Nanofoams in action: a universal tool for laser-plasma interaction experiments

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Nanostructured low-density materials, commonly referred to as nanofoams, are emerging as novel target concepts in the field of high-intensity laser-plasma interaction (LPI). Upon irradiation by intense ($I > 10^{14}$ W/cm^2) laser pulses, nanofoams are turned into a plasma that dynamically interacts with the laser pulse. Nanofoam characteristics – such as density, micro- and nano-scale morphology and geometrical thickness – ultimately control the physics of laser-target interaction processes. In particular, very low density (few to tens mg/cm^3) nanofoams enable the access to the near-critical interaction regime, where the laser energy is absorbed volumetrically in the whole target. Moreover, the properties of nanofoams can be finely tuned to engineer specific plasma density profiles, which are known to influence the development of laser-plasma instabilities, the refluxing of hot electrons, and the formation of very strong sheath fields due to charge separation.

Since these phenomena may increase the laser-to-plasma energy coupling and, thus, the generation of energetic particles and radiation sources, applications of nanofoams in LPI span a wide spectrum. Nanofoams are being explored for enhancing laser-driven ion acceleration, particularly in the Target Normal Sheath Acceleration (TNSA) scheme, where optimal laser-plasma coupling is crucial to sustain the charge separation and sheath fields that ultimately drive proton acceleration. Additionally, owing to their ability to increase number and energy of the ions and electrons accelerated during the LPI, nanofoams can consequently enhance the generation of secondary particles such as neutrons, photons, positrons, and radioisotopes. In inertial confinement fusion (ICF), low-density foams are being considered as advanced ablators that could improve implosion symmetry and shock delivery. Furthermore, the use of nanofoam targets rich in boron and hydrogen opens new possibilities for the study of aneutronic proton-boron (p-11B) fusion reaction.

Among the different synthesis techniques that can be employed to fabricate nanofoam-based targets, Pulsed Laser Deposition (PLD) has emerged as an ideal tool thanks to its unmatched versatility in the control of composition, structure, and thickness of the deposited material. PLD exploits laser pulses that are focused onto a solid target, ablating its surface layer. Ablated species may comprise ions, atoms, clusters of atoms or nanoparticles, depending on the specific ablation mechanism. In the presence of a background gas, the ablated species can cluster into micrometric aggregates, which subsequently land onto the substrate and form a nanostructured porous coating. The morphology of the resulting nanofoam is determined by the complex interplay between ablation dynamics, gas-phase aggregation, and deposition kinetics.

Understanding the physics of the PLD process is therefore essential to achieve reproducible nanofoam targets with controlled properties. Our recent studies [1, 2, 3] have systematically characterized the evolution of nanofoam morphology and density as a function of deposition conditions. Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy have shown that PLD nanofoams are made of primary nanoparticles aggregated into larger fractal-like clusters. On the one hand we have demostrated that macroscopic properties of the nanofoams, including the density profile, are determined by the size and composition of the primary nanoparticles, as well as the size of the aggregates and their fractal dimension, through a fractal scaling law. On the other hand we have highlighted how it is possible to control those features by properly tuning deposition parameters, including target composition, laser pulse duration and fluence, repetition rate, pressure and composition of the background gas, and setup geometry. In this way, PLD enables the fabrication of nanofoam targets with tailored morphology and composition down to the nanoscale, making it possible to optimize target characteristics for the specific needs of a chosen application.

The functional versatility of nanofoam targets produced via PLD has been exploited in several applications in the domain of LPI. Among the primary areas of interest is laser-driven ion acceleration. In recent studies [4, 5], Double-Layer Targets (DLTs) composed of a micrometric metallic substrate coated with a carbon nanofoam layer have demonstrated superior performance in terms of both proton energy and beam quality. Three-dimensional Particle-In-Cell (PIC) simulations including an accurate description of nanofoam morphology [5] reveal that such DLTs significantly enhance NSA, specifically hot electron production and sheath field formation, leading to an increase in maximum proton energy by a factor of two compared to single-layer solid foils. Experimental results confirm these findings, showing improved spectral shaping and higher ion flux [4].

Nanofoams also play a key role in the generation of secondary radiation. To enable efficient neutron production, high-energy proton beams accelerated by nanofoam-based DLTs are directed onto converter materials such as beryllium or lithium fluoride. We have shown that this pitcher-catcher configuration benefits substantially from the enhanced laser-to-proton conversion efficiency provided by nanofoams [6]. Simulations and measurements show neutron fluxes exceeding 10^9 neutrons per steradian per shot, enabling applications in fast neutron imaging, radiography, and activation analysis with relatively compact laser systems [6].

Medical applications have further highlighted the utility of nanofoams, particularly in the production of positron-emitting radioisotopes for Positron Emission Tomography and theranostics like copper-64. Nanofoam-based DLTs show the potential to ensure activity yields compatible with preclinical requirements with limited laser requirements, offering a path toward on-demand isotope production in hospital or laboratory settings [7].

Another emerging application of nanofoam-based DLTs lies in the generation of high-energy photons, including hard x-rays and gamma rays. When an ultra-intense laser pulse interacts with a DLT the structured density profile enables efficient laser-target coupling and electron acceleration mechanisms that can drive multiple photon emission processes. Three-dimensional PIC simulations have shown that such configurations can support both nonlinear inverse Compton scattering and bremsstrahlung as dominant photon generation mechanisms [8, 9]. These results underscore the potential of nanofoam-based targets not only for fundamental studies of strong-field QED effects, but also for developing compact, high-brightness photon sources for applications in imaging and photonuclear experiments.

Nanofoams have been proposed as advanced ablators to optimize laser absorption and implosion uniformity in the context of direct-drive ICF. The results of hydrodynamic simulations presented in [10] suggest that carbon nanofoams integrated as ablator in a ICF capsule can yield a higher pressure peak in the laser-induced shocks. This has also been confirmed by a recent experimental result obtained at the ABC laser facility hosted by ENEA Centro Ricerche Frascati.

Lastly, nanofoams are gaining attention in alternative fusion schemes, particularly for the proton-boron (p–11B) reaction. We have carried out an experimental campaign with the TARANIS laser system (sub-ps pulse duration, I ~ 10^{19} W/cm^2) where composite nanofoams containing boron and polyethilene were tested as bright sources of alpha particles exploiting an in-target approach. In [11] we report alpha particle yields of up to 5×10^7 sr^{-1} J^{-1}. These results, supported by ad-hoc simulations, position nanofoam targets as a promising platform for studying laser-driven proton-boron fusion schemes.

In summary, the synthesis of nanofoams via PLD provides a versatile method for producing targets with controlled features. The combination of tuneable density, controlled composition and tailored morphology can be exploited to shape the interaction of high-intensity lasers with matter according to specific experimental needs, from ion acceleration and neutron production to medical isotope generation and fusion energy research.

Looking ahead, several important issues remain open. One major challenge is the industrial scalability of the PLD process: to meet the growing demand for targets, especially in high-repetition-rate laser facilities, it is essential to investigate how PLD can be adapted to large-scale, automated production without compromising the precise control over nanofoam properties that defines its current success. Moreover, numerical modeling of laser-nanofoam interaction must be extended beyond current temporal limits. Most PIC simulations focus on sub-picosecond dynamics due to computational costs and hence phenomena occurring over longer timescales, particularly relevant for pre-pulse effects in ultrashort, ultraintense laser systems, remain largely unexplored. This limits our understanding of how the nanostructure evolves before the main pulse arrives. Likewise, in the context of ICF, going beyond hydrodynamic models and incorporating nanoscale structural effects in kinetic or hybrid frameworks is crucial to assess the true potential of nanofoams as advanced ablators. Another important issue concerns the compatibility of nanofoam targets with high-repetition-rate operation. In high-intensity regimes, a single laser shot may significantly alter the surrounding nanofoam, raising concerns about target integrity and consistency over successive pulses. Investigating how such local damage propagates – or can be mitigated – is essential for designing foam-based targets that can sustain stable performance under continuous operation. Addressing all these questions is not only crucial to consolidate the current role of nanofoams for the aforementioned applications but might also unlock new research lines and ideas in the broader context of high-intensity LPI experiments.

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