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To cite this article: Quan-Li Dong et al 2010 J. Phys.: Conf. Ser. 244 042024

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Broadening of the energy spectrum of ions accelerated by laser-driven shocks in over-dense slab plasmas

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Abstract. We investigated numerically the broadening mechanisms of the energy spectrum of ions accelerated by electrostatic shocks in over dense plasmas irradiated by intense ultra-short laser pulses. It was found that the width of the shock-accelerated ion spectrum could be ineluctably broadened by two mechanisms, which are the continuously decreasing speed of the shock front due to the energy dissipation into ions, and the further acceleration by the sheath field at target rears when energetic ions arrive there. Other effects, such like that of driving laser pulse duration, were also studied.

1. Introduction
It has been shown that ions located deep in plasmas can be accelerated by electrostatic shock waves driven by intense laser pulses. The formation of collisionless electrostatic shocks (CLEs) and their capabilities of accelerating ions were studied both theoretically and experimentally in plasma stream collisions or intense laser-plasma interactions [1-5]. With particle-in-cell PIC simulations it was found that the shock acceleration of ions can even dominate the sheath acceleration at the target rear when the target thickness is under a certain threshold, which is determined by the intensity of the incident laser pulses [2]. The accelerated ions are expected to present a plateau-shaped energy spectrum, which is proven recently by spherical mass-limited target experiments that manifest converging shocks producing collimated proton beams. Detailed studies of the shock formation and propagation, and its acceleration of ions have indicated that such a plateau shape is caused by two mechanisms: the energy dissipation from the shock front, and the indistinguishable acceleration by the sheath field at the target rear when the shock-accelerated ions arrive [3, 4]. Any proposal trying to produce mono-energetic ion beams with laser-driven shocks should take into consideration of the above two processes.

2. Accelerated ion spectrum broadening due to the energy dissipation of the electrostatic shocks
The speed of the shock front decreases as the wave propagates since the shock front loses energy to ions in the acceleration process. As the result, the ion energy spectrum widens as the shock propagates over longer distances. It was expected that by using a sandwich target, which consists in the central part an ultra-thin layer of heavier ions, mono-energetic heavy ion beam could be produced [4]. This target configuration was once brought out trying to avoid the ion energy spectrum broadening due to the decreasing shock speed by selecting a single shock speed with the thinner heavy ion layer positioned in the target middle area. The position of the heavy ion layer could help to select different shock speed. The energy spread of the heavy ion beam is still, however, determined by the thickness...
of the central layer. Fig.1 (a) and (b) show the temporal evolutions of the heavy ion distribution in their phase space when sandwich targets applied with central layers of different thickness. For both cases, the electron density is set as $n_e=20n_c$, the ion density of the Left and the Right light ion (helium) layers are set as $n_{iL}=n_{iR}=20n_c$, and the heavy ion (carbon) density is set as $5n_c$ with the charge set as $4^+$. In the case with a thicker heavy ion layers as in Fig.1(a), the thickness of the Left and the Right layer of light ions were set as $l_{iL}=0.625\lambda_0$, $l_{iR}=1.625\lambda_0$ and that of the central heavy ion layer $l_2=0.25\lambda_0$, respectively. In the second case with a thinner heavy ion layer, as in Fig.1 (b), $l_{iL}=0.625\lambda_0$, $l_{iR}=1.75\lambda_0$ and $l_2=0.125\lambda_0$. The bold lines in Fig.1 (b) show the positions of the light and the heavy ion layers. With the heavy ion layer as thin as $l_2=0.125\lambda_0$, the shock break through at $t=130\tau_0$, while the breaking out time for the central layer of $0.25\lambda_0$ is $t=175\tau_0$, as shown by the red crosses in Fig.1 (a) and (b). Here $\lambda_0$ and $\tau_0$ are respectively the wavelength and the period of the applied laser pulse shaped as $\sin^2(t)$ with the duration for both cases as $80\tau_0$. For the thicker heavy ion layer, the shock speed decreasing behavior is clearly shown when the shock propagates in the heavy ion layer, while for thinner heavy ion layer, such phenomenon is un conspicuous. From this point of view, the sandwich target works partially as expected to select a single shock speed. This can not, however, ensure the mono-energy ion beam generation, because after the shock's breakthrough the heavy ion layer, the shock-accelerated ion bunch might begin to explode due to the coulomb repulsion between ions, as shown in the heavy ion phase space, Fig.1 (a) and (b). This process causes the expansion of the ion bunch. A large extension in space will deteriorate the mono-energy quality of the ion bunch as it arrives at the target rear, where the sheath field is spatially and temporally variable. This phenomenon is discussed below in Section 3. Another important phenomenon in the simulations is that not all heavy ions experiencing the shock front could be accelerated. It has been pointed out by Chen and He in their simulation studies [3, 4] that the shock can not trap all the ions in its propagating path, resulting into a lower energy tail in the spectrum of shock-accelerated ions. To push all ions in the central heavy ion layer, the laser pulse needs to propagate through to the end of the layer. Of course, such ion acceleration should be attributed to that by the laser front, not by a shock. The effects on the laser pulse duration are discussed below in Section 4.

![Figure 1. The temporal evolutions of the heavy ion distributions in phase space when sandwich targets applied with central heavy ion layers of different thickness. The time is between $t=80\tau_0$ and $205\tau_0$ from the left to the right in the graph with the step of 15 $\tau_0$. (a) $n_{iL}=n_{iR}=4n_c$, $l_{iL}=0.625\lambda_0$ and $l_{iR}=1.625\lambda_0$, $l_2=0.25\lambda_0$, $a=5$, $T=80\tau_0$. (b) $l_{iL}=0.625\lambda_0$, $l_{iR}=1.75\lambda_0$ and $l_2=0.125\lambda_0$, other parameters are the same to that in (a). The red crosses in both cases are phase-space plots right after shocks breaking through the central heavy ion layers.]
3. Further acceleration of ions in the sheath field at target rears

It has been reported that the shock-accelerated ions can be further accelerated in the sheath field formed in the expanding plasma part at target rears [2]. The solid line in Fig.2 (a) indicates the temporal evolution of the longitudinal electric field experienced by one accelerated test ion. The increasing part of the electric field after $60\tau_0$ is the sheath field at the target rear. The dashed line in Fig.2 (a) is the longitudinal momentum of the accelerated ion [3]. It is obvious that the ion was accelerated between $25\tau_0$ and $45\tau_0$, after which period, it propagates with quasi-constant velocity through the unperturbed region of the plasma, and finally arrived at the target rear, where it is further accelerated. Fig.2 (b) shows the temporal evolution of the shock accelerated heavy ion energy spectrum in simulations with sandwich targets. The ion energy spectrum presents a narrow width around the peak of 0.26 MeV just after the shock breaks through the heavy ion layer at $130\tau_0$. After a long time propagation in the bulk plasma, the earlier accelerated part of the heavy ion bunch arrives at the sheath field at the target rear at $310\tau_0$, and continues to be accelerated to higher energies, as indicated by the shift of the peak to $\sim0.3$ MeV. The width of the spectrum is also broadened as expected. In the contrast, at this time, those ions at the relatively lower energy tail of the heavy ion bunch still keep their relatively lower velocity. The situation is changed at $400\tau_0$, when the ion bunch tail arrives at the target rear, where those ions are also accelerated to form the second energy spectrum peak at 0.16 MeV. Both peaks are broadened at later time of $450\tau_0$ and $500\tau_0$, which phenomenon appears $400\tau_0$ after the laser pulse finishes. The further acceleration by the sheath field at the target rear after the shock appears to be unavoidable. As Silva et al. pointed out that the energy spectrum of ions accelerated by shocks evolves into a plateau, which was demonstrated by Henig et al. as the significant feature of this accelerating mechanism in experiments.

![Figure 2](image.png)

**Figure 2.** The temporal evolution of the longitudinal electric field experienced by one accelerated test ion (solid line in (a)). The dashed line is the longitudinal momentum of the accelerated ion [3]. (b) The temporal evolution of the heavy ion energy spectrum. The further acceleration of heavy ions by the sheath field at target rear broadens the spectrum long after the finish of the shock acceleration process.

4. The duration effects of driving laser pulses on the energetic ion spectrum

During the pulse duration, the laser continues to heat the plasma to a higher temperature, which in turn determines the shock speed and the penetration depth of the laser pulse into the plasma. As mentioned above, to push forward the whole central heavy ion layer in sandwich targets, the laser pulse need to be long enough or the plasma density is low enough so that the intense part of the laser pulse can bore into the plasma until the end of the layer. With the same target configuration, we studied the pulse duration effects on the heavy ion acceleration in the central layer of the sandwich targets. Fig.3 (a) and (b) give the heavy ion distributions at different times in the phase space when the pulse duration are
130 $\tau_0$ and 180 $\tau_0$, respectively. Fig.3 can also be compared with Fig.1 (b), which is the phase space of heavy ions when the laser pulse is 80 $\tau_0$, showing a real shock-acceleration process. For the longest laser pulse situation, the whole heavy ion layer is pushed forward at 115 $\tau_0$. However, the quality of the heavy ion energy spread worsens as the whole layer propagate into the depth of the slab plasma due to effects of the existing light ion layer that are partially accelerated by the laser pulse.

![Figure 3](image)

**Figure 3.** The temporal evolutions of the heavy ion distributions in phase space with sandwich targets. Laser pulses with different durations were used, 130 $\tau_0$ for (a), and 180 $\tau_0$ for (b). Other simulation parameters are the same to those of Fig.1 (b). The red crosses are for the time when the heavy ion layers completely leave their original positions.

5. **Summary**
We have shown two kinds of mechanisms that broaden the ion spectrum of the ions accelerated by laser-driven shocks. By introducing the expected heavy ions as the central ultra-thin layer of sandwich targets, it is possible to select a single shock speed so that the energetic ion spectrum can partially avoid broadening due to the energy dissipation from the shock front to the accelerated ions. But the following exploding effects within the ion bunch, and the further acceleration of the shock-accelerated ion bunch that takes place long after the shock acceleration process, will ineluctably worsen the mono-energy quality of the ion beam in experiments. The collision between energetic ions and the background ions is also found to have effects (not described here). Analysis only of the characteristics of the early shock acceleration process might come into being a misleading conclusion. Even with a longer intense laser pulse that propagates through to the end of the central ultra-thin heavy ion layer of the sandwich targets, it is not easy to obtain a mono-energy ion beam.

6. **Acknowledgments**
This work is jointly supported by the Natural Science Foundation of China (Grant No. 60621063, 60678007, 10774184), the CAS project KJCX2-YW-T01, and the National Basic Research Program of China No.2007CB815101.

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