Energetic ions at moderate laser intensities using foam-based multi-layered targets

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1. Introduction

Superintense laser-driven ion acceleration today represents a research topic of unique interest, both for fundamental reasons and for its potential towards future applications [1, 2]. A possible improvement in the acceleration performances mainly relies on three major, interrelated issues: (i) a detailed theoretical understanding of the laser-ion acceleration physics, possibly leading to the identification of new and/or optimized acceleration schemes; (ii) further developments in laser technology, to provide laser pulses with improved parameters; and (iii) the availability of targets with novel properties, mainly to better exploit and control the laser–matter interaction phase. The scientific and technical communities have devoted great efforts to all of these areas in the last few years. An attractive direction to be followed is the research of methods to increase the efficiency of the ion acceleration mechanism through an enhanced laser absorption by the target. This would allow us to achieve an optimization of the acceleration for given laser properties, which is of great importance both to soften the request for continuous improvements of laser parameters and to meet the conversion efficiency levels required for specific applications.

In this context, a key role is played by the identification and production of novel, smart target designs [1, 2]. Several kinds of micro- and nanostructured targets have been investigated in the last few years, showing promising results [3–7]. Recently, some numerical studies investigated multi-layered target configurations, in which a near-critical film is superimposed on the surface of a thin solid foil directly illuminated by the laser [8–10]. The basic idea is to exploit the near-critical layer (called *foam* in the following) to increase the efficiency in the generation of relativistic electrons, to drive an enhanced target normal sheath acceleration (TNSA)-like process. These

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studies suggest that the maximum proton energy can be significantly increased using this target configuration if the foam parameters (density and thickness) values are adequately tailored for given laser pulse properties. Successful development of this scheme would be very interesting for several reasons. First, ion energies in the MeV range could be obtained using laser pulses with moderate intensity. Second, the gained amplification of the maximum ion energy could be exploited in combination with the highest available laser intensities to reach and overcome the 10^2 MeV/nucleon level, as required for several applications. Moreover, this scheme would allow us to achieve this enhancement while maintaining all the appealing features of TNSA, like the high degree of collimation and laminarity, high brilliance and low emittance of the accelerated ion beam [1, 2]. From an experimental point of view, such a multi-layered target configuration poses significant challenges because, to properly mimic the idealized conceptual system, it is required to produce a film with a mean density orders of magnitude lower than the usual solid density, with enough flexibility in properly tailoring its parameters while ensuring at the same time satisfactory adhesion onto the solid foil. These aspects make the target preparation itself an advanced fundamental research topic in the area of material science and engineering, and the experimental activity of target preparation must rely on techniques typical of nanoscience and technology.

In this paper we show the experimental feasibility of the multi-layered, foam-based, TNSA-like acceleration concept. Targets with the required features were produced and characterized, fully exploiting the potential of the pulsed laser deposition (PLD) technique. The produced targets were tested in acceleration experiments involving laser pulses covering a wide range of intensities, both at high and low laser contrast. Due to the characteristics of the targets that we have been able to produce so far, the most significant results were observed at relatively moderate intensities, in the 10^{16}–10^{17} W cm^{-2} range. For these pulses, we have successfully shown a systematic 2–3 fold enhancement in the maximum proton energy, thanks to a significant increase of the laser–target coupling with respect to the use of a plain solid foil, allowing us to reach and overcome the MeV range. Two dimensional particle-in-cell (2D-PIC) simulations have been exploited to support the interpretation of the experimental results.

2. Experimental details

The multi-layered targets were prepared at the Micro and Nanostructured Materials Laboratory of Politecnico di Milano. Foam layers were obtained by depositing very open and porous nanostructured carbon films by PLD, tuning the deposition parameters so to reach mean mass densities as low as a few mg cm^{-3} [11]. The adopted deposition process allows us to grow the C foam layers directly on top of thin solid foils (Al in this case), thus solving the problem of achieving complete adhesion between the two layers. Representative scanning electron microscope (SEM) images, showing the morphology at the mesoscale of a foam layer attached on a solid substrate, are given in figure 1. As a general remark, this method allows us to obtain foam layers of variable density and thickness, which we are presently able to control within defined ranges (further details can be found in [11]). For the present proof-of-principle experiments, two different Al-foil thicknesses, 1.5 μm and 10 μm, were used, while the C foams were produced with mass densities equal to 7 ± 2 mg cm^{-3} and thicknesses of about 12 μm (on the 1.5 μm-thick Al) and 23 μm (on the 10 μm-thick Al), respectively. These mass–density values, assuming total or partial ionization of the foam layer after interaction with the laser (depending on the interaction conditions; see below), should correspond to a nearly critical or slightly sub-critical foam-electron density n_f (with C^{6+} and $\lambda = 0.8$ μm; 1 n_cr corresponds to 5.7 mg cm^{-3}).

The ion acceleration experiments were performed at the Saclay Laser Interaction Center Facility, using the UHI100 laser, which delivers intense pulses at a central wavelength of 790 nm. Different laser conditions were explored. In particular, intensities in the range 5×10^{16}–5×10^{19} W cm^{-2} were adopted, by properly changing the focal spot size (3.5–150 μm, full width at half maximum (FWHM)) at the fixed pulse energy (2 J) and duration τ_p (25 fs). The size of the focal spot was changed by moving the target along the focusing optical axis. The focal spot was imaged at different distances (every 50 μm) on either side of the best focus, on a 12-bit charge-coupled device (CCD) camera through a 40× microscope objective. The beam wavefront control, due to our deformable mirror, allowed the focal spot to keep a Gaussian-like shape all over the explored optical axis region. The corresponding intensities were estimated taking into account the spot size and the laser energy included in it. Both low contrast (LC) and high contrast (HC) of the beam were adopted, equal to 10^8 and 10^{12}, respectively. The angle of incidence was 10°. Proton spectra were recorded with a Thomson parabola (TP) spectrometer, placed normally to the target surface at a distance of 600 mm and with an 200 μm diameter entrance pinhole, which allows for a $E/\Delta E$ about 20 (at about 5 MeV energies). Once dispersed by the magnetic and electric fields of the spectrometer, protons and ions were detected by a two-stage 40 mm diameter micro-channel plate (MCP) coupled to a phosphor screen. The image was recorded by a 12-bit CCD camera.

3. Results and discussion

Figure 2 shows the maximum proton energy, E_p(Max), as a function of laser intensity for two different sets of system parameters. Here, the change of laser intensity was achieved by means of a focal spot variation in the range 3.5 to 150 μm (FWHM), either in an LC (*a*) or in HC (*b*) configuration. It can be seen that by using a foam-attached target, we measured proton maximum energies in excess of 1 MeV, even well below 10^{18} W cm^{-2}, and above 300 keV (the detection limit) down to 10^{16} W cm^{-2}. From the highest intensity down to $\sim 10^{18}$ W cm^{-2}, the E_p(Max) obtained with the foam-attached targets are comparable to the case without foam. On the other hand, below 10^{18} W cm^{-2}, an increase of E_p(Max) is systematically observed with foam-attached targets, while the values obtained with bare solid targets soon fall below the

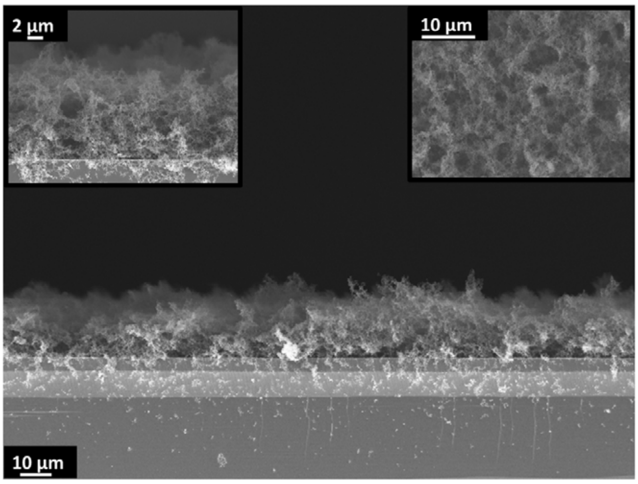

Figure 1. Representative cross-section SEM image of a typical carbon foam layer attached to a solid Si wafer. The foam density is about 5±2 mg cm^{-3} and its mean thickness is about 13 μm, while the silicon wafer thickness is 500 μm. The left inset shows the same area at higher magnification, while the right inset reports the foam top-view morphology at the mesoscale.

detection limit. These results prove that, contrary to what is widely reported about 'ordinary' TNSA using bare solid foils [1, 2], MeV protons become accessible already with 10^{16}–10^{17} W cm^{-2} laser intensities, by exploiting this target configuration. TP data (not shown) reveal that the number of highest-energy protons with multi-layer targets is always comparable or even higher with respect to the case of the bare solid foil. This results in the production of a bright, TNSA-like proton beam, different from what was recently obtained in schemes involving other kinds of nanostructured targets [7], for which low numbers of energetic protons with a broad angular distribution were observed. A further remarkable aspect, compared to other examples of target structuring [3, 4, 12, 13], is that even for LC laser pulses, an effect related to the foam layer is observed and leads to the enhancement of the maximum proton energy. This may allow less-stringent requirements for the laser systems.

Based on these experimental data and on previous theoretical–numerical investigation [9], a relatively simple, qualitative, interpretative picture can be drawn. At the highest available intensities in this experiment, around 4×10^{19} W cm^{-2}, we expect an almost complete ionization within the volume of the foam illuminated by the laser pulse, which implies the formation of a relatively thick ($\gtrsim$10 μm) slightly over-critical layer. At this intensity, the interaction between the laser pulse and either the solid or such a foam-attached layer will produce comparable accelerating fields, thus leading to a similar TNSA-like scenario (see also below). On the other hand, at lower intensities (10^{16-17} W cm^{-2}), only partial ionization of the C nanoparticles in the foam is to be expected, leading to the generation of a slightly sub-critical plasma. To quantitatively address this point, using the PIC code UMKA [14] with field ionization, we tested the case of a laser pulse with $I = 2 \times 10^{18}$ W cm^{-2} irradiating a low-density carbon layer. For this configuration, an average C^{4+} ionization has been observed. Also looking at the ionization energies of C,

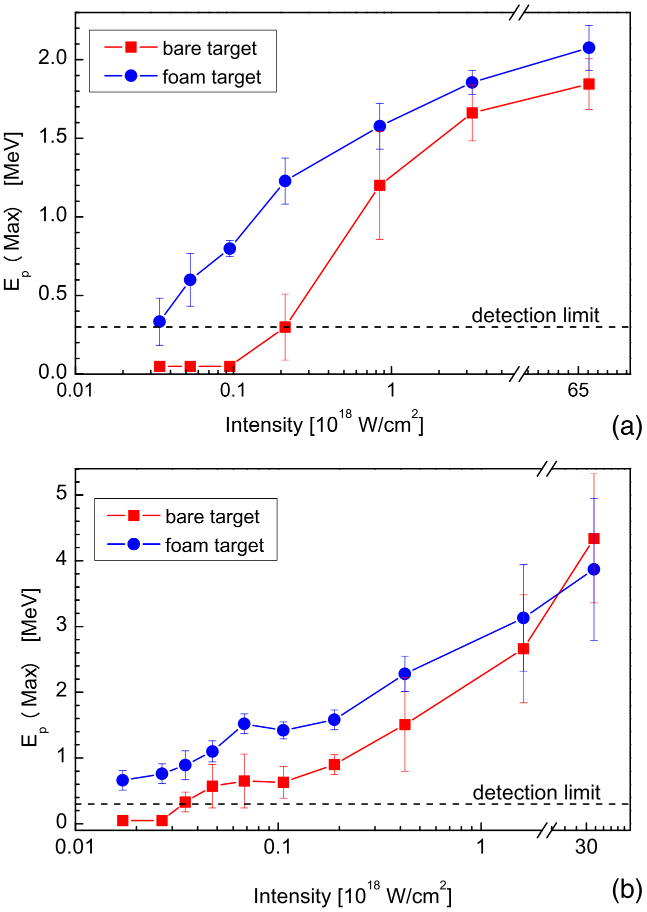

Figure 2. Maximum proton energy as a function of laser intensity, varied by changing the focal spot size on the target, both in LC configuration (*a*) and HC configuration (*b*) for ordinary (red squares) and foam-attached targets (blue circles). The detection limit of the TP is 300 keV.

we can therefore estimate that C^{2+}/C^{4+} are more likely to be formed by field ionization below 10^{18} W cm^{-2}, corresponding to $n_f = 0.4$–$0.5 n_{cr}$. In these conditions, the propagation of the laser pulse in the foam is possible even at sub-relativistic intensities and allows a volume interaction, leading to the efficient production of relativistically hot electrons [9]. On the contrary, in the case of interaction with a solid-density foil, the generation of hot electrons is strongly quenched below 10^{18} W cm^{-2}.

This physical scenario was checked with the help of numerical simulations. The relevant numerical studies available in the literature [8–10] cannot be directly compared with the experimentally investigated conditions, since the former mostly considered higher pulse intensities (above 10^{20} W cm^{-2}) and targets having idealized, near-critical/slightly overdense, thinner plasma layers. As a consequence, the experimental results presented here correspond to so-far numerically unexplored parameters. For this reason, dedicated 2D-PIC simulations were performed, using the code ALaDyn [15]. The laser pulse has $\lambda = 0.8$ μm, a 25 fs FWHM duration and a transverse Gaussian intensity space profile with a waist w_0 varying from 3 to 12 μm. The normalized vector potential a_0 was varied between 0.5

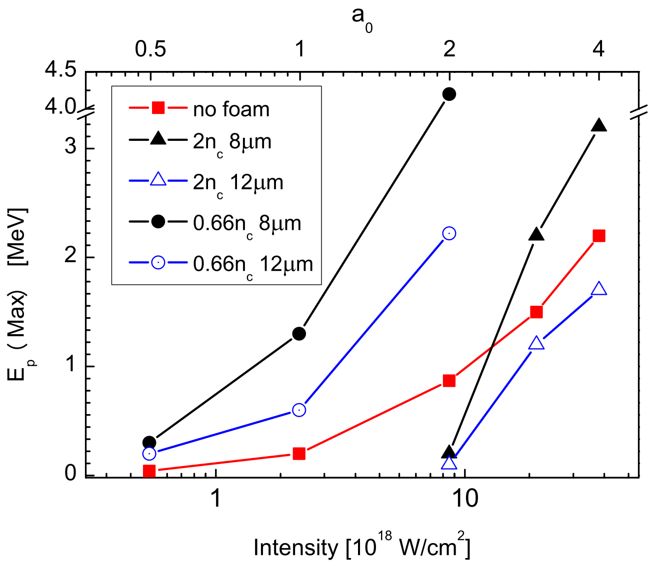

Figure 3. 2D-PIC results of maximum proton energy as a function of intensity, comparing the target with and without a foam layer (red squares). The foams have densities $n_{\mathrm{f}} = 2n_{\mathrm{cr}}$ (triangles) and $n_{\mathrm{f}} = 0.66n_{\mathrm{cr}}$ (circles) for two different thicknesses: 8 μm (black full symbols) and 12 μm (blue empty symbols).

and 4, corresponding to an intensity range of 5×10^{17}–3.5×10^{19} W cm^{-2}. The simulation box dimensions were $L_x = 80\lambda$ and $L_y = 120\lambda$ with $\Delta_x = \lambda/80$ and $\Delta_y = \lambda/40$. The foam-attached targets consist of three layers: foam, solid and contaminants (the target without foam having two layers). The foam layers have thickness 8–12 μm and densities $2n_{\mathrm{cr}}$ (for laser pulses having $2 \leqslant a_0 \leqslant 4$) and $0.66n_{\mathrm{cr}}$ (for $0.5 \leqslant a_0 \leqslant 2$, to take into account the partial ionization) and are initialized with 25 macro-ions ($Z/A = 1/2$ for $2n_{\mathrm{cr}}$ and $Z/A = 1/6$ for $0.66n_{\mathrm{cr}}$) and 25 macro-electrons per cell. The solid foil, having a thickness of 0.5 μm and a density of $40n_{\mathrm{cr}}$, is simulated with 25 macro-ions ($Z/A = 1/3$) and 49 macro-electrons per cell. The contaminant (proton) layer has 25 macro-protons and 9 macro-electrons per cell, a 50 nm thickness and density $10n_{\mathrm{cr}}$. In the simulations, time $t = 0$ corresponds to the instant when the laser starts interacting with the plasma, while the maximum proton energy has been evaluated at $t = 200$ fs. In figure 3, the numerically obtained values of E_{p}(Max) are shown as a function of laser intensity. For the highest intensities, the maximum proton energy is similar for both cases, with and without foam. As soon as the laser normalized intensity $a_0 \leqslant n_{\mathrm{f}}/n_{\mathrm{cr}}$ (for over-critical plasma), the laser cannot propagate through the foam, implying very low energy protons. If a lower foam density is considered ($0.66n_{\mathrm{cr}}$, circles in figure), even at moderate intensities (5×10^{17}–2×10^{18} W cm^{-2}, $a_0 = 0.5$–1) the laser propagates through the foam and effectively couples with the plasma, leading to the generation of a more-intense sheath field, resulting in an enhanced proton acceleration with respect to bare targets. As an example, in figure 4, the electron density and longitudinal electric field are plotted, showing that in the presence of a foam layer, the laser ($a_0 = 1$) accelerates a large number of electrons, building up a stronger accelerating field. We can consequently identify two regimes, depending on both laser intensity and foam parameters, relevant for the performed experiments. Above 10^{18} W cm^{-2}, up to 4×10^{19}, no clear distinction between targets with and without foams is observed, as far as the maximum proton energy is concerned. In this regime, numerical results suggest that either a lower foam density or a thinner foam layer should be used, in order to obtain a better laser–target coupling and higher proton energies. While in principle detailed control of the relevant foam parameters should be possible with suitable optimization of the adopted deposition technique [11], in the present experiments the foam layers were too thick, in connection with the specific values of electron foam density and available laser intensity. On the other hand, below 10^{18} W cm^{-2}, the foam-attached targets always lead to a significantly enhanced proton acceleration regime: numerical data confirm this picture, according to which an incomplete ionization of the foam leads to an effectively slightly under-dense plasma and, ultimately, to a much larger absorption of the laser energy, resulting in a more-intense accelerating field [9] and in proton energies up to three times higher with respect to the bare target case.

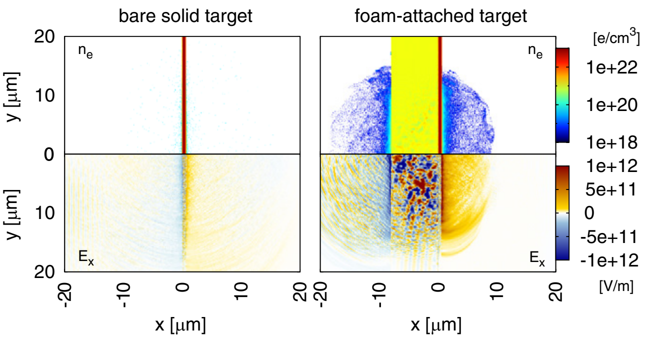

Figure 4. Comparison of the electron density and longitudinal electric field obtained in PIC simulations considering a bare solid target or a foam-attached target ($n_{\mathrm{f}} = 0.66n_{\mathrm{c}}$ $l_{\mathrm{f}} = 8$ μm) for $a_0 = 1$, at time $t = 100$ fs after the beginning of the laser–plasma interaction.

4. Conclusion

In conclusion, we have shown the feasibility of a novel and robust laser-ion acceleration scheme, based on the use of a multi-layer target, able to provide MeV proton energies using moderate pulse intensities, well below the relativistic threshold of 10^{18} W cm^{-2}. The role of the produced foam layers, obtained by depositing suitable nanostructured C films with PLD, on the increase of the laser energy absorption by the target, has been clarified, thanks to 2D-PIC analysis. These achievements also pave the way for further improvements, by exploiting the developed techniques to produce the novel foam layers and related multi-layered targets with parameters optimized for superintense pulses (above 10^{19} W cm^{-2}), to explore the possibility of reaching in this way values of maximum ion energies and laser-to-ion conversion efficiency of concrete interest for specific future applications.

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