Steps to optimization of maximum proton energy in target normal sheath acceleration

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Since the investigation of the interaction between super-intense laser pulses and matter had been undertaken [1] many intriguing physical phenomena have been discovered [2], such as particle acceleration, coherent X-ray and higher harmonics generation. During the last ten years of research a broad interest arose on the possibility to accelerate ions up to multi-MeV energies by irradiating solid targets, that showed outstanding properties such as high particles-per-bunch number and very peculiar spatial and spectral shaping. This kind of acceleration is observed to take place at intensities $>10^{18}$ Wcm^{-2} and the physical mechanism that is more likely to occur in most of the actual experimental conditions is the so-called Target Normal Sheath Acceleration (TNSA) [3]. Due to accelerated ions properties many possible applications might be reasonably considered in the future, for example in the fields of oncological hadrontherapy or proton-driven fast-ignitor approach in inertial confinement nuclear fusion. In the light of possible applications an optimum control of the beam parameters becomes an issue of crucial importance.

The focus of this work will be on one of the most important features of the accelerated ions, i.e. the maximum ion energy, and the possible roads towards its improvement by the optimization of laser and target parameters. We first investigate the scaling laws with laser intensity through a combined analytical and numerical interpretation of an experimental data set, by considering a system in which the target is an ordinary bulk solid foil. Then a more complex target composed by a solid density layer covered by a low-density “foam” on the illuminated side is considered. In this framework 2D Particle-In-Cell (PIC) simulations, performed to obtain the dependence of maximum ion energy on foam density and thickness and a preliminary experimental study on foam-attached C targets fabrication are presented.

The first part of the work is devoted to a study of the dependencies of maximum ion energy on *laser* properties with fixed target parameters. The experimental points come from CEA-IRAMIS Saclay [4] and are obtained thanks to backward TNSA from the front surface of a very thick plastic target, by varying pulse energy content while keeping other parameters (such as duration and focal spot) fixed. The theoretical part of the study combines an analytical [5] and

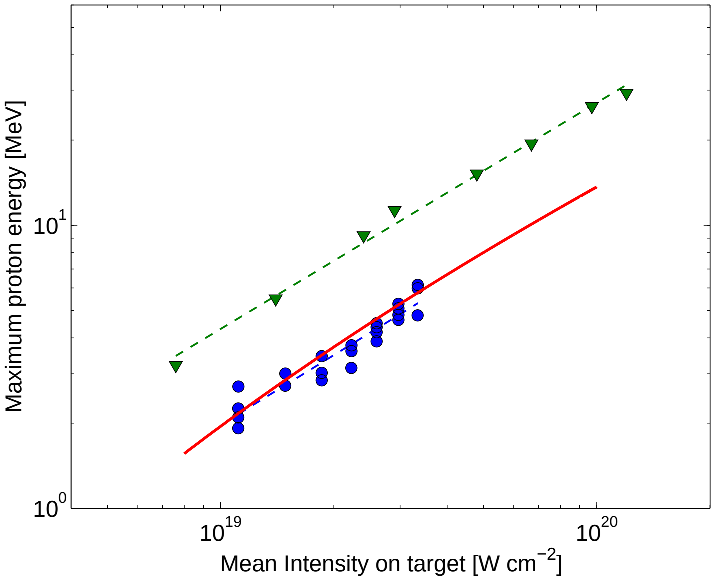

Figure 1: Maximum proton energy as a function of laser intensity: blue circles represent experimental points, green triangles 2D PIC simulations results while red solid line is the scaling obtained by the analytical model. All the three scalings show a similar power law dependence.

a 2D Particle-In-Cell numerical approach ([6] and Refs. therein). In Fig. 1 we have reported the experimental points (blue circles) measured for intensities varying in the range 1-3$\times10^{19}$ Wcm^{-2} while duration and focal spot on target (approximated by a circular section uniform profile) were fixed at 25 fs and 11.2 μm diameter respectively. In the same plot the corresponding analytical prediction is reported in red solid line, while the numerical data are presented as green triangles. Looking at the three scalings in Fig. 1 it is evident that they follow approximately the same power law within the considered intensity range: in particular it has been calculated to be quasi-linear and around $\sim I^{0.8}$. PIC data are systematically shifted by an almost constant factor with respect to experimental and analytical one. Two possible reasons of this systematic overestimation are discussed in Ref. [6].

In the second part of this work we present a study concerning the dependency of maximum proton energy on *target* properties. To this aim we consider a multilayered target composed by a main solid foil ($l \sim \mu$m) with a low density layer (“foam” in the following) on the illuminated side. The reason we choose such a target design lies in the fact that the pulse energy absorption improves when an intense laser interacts with a near-critical density medium [7]. This target design has been tested in different 2D PIC simulations in which we varied both foam density (n_f=1,2,4n_c) and thickness ($l_f \sim$0.5-8 μm). In Fig. 2 the maximum proton energy is plotted as a function of foam density for three different density values and all these results are much higher

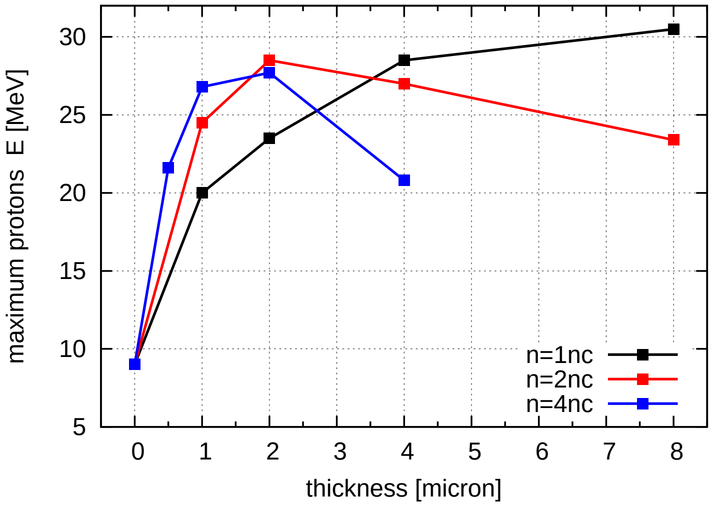

Figure 2: 2D PIC results of maximum proton energy dependence on foam thickness multilayered targets. The black squares represent foam density $n_f = n_c$, where n_c is the critical density for λ=0.8 μm; red circles correspond to $n_f = 2n_c$, while blue triangles to $n_f = 4n_c$.

than those calculated with solid target only (corresponding to thickness equal to 0 in Fig. 2). For each foam density value a corresponding optimum thickness exists; moreover maximum proton energy slightly increases with decreasing density.

We performed a preliminary experimental investigation on the fabrication of low density carbon foam layers onto a solid substrate using pulsed laser deposition (PLD). The PLD system in this experiments exploits a doubled Nd:YAG laser (532 mJ, 7 ns), a vacuum chamber ($\sim 10^{-2} \div 10^{-3}$ Pa) and a pumping system having a primary and a secondary pump, plus gas injection assembly. The most relevant deposition parameters for this system are laser fluence, background pressure and gas type, target-substrate distance and deposition time. Besides the possibility to deposit foam layers directly onto solid foils, PLD technique shows other benefits; since it potentially allows to fabricate foams with controlled thickness and mean density by properly tuning the process parameters. The mean density can be estimated by measuring the deposited mass over a fixed area once the mean thickness is known from cross-section Scanning Electron Microscopy (SEM) images. Fig.3 shows the decreasing foam density obtained with increasing buffer-gas pressure (in this case Helium) while other parameters are fixed at optimum values. The feasibility to produce with PLD foams having mass densities of the order of mg/cm^3, corresponding to the near-critical regime, has been shown. Nevertheless the production process has still to be optimized in order to obtain foams with a smaller inhomogeneity scale, below the μm level.

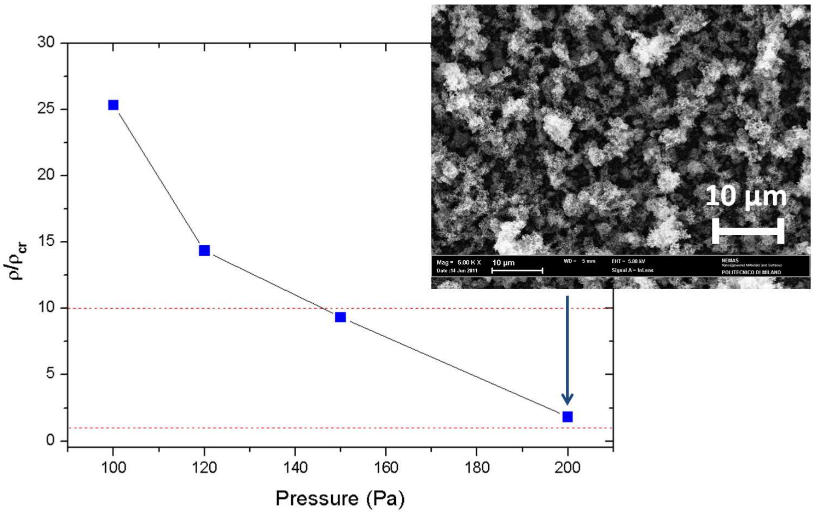

Figure 3: Foam mean density measured as a function of Helium pressure used during the deposition. Corresponding to 200Pa SEM image of the sample is reported.

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