Ultraintense laser-driven proton acceleration using foam-attached multi-layered targets

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Since the discovery of CPA technique in 1985 which allowed to obtain short (10^{-12}-10^{-14} s) and high intensity laser pulses ($>10^{18}$ W/cm^2), new regimes of laser-matter interaction have been explored, triggering the development of techniques to accelerate electrons [1] and ions [2] exploiting the huge electric fields generated in the plasma. An EM wave with frequency ω interacts with matter in two different regimes which are discriminated by plasma density n_e measured with respect to the parameter $n_c = m_e\omega^2/4\pi e^2$ so-called *critical* density. When $n_e < n_c$ the plasma is called "underdense" and the wave can propagate through it. Inside the interaction volume, the whole plasma itself, collisionless absorption of laser energy occurs via e.g. excitation of plasma waves which may break and accelerate electrons to energies that increase with increasing plasma density. If $n_e > n_c$ the plasma is "overdense" and the interaction takes place in a region limited by the skin layer, the distance the laser can cover inside the medium. Here other collisionless absorption mechanisms occur and the principal physical consequence is the formation of a relativistically hot electron population [1]. In this case the more the plasma density decreases the more the skin layer increases, together with the interaction volume and the absorption fraction. Considering a plasma of controlled density close to n_c a more efficient laser absorption and fast electron generation is observed [3] which may lead to significative improvements in laser-driven ion acceleration, where the issue of laser energy absorption is of paramount importance. However one of the main difficulties in exploring this "near-critical" regime is related to the production of such materials, having for laser wavelength ~ 1 μm densities in the order of magnitude of mg/cm^3.

In this work we study theoretically and experimentally laser-ion acceleration via the most investigated mechanism i.e. Target Normal Sheath Acceleration (TNSA), using a novel target configuration where a solid foil is covered by a low-density near-critical layer on the illuminated side (see Fig. 1(a)). The principles of laser plasma interaction in this regime have been numerically investigated performing 2D and 3D Particle-In-Cell (PIC) simulations, to address the role played by laser (direction of incidence, intensity) and target (density and thickness) pa-

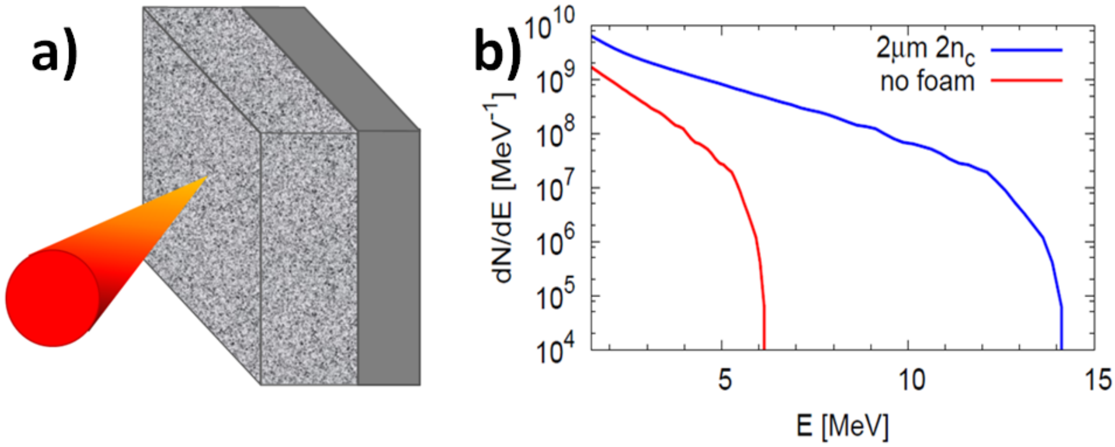

Figure 1: (a): illustrative picture of multi-layered target configuration under study. (b): 3D PIC simulation result where the gain in maximum proton energy is evident moving from a foam case in blue to a bare one in red.

rameters. The production of multi-layered targets having controlled thickness and tunable mean density has been tackled by means of pulsed laser deposition (PLD). First preliminary results of ion acceleration experiments on these targets are also reported.

Numerical simulations were performed using the `ALaDyn` PIC code. Target configuration in which a solid density thin plasma is coupled with a low density plasma layer (“foam”) attached on the illuminated side has been investigated in two and three dimensions [4]. The 3D simulations allowed to estimate quantitatively proton acceleration process and the gain factor in maximum proton energy between a “foam-attached” configuration and a ordinary one is found to be in excess of two (see Fig. 1(b)). The 2D simulations, less demanding, allowed to explore proton acceleration within a wide parameters range: different foam thicknesses 1-12 μm and densities 1-8 n_c, laser powers 3-128 TW and angles of incidence 0-60°. An optimum foam thickness is found at a given density and laser intensity which lead to a gain factor in proton cutoff energy greater than two with respect to the case of solid targets without foam. Concerning the angle of incidence, between 0 and 30° proton energy is not appreciably affected while at larger angles the efficiency in producing protons decreases. The larger proton energy is due to the much larger laser energy absorption by the electrons in a foam attached target with respect to a bare solid foil. The electron population then expands and builds up a stronger electrostatic field at the rear side. This process might be seen as a “volume” interaction instead of the “surface” one, taking place in a solid foil.

In order to cope with the not straightforward production of a multi-layered target configuration, a material production technique able to guarantee a good adhesion between solid and foam as

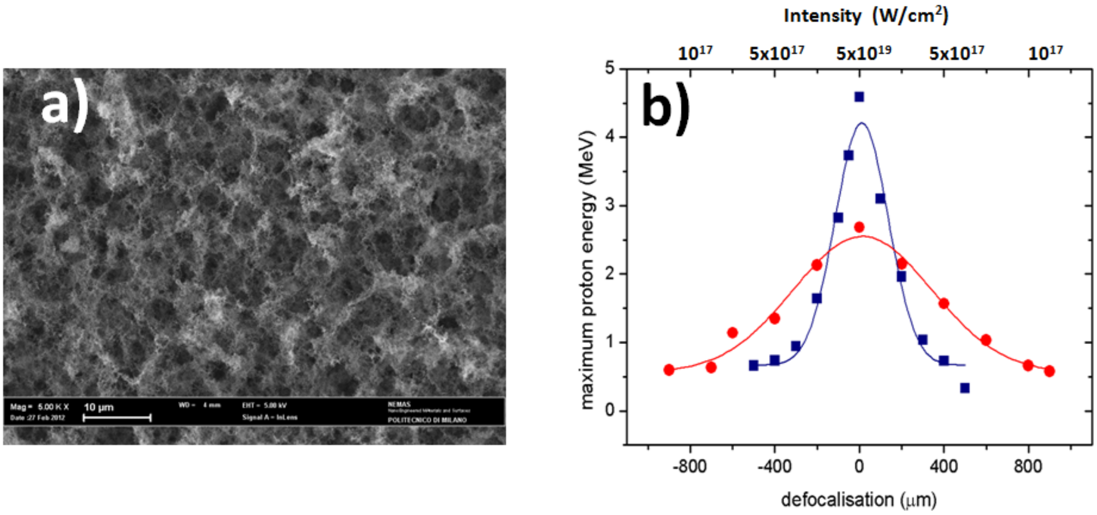

Figure 2: (a): exemplificative top view SEM image of the foam layer. (b): maximum proton energy as a function of laser intensity obtained moving along the focus axis in the case of foam (in red) and bare (in blue) target.

well as to control the nanostructure by a proper process parameter tuning is needed. Because of its properties we exploited pulsed laser deposition (PLD) which turns to be optimal for our purposes. We were able to deposit ultra-low density carbon layers having few-tens nm nanoparticles as elementary constituents, linked in random chains self-similarly till the mesoscale (see for example Fig. 2(a)) where the aggregation does depend on argon pressure in the deposition chamber. At increasing pressure morphology becomes opener leading to a decrease in mean density till the regime of mg/cm^3, i.e. near-critical. Both mean density and thickness are tunable within ~1-1000 n_c and 10-80 μm respectively [5]. A first test of these targets has been conducted at UHI100 laser facility in CEA-Saclay. Foam layers had to be deposited onto Al foils with thicknesses of 0.7, 1.5 and 10 μm. Foams in this case are produced with densities and thicknesses ranging between 0.5-2 n_c and 10-20 μm respectively, while the laser was changed in incident angle (10° - 45°), contrast (10^7, 10^{12}) and in intensity ($\sim 5\times10^{16}$-5×10^{19} W/cm^2) properly changing focal position (between -1.2 and +1.2 mm) energy (0.2-2 J) and duration (25-250 fs). The result is a collection of a wide set of maximum proton energy data, whose preliminary evidence is the existence of different interaction regimes depending on the laser and foam parameters. In particular at sufficiently low intensity (as shown in Fig. 2(b)) proton maximum energy with foam appears to be definitely higher. This might be a first proof that with foam a volume and not surface interaction takes place, generating more and more energetic electrons and hence higher energy protons.

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