Production of low-density targets for laser driven ion acceleration

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The possibility to control laser-matter interaction through the design of suitably engineered targets is one of the most interesting ways to enhance the performances of laser driven ion acceleration [1,2]. In this work we report on the production of multi-layered targets to be adopted in laser driven ion-acceleration experiments exploring enhanced acceleration regimes and we discuss results of the first experimental tests on these targets.

In Target Normal Sheath Acceleration (TNSA), ions at the rear surface of a target irradiated by ultra-intense (10^{18} – 10^{21} W/cm^2) ultra-short (10 – 100 fs) laser pulses are accelerated by the strong electric field produced by relativistic electrons generated in the interaction, escaping in vacuum. Thus an increase of the energy transfer from laser pulse to plasma electrons can lead to an enhancement of the maximum ion energy.

Target density is a crucial parameter in laser-matter interaction [3]; it defines the interaction regime and determines the efficiency of energy transfer from the laser beam to the target particles. In particular, the absorption of laser pulse energy can be enhanced if plasma density is around the so-called critical density, $n_c=m_e\omega^2/4\pi e^2$ (where m_e is the electron mass, ω the EM wave frequency and e the elementary charge), the density value beyond which electromagnetic radiation cannot classically propagate in a plasma. This is a boundary regime in which absorption mechanisms typical of under-dense plasmas ($n<n_c$), i.e. collisionless absorption via wavebreaking, and over-dense plasmas ($n>n_c$), such as vacuum heating and J×B heating, could cooperate and additional absorption phenomena occur, leading to a higher energy absorption. As a consequence, fast electrons generation efficiency can be increased. Actually, low-density materials, such as carbon foams, could be exploited in connection with various acceleration schemes besides TNSA, such as Hole-Boring Radiation Pressure Acceleration and Collisionless Shock Acceleration for which moderately overdense plasmas are required to increase the ion energy.

In the present work we focus on the production and test of foam-attached multi-layered targets for TNSA. Numerical PIC simulations [4,5] have shown that energy conversion, electrons energy and, therefore, maximum proton energy could be increased using a thin solid foil with a low density layer on its irradiated face to induce laser-plasma interaction in near-critical regime. In this configuration laser penetration into the target is increased, leading to stronger laser-plasma coupling and to efficient volumetric heating in foams with density around the transmission threshold. Simulations show that for such multilayer targets an optimal thickness exists for given foam density and pulse irradiance values. In particular, for laser intensities around 10^{20} W/cm^2 and near-IR wavelengths, the critical density is about 10^{21} cm^{-3}, which corresponds to extremely low mass density values (few mg/cm^3) depending on the ionization degree, and the optimum thickness is about 10 μm. Thus the production of such targets, as well as their characterization, is challenging because of their extremely low density and the requirements of proper control of the parameters of interest and of good adhesion of the film on the substrate.

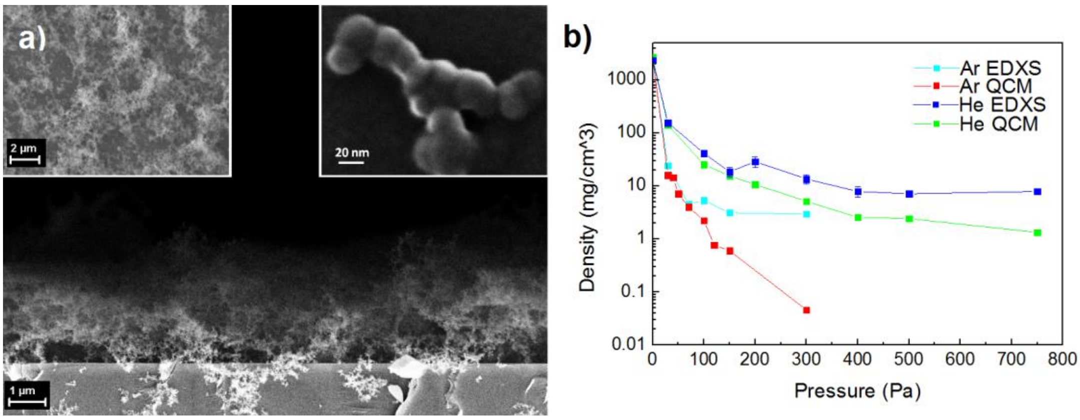

Figure 1 a) Representative cross-section SEM image of a typical carbon foam layer attached onto a solid foil. The left inset shows the foam top-view at the mesoscale, while the right inset reports an illustrative HR-STEM image from [5]. b) Comparison between density values measured using QCM and EDXS for foams produced in He and Ar atmosphere.

In this frame, we produced multi-layered targets composed by a thin Al solid foil (0.7-10 μm) and a near-critical density carbon foam layer (5-60 μm) directly grown on its surface to achieve complete adhesion to the substrate [6]. As a light element, carbon facilitates the achievement of low plasma densities. Moreover in principle the volatility of its oxides allows to produce monoelemental foams. Foam production is achieved by Pulsed Laser Deposition (PLD) through a proper choice of deposition parameters. In particular, low fluence (0.83 J/cm^2) and the presence of a room gas (Ar or He) are requested to obtain low density values and foam density can be controlled tuning gas pressure in the deposition chamber (30-1000 Pa) with all other parameters held constant, while various thickness values can be achieved selecting proper deposition times (5-60 minutes). Porous films with densities down to 5 mg/cm^3 and thickness in the range 5-150 μm have been produced.

Film morphology and thickness have been characterized through Scanning Electron Microscopy (SEM) images (see Fig.1a), while topological order and structure have been investigated through Raman spectroscopy. For He and Ar pressures respectively below 100 Pa and 30 Pa, cauliflower morphology is achieved, while for higher pressures porous random structures are observed and in Ar the substrate coverage begins to be incomplete above 500 Pa.

A crucial aspect of foam characterization is the measurement of their density. A relatively simple approach is to adopt a combination of thickness assessment from SEM cross section images and areal density measurements from a Quartz-Crystal Microbalance (QCM). However, QCM has been shown to be unreliable for densities below 20 mg/cm^2, making density evaluation a rather tricky issue. Thus, to properly measure the foam density a more refined technique based on Energy Dispersive X-ray Spectroscopy (EDXS) has been developed. This technique compares the characteristic X-rays produced in the sample by an electron beam to those generated in a proper reference with the same irradiation conditions [7,8]. Moreover, EDXS method allows to achieve a direct measurement of film areal density even for very low density foams and can be exploited to assess the foam inhomogeneity scalelength: areal density standard deviation increases sharply when the sampled area size becomes lower than inhomogeneity scalelenght. In Figure 1b, density values assessed with QCM and EDXS are compared for foams produced in He and Ar as buffer gas. In both cases density decreases with increasing gas pressure and beyond a threshold pressure (100 Pa in Ar and 200 Pa in He), corresponding to a threshold density value around 20 mg/cm^3, QCM measurements drop off to unrealistic values, underestimating film density. Thus, EDXS is more reliable for density values of a few mg/cm^3, comparable with critical mass density values for near infrared wavelengths, which makes this technique fundamental for multi-layered target characterization.

First tests of foam based multi-layered targets in ion acceleration experiments have been carried on at the Saclay Laser Interaction Center Facility, where targets composed by a thin Al foil (1.5 μm) and a carbon foam layer 12 μm thick with density around 5-6 mg/cm^3 have been irradiated using the UHI100 laser (Ti:sapphire, 790 nm) with intensities in the range 5×10^{16} W/cm^2 – 5×10^{19} W/cm^2 and contrast 10^{12}. As shown in Figure 2a, the maximum proton energy achieved with the adopted foam-attached targets is comparable with that obtained with bare aluminium for intensity values above 10^{18} W/cm^2, while below this threshold the presence of the foam determines a systematic increase in the cut-off energy.

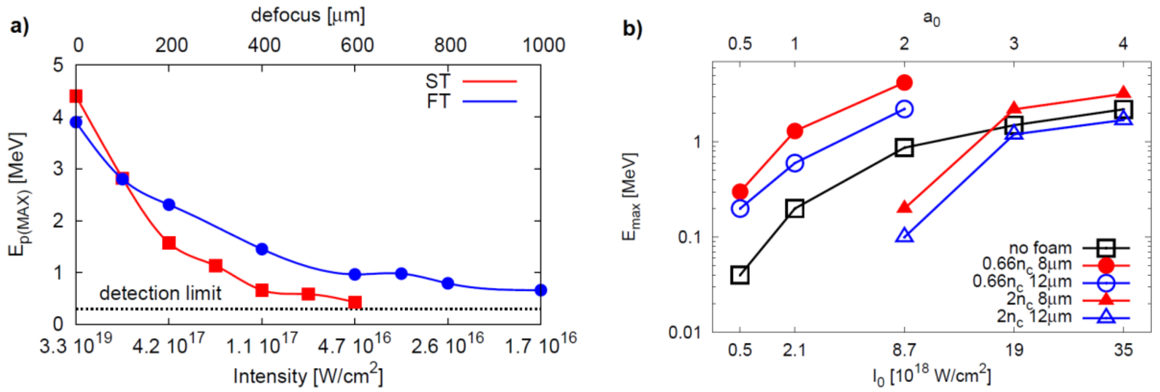

Figure 2 a) Maximum proton energy as a function of laser intensity obtained moving along the focus axis in the case of foam-attached (in red) and bare (in blue) target. b) Maximum proton energy calculated as a function of intensity in PIC simulations. In the range a = 2–4 intensity is varied by means of focal spot (3-12 μm), while in the range a = 0.5–1 changes by means of laser energy content.

This behaviour has been interpreted on the basis of dedicated PIC simulations, whose results are reported in Figure 2b, and is due to the ionization degree of plasma. For high intensity, i.e. 10^{19} W/cm^2, carbon ionization is expected to be complete, leading to the formation of a slightly over-critical plasma layer. In this condition the TNSA-like scheme leads to similar ion energies in bare and foam-attached targets because the foam thickness is higher than the optimal value. On the contrary, for intensity values around 10^{16} – 10^{17} W/cm^2 collisionless absorption mechanisms are quenched in solids. But, on the other hand, due to the partial ionization of carbon atoms (C^{2+}/C^{4+} turn to be the most likely ionization states), plasma density is around 0.5 n_c and relativistic electrons are produced in the foam layer, leading to significantly higher ion energies.

In conclusion, this work shows how PLD can be exploited as a versatile tool for the deposition of carbon foams with tunable and tailored density, thickness and uniformity, allowing the experimental investigation of novel laser-based ion acceleration schemes, such as the enhanced TNSA-like mechanism achieved with foam-attached multi-layered targets.

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