Effects of laser and plasma parameters on shock wave generation and acceleration of protons

Min-Qing He†, Quan-Li Dong, Zheng-Ming Sheng‡, Su-Ming Weng, Min Chen, Hui-Chun Wu, and Jie Zhang
Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Science, Beijing 100080, China

Abstract. Collisionless electrostatic shock (CES) waves induced by laser-plasma interactions are studied via a series of 1D and 2D particle-in-cell (PIC) simulations. Different target thicknesses, plasma densities and laser intensities have been used to investigate the shock characteristics, since all of them have significant effects on the absorption of the incident laser pulse and the electron temperature. An analytical model has been presented according to momentum conservation and considering the electrons’ circulation. Thinner target, lower plasma density and higher laser intensity help to obtain higher energy ions on condition that the CES is formed.

E-mail: †mqhe@aphy.iphy.ac.cn; ‡zmsheng@aphy.iphy.ac.cn

1. Introduction
In the past decades, the topic of ion acceleration from laser-irradiated plasmas has been extensively studied numerically and experimentally, since such beams may find applications in the fast ignition scheme of inertial confinement fusion[1], radiography[2], medical applications[3], compact particle accelerators[4]. Numerical simulations by Wilks et al. and previous theoretical studies[5] have shown that ions can be accelerated at the target front and back surfaces by the expansion of the hot electron cloud created by the laser pulse. Ions located deep in plasma can also be accelerated by electrostatic shock waves. Denavit used numerical simulations to study the acceleration of ions from the front surface by hole-boring, which in turn can evolve into an electrostatic shock[6]. Several groups recently reported their theoretical and experimental studies about the CES acceleration of ions in intense laser-plasma interactions [7, 8, 9]. Sliva et al. performed a parametric scanning study with PIC simulations about the interaction of a short relativistically intense laser pulse with an overdense plasma target of a wide range thickness[8].

In this paper, we observe the formation of an electrostatic shock with a high Mach number $M = u_s/c_s \approx 2 - 3$, where $u_s$ is the shock speed and $c_s = (Zk_BT_e/m_i)^{1/2}$ is the local sound speed. When the laser is incident perpendicularly from the front side of the target, the ions are accelerated by hole-boring. With the sweeping process of the electrons and ions, the ions located deep in plasmas can be trapped and reflected by a large electrostatic field, which is the shock layer. An analytical model of shock speed versus plasma thickness, density and laser intensity has been indicated in our paper according to momentum and energy conservation by using the electrons’ recirculation.
We use 1D and 2D PIC simulations to study the shocks in over dense plasma foils with target thicknesses of \( L = 1 - 25\mu m \), laser normalized amplitudes of \( a_0 = 2 - 20 \) and plasma densities of \( 10 - 40n_c \), where \( n_c = 1.1 \times 10^{21}/\lambda_0(\mu m)^2cm^{-3} \) is the critical density, \( a_0 = \sqrt{I\lambda_0^2/(1.37 \times 10^{18}Wcm^{-2}/\mu m^2)} \), \( I \) is laser intensity. The plasma foil is placed in the middle of the simulation box with a vacuum space of 7\( \mu m \) at the left side along the longitudinal direction. Circularly and s-polarized laser pulses are incident from the left boundary with sine-squared temporal profiles of different durations \( \tau \). The laser wavelength is \( \lambda_0 = 1\mu m \). The ions are set as protons with the mass \( m_i = 1836m_e \) in all simulations. For 2D cases, the simulation box is set as 16\( \mu m \times 15\mu m \). In the transverse \( y \) direction, the laser beams have Gaussian intensity distributions with the diameter of 5\( \mu m \).

2. Target thickness, target density and laser intensity effects

Target thickness, target density and laser intensity have significant effects on the shock characteristics, since all of them have significant effects on the absorption of the incident laser pulse and the electron temperature[5, 6]. According to the momentum conservation, we know the relation:\( M_i v_p^2 n_{i,eff} = I (\eta + 1)/c \), where the original \( n_i \) is replaced by \( n_{i,eff} = n_i \{ 1 - l_p/L \times \exp(- (L/L_0)^q) \} \), because the electrons can circulate back to the front[10]. We assume that the ions in the laser sweeping length \( l_p \) are pushed into the interior, which is approximately the local plasma Debye length \( l_p \approx \lambda_D = 2\pi v_{th}/\omega_p(x) \approx (2\pi/c/\omega_0)\sqrt{n_e\gamma_{los}/n_c} \).

The exponential factor \( \exp[-(L/L_0)^q] \) is used to take into consideration of the effects of the target thickness on the number of the electrons circulating back to the front. From the above equation, \( v_p = \sqrt{(1 + \eta)I/(m_i n_{i,eff}c)} \) is the piston speed, which is approximately shock speed. \( L_c = c\tau/2 \) is the critical target thickness for the accelerated electrons to finish one cycle between the front and the rear. In the calculation, \( q = 10 \) is used to ensure that no electrons circulate back when \( L > L_c \). \( \eta \) is the absorption ratio of laser intensities. Fig. 1 gives the plot of the initial shock speed and the Mach number versus target thickness. The symbols of pulses and crosses represent the initial shock speeds from 1D PIC simulations with circularly polarized laser pulses of \( a = 16 \) and \( a = 5 \), \( n_0 = 10n_c \) and \( n_0 = 20n_c \) respectively. It is noted that the shock speed decreases rapidly when the target thickness increases until about 5\( \lambda_0 \) and it is
velocity versus plasma densities and laser intensities on condition that wave forms in the interior of the target. Fig. 2 shows the scanning research about the shock to the vacuum both at the front and rear side of the target. As plasma density increases, shock \( a = 5 \) and \( n_0 = 20n_c \), respectively. While both of the two series 2D results indicate a higher speed due to the electron compensation from two sides of the laser pulse, the shock speed in the circular polarization case is roughly \( \sqrt{2} \) times that in the linear case, which agrees with the difference of the light momentum transfer in the two cases at the same \( a \).

The Mach number of the shock wave is also studied with the heated plasma treated as dual-temperature fluid. Then the effective temperature is \( T_{\text{eff}} = T_h \cdot T_l / (\zeta T_H + \zeta T_l) \), where \( \zeta = l_p / L \), \( \zeta = L - l_p / L \), \( T_h \) is the hot electron temperature and equals the ponderomotive potential \( \phi_p = m_e c^2 (\sqrt{a^2 + 1} - 1) \), and \( T_l \) is the cold temperature roughly set as one tenth of \( T_h \). The mach number \( M = v_p / c_s \) versus the target thickness is given in Fig. 1 as a dashed line, which shows a rapid decrease and then a slow increase when the target becomes thicker. It is worthy to point out that although the presented results from the PIC simulations and the analytical model show qualitative agreement with the 1D PIC simulations by Silva et al., our result does not show apparent dependence on the critical target length \( L_c \), as implied by Fig. 2 in Ref. [8]. In that work, for the used laser pulse of \( \tau_{\text{laser}} = 100\text{fs} \), the shock speed and the Mach number change their trend versus the target thickness at \( L = L_c = 15\mu m \).

In the simulations, not all the conditions we use can form shock waves. In the following paper, what we concern are all 2D PIC simulations. At lower plasma density, such as \( n_0 = 10n_c \), when \( a = 5 \) and \( L = 1.5\mu m \), there are only solitary waves in the plasma. Ions are expanding quickly to the vacuum both at the front and rear side of the target. As plasma density increases, shock wave forms in the interior of the target. Fig. 2 shows the scanning research about the shock velocity versus plasma densities and laser intensities on condition that \( a = 2 - 10 \), \( n_0 = 20 - 40n_c \). The shock velocities versus plasma densities are plotted in Fig. 2(a). Obviously, with increasing plasma density, the shock wave velocity decreases. It is in good agreement with our analytical model. If the laser intensity is lower, only sheath acceleration appears, whereas if the intensity increases to \( 1.38 \times 10^{18} W/cm^2 \), a shock wave is generated within the target. As the intensity increases further, there is only solitary wave inside the target. Fig. 2(b) shows the plot of the shock velocity versus laser intensities. It is clearly seen that with increasing laser intensity, the ratio of shock velocity, thus the shock velocity increases, which also agrees with our model.

For the effects of plasma density and laser intensity, the accelerated ions energy spectrum is another aspect. A plateau in the ion spectrum is a direct signature for acceleration in the electrostatic shock launched by the laser, which has been observed in Fig. 3. Whereas sheath
accelerated ions have a wide range spectrum. In general, the ions in the spectrums are a mixture of ions accelerated by sheath field and that by electrostatic collisionless shock. Fig. 3(a) and (b) show the ion spectrum with the initial plasma density \( n_0 = 20n_c \), and the relativistic laser intensity \( a_0 = 5 \) in Fig. 3(a), \( a_0 = 10 \) in Fig. 3(b) respectively. The ion energy in Fig. 3(b) is higher than that in Fig. 3(a). The ion energy spectrum of sheath acceleration in Fig. 3(a) is broader. From the above figures, with increasing laser intensities, the ions velocity reflected by shocks increases, that is, the ion energy increases. Fig. 3(c) shows the ion spectrum with the initial plasma density \( n_0 = 40n_c \), and the other parameters are the same as Fig. 3(a). The ion energy is lower in Fig. 3(c), and the plateau is narrower than Fig. 3(a). The initial plasma density affects shock velocity and thus affects the ion energy.

3. Conclusion

In conclusion, a parametric scanning study of shock characteristic has been presented via a series of 1D and 2D PIC simulations. We give an analytical model according to momentum conservation and considering the electrons’ circulation. The target thickness, plasma density and the laser intensity all have effects on the absorption of the laser energy.

Acknowledgments

This work is supported by the Natural Science Foundation of China (Grant No. 10425416, 10335020, 10575129, 10674175, 60678007), National Basic Research Program of China (No. 2007CB815101), the CAS project KJCX2-YW-T01, and the National High-Tech ICF Committee of China.

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