Numerical simulations of laser-plasma interaction with "nanostructured targets"

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Modern-day ultra-intense laser facilities are able to provide ultra short (∼30 fs) laser pulses with a very high temporal contrast (as high as $\sim 10^{10}$) and focused intensities greater than 10^{20}W/cm^2. The short duration and the high contrast of the laser pulses might allow sub-wavelength features of the targets (i.e. a nanostructure) to survive long enough to influence the interaction process.

The study of ultra-intense laser interaction with nanostructured targets has attracted significant attention recently for various applications[1, 2, 3](e.g. grating targets have been used to study plasmonic effects at high field intensities, arrays of nanowires have been irradiated to obtain extreme plasma temperatures...). In this contribution we are particularly interested in numerical simulations of nanostructured targets with a very low average density. Recent experimental campaigns [4, 5] have shown that targets consisting in a solid foil coupled with a near-critical foam layer[6] are a promising option for laser-driven ion acceleration[7], leading to higher ion energies and a higher total number of particles with respect to simple flat foils. This effect is attributed to the very efficient laser-target coupling in the near-critical plasma[8, 9] (it is worth to stress that nanostructured low-density foams are one of the very few available options to obtain a near-critical plasma for Ti:Sapphire laser system).

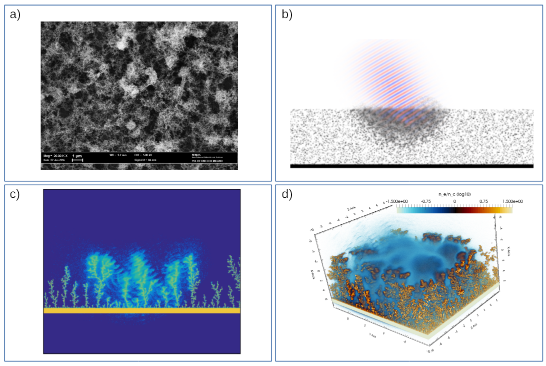

Figure 1: a) SEM picture of nanostructured low-density carbon foams b) a simple 2D model of foam targets consisting in dense random spheres, with an average density equal to $1n_c$ c) a more refined 2D model, which tries to reproduce some features of foam target (the structures are obtained aggregating spheres with DLA algorithm d) A 3D model of spheres assembled with DLA algorithm

3D numerical simulations of foam-attached targets are challenging both for the modeling of the foam structure and for the computational requirements (large simulation boxes, high spatial resolution to resolve the skin depth of a solid-density plasma and high number of particles-per-cell for the same reason). A foam target consists of nanoparticles (∼ 10nm radius) aggregated in larger structures, whose scalelength is close to the laser wavelength, thus with high contrast

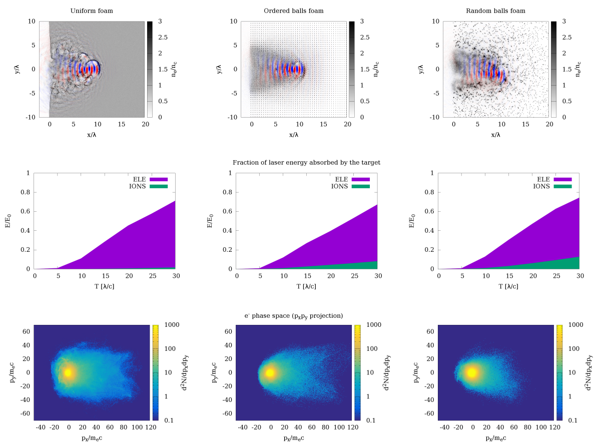

Figure 2: The first row shows a laser (P-polarized, a_0=10) propagating in a plasma with near-critical average density. Uniform plasma layer, ordered dense spheres and random spheres are used to simulate the plasma. The second row shows the conversion efficiency from laser energy to kinetic energy of the target (ions and electrons contributions are added). The third row shows the electron phase space projected onto the $p_x p_y$ plane for the three simulations.

laser systems a role played by the structure of the foam might be expected. In previous numerical simulations[8], foam targets had been modeled with a simple uniform near-critical plasma. In[4, 5] we've presented results of 3D Particle-In-Cell (PIC) simulations of laser interaction with a more realistic model of nanostructured foam targets, based on the well known Diffusion Limited Aggregation (DLA)[10] algorithm (see figure 1 for a comparison between a Scanning Electron Microscope (SEM) picture of low-density foams and a few possible numerical models). These more realistic simulations led to a better agreement with the experimental results if compared with simulations performed with uniform near-critical plasmas, highlighting also the role played by the nanostructure and suggesting possible strategies to improve the properties of the accelerated ions.

Due to the high computational cost of 3D "realistic" simulations, it is desirable to try to understand the main processes at play during laser interaction with nanostructured targets using 2D simulations. A first important point is that it is very difficult to simulate solid-density ($\sim 100 n_c$) connected structures with average near-critical density in 2D (e.g. in a λ^2 region only a $0.1\lambda \times 0.1\lambda$ square is filled with solid density plasma). Thus an initial exploration can be carried out with simplified models, like isolated nano-spheres ($r << \lambda_l$). Figure 2 shows numerical simulation results obtained with piccante code [11]. The simulations were performed with a 2D box $40\lambda \times 20\lambda$, 100 points per λ. The laser was P-polarized, with a spatial Gaussian profile, a normalized intensity $a_0 = 10$, a waist of 3λ and a FWHM temporal duration of $10\lambda/c$. The av-

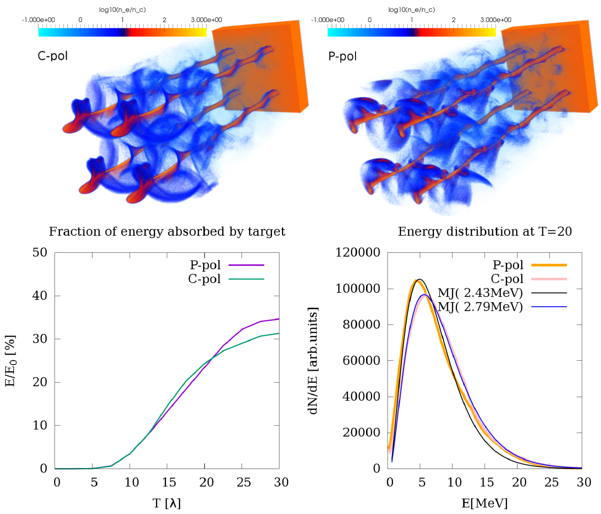

Figure 3: The first row shows two snapshots of 3D simulations showing the electron density of "wire-attached" targets during the interaction with an intense laser pulse. The two graphs show the energy absorbed by the target (kinetic energy over initial laser energy) as a function of time and the electron energy distribution for one wire.

erage density of the target was 1 n_c. For spheres targets, the radius of each ball was 0.025 λ and the density was 100 n_c. 144 particles per cell were used for electrons. In order to try to separate the effect of laser-interaction with dense, small clusters from the effect of random average density fluctuations we simulated both ordered arrays of spheres and randomly placed spheres, as well as a uniform foam for comparison. Results in figure 2 show that the density fluctuations of the random spheres plasma determine some asymmetries in the propagation of the laser pulse. Energy absorption by the target is similar, but for spheres targets a larger fraction of the laser energy is converted into kinetic energy of the ions (presumably due to the Coulomb explosion of the clusters). As far as the electron phase space is of concern, significantly less high energy electrons are observed for the random spheres plasma.

Also 3D simulations performed in reduced domains with periodic boundary conditions may provide insights on laser interaction with a nanostructure. Figure 3 shows some preliminary results of 3D simulations of simple nanostructured plasmas consisting in rectangular "nanowires" attached on a thick substrate. The average density in the region in front of the foil is 1 n_c, while the density of the plasma is $100 n_c$ (100 particles-per-cell were used). A grid of $60\lambda \times 2\lambda \times 2\lambda$ is simulated with a spatial resolution of 100 points per λ. The four wires are 5λ long and 0.1λ thick. The plane-wave laser has a FWHM duration of 15 λ/c and an intensity of $a_0 = 10$. Both C and P polarizations were simulated. The graphs in figure 3 show that a sizeable fraction of the laser energy is absorbed by the target ($\sim 30\%$), regardless of the pulse polarization (laser absorption by simple targets is known to depend strongly on pulse polarization). The energy distribution of the electrons of each wire is well described by a Maxwell-Juttner curve and very similar temperatures (15% difference) are found for the two polarizations. Qualitatively similar features (high energy absorption, little dependence on pulse polarizations) were observed in the 3D simulations reported in [5, 4].

In conclusion, simplified models of nanostructured plasmas may provide a useful tool to investigate ultra-intense laser interaction with nanostructured plasmas, allowing to understand the physical processes at play in these complex physical scenarios.

References

[1] K. Ostrikov, F. Beg, and A. Ng. *Colloquium* : Nanoplasmas generated by intense radiation. *Rev. Mod. Phys.*, 88:011001, Jan 2016.

[2] L. Fedeli, A. Sgattoni, G. Cantono, D. Garzella, F. Réau, I. Prencipe, M. Passoni, M. Raynaud, M. Květoň, J. Proska, A. Macchi, and T. Ceccotti. Electron acceleration by relativistic surface plasmons in laser-grating interaction. *Phys. Rev. Lett.*, 116:015001, Jan 2016.

[3] A.P. Michael, V. N. Shlyaptsev, R. Hollinger, C. Bargsten, A. Pukhov, A. Prieto, Y. Wang, B. M Luther, L. Yin, S. Wang, et al. Relativistic plasma nanophotonics for ultrahigh energy density physics. *Nature Photonics*, 7(10):796–800, 2013.

[4] I. Prencipe, A. Sgattoni, D. Dellasega, L. Fedeli, L. Cialfi, Il Woo Choi, I Jong Kim, K.A. Janulewicz, K. F. Kakolee, Hwang Woon Lee, Jae Hee Sung, Seong Ku Lee, Chang Hee Nam, and M. Passoni. Development of foam-based layered targets for laser-driven ion beam production. *Plasma Physics and Controlled Fusion*, 58(3):034019, 2016.

[5] M. Passoni, A. Sgattoni, I. Prencipe, L. Fedeli, D. Dellasega, L. Cialfi, Il Woo Choi, I Jong Kim, K. A. Janulewicz, Hwang Woon Lee, Jae Hee Sung, Seong Ku Lee, and Chang Hee Nam. Toward high-energy laser-driven ion beams: Nanostructured double-layer targets. *Phys. Rev. Accel. Beams*, 19:061301, Jun 2016.

[6] A. Zani, D. Dellasega, V. Russo, and M. Passoni. Ultra-low density carbon foams produced by pulsed laser deposition. *Carbon*, 56:358 – 365, 2013.

[7] A. Macchi, M. Borghesi, and M. Passoni. Ion acceleration by superintense laser-plasma interaction. *Rev. Mod. Phys.*, 85:751–793, May 2013.

[8] A. Sgattoni, P. Londrillo, A. Macchi, and M. Passoni. Laser ion acceleration using a solid target coupled with a low-density layer. *Phys. Rev. E*, 85:036405, Mar 2012.

[9] M. Passoni, A. Zani, A. Sgattoni, D. Dellasega, A Macchi, I Prencipe, V Floquet, P Martin, T V Liseykina, and T Ceccotti. Energetic ions at moderate laser intensities using foam-based multi-layered targets. *Plasma Physics and Controlled Fusion*, 56(4):045001, 2014.

[10] T. A. Witten and L. M. Sander. Diffusion-limited aggregation, a kinetic critical phenomenon. *Phys. Rev. Lett.*, 47:1400–1403, Nov 1981.

[11] A. Sgattoni, L. Fedeli, S. Sinigardi, A. Marocchino, A. Macchi, V. Weinberg, and A. Karmakar. Optimising piccante–an open source particle-in-cell code for advanced simulations on tier-0 systems. *PRACE white paper (arXiv preprint arXiv:1503.02464)*, 2015.