

# Laser plasma proton acceleration experiments using foam-covered and grating targets

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## ABSTRACT

Experimental results are reported for two different configurations of laser driven ion acceleration using solid foils with a structured layer on the irradiated side, aiming to improve the laser-target coupling by exploiting engineered surfaces. Two experimental campaigns have been performed exploiting a 100TW 25fs Ti:Sa laser capable of maximum intensity of  $4 \cdot 10^{19}$  W/cm<sup>2</sup>. "Grating" targets have been manufactured by engraving thin mylar foils (0.9, 20 and 40  $\mu$ m) with a regular modulation having 1.6  $\mu$ m period and 0.5  $\mu$ m depth. The periodicity of the grating corresponds to a resonant incident angle of 30° for the excitation of surface waves. Considering a target of 20  $\mu$ m and changing the angle of incidence from 10° to 45°, a broad maximum in the proton energy cut-off was observed around the resonant angle (about 5 MeV) which was more than a factor two higher than the case of planar target. "Foam" targets have been manufactured by depositing a porous 10  $\mu$ m nanostructured carbon film with an average density of 1-5 mg/cm<sup>3</sup> on a 1  $\mu$ m thick aluminium foil. At maximum focalization the foam targets gave a maximum proton energy similar to the case of bare aluminium target (about 6 MeV), while educing the intensity the presence of the foam enhanced the maximum proton energy, obtaining about 1.5MeV vs. 500KeV at an intensity of  $5 \cdot 10^{16}$  W/cm<sup>2</sup>. 2D Particle-In-Cell simulations have been used to support the interpretation of the experimental results.

**Keywords:** Laser-Plasma interaction, Ion acceleration

## 1. INTRODUCTION

The interaction between high intensity laser and solid targets is the key aspect for several applications and in particular for ion acceleration via Target Normal Sheath Acceleration mechanism (TNSA).<sup>1,2</sup> The TNSA regime is not the only possible mechanism for accelerating ions exploiting the laser-plasma interaction, but it is certainly the one that so far has been most widely investigated and is thus most established and controlled. In the usual scheme thin solid foils are used and several absorption mechanisms allow a considerable fraction of the laser energy to be transferred to the electrons. The expansion of this "hot" electron population builds up the strong electrostatic field which accelerates the ions. The improvements to the acceleration performances in the TNSA regime can be obtained increasing either the laser pulse parameters (energy, power, peak intensity) or the efficiency of the coupling between the laser pulse and the plasma, the latter being greatly dependent on

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target properties and geometry. The use of high intensity laser with near optical wavelength ( $\lambda = 0.8 - 1\mu\text{m}$ ) focused on solid foils, implies that the plasma obtained from the ionization of the material is highly overdense  $n_e \sim 200 \div 400n_c$  where  $n_c = 1.56 \times 10^{21} \text{ cm}^{-3}$  is the cut-off density. In these conditions the laser penetrates only in the thin “skin” layer of thickness  $\sim c/\omega_p = (\lambda/2\pi)\sqrt{n_c/n_e}$  leading to a surface rather than a volume interaction.

Here we present the results obtained in two experimental campaigns aimed at using alternative target configurations to enhance the laser-plasma coupling with respect to simple flat solid foils. The experiment were performed using the 100TW 25fs Ti:Sa UHI-100 laser pulse at CEA Saclay. The system delivered 80 TW ultra-short pulses (25 fs) at a central wavelength of 790 nm. We used two different target designs: (i) plastic foils with an engraved front surface and (ii) thin aluminium foils covered with a low density carbon foam on the irradiated side. The contrast of the beam was raised from  $\simeq 10^6$  (Low COntrast LC) to about  $10^{12}$  (High Contrast HC) thanks to a double plasma mirror<sup>3,4</sup> whereas the focal spot was optimized using a deformable mirror. The high contrast proved to be crucial in order to preserve the target structure before the arrival of the main pulse.

## 2. GRATING TARGETS

Several recent works aimed to optimize the laser-target coupling in the context of ion acceleration and it has been shown that various types of surface structuring can lead to enhanced energy absorption and possibly particle acceleration to higher energies.<sup>5-11</sup>

A particular case is that of targets with a periodic surface modulation which allows the resonant coupling of the laser pulse with surface waves (SWs),<sup>12</sup> as it is widely used in plasmonics applications at low laser intensity. Most studies on structured targets and on SW-induced absorption<sup>13-16</sup> have been limited to relatively modest intensities ( $I \lesssim 10^{16} \text{ W/cm}^2$ ) because of the effects of “prepulses”, typical of chirped pulse amplification (CPA) based laser systems,<sup>17</sup> which can destroy the surface structures before the interaction with the short intense pulse. Moreover, in the high-intensity regime, where relativistic effects may become dominant, a nonlinear theory of surface waves is needed. In Ref. (18,19) however, particle-in-cell (PIC) simulations of laser interaction with a grating target (designed for resonant SW excitation according to linear, non-relativistic theory) suggested the possibility of SW coupling at high intensity and showed a strong enhancement of both absorption and energetic electron and ion emission.

The experimental campaign we present exploited a  $P$ -polarized beam focused using an off-axis  $f = 300 \text{ mm}$  parabola, reaching an intensity of about  $2.5 \cdot 10^{19} \text{ W/cm}^2$ .<sup>20</sup> The grating target (GT) have been manufactured by thermal imprinting of a  $2\lambda$  periodic structure on a Mylar™ foils. Three different foil thicknesses (20, 40 and  $0.9 \mu\text{m}$ ) and two peak-to-valley depths (500 and 300 nm) have been used (see figure 1). A Thomson Parabola (TP) was employed to record the proton spectra emitted from the target rear side. In order to test different angle of incidence of the laser on the target, the TP was mounted inside the chamber on a special rail which allowed to move it and align its axis with the normal of the target each time the latter was rotated. The laser light specularly reflected by the target was collected on a frosted glass placed at about 200mm from the interaction center and recorded by a CCD. In selected shots, a stack of three radio chromic films (RCF) was arranged to form a 50 mm diameter ring around the target and collect the particle and radiation emission over an angle of about  $300^\circ$ .

Both the RCF stack and the frosted glass imaging line, gave confirmation that the grating structure was preserved during the interaction with the short ultra-intense pulse. Two spots were observed both on the RCF and the frosted glass at two different angular positions corresponding to the 0 and +1 grating diffraction orders. When the double plasma mirror was removed, the strong prepulse destroyed the gratings and no multiple-reflections were observed. The TP mounted on the curved rail allowed to measure the proton spectra when the target was irradiated at different angle of incidence. Figure 1(right) shows a survey of the proton maximum energy obtained using  $20\mu\text{m}$  flat simple target (ST) and  $23\mu\text{m}$  grating target (GT). While the ST data show the expected variation of proton energy due to both the variation of the normal component of the electric field<sup>21</sup> ( $\propto (\sin \theta)^2$ ) and of the focal spot size ( $\propto 1/\cos \theta$ ), the GT energies clearly show the presence of a local maximum at about  $30^\circ$  ( $\approx 2.5$  times the ST energy for the same angle), which corresponds to the grating resonant angle. At large incidence angle the cut-off proton energy was similar with GT and ST which is coherent with the

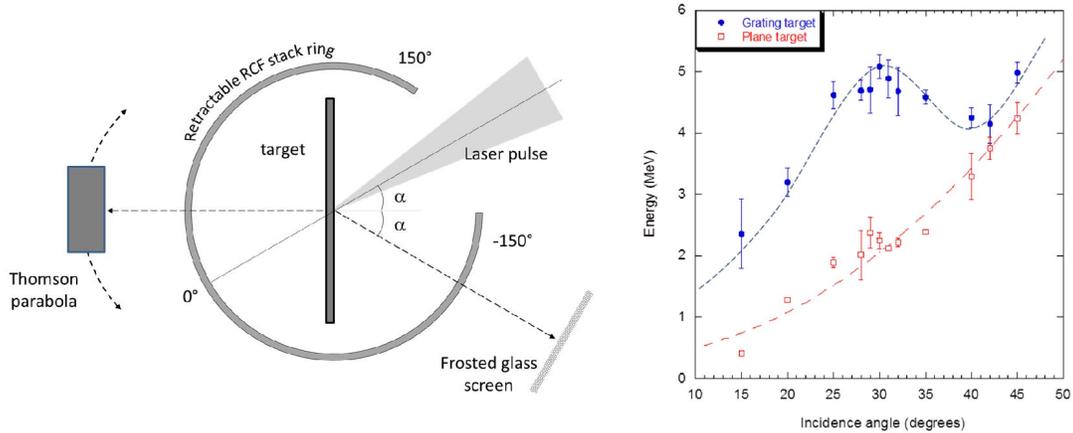


Figure 1. Left: Schematic top-view of the experimental set-up. The Thomson parabola and the frosted glass screen were located along the target normal direction and the laser specular direction respectively. Right: Maximum proton energies for grating ( $23 \mu\text{m}$  thick,  $500 \text{ nm}$  depth) and plane (Mylar,  $20 \mu\text{m}$  thick) targets in  $P$  polarization as a function of the laser incidence angle (solid circles and open squares respectively). The red large-dashes line is the fitting function cited in the text whereas the blue small-dashes line is just a guide for the eyes.

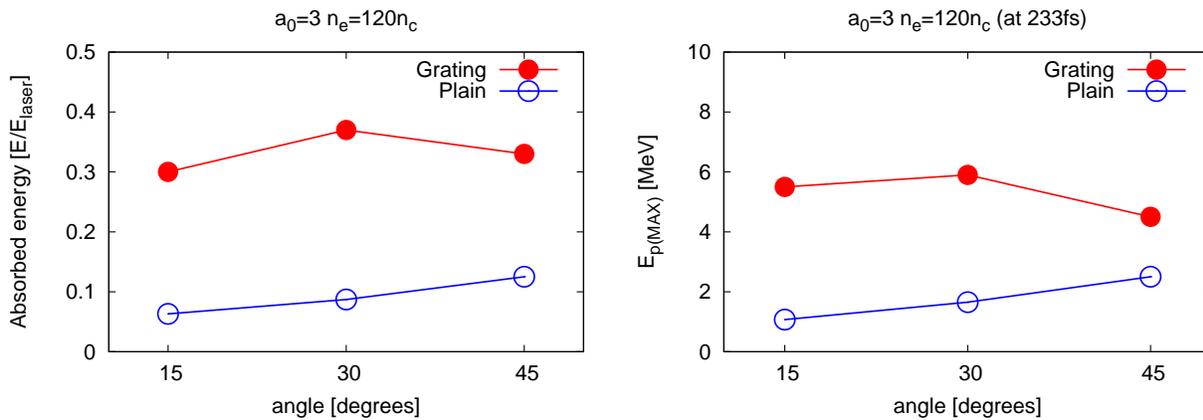


Figure 2. 2D PIC simulation results. The absorbed energy (left) and the cut-off energy of protons (right) as a function of the incidence angle, for both grating (filled circles) and flat (empty circles) targets.

assumption that far from the resonant angle the role played by the grating should be marginal. On the other hand for small angle of incidence, the GT give much higher energies than ST, which shows that the grating surface leads to enhanced coupling also out of the expected resonance.

The experimental results thus indicate an enhancement of the energy absorption around the resonant angle and are in agreement with a set of 2D Particle In Cell (PIC) simulations, run with the PIC code ALaDyn.<sup>22,23</sup> We considered flat and grating target with the same periodicity as in the experiments and  $0.4 \mu\text{m}$  peak-to-valley depth, irradiating the plasma at three different angle of incidence  $15^\circ$ ,  $30^\circ$  and  $45^\circ$ . The plasma was a  $0.8 \mu\text{m}$  thick slab of  $Z/A = 1/2$  ions with a  $0.05 \mu\text{m}$  H layer at the rear surface, the electron density  $n_e = 120n_c$  where  $n_c = 1.56 \times 10^{21} \text{ cm}^{-3}$  is the cut-off density. The laser parameters are: peak intensity  $I = 2 \times 10^{19} \text{ W/cm}^2$ , duration  $\tau = 25 \text{ fs}$  and focal waist  $w_0 = 4 \mu\text{m}$ . Figures 2 show the proton cut-off energy  $E_{\text{max}}$  and absorption coefficient  $A$  as a function of the angle for both flat and grating targets. It is apparent how for both quantities, with GT a maximum is obtained at  $30^\circ$  in agreement with the experimental results. The relative enhancement in the proton energy is higher in the simulations than in the experiment and the energy vs. angle curve is also smoother. This discrepancies may be due to some idealization which are necessary in the PIC scheme. Other simulations also proved how either reducing the plasma density or increasing the laser intensity, with GT the resonance smears out. This suggests that the discrepancy may be partly due to the simulated plasma density which is lower than what is expected for solid plastic (full ionization implies  $n_e \simeq 300n_c$ ).

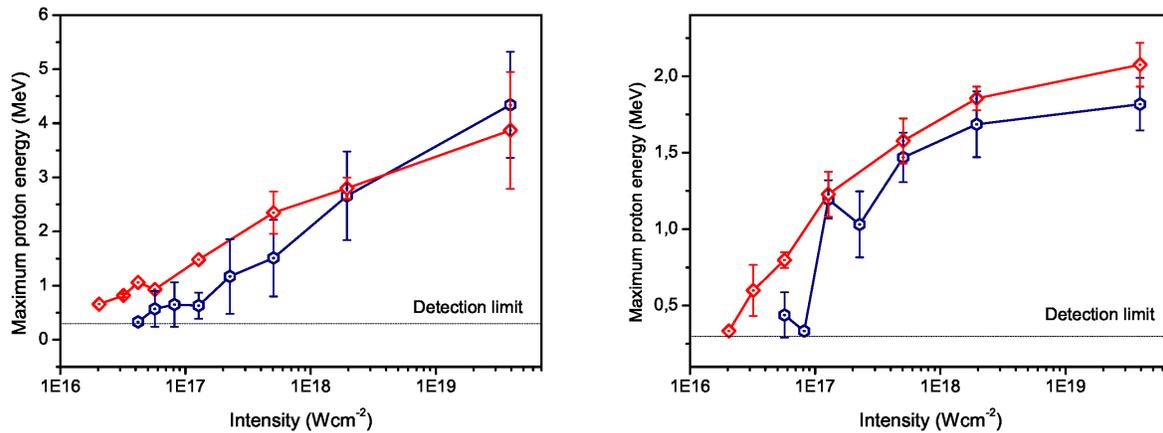


Figure 3. Proton cut-off energy observed with TP on the rear side of simple target (blue squares) and foam target (red circles) in high contrast configuration (left) and low contrast (right).

### 3. FOAM-COVERED TARGETS

For a highly “overcritical” densities the laser penetrates only in a very thin “skin” layer, on the other hand, if the plasma density is at the boundary between underdense and overdense  $n_e \simeq n_c$ , a volume rather than a surface laser-plasma interaction may be achieved. The use of “near critical” plasma target may then lead to an efficient absorption and fast electron generation as suggested by several works.<sup>24–26</sup> Recently some numerical works<sup>27–29</sup> proposed to use a two layer target where a low density “foam” layer ( $n_f \simeq n_c$   $l \simeq 10\mu\text{m}$ ) is coupled to a thin solid foil ( $n_e \simeq 100n_c$   $l \simeq 1\mu\text{m}$ ). These works reported a significant increase with respect to simple solid targets, in both the energy absorption and the proton acceleration. The idea is to exploit the low density plasma obtained from the ionization of the foam, to increase the production of fast electrons. A crucial point to test this configuration in an experiment is the manufacture of the targets with such low density material, which should be as low as few  $\text{mg}/\text{cm}^3$ , with particular attention to the adhesion to the solid foil.

We present the results of an experiment<sup>30</sup> where novel targets realized at the Micro and Nanostructured laboratory of Politecnico di Milano were employed.<sup>31</sup> The Pulsed Laser Deposition (PLD) technique allowed to grow a carbon “foam” with a mean density of  $5 \div 10\text{mg}/\text{cm}^3$  and thickness  $l_f \simeq 10\mu\text{m}$  directly on aluminium foils ( $0.75\text{-}1.5\mu\text{m}$ ). Using an off-axis  $f = 200\text{ mm}$  parabola, the UHI100 laser system at full power delivered a beam with maximum intensity up to  $4 \cdot 10^{19}\text{ W}/\text{cm}^2$ . Several laser conditions have been tested by changing the focal spot size (from  $3.5\mu\text{m}$  to  $100\mu\text{m}$  FWHM), reducing the pulse energy (from  $2\text{J}$  to  $0.2\text{J}$ ), or increasing the time duration  $\tau_p$  (from  $25$  to  $250\text{ fs}$ ), with double plasma mirror (HC) and without (LC). The beam peak intensity consequently ranged from  $5 \cdot 10^{16}$  to  $4 \cdot 10^{19}\text{ W}/\text{cm}^2$  and the angle of incidence on target was  $10^\circ$ . A TP placed outside the chamber recorded the energy spectra of the protons emitted from the target rear side.

The main results are summarized in figure 3 where the maximum proton energy at different laser intensities is reported for both cases the case of foam target (FT) and of simple target (ST). The proton cut-off energy achieved with FT and with ST is comparable at the highest tested intensities, whereas for lower values the FT gave a consistent advantage over ST. This results proved to be remarkably robust and has been confirmed in every condition that allowed to reach intensities below  $10^{18}\text{ W}/\text{cm}^2$ : both for HC and LC, longer or shorter pulse, at maximum or reduced pulse energy, for tightly focused or defocused pulse. Protons were accelerated in the MeV range already with laser intensity  $I = 10^{16} \div 10^{17}\text{ W}/\text{cm}^2$ , which is not possible for “ordinary” TNSA. The parameters of the foam plasma, expected from the experiments, are:  $n_f = 1 \div 2n_c$  (in the hypothesis of full ionization) and  $l_f = 10 \div 12\mu\text{m}$  (with local fluctuations). We ran dedicated 2D PIC simulations considering low to moderate pulse intensities ( $a_0 = 0.5 \div 4$  corresponding to  $I = 5 \cdot 10^{17} \div 3.5 \cdot 10^{19}\text{ W}/\text{cm}^2$ ) and Al

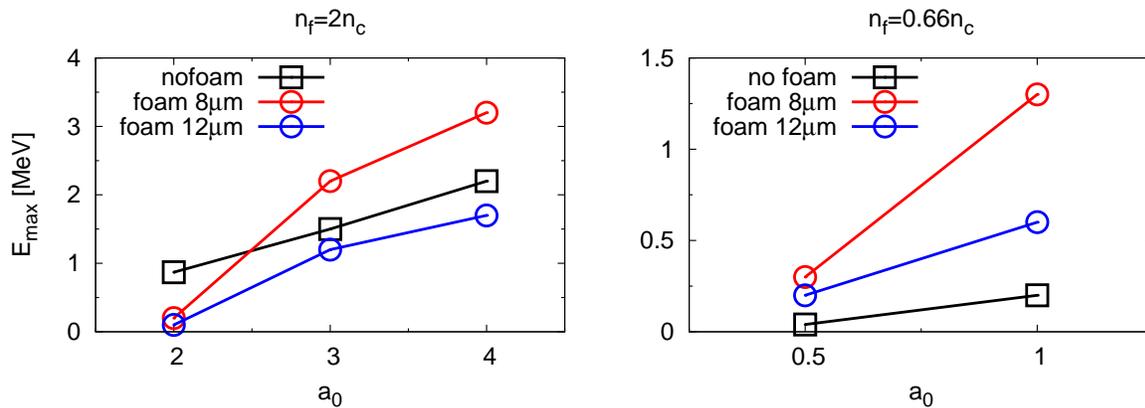


Figure 4. Proton cut-off energy observed in 2D PIC simulations considering for ST or FT with  $n_f = 2n_c$  (left) and  $n_f = 0.66n_c$  (right).

targets ( $l_m = 0.5\mu\text{m}$ ,  $n_e = 40n_c$ ) with foam ( $l_f = 8 \div 12\mu\text{m}$ ) and without. The foam density has been set to  $n_f = 2n_c$  for the higher intensities while at lower intensities, assuming partial ionization, a slightly subcritical value ( $n_f \simeq 0.66n_c$ ) has been chosen. In the first case, (see Figure 4, left) comparable values of the cut-off proton energy are found with FT or ST, slightly higher or lower depending on foam and laser parameters. On the other hand (see Figure 4, right) at lower intensities, the presence of a subcritical plasma leads to proton maximum energy higher with FT than with ST. The simulation data suggest that in the explored regime the foam layer needs to be underdense in order to lead to proton energy enhancement. This is qualitatively consistent with the experiment since on the low intensity side only a partial ionization of Carbon is expected, which should turn the electron density in the foam below the cut-off density.

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