Generation of quasi-monoenergetic heavy ion beams via staged shock wave acceleration driven by intense laser pulses in near-critical plasmas

W L Zhang¹,², B Qiao¹,², X F Shen¹, W Y You¹, T W Huang¹, X Q Yan¹, S Z Wu¹,², C T Zhou¹,³ and X T He¹,³

¹ Center for Applied Physics and Technology, HEDPS, and State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, People’s Republic of China
² Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, People’s Republic of China
³ Institute of Applied Physics and Computational Mathematics, Beijing 100094, People’s Republic of China

E-mail: bqiao@pku.edu.cn

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Abstract

Laser-driven ion acceleration potentially offers a compact, cost-effective alternative to conventional accelerators for scientific, technological, and health-care applications. A novel scheme for heavy ion acceleration in near-critical plasmas via staged shock waves driven by intense laser pulses is proposed, where, in front of the heavy ion target, a light ion layer is used for launching a high-speed electrostatic shock wave. This shock is enhanced at the interface before it is transmitted into the heavy ion plasmas. Monoenergetic heavy ion beam with much higher energy can be generated by the transmitted shock, comparing to the shock wave acceleration in pure heavy ion target. Two-dimensional particle-in-cell simulations show that quasi-monoenergetic C⁶⁺ ion beams with peak energy 168 MeV and considerable particle number 2.1 \times 10^{13} are obtained by laser pulses at intensity of 1.66 \times 10^{20} W cm⁻² in such staged shock wave acceleration scheme. Similarly a high-quality Al^{10⁺} ion beam with a well-defined peak with energy 250 MeV and spread \delta E/E₀ = 30% can also be obtained in this scheme.

1. Introduction

High quality heavy ion beam generated from high-Z material can potentially be used for wide-ranging fields, including carbon ion-based fast ignition [1], injector for conventional heavy ion accelerators [2], nuclear reaction [3], study of exotic phenomenons in the interior of stars [4], and creation of quark-gluon plasma [5], etc. The advent of ultra-high intensity laser provides access to laboratory-sized compact ion accelerator via laser-plasma interactions. While the accelerations of protons and light ions have been extensively investigated, little has been reported on acceleration of heavy ions. In particular, the aforementioned applications [6] require the heavy ion beams have simultaneous high peak energy, high directionality, narrow energy spread, and high intensity flux, etc, which impose great challenges to the heavy ion acceleration.

Shock wave acceleration (SWA) [7–9] by ion reflection in near-critical plasmas is a promising candidate as a source of high quality ion beam. For the SWA in near-critical plasmas, the ions are continuously reflected to twice of the shock velocity during the shock wave stable propagation, resulting in production of intense quasi-monoenergetic ion beam with comparatively high particle number. These are in stark contrast to the target normal sheath acceleration [10–12], which typically produces an ion beam with exponential spectrum, large angular divergence, and low particle number. Furthermore, SWA can be achieved under a much relaxed experimental condition. This is also in contrast to the radiation pressure acceleration [13–18] which is exposed to various transverse instabilities and faces formidable experimental challenges. While for heavy ions with low Z/A, the shock velocity is slow due to the slow ion acoustic wave speed, i.e., c_s = \sqrt{T_e/m_p}, where T_e is the electron temperature and m_p is the proton mass. In addition, the condition for ion reflection, i.e.,
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Figure 1. A schematic figure for the staged shock wave acceleration dynamics at moments (a) before the laser-driven shock arrives at the interface region and (b) after the transmitted shock is completely formed. The black solid lines represent the initial plasma density profile with electron density $n_{e1}$ and $n_{e2}$, respectively. The blue dashed lines are the electrostatic fields induced at the interface region ($E_{\text{int}}$) and the rear side ($E_{\text{sheath}}$), respectively. The electric field associated with the shock front $E_{\text{sh}}$ is not shown here. The black dashed line in (a) is the laser–compressed ion density profile acting as the downstream of the laser-driven shock. Similarly, the black dashed line in (b) represents the downstream of the transmitted shock. The hot electrons move toward the rear side with relativistic velocity and a portion of them will be turned back under the action of $E_{\text{sheath}}$.

$Ze\phi = 1/2Am_p v_s^2$, indicates the heavy ion reflection requires higher potential barrier given the same shock velocity, which limits the resultant beam density. Here $e$ is the charge of electron, $\phi$ is the electrostatic potential of shock, and $v_s$ denotes the shock velocity. The quick dissipation by the heavy ion reflection further drags the shock wave during its propagation, which will significantly broaden the resultant energy spread.

In this paper, a staged SWA scheme for production of high quality heavy ion beam is proposed, where, a light ion layer is used in front of the heavy ion target. When the light ion layer is irradiated by an intense laser, a high-speed collisionless electrostatic shock wave is firstly launched. Before this shock arrives at the interface between the light and heavy ion plasmas, a strong electrostatic field is induced at the interface, resulting in early recirculation of hot electrons in the light ion layer and pre-acceleration of the heavy ions. Both of these effects lead to a much enhanced transmitted shock wave in the heavy ion plasma. The transmitted shock can reflect heavy ions which gives rise to a monoenergetic ion beam. These features and the exciting enhancement on the beam quality compared with the typical SWA in pure heavy ion plasmas are confirmed by two-dimensional PIC simulations. The resultant energy spectrum is adjustable by varying the mass density jump between the two adjoining plasmas.

This paper is organized as follows. In section 2, the theoretical model for the staged SWA are depicted. In section 3, the 2D PIC simulation results are presented to confirm our theory. In section 4, further insights into the staged SWA dynamics are given and the parameter range for optimal acceleration is proposed. In section 5, discussion on the experimental feasibility of our proposed scheme is given. Section 6 is dedicated to the conclusion.

2. Theoretical model

A schematic figure for the staged SWA dynamics is shown in figure 1. The front light ion layer is irradiated by intense laser, which drives a high-speed shock wave under the conditions of appropriate density piling-up and electron heating [9]. This laser–driven shock (black dashed line in figure 1(a)) is hereinafter referred to as ‘the first shock’. A shock has the nature of compression due to the acceleration of the post-shock medium. So when the first shock strikes the interface, the heavy ion plasma is compressed and piled up under the action of the shock field $E_{\text{sh}}$. A transmitted shock capable of reflecting heavy ions is thus formed (black dashed line in figure 1(b)). At the same time, either a shock wave or rarefaction wave (RW) is backscattered into the light ion layer. The character of the backscattered wave depends on the ion mass density jump between the two adjoining plasmas, i.e., $\rho_1/\rho_2 = (A_1/Z_1)n_{i1}/(A_2/Z_2)n_{i2}$, and their respective thermal properties [19]. In addition, the velocity of the transmitted shock increases with $\rho_1/\rho_2$. Consequently, the resultant heavy ion spectrum in this staged SWA scheme can be adjusted by varying the density jump condition.

It is worth noting that there are some crucial merits in this staged SWA scheme. Before the first shock arrives at the interface where plasma density drops, the two plasmas expand into each other which induces an intense field $E_{\text{int}}$. On the other hand, hot electrons generated in the front laser-plasma interaction region move to the
rear side and will enhance $E_{\text{int}}$ by losing some kinetic energy when passing by the interface. A portion of the hot electrons even turn back under the condition $\gamma_e - 1) m_e c^2 < e \phi_{\text{int}}$, where $\gamma_e$ is the electron gamma factor, $m_e$ is the mass of electron, $c$ is the light speed in vacuum, and $\phi_{\text{int}}$ denotes the electrostatic potential across the interface. This early recirculation contributes to the uniform heating and accordingly a high temperature $T_e$ in the light ion layer. The high temperature promises a low Mach number given the same radiation pressure drive. So the light ion reflection is minimized in the first shock, which greatly benefits our staged SWA scheme. On the contrary, if large number of light ions are reflected in the first shock, e.g. in the case using short pulse or thick light ion layer, the layer energy will be heavily depleted. This effect decreases the transmitted shock velocity and the final energy conversion efficiency from laser into the reflected heavy ions.

It is noted that the heavy ion reflection is assisted by the pre-acceleration of heavy ions by $E_{\text{int}}$, because the upstream ions will become less energetic in the shock-rest frame. When the mass of electron is neglected, $E_{\text{int}}$ can be estimated as $E_{\text{int}} = - \nabla n_e / n_{\text{eq}}$, where the pressure gradient $\nabla n_e = T_e \nabla n_e = T_e (n_{e1} - n_{e2}) / l_{\text{int}}$ and $n_{\text{eq}} = 1 / 2 (n_{e1} + n_{e2})$. $l_{\text{int}}$ is the scale thickness of the interface region which is assumed to have the same order of Debye length, i.e., $l_{\text{int}} = \delta \lambda_D$, where $\delta = O(1)$, $\lambda_D = \sqrt{\varepsilon_0 T_e / n_{\text{eq}}}$, and $\varepsilon_0$ is permittivity constant of vacuum. After some algebra, $E_{\text{int}}$ is given by

$$E_{\text{int}} = \sqrt{2 n_{e1} T_e / \varepsilon_0} \frac{1 - n_{e2} / n_{e1}}{\delta^2 + n_{e2} / n_{e1}}. \quad (1)$$

This indicates that $E_{\text{int}}$ increases with the front layer density $n_{e1}$ and density jump $n_{e1} / n_{e2}$ (or $\rho_{i1} / \rho_{i2}$). When $n_{e1} / n_{e2}$ are sufficiently large, $E_{\text{int}} \approx \sqrt{2 n_{e1} T_e / \varepsilon_0} / \delta$ which does not sensitively depend on $\rho_{i1} / \rho_{i2}$. So $E_{\text{int}}$ has a weak scaling with $\rho_{i1} / \rho_{i2}$ in the high $\rho_{i1} / \rho_{i2}$ regime, which suggests that too large $\rho_{i1} / \rho_{i2}$ will not help further boosting the first shock velocity via $E_{\text{int}}$.

3. Two-dimensional PIC simulation results

The proposed novel acceleration scheme is confirmed by 2D PIC EPOCH simulations [20]. In the simulations, the laser pulse with wavelength $\lambda = 1 \mu m$ is polarized along $y$ direction and propagates along $+x$ direction. The transverse intensity distribution is a supergaussian ($I(r) \propto I_0 \exp\left(- (r / r_0)^4\right)$) giving a full-width-at-half-maximum focal spot radius of $24 \mu m$ centered at $y = 30 \mu m$. The peak intensity $I_0 = 1.66 \times 10^{20} \text{ W cm}^{-2}$ corresponding to the normalized amplitude $a_0 = 11$. The laser has a flat-topped temporal profile (i.e., constant intensity) with duration $\tau = 267 \text{ fs}$. The simulation box is $46 \times 60$ ($\mu m^2$) in the $(x, y)$ plane. The light and heavy ions are chosen to be fully ionized proton ($H^+$) and carbon ($C^6^+$) ions, respectively. In front of the heavy ion target is a $5 \mu m$ thick proton layer with electron density $n_{e1} = 10n_c$. Here $n_c$ is the critical density $n_c = m_e e_0 \omega_0^2 / e^2$, where $\omega_0$ is the laser frequency. The carbon target consists of a $5 \mu m$ thick layer with density $n_{e2} = 2.5n_c$, followed by a rear plasma with an exponentially decaying profile. So the light and heavy ions plasma have a ion mass density jump $\rho_{i1} / \rho_{i2} = 2/1$. The decaying $C^6^+$ plasma, with a scale length of $L_p = 8 \mu m$, guarantees a suitably smooth density gradient which leads to a mitigated and constant sheath field at the rear side (i.e., $E_{\text{sheath}}$, figure 1). This effect benefits the generation of high quality ion beam in SWA [7, 9, 21]. The cell dimensions are resolved by the initial collisionless skin depth of light ion layer as $\Delta x = 0.24c / \omega_{pe}$ (12 nm) and $\Delta y = 0.4c / \omega_{pe}$ (20 nm), respectively, where $\omega_{pe} = \sqrt{n_{e1} e^2 / m_e e_0}$. There are 64 particles per cell per species. With higher number of particles, the simulation results are converged.

Figure 2 shows the evolutions of transverse electric field $E_y$, proton density $n$ ($H^+$), and carbon charge density $6n$ ($C^6^+$), respectively. In our simulation, when the laser interacts with the front hydrogen layer, the density piling-up due to the radiation pressure compression is obvious, see $n$ ($H^+$) at $t = 100 \text{ fs}$ (purple part in figure 2(a)). The piling-up ultimately evolves into a collisionless electrostatic shock wave whose front can be observed in figures 3(a) and (d). With the density jump, a strong electric field $E_{\text{int}}$ (figure 3(d)) is induced at the interface as expected in theory. The simulation shows that $E_{\text{int}} \approx 1$ which is comparable to the first shock field $E_{sh} \approx 2$. On the other hand, the temperature is measured to be $T_e = 3.0 \text{ MeV}$, so $\lambda_D = 0.15 \mu m$. The scale length of the interface region is measured to be $l_{\text{int}} = 1.1 \mu m \sim 7\lambda_D$. It suggests $E_{\text{int}} \approx 1.1$ from equation (1), which agrees well with the simulation result. $E_{\text{int}}$ can accelerate both $H^+$ and $C^6^+$ before the arrival of the first shock. This pre-acceleration makes it more feasible for the $C^6^+$ ion reflection, because these $C^6^+$ ions will become less energetic in the shock-rest frame.

When the first shock is striking the interface, a superposition of $E_{sh}$ and $E_{\text{int}}$ is observed (figures 3(b) and (e)) which leads to a very strong field ($E \sim 3$). The $C^6^+$ layer is profoundly accelerated and compressed which shows the enhanced compression ability of the current shock. The large $C^6^+$ piling-up can be seen in figure 2(b). Consequently, the first shock is being transmitted into the $C^6^+$ plasma and the $C^6^+$ ion reflection starts (see its phase space in figures 3(e) and (f)). With the current simulation setup, a RW is backscattered into the proton layer resulting in a much rarefied hydrogen plasma (purple part in figure 2(b)).
After the first shock is completely transmitted into the \( ^6 \text{C}_6 \) plasma, the transmitted shock front is clearly shown in figures 2(c) and 3(c). The plateau in phase space (figure 3(f)) indicates a monoenergetic \( ^6 \text{C}_6 ^+ \) ion beam has been produced. For comparison with the staged SWA case, another PIC simulation, in which a target made up of pure \( ^6 \text{C}_6 \) plasmas with thickness \( m_1 = 10 \mu \text{m} \) and electron density \( 10^{14} \text{cm}^{-3} \), are performed. Other parameters are kept unchanged. The energy spectra of both cases are compared in figure 4(a). In the staged SWA case (red line, \( \rho_{1}/\rho_2 = 2/1 \), due to the lower density of the \( ^6 \text{C}_6 ^+ \) layer, the number of reflected \( ^6 \text{C}_6 ^+ \) ions (2.1 \times 10^{13}) is about one half of that in pure carbon case (4.1 \times 10^{13}, green line). The spectrum in pure carbon case barely shows a peak with energy \( E_0 = 60 \text{ MeV} \) and spread up to be \( \delta E/E_0 = 73\% \). In striking contrast, the spectrum in the staged SWA case shows a well-defined peak with \( E_0 = 168 \text{ MeV} \) and \( \delta E/E_0 = 31\% \). The strong adaptability of this staged SWA scheme is confirmed by replacing the carbon ions by heavier aluminum (\( Z = +10, A = 27 \), \( \rho_{1}/\rho_2 = 1.48/1 \)) and keeping other parameters unchanged. The results (figure 4(b)) also indicate a high quality...
Al^{10+} ion beam with well-defined peak of $E_0 = 250$ MeV and $\delta E/E_0 = 30\%$ is generated in the staged SWA case. While in the comparison case with pure aluminum plasma, the spectrum shows a small peak with $E_0 = 90$ MeV and spread up to be $\delta E/E_0 = 71\%$. These simulations show that both the peak energy and spread, through our novel scheme, are greatly improved compared with the typical SWA in pure heavy ion plasmas.

4. Analysis of the acceleration dynamics and the parameters for optimal acceleration

The essential idea of the staged SWA scheme is that the formation of the shock wave in heavy ion plasmas is separated from the intense driving laser. Two merits based on this separation should be pointed out. First, we could apply very intense laser in the light ion layer to drive a high-speed shock. Having high charge-to-mass ratio $Z/A$, the light ions can respond to the electrostatic field quickly and accordingly have sufficient piling-up. This mechanism for remaining relativistically opaque by large piling-up and obtaining a high-speed shock wave is similar with the idea in reference [22]. Second, the heavy ion layer could have relatively low density which leads to a stable shock velocity with mild dissipation. While in the typical SWA scheme using pure heavy ion plasma with high density, the continuous reflection of heavy ions will impose a strong loading for the shock structure. This loading will drag the shock and diminish the corresponding potential $\phi_s$ dramatically. The declination in shock velocity (figure 5(b)) will result in a progressive broadening effects on the ion spectrum (green line in figure 4(a)).

The energy evolution in the whole simulation box offers further insights into the staged SWA mechanisms, see figure 5(a). The laser energy (blue line) is continuously injected into the system until it is switched off. The electron energy (black solid line) increases sharply with the effective heating by $J \times B$ effects, plasma waves excitation, etc. The $H^+$ population gains energy (green solid line) mainly through the laser-induced electrostatic field during the ponderomotive force compression stage and the first shock propagation. After $t \sim 200$ fs, the total energy of $C^{6+}$ (red solid line) increases rapidly due to the acceleration of $C^{6+}$ ions (figure 3(e)). The growth rate of the total $C^{6+}$ energy in staged SWA case is higher than the pure carbon case (red dashed line), because the transmitted $C^{6+}$ shock in staged SWA case is much faster. This is also consistent with their peak energy difference (figure 4(a)). The final value of the total $C^{6+}$ energy is higher in staged SWA case which shows the enhancement of the energy conversion efficiency (blue line in figure 6(b)). After the laser is off ($\sim 267$ fs), the total $C^{6+}$ energy gain approaches a saturated level in the pure carbon case. This is because the shock will lose its momentum rapidly when it is reflecting large number of heavy $C^{6+}$ ions. While in the staged SWA case, the transmitted $C^{6+}$ shock has a relatively stable velocity with mild ion reflection when propagating in lower density plasma.

The property of the transmitted shock mainly depends on the ion mass density jump $\rho_1/\rho_2$ [19], which lays the theoretical foundation for the adjustability of heavy ion spectrum by varying $\rho_1/\rho_2$ in the staged SWA scheme. So a series of PIC simulations are performed to study the parameter range for optimal staged SWA.
Figure 6 shows the dependences of peak energy $E_0$ (black solid circle) and spread $dE_0$ (blue solid square) of the $^{+}C_6$ ion beams on $r_{i12}$. It indicates that $E_0$ in all of the staged SWA cases increase with $r_{i12}$ as expected, and is also superior to the comparison case ($60$ MeV, black dashed line). $dE_0$ shows the similar trend with $r_{i12}$ and advantage over the comparison case ($73\%$, blue dashed line). It is noted that the improvements of $E_0$ and $dE_0$ still exist even without the help of ion mass density jump (see the cases with $r_{i1}/r_{i2} = 0.5$ and $r_{i1}/r_{i2} = 1$). In addition, in the case with $r_{i1}/r_{i2} = 0.5$ (i.e., $n_{i1}/n_{i2} = 1$), there is no interface-induced field $E_{int}$ which could enhance the first shock velocity, but the peak energy ($\sim 72$ MeV) is still enhanced. So the light ion layer used in staged SWA scheme does help in boosting the final heavy ion energy.

Figure 6(a) shows the dependences of peak energy $E_0$ (black solid circle) and spread $\delta E/E_0$ (blue solid square) of the $^{+}C_6$ ion beams on $r_{i1}/r_{i2}$. It indicates that $E_0$ in all of the staged SWA cases increase with $r_{i1}/r_{i2}$ as expected, and is also superior to the comparison case (60 MeV, black dashed line). $\delta E/E_0$ shows the similar trend with $r_{i1}/r_{i2}$ and advantage over the comparison case (73\%, blue dashed line). It is noted that the improvements of $E_0$ and $\delta E/E_0$ still exist even without the help of ion mass density jump (see the cases with $r_{i1}/r_{i2} = 0.5$ and $r_{i1}/r_{i2} = 1$). In addition, in the case with $r_{i1}/r_{i2} = 0.5$ (i.e., $n_{i1}/n_{i2} = 1$), there is no interface-induced field $E_{int}$ which could enhance the first shock velocity, but the peak energy ($\sim 72$ MeV) is still enhanced. So the light ion layer used in staged SWA scheme does help in boosting the final heavy ion energy.

Figure 6 shows that the range of $r_{i1}/r_{i2}$ for optimal staged SWA scheme lies in $1 \leq r_{i1}/r_{i2} \leq 5$. In this range, both $E_0$ and $\delta E/E_0$ are greatly improved compared with the SWA in pure carbon plasma. At the same time, the reflected $^{+}C_6$ ion number and the energy conversion efficiency increase with $r_{i1}/r_{i2}$ dramatically (figure 6(b)).
For example, in the case with $\rho_{j}/\rho_{2} = 5$, $E_{0}$ is boosted to be 174 MeV and $\delta E/E_{0}$ drops to be only 22%. In addition, the ion beam has a considerable particle number of $3.6 \times 10^{11}$ and high conversion efficiency of $\sim 6\%$. It is noted that very intense $E_{\text{int}}$ is established in this case due to large density jump (equation (1)). More hot electrons will be turned back by $E_{\text{int}}$, which leads to high $T_{\text{e}}$ in the front layer. Such high temperature and intense $E_{\text{int}}$ give rise to fast expansion of the proton layer, so the laser will penetrate the target when the first shock is striking the interface. Large number of hot electrons will be generated and expand into vacuum. This leads to a strong sheath field which accelerates the upstream $C^{6+}$ plasma. Such acceleration effects will help more upstream ions to be reflected by the transmitted shock, because the accelerated ions will become less energetic in the shock-rest frame. This explains the high particle number and high conversion efficiency in this case. But another two problems will arise for the high density jump regime ($\rho_{j}/\rho_{2} \geq 5$). First, the velocity of the reflected $C^{6+}$ ions is given by $v_{i} = 2v_{i} - v_{0}$ in the non-relativistic limit, where $v_{0}$ is the expanding velocity of the upstream plasma. Consequently, the peak energy can no longer be boosted to a much higher value with larger $\rho_{j}/\rho_{2}$ as the expanding velocity $v_{0}$ cancels out part of the velocity gain by shock reflection. This explains the limited gain of the peak energy from the case with $\rho_{j}/\rho_{2} = 2$ to the case with $\rho_{j}/\rho_{2} = 5$ (figure 6(a)). Second, some reflected particles will obtain more energy under the action of the intense sheath field, which leads to the high energy tail in the spectrum (blue line in figure 4(a)). So, too large $\rho_{j}/\rho_{2}$ is not suitable for the high quality ion beam generation.

5. Discussion on experimental feasibility

With the rapid progress of target fabrication technology, targets of relativistically near-critical density ($n_{c} \sim 10^{21} \text{ cm}^{-3}$, corresponding to laser with short wavelength) are not only makable but also controllable through various methods in experiments to date. Hydrogen target at density of $\sim 40n_{c}$, which has been produced either by extrusion from a liquid-helium-cooled cryostat [23] or by a cooling finger from a cryogenic system [24] in laser-plasma experiments, can be used as the low-$Z$ layer in the staged SWA scheme. Foams with high hydrogen concentration can also provide well-characterized uniform density and temperature near-critical plasmas [25, 26]. As for the carbon target, carbon nanotube foams [27] can provide spatially well-defined carbon plasmas with electron densities at $\sim (3.4 \pm 1.7) \times 10^{21} \text{ cm}^{-3}$, which are very close to those used in the simulations of this paper. The exponentially decaying profile [8, 9, 28] at rear side of the target can be produced through the thermal expansion of the carbon target via either a low-power pre-heater pulse or a separate low-intensity ultraviolet (UV) laser [29], where the density scale length can be controlled via adjusting the expansion time of the carbon target, i.e., the delay time between the main pulse and the pre-heater pulse or the UV beam.

The proposed staged SWA scheme in this paper is rather robust. The basic physics of this scheme will not change even if the preplasma effect is take into account. The latter can influence the maximum piling-up of plasma density and the electron heating during the shock formation process [9]. The precise dependence of the resultant beam quality on the preplasma needs further systematic investigation. Another consideration is for the presence of non-planar interface between light and heavy ion plasmas. The non-planar interface may lead to spatially non-uniformity and modulate the transmission of the first shock into the heavy ion target, increasing the angular divergence of the shock-reflected heavy ions. In practical experiments, using a comparatively large spot size of the laser pulse, including the main pulse and the separate UV beam (for creating required plasma profile as stated above), can suppress this potential detrimental effect.

6. Conclusion

In this paper, a novel heavy ion acceleration scheme via staged shock waves is proposed in which a light ion layer is deployed in front of the heavy ion target. When the laser-driven shock in the light ion layer is transmitted into the heavy ion target, a quasi-monoenergetic heavy ion beam is generated. The resultant ion spectrum can be adjusted by varying the ion mass density jump between the adjoining plasmas. The interface-induced field $E_{\text{int}}$ can enhance the first shock velocity and amplitude, which greatly benefits the ensuing heavy ion acceleration. 2D PIC simulations have confirmed our theory and show that a $C^{6+}$ ion beam with peak energy of 168 MeV and considerable particle number of $2.1 \times 10^{11}$ can be obtained in the staged SWA scheme with $\rho_{j}/\rho_{2} = 2/1$ at the laser intensity of $1.66 \times 10^{20} \text{ W cm}^{-2}$. This acceleration scheme also applies to heavier ion species, such as $\text{Ar}^{10+}$ ion beam with well-defined peak of $E_{0} = 250 \text{ MeV}$ and $\delta E/E_{0} = 30\%$ can be generated in the staged SWA scheme with the same laser.
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