Carbon nanofoam targets for inertial confinement fusion experiments

A. Maffini[1], M. Cipriani[2], M. S. Galli De Magistris[1], D. Orecchia[1], M. Passoni[1], P. Andreoli[2],
G. Cristofari[2], F. Consoli[2], M. Sicsciò[2], V. Ciardiello[3], D. Davino[3], and V. P. Loschiavo[3]

[1] *Politecnico di Milano, Milano, Italy*
[2] *ENEA Centro Ricerche Frascati, Frascati, Italy*
[3] *Università del Sannio, Benevento, Italy*

Porous materials, commonly known as foams, are a focal point of extensive research in the field of laser-matter interaction and Inertial Confinement Fusion (ICF). Foams composed of low atomic number (Z) elements have been suggested for the development of bright X-ray sources [1], equation of state studies [2], and more recently, for effective electron acceleration [3]. In ICF, foams are proposed as components of the capsule's outer layer thanks to their potential in smoothing out laser inhomogeneities [4], improving laser absorption efficiency [5], and enhancing the ablation loading on a substrate [6]. These properties suggest that foam ablators could play a crucial role in boosting laser-target coupling, thus improving the transfer of laser energy to compress the capsule's inner layers. Most experimental data currently available focus on plastic (low-Z) foams produced through chemical methods, which have a internal structure comprising filaments, membranes and voids of mircometric or sub-millimetric size. Nonetheless, exploring porous materials with different composition and morphology is essential to unlock the full potential of foam-based target for ICF applications. Recent studies have highlighted the benefits of mid-Z ablators, which can mitigate the effects of Laser Plasma Instabilities and consequently enhance target performance. High-Density Carbon, often used in indirect-drive experiments, shows promise for improving capsule performance in both indirect and direct-drive configurations [7, 8]. Moreover, potential benefits may arise from the presence of a sub-wavelength (i.e. nanometric) target structuring, in contrast with the micrometric size of the structural elements of conventional plastic foams. In this context, an interesting possibility for ICF target ablators is given by a novel class of porous materials, namely nanostrucutred foams (or nanofoams) produced by means of the Pulsed Laser Deposition technique

(PLD) [9, 10], as low-density carbon nanostructured materials could offer a combination of the advantages offered by mid-Z element and the unique plasma behavior arising from their internal structure.

In previous works we have already investigated the potential of PLD carbon nanofoams in the framework of high intensity (I> 10^{18} W/cm^2), ultra fast ($\tau < 100$ fs) laser-matter interaction [11]. We have shown –both theoretically [12] and experimentally [13]–that nanofoams can be employed as a near-critical layer in double-layer targets to strengthen the coupling between the laser pulse and the plasma species resulting from target ionization. As a consequence, we observe an enhancement in terms of number and energy of accelerated particles, including high-energy photons [14], neutrons [15], ions [16] and radioactive nuclides [17]. In addition, we have also carried out a preliminary, numerical investigation of the behaviour of carbon nanofoams under irradiation with laser conditions relevant for ICF studies ($\tau = 3$ ns, I= 10^{14} W/cm^2) [18]. More specifically, we used the hydrodynamic MULTI-FM code [19], previously validated with experiments on conventional plastic foams [20], to study the propagation of laser-driven shock in a nanofoam-based ICF target. Different nanofoam parameters (in terms of average density and pore size) have been considered. We observed that the shockwave propagation is not only affected by the average density but also by the internal nanofoam structure: the peak pressure at the shock boundary is significantly enhanced in nanofoams compared with homogeneous media of the same density, thus increasing the ablation loading on a subsequent layer along with the overall compression efficiency [18].

In this work, we report about the experimental investigation of PLD carbon nanofoams as ICF ablators at the ABC laser facility hosted at ENEA Centro Ricerche Frascati, Italy. We have selected two different kind of carbon nanofoams, each characterized by a specific nanoscale morphology (namely *fractal-like* and *tree-like*) and average density ($\simeq$ 6 and $\simeq$ 18 mg/cm^3 respectively), deposited on aluminum substrates with different thickness, (i.e. $\simeq 1\mu$m foils and $\simeq$ 1 mm thick disks). Nanofoams' mass thickness ranges from 800 mg/cm^2 to 1600 mg/cm^2.

Nanofoam depositions have been performed at Micro and Nanostrucutred Material Laboratory of Politecnico di Milano using the second harmonic ($\lambda = 532$ nm) of a Q-switched Nd:YAG laser (pulse duration ≈ 7 ns) and operating at a repetition rate of 10 Hz [9, 10]. The laser impinges on a pyrolitic graphite target with an incidence angle of $45\ ^\circ$, causing the vaporization of carbon species. The species expand in the deposition chamber and interact with the background atmosphere, until they reach the substrate. For what concerns the synthesis of nanofoams employed in this work, the laser energy was 500 mJ and the laser spot size was $\simeq 0.7$ cm^2, yielding a fluence per pulse $\simeq 710$ mJ/cm^2. The target-to-substrate distance was fixed at 70 mm, and the substrate holder rotated at $11\ rpm$ to ensure deposition uniformity. The vacuum chamber was filled with Ar ($99.9\ \%$ purity), tuning its pressure to produce carbon nanostructured films with different densities and morphologies. Specifically, low-density (6 mg/cm^3) *fractal-like foam* were obtained with a pressure of 200 Pa Ar, while intermediate-density (6 mg/cm^3) *tree-like foam* were grown with 50 Pa Ar. Different mass thicknesses (i.e. mass density $\times$ thickness) were obtained by properly adjusting the deposition time.

The ABC laser is a Nd:glass phosphate laser, which can deliver two counter-propagating beams of 100 J each at the fundamental wavelength $\lambda_L = 1054$ nm, with a pulse duration of $\tau_L = 3$ ns. One of the two beams was exploited to irradiate the samples in a planar geometry. The focal spot was kept fixed to 100 μm in diameter. The pulse energy was energy was set to 40 J, and the resulting irradiance on target was about 2×10^{14} W/cm^2. Multiple particle and radiation diagnostics were employed in the study of the laser-plasma interaction, including shadowgraphy, optical emission spectroscopy, analysis of transmitted and reflected light, time-of-flight detection of charged particles. In order to assess the effectiveness of laser energy conversion into compressive loads, we measured the volume of the crater left after the interaction on the massive disc of aluminium, following the approach reported in [6]. Post-irradiation analysis of the samples has been carried out with both optical microscopy (Leica DMI5000 M Inverted microscope equipped with the LAS Montage module, with the resolution of about $1\ \mu$m) and electron microscopy (Zeiss Supra 40 field emission scanning electron microscope, accelerating voltage 3-20 kV).

We observe that the crater imprinted on the bare aluminium target has a sharp edge and a very regular shape, which corresponds to the transverse profile of the laser beam. On the contrary, the crater left on the Al disc coated with the fractal-like nanofoam shows very irregular margins and is not symmetrical about its center. We assume that this behaviour is explained by the fact that the nanofoam buffer diffuses the incoming laser radiation, thus enlarging and deforming the shape of the crater. Finally, the shape of the crater observed on the Al disc coated with the tree-like nanofoam is intermediate between the bare target and the target coated by fractal-like foam.

Target type	Foam thickness [μm]	Foam density [mg/cc]	Crater volume [$\times 10^7 \mu\mathrm{m}^3$]
Bare aluminium disc	-	-	3.41
Fractal-like nanofoam	267	6	3.97
Tree-like nanofoam	60	26	6.02

Table 1: Crater volumes for bare and foam-covered targets.

In Table 1 we report the crater volumes for the different targets. While the crater volumes are similar in the cases of bare Al and fractal-like nanofoam, we observe that the crater volume is almost doubled when tree-like nanofoam is employed. This indicates that the nanofoam buffer has ensured a higher efficiency in target compression, confirming the potential role of this class of materials in the development of advanced targets for future laser-driven ICF experiments.

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