Ultra intense laser interaction with nanostructured targets

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Superintense ($I > 10^{18}$ W/cm^2) laser-plasma interaction with near-critical plasmas is a topic of great interest for a wide range of applications, from laser-driven particle and radiation sources [1, 2, 3], to the exploration of astrophysically relevant scenarios [4]. In this regime the laser pulse frequency matches the plasma frequency, so that the governing physics is extremely rich and complex, which makes the topic of interest also for fundamental research.

Near-critical plasmas are plasmas with an average electron density close to the critical density $n_c(\lambda)$ that marks the threshold for λ-wavelength electromagnetic wave propagation through the plasma. In the non-relativistic limit, the critical density is given by $n_c(\lambda) = \pi m_e/(\lambda e)^2$. Taking into account relativistic effects and assuming a ponderomotive scaling [5], the critical density can be extended as $n_c^{rel}(\lambda) = (1 + a_0^2/2)^{1/2} n_c(\lambda)$. For the typical wavelengths of ultra-intense laser systems ($\lambda \sim 0.8 - 1\mu$m) the critical electron density corresponds to mass densities of few mg/cm^3, which is an intermediate value between typical gas densities and typical solid densities (i.e. typical gas-jets are well undercritical, while typical solids are well overcritical). Being in this weird range of densities, it is challenging to produce near-critical plasmas from the materials science and targetry point of view. Two possibilities would be to pre-heat a solid material or to exploit cryogenic gas-jets, but these methods do not allow for a good control of some of the plasma properties and/or require non-trivial setups. Another appealing solution is to irradiate nanostructured low-density, solid materials, such as nanotubes [6], nanowires [7] or foams [8]. In this way it is possible to produce plasmas with quite controlled properties (e.g. density gradient and composition). These materials, while being near-critical on average, are characterized by alternating voids and solid-density structures on the sub-μm scale. Due to the combined extremely fast dynamics ($\sim 10 - 1000$ fs) and high temporal contrast (up to 10^6 on the 1 ps timescale) of modern-day ultra-intense lasers, the nanostructure may survive long enough to influence the interaction. Moreover, the behavior of this kind of materials upon the irradiation by a high-intensity laser has not been investigated much in the literature.

In this contribution we present an overview of an extensive numerical investigation of laser interaction with near-critical nanostructured plasmas, via 2D and 3D Particle-In-Cell (PIC) simulations [9] carried out in [10] and [11]. We performed an extensive parametric scan in 2D geometry to assess the main features of the interaction in the presence of a nanostructure. This evaluative scan allowed us to pick the most interesting scenarios to be simulated also in 3D geometry. We considered an ultra-short duration (30 fs FWHM) laser pulse impinging at normal incidence onto a plasma slab of 100λ-thickness. For the plasma we considered idealized models in 2D and realistic nanostructured morphologies in 3D. As a reference, we took a homogeneous plasma with the same density as the nanostructured ones.

To describe the plasma nanostructure in 2D geometry we used a very simplified model: the plasma consists of a collection of solid-density nanospheres randomly arranged in space. We let both the laser intensity and the initial average electron density vary in the ranges $a_0 = 5, 15, 45, 135$ and $n_0 = 1, 3, 9n_c$. We chose the parameters so that the electron density normalized with respect to the relativistic critical density $\bar{n} = n_e/n_c^{rel}$ is constant in some specific subsets of simulations. A qualitative view of the results can be seen in figure 1a). From this investigation, we found that the theory of the relativistic similarity [12] also applies to our nanostructured plasmas. For this reason, we chose three cases with different $\bar{n}$ value to be simulated in 3D.

In 3D geometry we described the foam nanostructure using two different aggregations models: an extension of the Diffusion-Limited Cluster-Cluster Aggregation model [13] (DLCCA) and the Diffusion-Limited Aggregation model [14] (DLA). Our extension of the DLCCA model starts with a collection of spherical particles, randomly disposed into a 3D cubic mesh. These particles can move in random directions, to simulate the Brownian diffusing motion; when the spheres touch each other, they stick together to form a rigid dimer, which can undergo random motion as well. This mechanism is repeated until all the particles in the box aggregate together in a large fractal structure. This procedure is used to produce aggregates with different particle numbers, which follow an exponential distribution. Then, the aggregates are vertically deposited onto a substrate to form the foam structure. The DLA foam is obtained with a simple diffusion model on lattice that works as follows. Particles are injected into a 3D uniform lattice from random sites located on the top of the lattice itself. Then, they are allowed to randomly walk in the lattice until they are halted because either they occupy a point adjacent to a preformed cluster or they end up onto the bottom of the lattice, i.e. the substrate. Both these models can be representative of the physical process by which the foams are produce (i.e. the Pulsed Laser Deposition technique [8]); indeed, figure 1b) shows that they are able to catch the main features of real foam materials.

To assess the influence of the foam nanostructure in full 3D geometry, we compared the behavior of a homogeneous plasma with $3n_c$ density and that of a DLCCA foam plasma with $3n_c$ average density, at different laser intensities $a_0 = 5, 15, 45$. Our results show that the nanostructure has a strong influence on the interaction process. At the lowest intensity ($a_0 = 5$), the most striking effect is seen in laser energy absorption by the plasma populations, especially ions (see

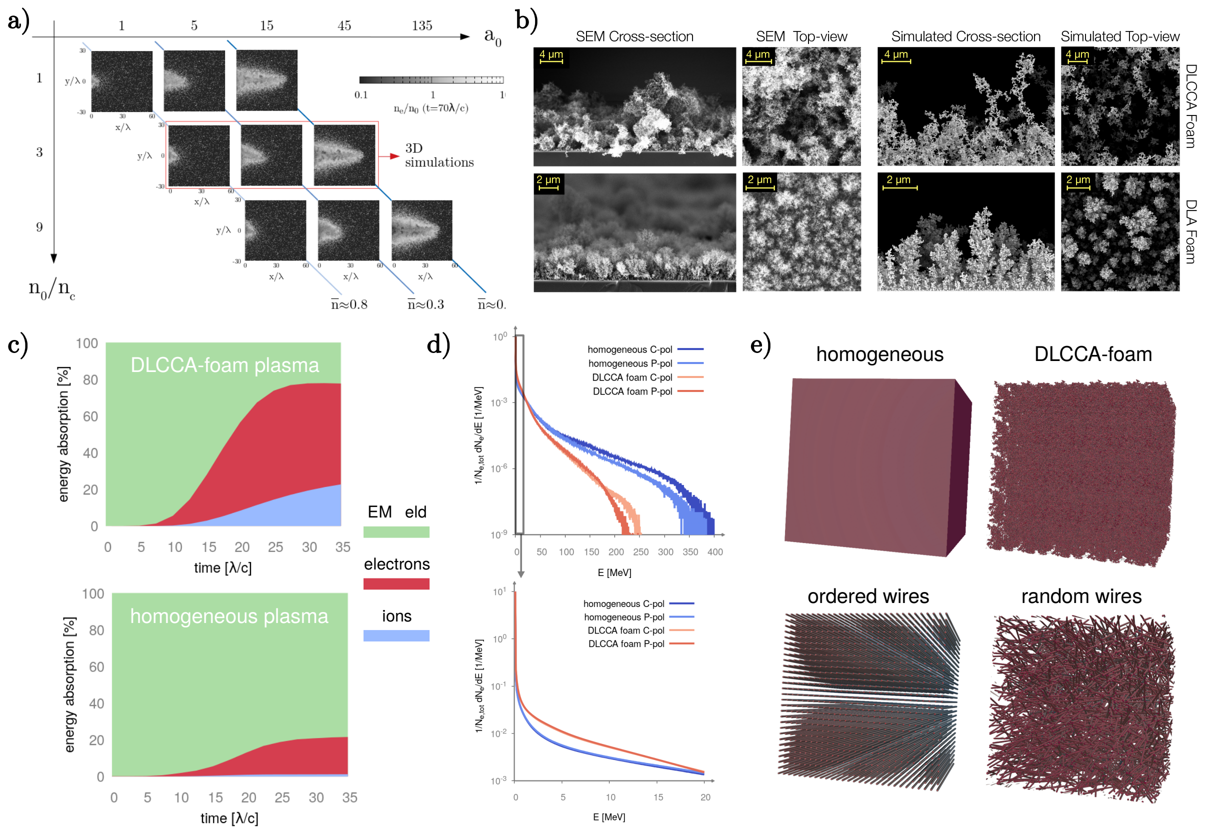

Figure 1: *a) Electron density plots of an evaluative scan in 2D geometry in the parameter space $(a_0, n_0/n_c)$. b) Comparison between two aggregation models for the nanostructure and real foam materials. c) Energy absorption and energy repartition among plasma populations in time at $a_0 = 5$ for nanostructured (top) and homogeneous (bottom) plasmas. d) Electron energy spectra at time $30\lambda/c$ for both homogeneous and nanostructured plasmas at different laser polarizations for $a_0 = 45$ $(P-pol)$ and $a_0 = 45/\sqrt{2}$ $(C-pol)$. e) Different nanostructure morphologies used in our simulation campaign.*

figure 1c)). The total absorption is enhanced by a factor of 4 and while with the homogeneous plasma the ions absorb a very small amount of energy (less than 2%), with the nanostructure they absorb more than 20% of the laser energy. This is because the ions, due to their much higher inertia if compared to electrons, gain energy from the quasi-static self-consistent fields that arise from the explosion of the nanoparticle aggregates. Of course, this does not occur with a homogeneous plasma. At the highest intensity ($a_0 = 45$), the nanostructure mostly affects electron acceleration (see figure 1d)). The highest-energy electrons are directly accelerated by the laser pulse, with and without the nanostructure: this process is less efficient with a nanostructure. This is because the self-consistent electromagnetic field that arises with a nanostructured plasma is more disordered and less clean than the one that sets up within the corresponding homogeneous plasma. On the other hand, the nanostructure allows for a more efficient acceleration of mildly energetic electrons. At the intermediate intensity ($a_0 = 15$) both effects are present, both mitigated. In all cases the nanostructure removes polarization dependence. It is worth mentioning that most of these results also appeared in the aforementioned 2D scan, even if only in a qualitative fashion.

We also investigated the effect of different nanostructure morphologies on the interaction, shown in figure 1d). We performed this study at the lowest intensity ($a_0 = 5$), so that the plasma homogenization plays a less important role. We considered realistic nanostructure morphologies: fractal-like foam aggregates (both DLCCA and DLA foams), ordered and random arrays of nanowires. All plasmas have the same average electron density ($3n_c$). All the nanostructured plasmas lead to a similar, strong laser energy absorption ($\sim 60\%$ total absorption, $\sim 20\%$ ion absorption). On the other hand, important difference arise in angular and energy distributions of both electrons and ions. While the nanowire arrays accelerate ions and electrons with a non-uniform angular distribution, foam-like plasmas lead to a higher isotropization of both populations. This is strongly related to distribution of the self-consist fields within a wire plasma.

In conclusion, our results show that it is important to include a realistic description of the nanostructure and of the morphology (if any) of the plasma to properly understand the physical mechanisms at play and to be able to perform simulations that may claim to be predictive in some way. These results could suggest possible paths to guide the design of future experiments involving near-critical plasmas. Of course, to actually support experimental works, it will be necessary to explore these physical scenarios taking into account the role of a pre-pulse (ns, ps timescale) and of the contrast of the laser.

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