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Intense laser-driven electrostatic shocks and its acceleration of ions in overdense plasmas

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Abstract. We investigated numerically the formation and propagation of the electrostatic shocks in overdense plasmas irradiated by intense ultrashort laser pulses. The dependence of the initial shock speeds on the parameters of the plasma and the laser is explained by invoking the modified momentum conservation model. The acceleration of ions by the shocks is also discussed.

1. Introduction
The generation of multi-MeV ion beams in the ultrashort intense laser-plasma interaction is a rapidly evolving field of great interests due to its potential applications in the fast ignition of fusion targets, radiography, medical applications, compact particle accelerators [1], etc. Although many mechanisms have been invoked theoretically and experimentally for high quality ion beam production, the acceleration by the sheath fields from the surface of the plasma is often regarded as the primary mechanism, and also a successful one in the production of monoenergetic proton beams by applying deliberately designed targets of manipulated composition and structure as shown by Schwoerer et al. However, ions originally located deeply in the plasma can also be accelerated to high energy with a relatively narrow spectrum extension by collisionless electrostatic shock waves (CLES)[2]. Silva et al. studied the effects of the laser intensity and the target thickness on the ion acceleration by shock waves in laser-plasma interaction, and found that the shock acceleration mechanism dominates the sheath acceleration when the shock accelerated ions reach the sheath field in the target rear with a higher velocity than the ions already accelerated there [3]. Laser-plasma experiments with gas targets were also conducted, demonstrating the existence of the ion shock acceleration by the plateau in the ion spectrum also predicted by Silva et al[4].

In this work, we report our studies about the the shocks in over dense plasmas irradiated by intense femtosecond laser pulses. We have used both 1D and 2D PIC simulations. The foil targets were placed in the middle of the simulation boxes with a vacuum space of 7µm at the left side. The ions are set as protons with the mass \( m_i = 1836m_e \) in all simulations when only one species of ions is considered. The plasma temperature is set as low as 50 eV. Circularly or linearly s-polarized laser pulses are incident from the left boundary with a sine-squared temporal profile of \( \tau \). The laser wavelength is \( \lambda_0 = 1\mu m \). In the studies, we have adopted different plasma densities, target thicknesses, and incident laser intensities represented
Figure 1. (color online) (a) Snapshot of the ion density in 2D space at $t = 40\tau_0$; (b) The space-time evolution of the laser fields ($E_z$). The ion density contour lines of $45n_c$ are also overplotted; (c) The longitudinal density distributions of the ions and electrons, and the longitudinal electric field on the laser axis at $t = 30\tau_0$; (d) The space-time evolution of the ion density distribution on the laser axis. The used parameters are the same as in Fig. 1(a).

by the dimensionless variable $a$. For the 2D case, the simulation box is set as $16\mu m \times 15\mu m$. In the transverse $y$ direction, laser beams have Gaussian intensity distributions with the diameter of $5 \mu m$. We will show the structures of the shock’s electrostatic fields and the characteristics of the ion acceleration by the shocks and the solitary waves.

2. Formation and propagation of the electrostatic shocks

Fig.1 shows the characteristics of the shocks simulated by 2D PIC codes. Fig.1(a) shows the ion density distribution at $t = 40\tau_0$ in the coordinate space with $a_0 = 5$, $n_0 = 20n_c$ and $L = 1.5\lambda_0$. At the first stage, the laser pulse compresses the thin layer target at the front surface and driving it forward with a speed of $v_p$. The space-time evolution of the plasma density and the incident laser field at position $y = 7.5\lambda_0$ is shown in Fig. 1(b), where the contour is the plot of the ion density at $n_i = 45n_c$. One can see that the compressed plasma layer slowly separates from the laser field, which propagates forward even without the further push of the laser ponderomotive force. It indicates that the accelerated thin plasma layer acts as a shock, which differs from the ion acceleration in the radiation-pressure dominated regime [5]. The peaks of the ion and electron densities overlap with each other as shown in Fig. 1(c). This distinguishes the shock acceleration process from the ion acceleration at the target front, where the charge separation field is formed due to the laser push of the front electron layer. However, due to that fact that the electron temperature is much higher than that of ions, i.e., $T_e > T_i$, in the situations of the electrostatic shock, bipolar charge separation fields are produced in the Debye sheath of the compressed plasma layer. This quickly propagating shock wave play key roles in the acceleration of ions deeply locating in the overdense plasma. As an example, a bunch of ions accelerated is shown clearly in Fig. 1(d).

Simulations indicate that the plasma foil thickness $L$, the initial target density $n_e$, and the laser intensity have significant effects on the shock characteristics. The three physical variables can be related to the shock speed by Denavit’s momentum conservation model [6], which is modified by taking into account of the electron circulating behavior between targets’ front and rear, and 2D or 3D effects, allowing electrons besides to compensate the charge separation field behind the compressed plasma layer [7]. We have $m_i v_p^2 n_{i,eff} = I(1 + \eta)/c$. The original ion density $n_i$ is replaced by $n_{i,eff} = n_i\{1 - l_p/L \times \exp[-(L/L_c)^q] - \delta\}$ [8], where $\delta$ is a function of the plasma density and laser focus width, showing the electron compensation due to 2D or 3D
3. Ion acceleration by shocks and its effects on the shock’s propagation

The quickly propagating bipolar electrostatic field around the shock front play key roles in the acceleration of ions locating on the path of the shock wave. In the shock frame, only ions that satisfy $\frac{1}{2}m_i v_s^2 \leq \phi$ could be reflected from the shock front and accelerated to $2v_s$. $\phi = eE/\lambda_D$, and $E = k_B T_e/e\lambda_D$. Those ions can pass through two times of the peak of the positive part of the electrostatic field. For ions that have larger energy and propagate against the shock, they will pass through the positive part of the bipolar electrostatic field and fall into the negative part or the disturbed part, where these ions could be heated to a lower energy. So for plasmas consisting of two kinds of ions with same mass but different charges, the shock can accelerate those ions to the same energy. To check this idea, we performed PIC simulations with Helium plasmas. Fig. 3(a) shows the distributions of the differently charged ions in the phase space at $t = 40\tau_0$. It is shown that He$^+$ and He$^{2+}$ locating deeply in the plasma has the same acceleration behavior, while at the rear of the plasma target, He$^{2+}$ has been accelerated to twice the momentum of He$^+$ in the rear sheath field. Experiment with Helium plasmas has been conducted by Wei et al [4]. We noticed that the energy distributions of He$^{2+}$ and He$^+$ they obtained in the perpendicular direction of the laser beam have large discrepancy between each other. It seems that there is other mechanisms playing roles in the ion accelerating processes besides the shocks induced by the transverse ponderomotive force of the laser pulse pushing, compressing and accelerating the plasma.

If the shocks is expected to propagate through the interface of plasma layers with different kinds of ions, the shock shape could be affected, or even destroyed. Fig. 4 shows the situation when the shock propagates from a plasma with heavier ions to a plasma of lighter ions. The mass ratio of the two kinds of ions are 10:1. It is found that the shock dissipates after it arrives into the plasma consisting of lighter ions. This happens due to the fast acceleration process of...
the lighter ions by the bipolar electrostatic field around the shock front. The rapidly moving electrostatic field is constructed by heavier ions and the background electrons. The lighter ions suddenly falling into it can be accelerated to a much higher speed than that of the shock itself. Such lighter ion’s behavior enlarge gradually the spatial extension and lower down the peak of the shock front density, and in turn the strength of the electrostatic field. This results in a low speed of the ions accelerated at later time. When this phenomenon continues, the shock will decay into a plasma layer consisting of ions and electrons with largely different velocities. The shock dissipates.

**Figure 3.** The distributions of He$^{2+}$ and He$^+$ in the phase space.

**Figure 4.** Shock dissipates after propagating through the interface of different plasma layers.

4. Summary
We have shown details of the shock formation and its propagation in the overdense plasmas. The shock accelerates ions with the same mass but different charges into the same energy, which might be used to explain experimental data. Ion acceleration by shocks can in turn affect the propagation of the shock, which may dissipates when propagating through the interface between a plasma layer with heavier ions and the other with lighter ions.

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