Collisionless shocks driven by intense lasers: ion beams and the transition to electromagnetic shocks

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It is now possible to drive powerful collisionless shocks in the laboratory with state-of-the-art laser systems [1]. This allows us to answer fundamental questions in astrophysics and opens a wide range of applications from fusion research, to medical physics, in particular regarding the acceleration of high energy monoenergetic ion beams [2]. We have identified the three governing regimes that mediate collisionless shocks in unmagnetized plasmas - a purely electrostatic regime, an electromagnetic regime, and a regime showing a transition from a shock with initially electrostatic properties to an electromagnetic shock [3]. The consequences for ion acceleration of the distinct microphysics have also been identified, with a quasi-monoenergetic spectrum in the electrostatic regime and a wide spread energy spectrum in the electromagnetic and transition regimes. Interestingly, in the downstream region of purely electrostatic shocks large scale magnetic fields can still be generated. This is due to the anisotropy of the distribution function of the trapped electrons in the region between the shock fronts that is Weibel unstable, with growth rates much faster than those associated with colliding hot electron–cold ion plasma flows [4]. Moreover, shock generation in spherical mass limited H_2 targets has been explored and we have demonstrated what are the optimal target conditions such that ion acceleration in the shock dominates over TNSA. Our findings are supported by 3D full scale one-to-one particle-in-cell simulations.

Collisionless shocks are of interest in various fields, ranging from space and astrophysics to plasma physics with applications for medical purposes. Cosmic rays are believed to be shock-accelerated to energies above 10^{15} eV. The efficient mechanism for particle acceleration makes it a powerful tool and strong effort is being persued in order to realise this acceleration process in the laboratory [1]. A plasma target is irradiated by an intense laser pulse. The ponderomotive force heats the electrons to energies $E_e \approx m_e c^2 \left(\sqrt{1+a_0^2}-1\right)$ with $a_0 = eA_0/m_e c^2$, while the heavier ions remain cold. An electrostatic field appears due to the charge imbalances between electrons and ions and a shock is formed if the velocity of the heated electrons exceeds the characteristic speed in the target medium, which is the ion sound speed $c_s = \sqrt{k_B T_e/m_i}$. The background ions are picked up by the electrostatic potential (Fig. 1), which is moving through the plasma target, and are accelerated to approximately twice the shock velocity. This electrostatic shock formation comes along with a quasi mono-energetic spectrum for the accelerated ions, making it interesting for several industrial or medical applications.

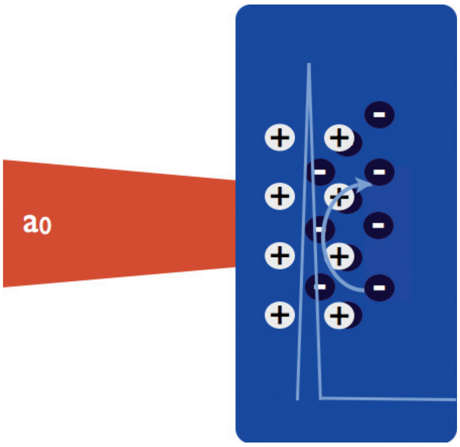

Figure 1: *Setup for collisionless shock acceleration of ions with a laser. Electron heating due to the laser ponderomotive force creates an electrostatic field inside the plasma target. Ions are reflected from the associated electrostatic potential.*

A good beam quality is guaranteed only if the collisionless shock is of electrostatic nature, meaning that it is characterised by a strong electrostatic potential, which is able to reflect the electrons. In the shock rest frame the electrostatic energy has to exceed the ion kinetic energy, $e\varphi > m_i c^2(\gamma_i - 1)$. The shock velocity is then a function of the laser intensity and the target density, given by $v_{sh}/c = \sqrt{m_e n_{cr} a_0^2 / 8 m_p n_0} (1+\kappa_{ad})$ with adiabatic coefficient $\kappa_{ad} = 5/3$ from ideal 3D gas theory [6]. The resulting ion energy is given by $E_{i,sh} \approx 1.8 m_e c^2 a_0^2 n_{cr}/n_e$.

In order to increase the ion energy, stronger lasers with higher a_0 are required. However, the electron heating is not an isotropic process. Only a fraction goes into isotropic heating, while another part goes into a forward push of the electrons. This can give rise to electromagnetic modes and might destroy the beam quality. The time scales of the electrostatic shock formation process were compared with the time scales of the electromagnetic Weibel and filamentation instabilities and governing regimes could be defined (see Fig. 1 of [3]). Pure electrostatic shocks, which maintain the good acceleration features, are obtained for low fluid velocities and high electron temperatures, while electromagnetic modes become important for high fluid velocities and low temperatures. Fig. 2 shows the transition from the pure electrostatic case to the regime in which electromagnetic modes become important for a fluid velocity $v_{fl}/c = 0.1$ and $k_B T_e / m_e c^2 = 20$ (a,c) and 3.5 (b,d). In the electrostatic case the proton phase space shows reflection into the upstream with an almost constant momentum of ≈ 0.25 (a), while electromagnetic

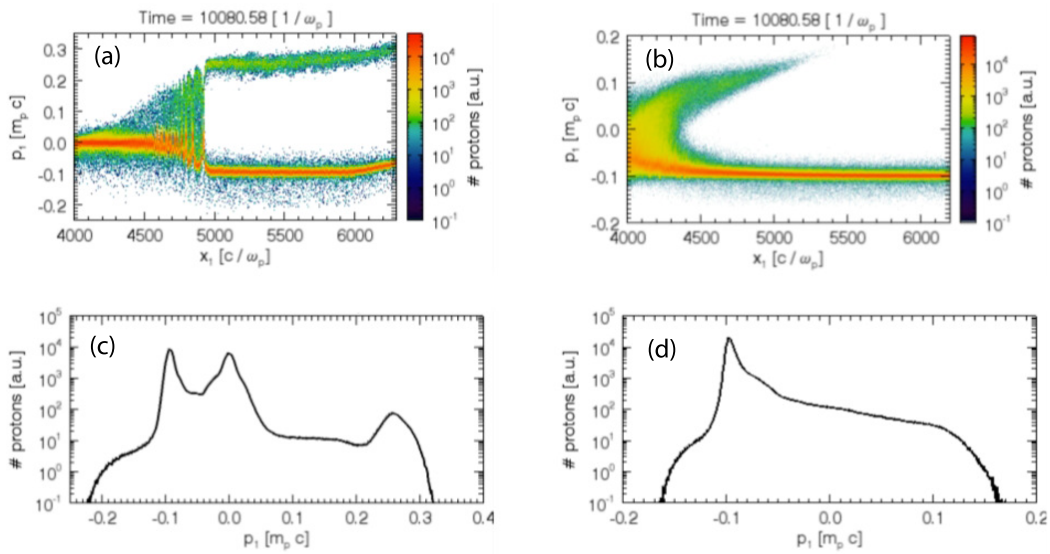

Figure 2: *Proton phase spaces in the purely electrostatic regime ES (a) and in the transition regime ES/EM (b) with respective average distributions* dn_p/dp_1 *(c,d).*

modes decrease the potential energy and lead to a diffuse phase space (b). The proton distribution averaged over the entire box shows an isolated peak in the first case (c) and a wide-spread spectrum in the latter case (d).

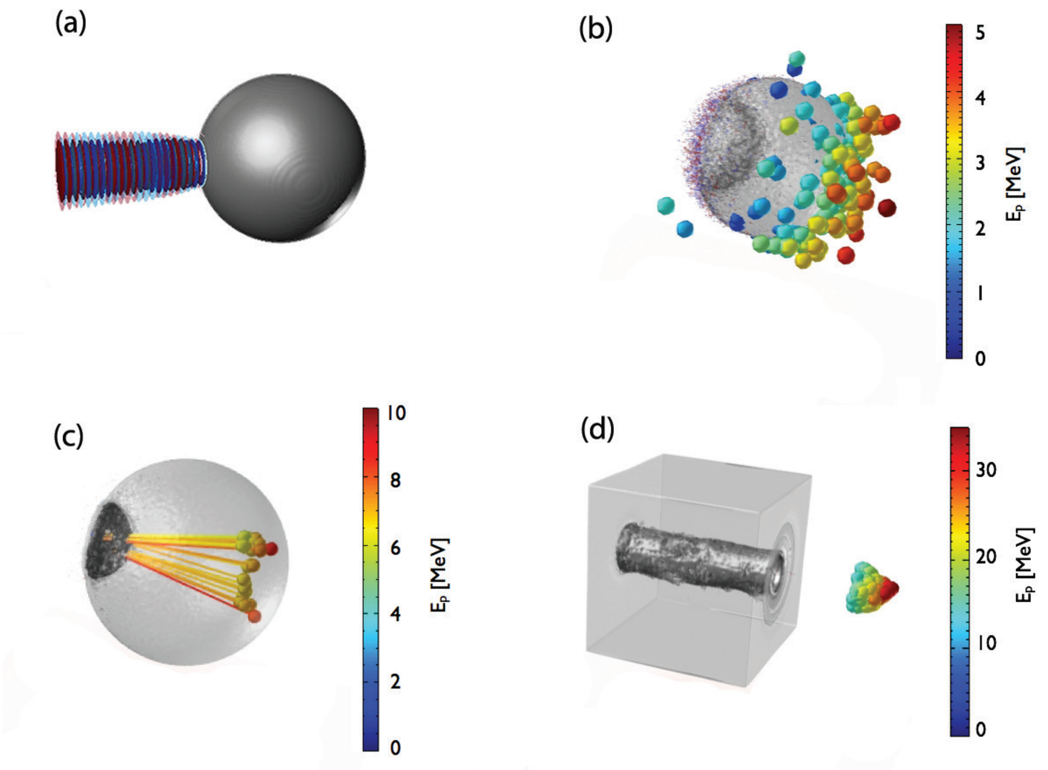

Figure 3: *(a) Experimental realisation of laser-acceleration of ions and different dominating acceleration regimes: (b) TNSA, (c) collisionless shock acceleration and (d) wakefield acceleration plus break through the rear surface.*

3D particle-in-cell simulations were performed with OSIRIS in order to investigate the shock acceleration process in a realistic experimental setup. A frozen H_2 pellet is irradiated by a laser pulse with $a_0 = 10$ (see Fig. 3a). The target density is varied from overdense to underdense. In the overdense case ($n_e = 4n_{cr,\gamma}$ in Fig. 3b) shock acceleration is not strong. The particles are mainly accelerated at the rear side of the target due to target-normal-sheath-acceleration and the highest proton energies obtained are around 5 MeV. Near-critical density targets show efficient shock acceleration (see Fig. 3c for $n_e = n_{cr,\gamma}$) with a maximum of 25 MeV for $n_e \approx 0.5n_{cr,\gamma}$. The highest proton energies (> 35 MeV, Fig. 3d) were obtained in the underdense regime for $n_e = 0.1n_{cr,\gamma}$ where the laser could penetrate and leave the target at the rear surface.

In conclusion, collisionless electrostatic shock acceleration seems to be a promising mechanism in order to obtain ion beams of high energy and low energy spread. State-of-the-art high intensity laser systems are entering now a new physical regime in which competing electromagnetic modes have to be considered. An accurate control and optimisation of the experimental parameters is required which can only be obtained from realistic 3D particle-in-cell simulations.

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