IL NUOVO CIMENTO Vol. 32 C, N. 2 Marzo-Aprile 2009
DOI 10.1393/ncc/i2009-10380-1

Colloquia: CSFI 2008

Highlights from particle-in-cell simulations of superintense laser-plasma interactions

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(ricevuto il 22 Giugno 2009; pubblicato online l'1 Settembre 2009)

Summary. — A selection of results from particle-in-cell simulation of laser-plasma interactions in two and three spatial dimensions are presented. The generation of coherent, long-living electromagnetic structures and the 3D dynamics of self-channeling have been studied in low-density plasmas. The acceleration of ions driven by radiation pressure in high-density, thin targets is also investigated.

PACS `41.75.Jv` – Laser-driven acceleration.
PACS `52.38.Fz` – Laser-induced magnetic fields in plasmas.
PACS `52.38.Hb` – Self-focussing, channeling, and filamentation in plasmas.

1. – Introduction

As the trend towards higher intensity laser sources proceeds with the proposal of novel infrastructures such as the ELI and HiPER European projects, laser-plasma interaction opens up novel possibilities for both basic physics and applications. Numerical simulations are required to support the interpretation of present experiments and the modeling or design of future ones. To this aim the particle-in-cell (PIC) method, providing a solution of the Maxwell-Vlasov system, has been the most used approach so far. The use of supercomputing power is also essential due to the highly nonlinear and multidimensional nature of the involved phenomena as well as to approach the "realistic" spatial and temporal scales of experiments.

In this paper we show highlights from two simulation campaigns performed at the CINECA facility in Bologna (Italy). The first series of simulations in two (2D) and three spatial dimensions (3D) considered the interaction with underdense (optically transparent) plasmas addressing the generation of "coherent", long-living electromagnetic structures such as vortices and cavitons, resembling experimental observations based on the Proton Imaging technique. The 3D dynamics of the self-channeling of the laser pulse

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was also investigated. The second series of simulations for overdense (optically reflecting) plasmas addressed the 3D regime of Radiation Pressure Acceleration of high-density thin targets, relevant to the generation of high-energy ions for applications.

2. – Underdense plasmas: self-channeling and coherent structures

The simulations of the interaction of a relatively "long" (1.0 ps) laser pulse of $\sim 10^{19}\,\mathrm{W\,cm^{-2}}$ intensity with a low-density plasma (up to $n_e \simeq 10^{19}\,\mathrm{cm^{-3}}$) were motivated by experimental investigations based on the recently developed Proton Imaging (PI) technique [1]. Details on the set-up of both the experiment and the related simulations are reported in ref. [2] where the first stage of the interaction is analyzed. PI employs a proton beam as a probe to detect slowly varying electric and magnetic fields in the plasma with spatial resolution of a few microns and temporal resolution of a few picoseconds, depending on the probe beam energy and the dimension of the field structures. These characteristics make PI a unique tool to investigate the laser-plasma dynamics. The latter is characterized by strongly nonlinear effects which may occur on the timescale of a laser period (a few femtoseconds) generating field structures which may survive for much longer times (several picoseconds); examples of particular interest are "coherent" structures such as magnetized vortices or electromagnetic solitons [3]. Hence, in this context the challenge of PIC simulations is to simulate the short-pulse interaction and the later evolution of the plasma up to times accessible to the PI measurements, to trace the observed features back to the physical phenomena which generated them.

The choice to simulate a plasma size and pulse duration quite close to the experimental ones and up to times accessible to the PI diagnostic forced the reduction to a 2D geometry for most of the runs. A typical 2D simulation employed a 6500×1200 grid with a spatial resolution of $\lambda/10$ (where $\lambda = 1\,\mu\mathrm{m}$ is the laser wavelength) and 16 particles per cell ($\sim 2 \times 10^8$ in total), and ran for $\sim$ 13500 timesteps requiring $\sim$ 24 CPU hours on 50 processors. In the simulation the laser propagates along x in the (x, y)-plane and it is linearly polarized in the z-direction. Figure 1 shows a snapshot of the electric-field component E_z and the ion density n_i in the central region of the simulation box at a time $t = 4.5\,\mathrm{ps}$ from the start of the run. The main channel drilled by the laser pulse as well as secondary channels and local density depressions, either as a repeated modulation or solitary cavities, are apparent.

Figures 1 b and c show two details of B_z, in two different regions, at $t = 3.3\,\mathrm{ps}$. The field B_z is characterized by a dipole vortex topology, appearing either as a row pattern (figs. 1 b) or as an isolated structure (c). In correspondence with each vortex, a density depression (cavity) is observed together with a radial electric field. Their origin and dynamics may be explained by the effect of the internal magnetic pressure of the vortex. However, the frequency-resolved analysis of the fields reveals also an oscillating electromagnetic component corresponding to radiation "trapped" inside the cavity, so that some magnetic structures appear to have a "hybrid" nature sharing features of both magnetized vortices and electromagnetic "cavitons" [4].

The 3D topology of the observed structures is a complex issue. Since magnetic field lines form closed loops in real space, it is natural to infer that the magnetic structures in 3D will appear as "vortex rings" with a toroidal geometry. Presently these structures have been not clearly observed yet in 3D simulations, which however had to be performed on quite shorter scales for computational reasons. We show preliminary results for a 3D run with a box corresponding to a $400\lambda \times 40\lambda \times 40\lambda$ region. The pulse width and duration were approximately half the values used in 2D. A $3200 \times 320 \times 320$ grid and 8 particles

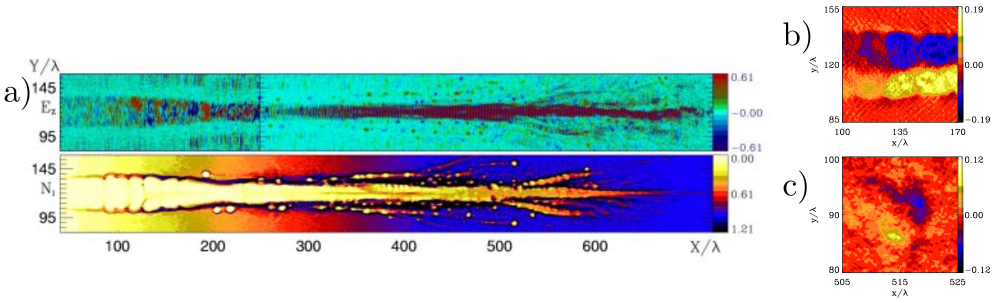

Fig. 1. – (Colour on-line) 2D PIC simulations of laser interaction with an underdense plasma. a) Contours of the electric field of the laser pulse E_z and the ion density n_i at $t = 3.3\,\text{ps}$. The field and density are normalized to $E_0 = 3.2 \times 10^{10}\,\text{V}\,\text{cm}^{-1}$ and $n_0 = 0.1 n_c = 1.1 \times 10^{20}\,\text{cm}^{-3}$, respectively. The contour levels of E_z in the $50 < x < 250$ region have been rescaled by a factor of 3 to show the presence of field structures with relatively low amplitudes. b) and c) Details of the quasi-static magnetic field B_z, normalized to $B_0 = 1.1 \times 10^8\,\text{G}$, in two regions corresponding to the main channel (b) and a secondary filament (c).

per cell were used. The anisotropy of the solid self-channeling process was observed indeed, as shown in fig. 2. The channel drilled by the laser pulse is elongated along the direction of polarization. In the higher density region, beam breakup and a tendency to form small cavities is still observed; the density pattern is almost axially symmetrical in the plane perpendicular to the polarization, while an evident asymmetry is observed in the polarization plane.

3. – Overdense plasmas: ion acceleration with circularly polarized pulses

The acceleration of solid, ultrathin targets by the radiation pressure of a superintense pulse has been proposed as scheme for the acceleration of large number of ions up to relativistic energies. Previous theoretical work has shown that the use of circularly polarized (CP) pulses leads to more efficient acceleration as it quenches electron heating [5-8]. A CP pulse carries a net angular momentum, whose conservation gives an additional constraint on the interaction in 3D geometry. This issue gave a strong motiva-

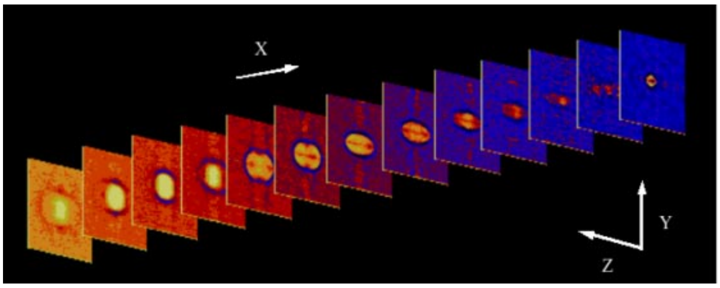

Fig. 2. – (Colour on-line) Anisotropic self-channeling observed in 3D simulations. Slices plots of the electron density are shown between $x = 110\,\mu\text{m}$ and $x = 370\,\mu\text{m}$ at $t = 1.65\,\text{ps}$ after the simulation start. Each slide is $40\,\mu\text{m} \times 40\,\mu\text{m}$ wide.

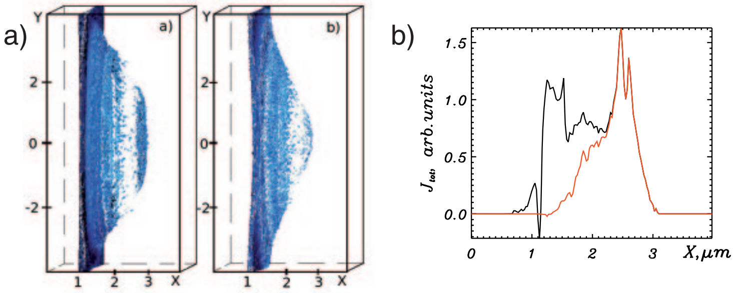

Fig. 3. – (Colour online) 3D simulations of radiation pressure acceleration of a thin foil target by a CP pulse. a) The ion density n_i at $t = 130\,\mathrm{fs}$ for "flat-top" (left) and Gaussian (right) radial intensity profiles. The acceleration is more efficient in the flat-top case. b) The azimuthal ion current $J_{i,\varphi}$ averaged over the transverse plane (y, z) *versus* x, showing the angular-momentum absorption into ions (black and red lines correspond to an average over a circle with radius $r = 4.5\lambda$ and 2.5λ, respectively, around the x-axis).

tion for model studies of this regime in 3D [9]. The choice of the parameters arised from a necessary compromise between physical realism and computational feasibility; in particular, the experience based on 1D and 2D runs [5] showed the need of a proper resolution to resolve very short scales. A typical simulation considered a $0.3\,\mu\mathrm{m}$ thick, $1.8 \times 10^{22}\,\mathrm{cm}^{-3}$ dense plasma and a $3.4 \times 10^{19}\,\mathrm{W\,cm}^{-2}$, 50 fs laser pulse; a $320 \times 1050 \times 1050$ grid with cell size $\lambda/80$ and 27 particles per cell ($\sim 1.5 \times 10^9$ in total) were used.

Selected results are shown in fig. 3. A few per cent of the angular momentum of the pulse is absorbed by the electrons and, ultimately, by the ions. This is a signature that non-adiabatic processes play a role in the conversion of the laser pulse energy into kinetic energy of the plasma, because adiabatic processes conserving the total number of photons would yield no absorption of angular momentum. A net azimuthal ion current (fig. 3 b) and small-scale magnetic structures (not shown) at the edge of the laser spot are generated. It was also found that "flat-top" radial intensity profiles are needed for efficient acceleration because for Gaussian pulses a thin target may become transparent during the interaction due to the lateral pushing by the radiation pressure.

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The simulations were performed at CINECA sponsored by the CNR/INFM supercomputing initiative.

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