Laser oriented electrostatic shocks in low density plasmas to produce energetic collimated ion beams and study low velocity astrophysical shocks

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A high intensity laser pulse interacting with a thin dense foil can lead to the production of energetic ions. These ion beams of short duration and high density are relevant for the fast ignitor scheme in the inertial confinement fusion concept, medical applications, and dense plasma diagnostics and probing. A promising way to accelerate ions to high energies with a laser is to use underdense targets. Compared to solid targets where laser absorption is limited to the target surface, the laser pulse inside low density plasmas heats electrons over a large volume leading to higher laser absorption. This acceleration regime is also advantageous for applications as less debris are produced in each shot and it is better adapted to high repetition rate lasers. After preliminary theoretical [1] and experimental [2] studies on ion laser acceleration using underdense targets, strong longitudinal proton acceleration has been achieved using high intensity lasers [3]. Acceleration of energetic ions observed in [3] has been explained in terms of strong inductive electric fields due to magnetic fields variations on a steep density gradient [4]. Another acceleration process may be operational on a long descending density profile. Here, a collisionless shock can develop on the rear side of the target and strongly increase the maximum proton energy [5].

Collisionless shocks have already been studied on decreasing density gradients for spherical plasmas [6] and for plasmas located at the back of a solid foil irradiated by a laser [7]. It was shown in [8] that protons can be accelerated efficiently in terms of energy in a shock in underdense plasmas. The low and high intensity limits of the shock regime were also investigated using 2D Particle-In-Cell (PIC) simulations and the efficiency of this regime was demonstrated. In [8, 9], the shock regime and the two step process were studied in detail. The first step, the launch of a fast ion wave, requires a hot electron population and a descending density profile. It occurs in a zone of high amplitude magnetic fields. The second step, the development of a strong electrostatic shock, which boosts the energy of the ions, happens when the ion bunch resulting from the first step enters a low density plasma region where the magnetic field has strongly decreased. In [9], the first 3D simulation of this regime was also presented and confirmed the 2D simulation results. In this paper, we report new results on ion acceleration with high intensity laser pulses interacting with low density plasmas. It is shown with 2D Particle-In-Cell simulation that a high intensity (> 10^{21} W/cm^2) and short pulse laser (few tens of fs) can accelerate protons to energies higher than hundred MeV in an underdense plasma with a cos^2 density profile. A Boltzmann-Vlasov-Poisson (BVP) model [10] has been used to study in more details the processes described and to confirm the results obtained in [9] using PIC simulations. New insights on the shock regime of laser underdense ion acceleration are obtained in 2D PIC simulations performed with the code PICLS [11]. The incident laser wavelength is λ = 1 μm, the full-width-at-half-maximum (FWHM) of the focal spot is 6 μm. The pulse interacts with the target in normal incidence. Its electric field is in the simulation plane (p-polarization). The spatial and temporal profiles are truncated Gaussian functions. We present in Fig. 1 the proton phase space when maximum proton energy starts to saturate. The plasma is composed of protons and electrons with a 0.08 n_c maximum density in the first case (panel a) and 0.2 n_c maximum density in the second case (panel b). The plasma has a cosine-square density profile with a 100 μm FWHM in the *x*-direction and uniform in the *y*-direction, in the first case, and it has with a 75 μm FWHM in the *x*-direction and uniform in the *y*-direction, in the second case. Here, n_c refers to the critical density (1.1×10^{21} cm^{-3} for λ = 1 μm). In the first case, the laser pulse duration is τ_p = 33 fs and its maximum intensity is I = 5×10^{21} W/cm^2, and in the second case, the laser pulse duration is 46 fs and the intensity is 10^{21} W/cm^2. The maximum proton energy reaches 124 MeV after 2.35 ps of simulation in the first case, and 107 MeV after 1.23 ps of simulation in the second case. Our results show that a high intensity and short pulse laser with energy of 150 J can accelerate protons to energies higher than 100 MeV in an underdense plasma of a hundred microns length.

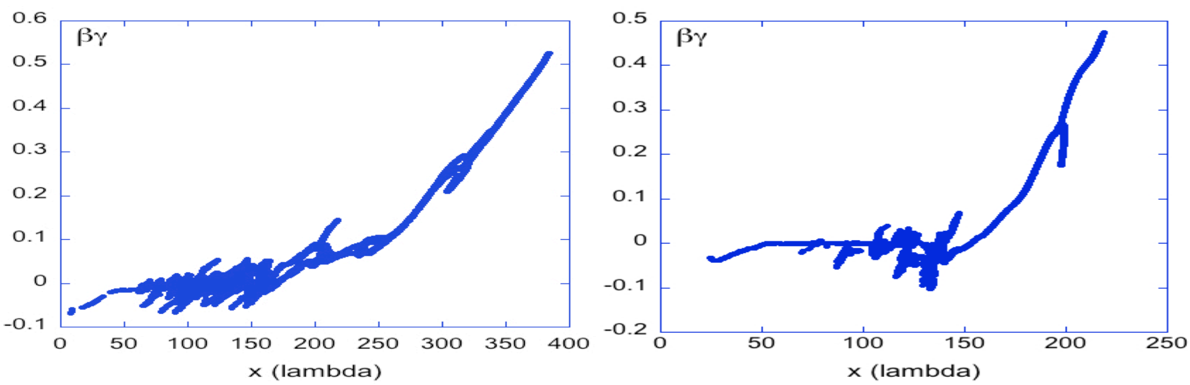

Figure 1: Proton phase space at the center of the box in the *y*-direction: (a) first case: 100 microns FWHM cos^2 plasma at 0.08 n_c, $I = 5\times10^{21}$ W/cm^2, τ_p = 33 fs, and front surface focalization, t = 2.35 ps; (b) second case: 75 microns FWHM cos^2 plasma at 0.2 n_c, $I = 10^{21}$ W/cm^2, τ_p = 46 fs, and back surface focalization, t = 1.23 ps. The *x*-axis is in microns and the *y*-axis for the phase spaces represents the momentum $\beta\gamma$, where β is the proton velocity in the units of the velocity of light and γ is the proton Lorentz factor.

As explained in [9], the acceleration process proceeds in two steps: the first step requires a hot electron population and a descending density profile, and the second step develops if the ion bunch resulting from the first step enters in a low density plasma. The two-step mechanism can be modeled using a Boltzmann-Vlasov-Poisson (BVP) model [10] considering a hot initial electron population in a gradient with a postplasma. In this model, the expansion dynamics of the plasma ions is described by the Vlasov equations. The self-consistent electric field is determined by the electrostatic potential. The electron plasma component consisting of cold (target) and hot (laser-accelerated) electrons plays a key role in the formation of the electrostatic field. We assume that both the hot and cold electrons obey Boltzmann distributions with correspondent given temperatures. The electrostatic potential that enters into the Vlasov equation for the ions is described by the Poisson's equation.

The plasma has a maximum density of 0.08 n_c, and is composed of a first region with a decreasing density profile linked to a second region where the density is constant and equal to the minimum density of the first part, that is, 5% of the maximum density of the first region. The hot electron temperature is T_h = 5 MeV. The hot electrons quickly start to accelerate protons in the decreasing density gradient. A high velocity ion wave is therefore launched (Fig. 2). When this wave propagates through the constant density plasma, the proton density increases at the front of the wave and after fifteen laser periods (15 T_0) a large electrostatic field appears. A sharp increase in proton velocity quickly follows and a strong electrostatic shock develops. The results of the BVP simulation are in good qualitative agreement with the recently proposed two step model.

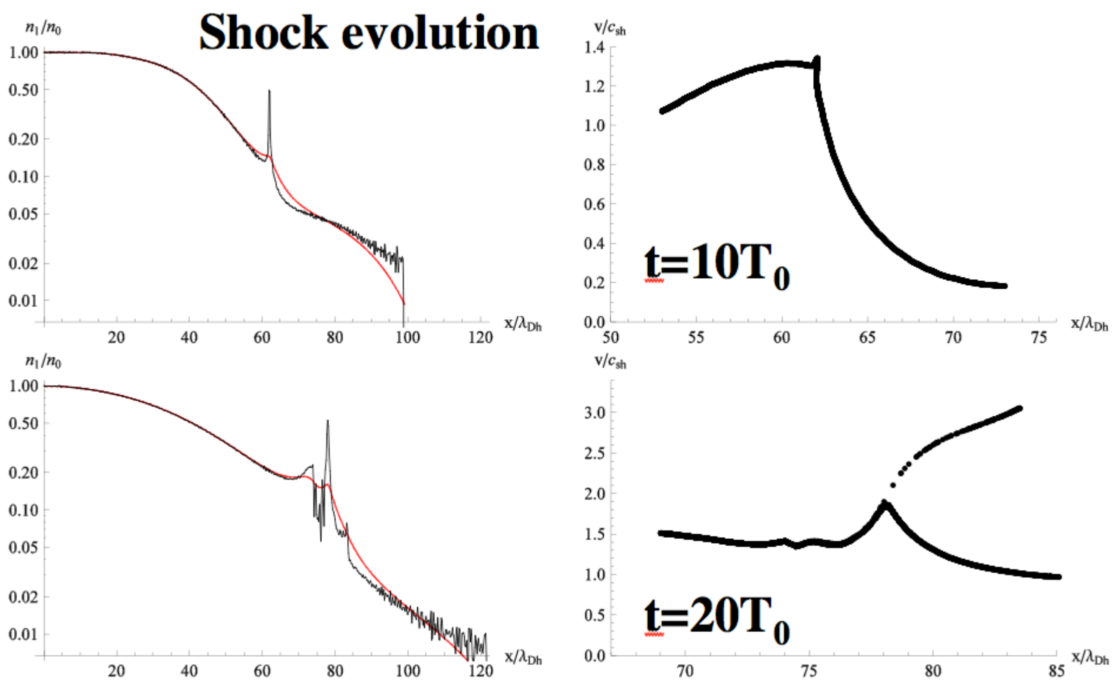

Figure 2: Density (left) and proton phase space (right) obtained using the BVP model at two time instants. The parameters are given in the text. Time is measured in units of the inverse electron plasma frequency. The density is normalized to the maximum plasma density, x to the Debye length (~1.4μm), and ion velocity to the acoustic velocity (~0.07 c), where c is speed of light.

The PIC simulations and BVP model provide complementary results concerning the proton acceleration in underdense targets. The two-step mechanism already described in previous publications [8, 9] is confirmed. New 2D PIC simulations show that a high intensity (> 10^{21} W/cm^2) and short pulse laser (few tens of fs) can accelerate protons to energies higher than 100 MeV when it interacts with a short underdense plasma with a $\cos^2$ density profile. A BVP model provides more details of the dominant accelerating mechanism and confirms the PIC results obtained in [9]. It helps to study in more details the process of shock formation in plasma and to obtain scaling laws of the maximum proton energy and accelerated proton numbers with laser and target parameters. The underdense shock mechanism of ion acceleration opens perspectives for further optimization of high-energy proton beams for medical applications and for the Fast Ignition scheme. The strong electrostatic shock launched by the laser pulse in underdense plasma is easy to control and can be applied to study low velocity astrophysical shocks relevant to supernovae explosions and gamma ray bursts.

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