Stable quasi-monoenergetic ion acceleration from the laser-driven shocks in a collisional plasma

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Effect of collisions on the shock formation and subsequent ion acceleration from the laser-plasma interaction is explored by means of particle-in-cell simulations. In this setup, the incident laser pushes the laser-plasma interface inside the plasma target through the hole-boring effect and generates hot electrons. The propagation of these hot electrons inside the target excites a return plasma current, leading to filamentary structures caused by the Weibel/filamentation instability. Weakening of the space-charge effects due to collisions results in the shock formation with a higher density jump than in a collisionless plasma. This results in the formation of a stronger shock leading to a stable quasi-monoenergetic acceleration of ions.

Collisionless shocks naturally occur in astrophysical environments such as supernova remnants, gamma ray bursts etc. [1]. They can accelerate particles to very high energies and are believed to be responsible for high energy cosmic rays and non-thermal particles in astrophysical scenarios [1, 2]. Collisionless shocks can also be generated in a laboratory [3]. Since collisionless shocks are efficient accelerators of particles (both leptons and hadrons), they can be used to accelerate ions in a laboratory [4–6] which can be beneficial for medical science, particularly for the treatment of cancer [7, 8]. In general, the laser produced shock waves can have a wide range of applications from nuclear fusion to material sciences [9].

Despite their ubiquity in nature, the microphysics involved in the formation of collisionless shocks is not yet fully understood. In recent years, there have been growing number of efforts to understand the roles of various plasma instabilities in the formation of collisionless shocks in a laboratory [10, 11]. Such studies are subject to the scaling laws with regard to the interpretation of astrophysical observations [12] but nonetheless are also complementary to the rich literature of the plasma instabilities [13–15]. A straightforward configuration to study the collisionless shocks, in a laboratory, is the one where two counter-propagating unmagnetized plasma flows are allowed to collide [12, 16]. In this set-up, the interaction region of the two plasma flows is susceptible to numerous plasma instabilities e.g. two-stream and Weibel/filamentation instabilities [14]. For the relativistic plasma flows, the Weibel/filamentation instabilities (henceforth referred to as the Weibel instability) is dominant and generates a strong magnetic field [17]. The particles get scattered in this magnetic field and piled up to create a shocked region. Then a smaller number of particles gets accelerated from this shock by the Fermi 1st or 2nd order acceleration processes, yielding an energy spectrum which is a power-law distribution [2]. Since the Weibel instability generates a stronger magnetic field these shocks are also called the Weibel mediated or electromagnetic shocks [11]. However, experimental investigation of such shocks has been challenging as one needs very energetic laser-systems to drive relativistic collisionless plasma flows from the overdense plasma targets [12, 17]. For non-relativistic flows, where the Weibel instability does not dominate, generation of the magnetic field is weak and these shocks are called the electrostatic shocks [18].

Both the electrostatic and electromagnetic shocks can also be generated when an intense laser is incident on an overdense plasma target [4, 19–21]. In this configuration, the laser ponderomotive force heats the electrons and launches an electrostatic shock at the target surface [4, 19]. The hot electrons then propagate inside the target and while traversing through the target they excite a return plasma current. These counter-propagating electronic currents get filamented due to the Weibel instability and a strong magnetic field is generated. Due to this strong magnetic field generation, the electrostatic shock evolves and enters the electromagnetic phase of the shock formation [20, 21]. If the incident laser intensity is high \( I_0 > 10^{18} \text{W/cm}^2 \), the target surface also moves because of the hole-boring effect. Due to the difference in the electron and ion masses, there is a longitudinal electric field present at the shock-front which can reflect the background ions leading to ion acceleration [5, 6, 21]. The onset and dynamics of the return plasma current is crucial in this scheme. The return plasma current is dense and has a rather low velocity. Hence, collisions between the plasma electrons and background plasma ions become important. This necessitates the inclusion of the collisions in the return plasma current as the dynamics of the Weibel instability is considerably changed in such a case. This can affect the shock formation and hence the resulting ion acceleration in this case.

In this Letter, we include both the electron-electron and electron-ion collisions and investigate their impact on the shock formation and ion acceleration in the laser interaction with a near critical density plasma by particle-in-cell (PIC) simulations. We observe that collisions affect the shock acceleration of ions in three ways: collisions weaken the space-charge effects. Since the electrostatic field generated due to the space-charge effects competes

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with the laser ponderomotive force, the latter—due to the collisional weakening of the space-charge effects—is able to compress the plasma density to a higher value at the laser-target interaction surface. This extra compression of the plasma density arising due to collisions leads to a higher density jump than studied before, but closer to the value given by the Rankine-Hugoniot relations for a Maxwellian plasma in high Mach numbers limit. Second, collisions suppress the hot electron transport and weaken the target normal sheath acceleration (TNSA) from the back of the target. This can improve the ion acceleration spectra as TNSA has an adverse impact on the spectrum of the accelerated ions. Third, collisions also reduce the growth rate of the Weibel instability which affects the generation of the magnetic field turbulence. We find that the inclusion of collisions in PIC simulation leads to a stronger and stable shock formation and the energy spectrum of a small population of shock reflected ions gets significantly enhanced as it leaves from the back of the target. Thus, collisions enhance the shock acceleration of ions without requiring the tailoring of the target density at the back.

We carry out 2D PIC simulations using EPOCH PIC code [22] in which an electron-proton plasma target of density \( n_0 = 50n_e \), is irradiated with a linearly polarized laser with normalized vector potential \( a_0 = eE_0/m_e\omega_0c = 60 \) \((I_0 = 5 \times 10^{21} \text{ W/cm}^2)\). Here, \( E_0 \) is the electric field of the laser, \( m_e/m_i = 1836 \), \( Z_i = 1 \), where \( m_i \) and \( m_e \) are the masses of electron and ion respectively and the critical density for 1\( \mu \)m light, \( n_c = m_e\omega_0^2/(4\pi e^2) \), where \( e, c, \omega_0 \) and \( e \) are the electronic charge, the laser frequency and the velocity of the light in vacuum respectively. The target has a thickness of \( L_d = 50\mu \text{m} \) and the initial plasma temperature is taken to be 850 eV. This configuration is similar to the one in [6]. We use collisions module of EPOCH (version 4.8.3) to account for collisions between the plasma electrons as well as between electrons and ions. It should be noted that electron-electron collisions here should not be neglected because of the two interpenetrating electrostatic streams. The collision frequency for such a target configuration is about \( \nu_0 \approx 0.01\omega_{pe} \). The simulation grid contains \( 9000 \times 2000 \) cells with mesh size \( \delta_x = \delta_y = 0.44c/\omega_{pe} \), where \( \omega_{pe} = \sqrt{4\pi ne^2/m_e} \) is the electronic plasma frequency. Each cell has 40 macro particles of each species that makes up to \( \sim 10^9 \) superparticles. Fig.1 shows the time evolution of the transversely averaged proton density for the case of collisionless interaction (upper panel) and a collisional (lower panel) one. One can clearly notice some salient features of the interaction dynamics. First, the density jump is higher and the shock formation time is lower compared to the collisionless case. Moreover, the density of shock accelerated ions at time \( t = 1200 \) fs is also higher in the collisional case. Second, the acceleration of ions due to the TNSA from the back of the target is severely suppressed in the collisional case (lower panel). The density jump is \( n_d/n_u \approx 4 \), where \( n_d \) and \( n_u \) are the densities of the downstream and upstream ions respectively. This density jump is higher than the jump \((n_d/n_u \approx 3.2)\) seen in upper panel for the collisionless case and also calculated in Refs. [21, 23, 24]. However, this jump is closer to the value predicted by the Rankine-Hugoniot relations for a Maxwellian plasma in high Mach numbers limit [25]. The origin of the higher density jump is depicted in Fig.2. One can see that in the beginning of the interaction, density compression is the same in both collisionless and collisional cases. However, when the hole-boring starts dominating (after two laser periods) on account of collisions, a higher plasma density jump is obtained as compared to the collisionless case. This is due to the collisional weakening of the space-charge effects, which results in a higher plasma density compression by the laser ponderomotive force. At this instant, the hole-boring velocity acquires a constant value and no further compression is possible. Thus, an electrostatic shock is formed and it has a density jump higher than the collisionless case. Later on, as this shock propagates inside the plasma the shock width increases primarily due to its dissipation occurring in accelerating a bunch of ions ahead of it as seen in the Fig. 2. The velocity of the shock \( u_{sh} \) is about 7\% higher in the col-
neral case ($\nu_{sh} = 0.17c$) compared to the collisionless case ($\nu_{sh} = 0.16c$). It may be noted that, in this case, the hole-boring velocity is $v_{HB} = 0.12c$.

Apart from compressing the plasma density, the laser also generates hot electrons. These electrons traverse the target and cause acceleration of ions due to the TNSA. Fig.1 shows that the collisions inhibit the hot electron transport within the target; a fact also noted in Ref. [26]. Since the hot electrons excite a return plasma current leading to the Weibel instability, one can expect the Weibel instability to be less prominent in the collisional case. Indeed one can clearly see this effect in Fig.3 where the filamentation caused by the Weibel instability is not as strong as in the collisionless case. One can also see (lower panel) a bunch of ions ahead of shock which is being accelerated by the shock. Thus, in the collisional case, instead of having a transition from the electrostatic to electromagnetic phases of the shock formation, we have both the electrostatic and electromagnetic phases coexisting together. This development can be better seen in Fig.4 where electric and magnetic field energies evolutions are depicted. In the collisionless case (first column) one sees a significant build-up of magnetic field energy (panel (a)) exceeding the electric field energy at the target surface. This is due to early stage of the filamentation generated magnetic field in the shock width. Further away from the interaction surface, electric field energy dominates over the magnetic field energy. At the interaction surface, one can also see that the energy associated with the longitudinal electric field ($<\varepsilon_{E_x}>$) dominates, while away from the interaction surface, the energy associated with the transverse electric field ($<\varepsilon_{E_y}>$) dominates over the former. This is expected since closer to the interaction surface, electron-ion separation causes a strong longitudinal electric field which decays away from the interaction surface inside the plasma. While at the same time due to the onset of the return current, filamentation of the electron beams starts and the energy associated with the transverse electric field ($<\varepsilon_{E_x}>$) grows. Eventually, Weibel instability filaments the plasma ahead of the shock and magnetic field energy dominates as shown in panel (e) of Fig. 4. On comparing with the collisional case (second column), one sees a resistive suppression of magnetic field generation due to the Weibel instability at earlier times. Later on, the longitudinal electric field energy ($<\varepsilon_{E_x}>$) always dominates over the magnetic field energy ($<\varepsilon_{B_z}>$) be-
cause of the density compression and charge separation caused by the hole-boring effect. Panel (f) shows the appearance of an additional peak in the magnetic field energy which arises because of the ion-ion Weibel instability occurring due to shock reflection and acceleration of a bunch of ions.

The impact of collisions — clearly visible on the field energies development in Fig.4 — also has an important implication for the shock acceleration of ions. Since TNSA mechanism is suppressed in this case and the Weibel instability is also not dominant, the acceleration of the ions occurs primarily due to the reflection from the electric field generated at the shock front. The deleterious effect of the TNSA on the ion energy spectrum is also not dominant in this case. Hence, the target engineering proposed in [6] is not required. Indeed, Fig. 5(a) shows the ion energy spectrum from both collisional (solid line) and collisionless plasmas (dash-dotted line), and one can clearly see the significant improvements (higher energy and the lower FWHM) in the ion energy spectrum in a collisional target case. Moreover, in a collisional plasma, one gets a quasi-monoenergetic ion spectrum without any target engineering and the maximum energy and the FWHM is also better than the case of a collisionless plasma with target engineering [6]. Panels (b)-(g) show the dependence of the maximum energy and the energy spread on the laser vector potential $a_0$ and the collisional plasma density. For the case, $a_0 = 60$, one can see that at higher plasma density, where collisions are important, the energy spread (panel (d)), is getting smaller. However, at higher plasma density the maximum ion energy is also smaller. This is due to the lower hole-boring and the shock velocities at high plasma density which reduce the energy gain of the ions. Because of the lower maximum ion energy, the FWHM ($\Delta E/E_{max} \sim 17\%$) of the energy spectrum is larger at higher plasma densities. Nevertheless, the maximum energy ($E_{max} \sim 80$ MeV) and the FWHM ($\Delta E/E_{max} \sim 9\%$) at lower plasma density ($n_c = 30 n_c$) can be used for the cancer therapy. While comparing the same case for a collisionless plasma, one gets lower energy ($E_{max} \sim 74$ MeV) and a higher FWHM ($\Delta E/E_{max} \sim 60\%$). Hence, the improvements in a collisional target case are substantial. At higher laser vector amplitude ($a_0 = 200$), one sees a similar trend. However, in this case, the dispersion of the shock in a high density plasma can cause non-uniform shock velocity across the shock front. This leads to a higher energy spread ($\Delta E/E_{max} \sim 12\%$) in panel (g). Also, the maximum energy in this case ($E_{max} \sim 108$ MeV) at lower plasma density ($n_c = 170 n_c$) can be used for the cancer therapy. It may be noted that in the case of a collisionless plasma, one doesn’t get a quasi-monoenergetic ion energy spectrum for the same parameters ($a_0 = 200$, $n_c = 170 n_c$).

To summarise, we have examined the shock acceleration of ions in a realistic scenario where the effect of plasma collisions is indeed important. Inclusion of collisions, contrary to common perception, leads to improvement in the ion energy spectra due to a complex interplay between the electrostatic and electromagnetic phases of the shock formation. The shock formation, in this case, exhibits a higher density jump than in a collisionless plasma and leads to a stable quasi-monoenergetic ion acceleration. Improvement in the shock acceleration of ions is not only about the numerical numbers in the ion spectra but it also facilitates the experimental realisation of the scheme in a laboratory since one does not need target engineering in this case.

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5

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