Investigation of efficient shock acceleration of ions using high energy lasers propagating in low density targets

M. Gauthier[1,2], A. Lévy[1], E. d'Humières[3], B. Albertazzi[1,4], P. Antici[5], C. Beaucourt[3], S. Chen[1], V. Dervieux[1], J.L. Feugeas[3], M. Glesser[1,4], P. Nicolaï[3], V. Tikhonchuk[3], J. Fuchs[1]

[1]*LULI, École Polytechnique, CNRS, CEA, UPMC, route de Saclay, 91128 Palaiseau, France*
[2]*CEA, DAM, DIF, 91297 Arpajon, France*
[3]*Université de Bordeaux, CNRS, CEA, CELIA, 33400, Talence, France*
[4] *INRS-ENT, Varennes, Québec, Canada*
[5]*Dipartimento di Energetica, Universita` di Roma 1 "La Sapienza", Roma, Italy*

Abstract: It was recently shown that a promising way to accelerate ions forward to high energies and in a collimated beam is to use under-dense or near-critical density targets instead of solid ones [1, 2]. Simulations have revealed that the acceleration process depends strongly on the density gradient. Indeed, under certain condition, the most energetic protons are predicted to be accelerated by a collisionless shock mechanism that significantly increases their energy [3]. We present a recent experiment performed on the 100 TW LULI laser facility (France). We obtained proton energies up to 7 MeV when irradiating a 500 nm plastic foil that has been pre-ionized by a long pulse in order for it to be lower-than-critical density, with significant gradients. This is comparable, in the same experiment, with what was obtained under similar laser conditions, but with solid targets. We show as well that varying the plasma density gradient of the target modifies the measured proton spectra.

Intense research is being conducted on sources of laser-accelerated ions and their applications. This is motivated by the exceptional properties that have been demonstrated for proton beams accelerated from planar targets, such as high brightness, high spectral cut-off, high directionality and laminarity, and short duration (~ps at the source) [4]. However, for future applications, ion energy and laser-to-ion efficiency need to be significantly enhanced compared to what can be currently produced using Target Normal Surface Acceleration (TNSA) from solid targets. Another aspect of the ion beam that would be valuable to improve, compared to TNSA-produced beams, is its spectrum. Standard TNSA beams are broadband (from 0 to a well-defined maximum ion energy that depends on laser and target conditions). Producing monoenergetic beams would be of interest for applications like proton therapy [5], inertial confinement fusion [6], or accelerator injectors [7]. Recent works [2] have shown that a promising way to realize such improvements would be to use underdense or near critical density targets as accelerating media instead of solids. Indeed the laser interacts with not only the target surface but the entire bulk, improving significantly the efficiency of the laser-to-ions energy conversion [4]. This is in contrast to TNSA where the high intensity laser beam needs to interact with a very sharp plasma gradient. Moreover, the possibility of using gaseous target is interesting in its own right as it produces less debris and can be used at high repetition rate.

Simulations have shown that efficient underdense plasma ion acceleration relies on laser driven collisionless chocks with sub and near-critical density short-length plasmas. At the opposite of TNSA, this method requires a smooth density gradient, and can produced a strongly peaked energy distribution. This new method has been successfully demonstrated by Palmer and Harberberger [2] with a CO_2 laser system (λ= 10 µm) using near critical gas targets. They both measured monoenergetic ion spectra.

However the amount of accelerated ions and the energy reached in these recent experiments still need to be enhanced for future applications. One possibility is to increase the intensity of the short pulse laser interacting with the smooth plasma gradient. The use of shorter wavelength lasers that can currently reach intensities up to $10^{20\text{-}21}$ W/cm² on target (compared to I ~$10^{16\text{-}17}$ W/cm² for CO_2 lasers) is limited by the lack of availability of short and high density (n_{crit} (λ = 1 µm) ~ 10^{21} electrons/cc) gas target, as required for shock acceleration to occur. This is why we pursued instead using near critical density plasma produced by exploding thin solid foils by a long pulse laser beam. The expansion process produced after ~1 ns the smooth plasma gradient necessary for shock acceleration. Changing the delay between the long and the short pulse allows us to scan various plasma conditions.

In this paper, we show that protons up to 7.1 MeV were obtained when irradiating a 500 nm exploded plastic foil with a high intensity picosecond laser beam. This is comparable with what was obtained under similar laser conditions, but with thicker solid gold targets, i.e. in the TNSA regime. We show as well that changing the delay between the ns and the picosecond pulses changes the plasma gradient characteristic length and thus modifies the proton energy cuttoff. The number of accelerated protons measured was ~10^{10} part/MeV/sr at half energy of the maximum and up to 10^9 part/MeV/sr at the maximum energy.

The experiment was carried out using the ELFIE laser facility at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI). The experimental set-up is shown in Figure 1. A chirped laser pulse of 30-40 J energy, τ = 450 ps pulse duration, and 10^{14} W/cm^2 on target intensity, is used to irradiate a very thin plastic foil (100 or 500 nm). The target expands rapidly in the vacuum, reducing its density to around or below the plasma critical density. The picosecond laser pulse of 5-8 J energy, 400 fs pulse duration, and 5 x 10^{18} W/cm² intensity, interacts with the smooth plasma gradient created by the expansion, accelerating

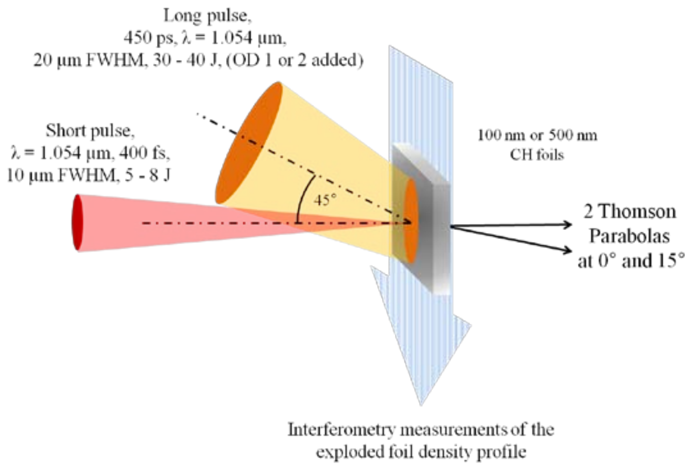

Figure 1: Experimental set-up

protons forward through TNSA or shock acceleration mechanisms, depending on the local plasma density gradients at the time of the short pulse irradiation. As diagnostics, we used two Thomson parabolas (TPs) located at 0° and 15° with respect to the impinging laser-beam axis to measure the forward generated proton spectrum, as well as transverse interferometry to diagnose the plasma conditions (i.e. its gradients). This uses a low-energy, short (400 fs), optical probe laser. By varying the time delay (from -600 to 200 ps) between the main short pulse laser and the long pulse laser, as well as the initial target thickness or the long pulse intensity, we could vary the characteristics (length, density, gradient) of the low density plasma at the time of the main interaction with the short pulse. A delay of 0 ps means the ps and the peak of the long pulse laser are synchronized, negative delay means the short pulse arrives on the target before the center (in time) of the ns beam.

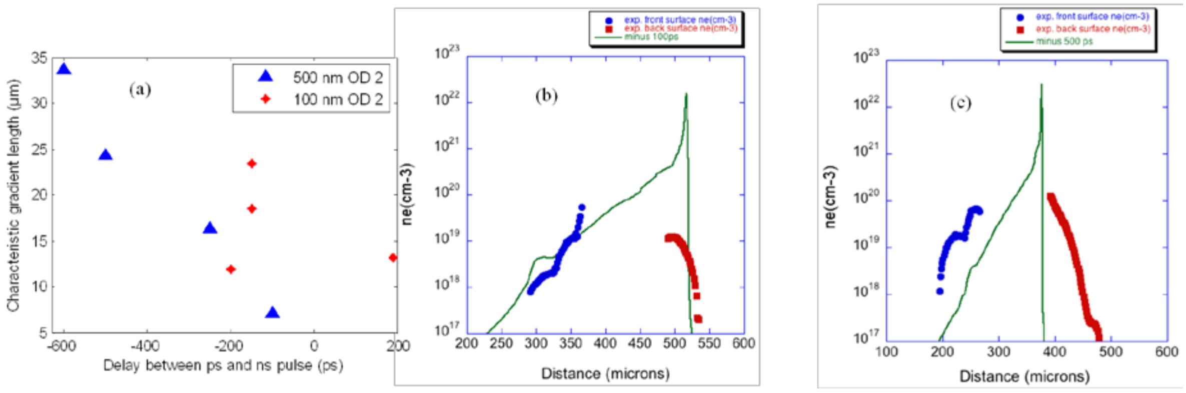

Figure 2: (a)Density gradient characteristic length of a plastic foil exploded by a 10^{12}W/cm² ns laser as measured by interferometry at different times (0 ps marks the peak of the ns beam arriving on target); Comparison of the electronic density of the exploded plasma measured by interferometry (dot) and CHIC simulation (plain line) of a 500 nm plastic foil exploded by (b) a 10^{12} W/cm² ns pulse with a -100 ps delay, (c) a 10^{13} W/cm² ns pulse with a -500 ps delay

For 500 nm CH foils exploded by a 10^{12} W/cm² ns laser pulse, the back side interferometry measurements show a linear variation of the characteristic plasma gradient length (e-fold) from 35 to 7 µm at respectively -600 ps to -100 ps (see Figure 2a). As also shown in Figure 2a, thinner CH foils (100 nm) are more sensitive to the laser intensity fluctuations from shot to shot, so there is in this case no clear relation between the delay and the plasma gradient length. Similarly, when the ns laser beam intensity on target is high (10^{14} W/cm²), the profile shape was not anymore sensitive to the time delay in our timing range, and the plasma always displays longer gradients (~ 55 - 65 µm). Simulations have been performed using the 2D hydrodynamic code CHIC [8] in order to confirm our measurements. One can see that the simulated plasma density profiles obtained for two different plasma conditions (see Figure 2b and c) are in good agreement with the experimental back side plasma profiles.

The resulting proton spectra, obtained for different delays between the ns and the ps beam and different intensities of the long pulse (10^{13} W/cm²/-100ps and 10^{12} W/cm²/-500ps), are shown in Figure 3, all for a 500 nm thick CH. The number of accelerated protons measured is of the order of 10^{10} part/MeV/sr at half energy of the maximum and up to 10^{9} part/MeV/sr at the maximum energy. We stress that this is comparable with what we measured, in the same experiment, using TNSA, and with an optimal solid density target (10 µm gold) irradiated by the same ps laser (in this case the energy energy cutoff was 8-9 MeV). Interestingly, we observed in the experiment that the accelerated proton beam is angularly twisted. Indeed, the proton energy cutoff is higher on the TP positioned at 15° (5 and 7.1 MeV) than on the other at 0° (< 1.3 MeV and 3.3 MeV). This is likely due to the explosion of the target induced by the ns beam at 45°, making the density profile not symmetric, but will be further investigated.

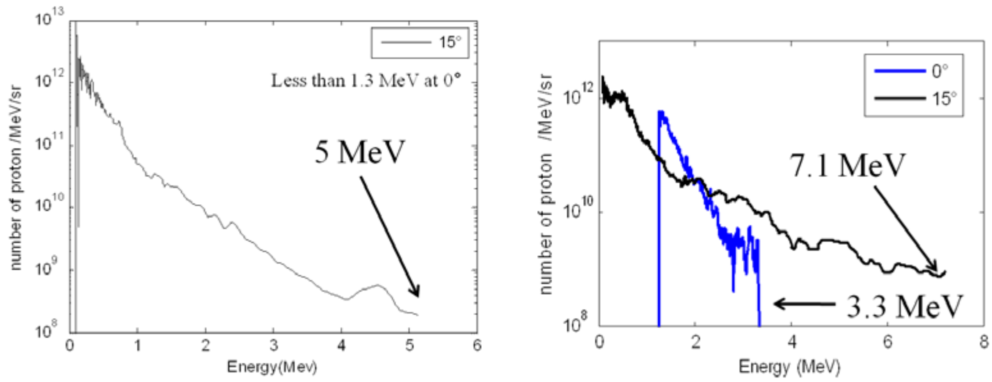

Figure 3: Spectra of the protons accelerated by the ps laser pulse interacting with a 500 nm foil exploded by the ns pulse (10^{12} (a) and 10^{13} W/cm²(b)) 100 (a) and 500 (b) ps prior to the ps peak.

In summary, these results demonstrate that a low-density target, being at least comparable to TNSA, is a promising candidate for an efficient proton source. Moreover, in our setup, as the plasma gradient can be varied, it allows to have a flexible particle source.

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