Investigation of high intensity laser proton acceleration with underdense targets

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Abstract. In the last few years, intense research has been conducted on laser-accelerated ion sources and their applications. Recently, experiments have shown that a gaseous target can produce proton beams with characteristics comparable to those obtained with solid targets. In underdense laser proton acceleration, volume effects dominate the acceleration, while in target normal sheath acceleration, the electric field value is directly related to the electron surface density. Using Particle-In-Cell simulations, we have studied in detail the effect of an underdense density gradient on proton acceleration with high intensity lasers. Underdense laser ion acceleration strongly depends on the length, the shape and the amplitude of the density gradient and on the laser pulse shape. The accelerated proton beam characteristics in the shock-like regime are very promising.

1. Introduction
The production of energetic ions demonstrated recently [1,2] by focusing intense laser pulses on solid foils has triggered a number of theoretical and experimental studies, relevant for the fast ignitor scheme in the inertial confinement fusion concept [3], medical applications [4,5,6], and dense plasma diagnostics and probing [7]. The dominant acceleration mechanism in these experiments was the Target Normal Sheath Acceleration (TNSA) mechanism [8]. Another promising way to accelerate ions to high energies is to use underdense or near-critical density targets. Compared to solid targets where laser absorption is limited to the target surface, the laser pulse inside low density plasmas heats electrons on a large volume leading to higher laser absorption. This acceleration regime is also advantageous for several applications as less debris are produced. It is also more adapted to high repetition rate lasers. The laser contrast, which can be problematic with thin solid targets, is less detrimental as gas jets are transparent for laser intensities below $10^{13}$ W/cm². Ion acceleration due to the interaction of a very high intensity laser with underdense targets has already been studied with PIC simulations [9] but the simulated plasmas never reproduced the gaseous targets available for experiments. The first experiments of ion acceleration via laser interaction with an underdense target
showed radial acceleration [10]. Recent experiments showed that strong longitudinal proton acceleration can be achieved using high intensity lasers [11]. The longitudinally accelerated protons are in this case far more energetic than the transverse accelerated protons. The exact accelerating mechanism leading to the acceleration of energetic ions observed in [11] has not yet been described in detail and therefore is the center of an ongoing debate [12]. For an underdense target, it is not easy to produce a sharp gradient plasma experimentally. It is therefore important to understand the dependence of ion acceleration on the density gradient to optimize it. In this article, we show that even using underdense plasmas, protons can be accelerated efficiently in term of energy, charge, and collimation. Using Particle-In-Cell simulations, we studied in detail the interaction of a high intensity laser pulse with an underdense plasma. In section 2, we describe the shock-like regime of underdense laser ion acceleration. We discuss the dependence on laser and target parameters of the shock-like regime in Section 3. Section 4 addresses the possibility to study the shock-like regime experimentally by coupling a Particle-In-Cell code with a hydrodynamic code.

2. Detailed description of the shock-like accelerating mechanism

In this section, we demonstrate the efficiency of the shock-like regime of laser underdense ion acceleration using 2D Particle-In-Cell simulations performed with the code PICLS [13]. The wavelength of the incident pulse is 1 µm, its pulse duration 23 fs and its irradiance $3.2 \times 10^{19} \text{ W/cm}^2$. 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 Gaussians. The plasma is composed of protons and electrons with a 0.08 n maximum density, a cosine-square density profile with a 100 microns FWHM in the x-direction and uniform in the y-direction. Protons are accelerated with a shock-like structure [14] as shown in Fig. 1.c. After 3.3 ps, the maximum proton energy saturates at 8.4 MeV (Fig. 1.a) showing the efficiency of this acceleration mechanism compared to the TNSA mechanism with similar laser parameters. Figs. 1.a and 1.b also demonstrate that the number of accelerated protons and their divergence are comparable with TNSA-accelerated beams. The number of accelerated particles is calculated using the conservative hypothesis that the characteristic dimension in the third direction corresponds to the laser pulse FWHM.

The shock-like mechanism starts as a strong asymmetrical Coulomb explosion in the decreasing density gradient and evolves into wave breaking driven by the strong electric field present in this region. In 1D, this field is created by energetic electrons accelerated during the laser pulse propagation. In 2D and 3D, this field is also enhanced by the electric field generated due to the fast evolving strong magnetic field gradients in this region. If the ion wave launched during this process is
fast enough and crosses other ions, these ions can be reflected on this ion wave and accelerated at twice the velocity of the incoming ion wave. This is clearly visible in Fig. 2.a in the strong acceleration phase between $t=1.5$ ps and $t=1.8$ ps (same times as in Fig. 1.c). The velocity increase during this phase is not correlated to the variation in maximum electric field. This acceleration process is therefore referred to as the shock-like regime of underdense laser ion acceleration.

3. Dependence of the shock-like mechanism on laser and target parameters

The shock-like regime depends strongly on the characteristics of the density gradient. For sharp density gradients, most energetic protons are accelerated at the back surface, similarly as in TNSA. For small density gradients, the most energetic protons are accelerated close to the back surface and wave breaking is observed. For intermediate density gradients, the most energetic protons are accelerated by a shock-like mechanism in the decreasing density ramp. If the density profile becomes too long, wave breaking is again the dominant mechanism. The plasma scale length plays an important role in the optimization process as it controls laser absorption in energetic electrons responsible for the strong accelerating longitudinal electric field. Other target parameters like the maximum density and the overall length of the plasma also influence the efficiency of the process as they act on the initial asymmetrical Coulomb explosion and the topology of the mentioned magnetic field. Laser intensity, pulse duration and laser focal spot width also play a role on the efficiency of the acceleration process. For each set of laser parameters and target density and shape, an optimum configuration exists. Fig 2.b shows the evolution of the maximum proton energy in the case of 1D simulations of the interaction of a $6 \times 10^{19}$ W/cm$^2$, 23 fs laser pulse with a 33 microns FWHM cosine-square target.

![Figure 2: (a) Evolution of the maximum longitudinal electrostatic field (blue) and of the maximum proton energy (red) as a function of time. (b) Evolution of the maximum proton energy as a function of target density.](image)

4. Coupling of a Particle-In-Cell code and a hydrodynamic code to assess the possibility of investigating the shock-like regime in experiments

As mentioned above, part of the optimization of this acceleration process comes from achieving plasmas with particular densities and gradients. For this, it is possible to explode a thin foil using a long pulse laser. We have performed 2D hydrodynamic simulations of such plasma production using the code CHIC [15]. Figure 3.a shows the result of the interaction of a $5 \times 10^{15}$ W/cm$^2$, 1 ns laser pulse focused to 10 microns FWHM focal spot with CH foils with different initial thicknesses after 800 ps of interaction. Using variable initial foil thickness or interaction duration allows to investigate the interaction of a short pulse with targets presenting different maximum density, length and density gradients. We used these results in PICLS to simulate in 2D the interaction of a $5 \times 10^{19}$ W/cm$^2$, 350 fs laser pulse with a 10 microns FWHM focal spot on the exploded foil to accelerate protons to high energies. After 500 ps of interaction in the hydrodynamic simulation, the target has approximately a cosine-square density profile with a 120 microns FWHM. The maximum proton energy measured 3.3
ps after the beginning of the PIC simulation is 32 MeV (Fig. 3.b). This energy is comparable to the maximum proton energies obtained using similar laser parameters with solid targets.

Figure 3: (a) Electron density profile at the center of the simulation box for various initial CH target thicknesses after 800 ps (the x-axis is in cm and the y-axis is in cm$^{-3}$). (b) Proton energy spectrum in the forward direction after 3.3 ps using an initial thickness of 400 nm.

5. Conclusions
PIC simulations were used to study proton acceleration with underdense targets in various density gradient conditions. The propagation of a high intensity laser pulse in an underdense target can lead to the production of energetic proton beams. The most efficient acceleration observed in such targets is the result of the formation of a shock-like structure in the decreasing density gradient. This regime is strongly dependent on the density gradient length and shape and on the shape of the laser pulse. It features a very high ratio of maximum proton energy over laser energy, a low divergence and a high number of accelerated protons but is nowadays difficult to achieve experimentally with short pulse lasers because it requires short, dense and sharp underdense plasmas. A setup including a long pulse laser to explode a thin solid foil is proposed to study this regime experimentally. This mechanism could open important perspectives for the optimization of high-energy proton beams.

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