method is so effective and practical that the energy of the heavy ions can easily be raised by nearly 100% (or higher for heavier ions) under the same laser conditions. The qualities of the heavy-ion beam, including the energy and space divergence, are significantly improved by using the microstructured target. As an estimate, the LULI laser (wavelength $\sim 1\ \mu$m, intensity $\sim 10^{19}$ W cm$^{-2}$, focal aperture 5–10 $\mu$m, and duration about 300 fs) should be able to generate a carbon beam with a peak energy of 12 MeV and a total carbon ion number of $\sim 10^8$ while the energy divergence is still kept at 5%.

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