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Ion dynamics and coherent structure formation following laser pulse self-channeling

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Abstract

The propagation of a superintense laser pulse in an underdense, inhomogeneous plasma has been studied numerically by two-dimensional particle-in-cell simulations on a time scale extending up to several picoseconds. The effects of the ion dynamics following the charge-displacement self-channeling of the laser pulse have been addressed. Radial ion acceleration leads to the ‘breaking’ of the plasma channel walls, causing an inversion of the radial space-charge field and the filamentation of the laser pulse. At later times a number of long-lived, quasi-periodic field structures are observed and their dynamics is characterized with high resolution. Inside the plasma channel, a pattern of electric and magnetic fields resembling both soliton- and vortex-like structures is observed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The propagation of superintense laser pulses through low-density plasmas gives rise to a variety of nonlinear electromagnetic phenomena [1, 2]. As a general issue the response of the plasma is nonlinear due to both relativistic effects (hence the definition of ‘relativistic optics’ [3]) and the intense ponderomotive force (i.e. the radiation pressure), which strongly modifies the local plasma density. Probably, the example of such dynamics which has been mostly investigated is the self-focusing, channeling and filamentation of the laser pulse [4–10]. Another prominent effect is the generation of coherent structures such as electromagnetic solitons or vortices. Numerical simulations (see e.g. [11–13]) show that such structures are generated during the interaction with the laser pulse on an ultrafast (femtosecond) time scale, but they may lead to typical field structures which last for much longer times (e.g. ‘post-solitons’) [12], i.e. in the picosecond range, allowing for their experimental observation [14]. On such a scale

the temporal evolution of such field structures must be studied including the effects of the motion of the plasma ions. Stability and evolution of coherent structures on the ion time scale has been studied theoretically and numerically in several papers, for various regimes and dimensionalities [11–13, 15–20].

In this paper we report a theoretical study of nonlinear effects during and after the propagation of a superintense laser pulse in an underdense, longitudinally inhomogeneous plasma. The work was motivated by experiments on laser propagation in a low-density plasma where the dynamics of self-generated, slowly varying electromagnetic fields was investigated using the proton diagnostic technique [21]. In this paper we focus on the simulation results and on their theoretical interpretation, while a comparison with the experimental results will be reported elsewhere [22, 23].

2. Simulation set-up

The laser–plasma interaction simulations were performed using a particle-in-cell (PIC) code in 2D with Cartesian geometry. Reduction to 2D was dictated by the need to address relatively long spatial and temporal scales, close to the experimental ones. Moreover (as will be clear from the discussion of the results) during the interaction sharp gradients in the field and current patterns are generated. Thus, a reasonable resolution is mandatory to resolve such details, pushing the memory requirements in 3D much beyond present-day supercomputing capabilities. Among the set of 2D simulations that were performed for this study, the largest ones employed a 7750×2400 grid, with spatial resolution $\Delta x = \Delta y = \lambda/10$ (where λ is the laser pulse wavelength) and 16 particles per cell for both electrons and ions, requiring a total of 5000 CPU hours on 100 processors to simulate more than 1500 laser periods of the interaction. The code is fully parallelized and the simulations were performed at the CINECA supercomputing facility in Bologna (Italy).

In the following, lengths are given in units of λ , times in units of $T_L = \lambda/c = 2\pi/\omega$, electric and magnetic fields in units of $E_0 = m_e \omega c/e$, and densities in units of $n_c = m_e \omega^2/4\pi e^2$. For $\lambda = 1 \mu\text{m}$, $E_0 = 3.213 \times 10^{10} \text{ V cm}^{-1} = 107.1 \text{ MG}$ and $n_c = 1.11 \times 10^{21} \text{ cm}^{-3}$. The dimensionless parameter a_L , giving the peak field amplitude of the laser pulse normalized to E_0 , is related to the laser intensity I and the wavelength by $a_L = 0.85(I\lambda^2/10^{18} \text{ W cm}^{-2} \mu\text{m}^2)^{1/2}$.

In all the 2D simulations reported below, the plasma is inhomogeneous along the x axis, i.e. in the direction of propagation of the laser pulse. The electron density profile rises linearly from zero value at $x = 25\lambda$ to the peak value $n_0 = 0.1n_c$ at $x = 425\lambda$, and then remains uniform. The pulse duration τ_L was either 150 or 300 T_L , corresponding to 0.5 and 1 ps, respectively, for $\lambda = 1 \mu\text{m}$.

The laser pulse was S -polarized, i.e. the electric field of the laser pulse was in the z direction perpendicular to the simulation plane. In the following we restrict the discussion to the S -polarization case which has some advantages for the data analysis and visualization (for instance, the space-charge field generated in the radial (y) direction during self-channeling is separated by the electromagnetic field E_z , which is representative of the pulse evolution). It is known, however, that at high intensity the details of nonlinear effects in pulse propagation depend on the polarization leading to differences between the S - and P -polarization cases in 2D geometry and to asymmetry effects in 3D for what concerns self-focusing [24] and also to differences in the type and stability of solitons and vortices [2, 3] and references therein]. A preliminary simulation performed for P -polarization showed slight, but no substantial differences for what concerns the early self-channeling evolution which we discuss in section 3.1. The discussion of the effect of different polarizations on the coherent structures generation and evolution is more involved and will be addressed in future work.

Figure 1. Contours of the electric field of the laser pulse E_z and the ion density n_i from a 2D PIC simulation, at $t = 1000T_L$, showing the self-channeling and filamentation of the laser pulse and the generation of isolated solitary structures and of field patterns. The laser pulse propagates from the left to the right. In the E_z frame, the contour levels in the leftmost region ($50 < x < 250$) has been rescaled by a factor of 3 to show the presence of field structures with relatively low amplitudes. The laser pulse parameters are $a_L = 2.7$, $r_L = 8\lambda$ and $\tau_L = 300T_L$.

3. Results

To illustrate the variety of nonlinear effects observed in the simulation results, figure 1 shows snapshots at $t = 10^3 T_L$ of the ion density (n_i) and the electric field of the laser pulse (E_z) over nearly the whole length of the plasma, for a simulation with $a_L = 2.7$ and $\tau_L = 300T_L$. Figure 1 contains most of the prominent features we observed throughout the set of our simulations, which may be summarized as follows.

In the low-density region, the laser pulse bores a single charge-displacement channel, which in the higher density region breaks up into three main channels and a few secondary, narrow filaments. In the following (see section 3.1) we trace back the appearance of the ‘trifurcated’ channel to the effects of radial ion acceleration, which lead to the ‘breaking’ of the channel walls.

Different types of electromagnetic structures are observed in regions of different density. In the lower density region (approximately between $x = 100$ and $x = 150$ in figure 1) a pattern of fields with approximate axial symmetry is observed. A detailed analysis of the electric and magnetic fields, including an estimate of their characteristic frequency from the simulation (see section 3.4), shows that this type of structures combines both features of low-frequency electromagnetic post-solitons or ‘cavitons’ and steady current vortices. In the higher density region a number of slowly evolving field structures, either appearing as ‘solitary’ structures or organized into patterns, are observed both outside the main low-density channels and inside the latter. There is some experimental indication of the growth of regularly spaced field structures into the main channel [23].

3.1. Ion and electric field dynamics following self-channeling

For intensities up to $a_L \simeq 2$, in the early stage of the interaction the laser pulse bores a regular charge-displacement channel in the inhomogeneous region of the plasma, i.e. at densities $n_e < 0.1n_c$. This is the case for the simulation of figure 2 ($a_L = 2$, $\tau_L = 300T_L$, transverse width $r_L = 4\lambda$), which shows a snapshot of the ion density n_i and the electric field components E_z and E_y (results from this simulation are also reported in [22]). The laser pulse undergoes self-focusing as indicated both by the reduction of its transverse radius to $\simeq 3\lambda$ and by the increase in its amplitude by a factor $\simeq 1.2$.

In the leading edge of the channel the transverse field E_y is in the outward direction from the axis, indicating that the channel is positively charged due to the radial expulsion of electrons. In the trailing part of the pulse, the radial profile of E_y changes qualitatively, as two ambipolar fronts appear on each side of the channel. On the inner side of the ambipolar fronts

Figure 2. Simulation results addressing electric field dynamics following self-channeling, showing the transition in the radial field profile [22]. Left column: 2D PIC results. Top frame: ion density (n_i) and electric field components (E_z and E_y) at $t = 600T_L$. Bottom frame: lineout of E_y (blue) and n_i (red) along the y -axis at two different x -positions. Parameters are $a_L = 2$, $\tau_L = 300T_L$, $r_L = 4\lambda$. Right column: snapshots at various times of radial electric field E_r (blue, thick line) and ion density n_i (red, dashed-dotted line), and the phase space distributions of ions $f_i(r, p_r)$ and electrons $f_e(r, p_r)$ from 1D simulations using a ponderomotive, electrostatic model [25]. Parameters are $a_L = 2.7$, $n_e/n_c = 0.01$, $r_L = 7.5\lambda$, $\tau_L = 300T_L$.

E_y now points in the inward direction, i.e. towards the axis. The onset of an ‘inversion’ in the radial field has been noticed in experimental investigations of channel dynamics [22].

3.2. One-dimensional modeling and the electric field ‘echo’

The dynamics leading to the evolution of the radial electric field can be studied in detail using a one-dimensional, electrostatic PIC model where the laser pulse action is taken into account only via the ponderomotive force. The model assumes a non evolving radial profile of the laser pulse and cylindrical symmetry taking only the radial, cycle-averaged dynamics of electron and ions into account. Details about the model and its results are reported elsewhere [25]. Here we focus on the most prominent features of electric field dynamics.

Figure 2 shows snapshots of the radial electric field E_r and the ion density n_i at various times, for a 1D simulation in the same regime of 2D electromagnetic runs. Initially, the ponderomotive force F_p pushes electrons away from the axis, creating a back-holding space-charge field which is found to balance F_p almost exactly. At the end of the pulse, when $F_p = 0$, E_r has almost vanished. However, E_r appears back at a later time, with an ambipolar profile very similar to that observed in the 2D simulations. This ‘echo’ effect originates from the ion dynamics of ions which are accelerated by the electric force $ZeE_r = ZF_p$ during the laser pulse. The spatial profile of F_p is such that the ions are focused towards a very narrow region at the edge of the channel, producing a very sharp spike of the ion density and leading to hydrodynamical breaking as the fastest ions overturn the slowest ones. Looking at the profile of the ion density we observe that the latter may be said to ‘break’ in literal meaning, as a secondary density spike moving outwards is formed. The process is also accompanied by strong heating of electrons near the breaking point, leading to the appearance of an ambipolar sheath field around the density spike. The negative field is strong enough to slow down and invert the velocity of the slowest ions, which are directed back to the axis where they are found to form a local density maximum at later times.

3.3. Laser beam breakup

A simple analytical model shows that the time required for the ions in the channel to reach the ‘breaking’ point is proportional to the channel radius and inversely proportional to the

Figure 3. Evolution of the laser field E_z at different times showing the breakup of the laser pulse into three main beams. The two secondary beams propagating in the oblique direction originate from near the location of the ‘breaking’ of the channel walls. The laser pulse parameters are $a_L = 2.7$, $r_L = 8\lambda$ and $\tau_L = 150T_L$.

laser field amplitude [25]. For high intensities, the ‘breaking’ effect due to ion acceleration may occur early during the laser pulse, i.e. when the electromagnetic energy density inside the channel is very high, and cause a fast, strong variation of the density at the edge of the channel. In turn, this may affect the propagation of the laser pulse, similarly to what would happen in a wave guide where a sudden ‘leak’ in its walls occurs. A possible signature of this effect is the appearance of two secondary beams, propagating in the oblique direction, and originating near the point where the breaking of the channel walls occurs, as can be observed in figure 3.

From the ‘leaking waveguide’ picture we roughly estimate these secondary beams to propagate at an angle θ with respect to the axis given by $\tan \theta \simeq k_y/k_x$, where $k_y \simeq \pi/d$ is the transverse wavevector of the guided mode, d is the local channel diameter and $k_x \simeq \sqrt{\omega^2/c^2 - k_y^2}$. In this estimate the pulse in the channel is modeled as a TE mode of lowest order in a square guide. From the simulation result we get $\tan \theta \simeq 0.065$, while with $d \simeq 7\lambda$ we obtain $k_y/k_x \simeq (\pi/7\lambda)/(2\pi/\lambda) = 0.071$.

3.4. Slowly varying electromagnetic structures

As already noted in figure 1 an impressive number of localized, slowly varying structures are generated in the interaction. In the denser plasma region, the several small-scale structures whose most evident signature is a strong depression in the plasma density are likely to be rather similar to the so-called post-solitons [12, 14] having zero propagation velocity and slowly expanding due to ion acceleration driven by the internal radiation pressure. They may be described as small cavities trapping electromagnetic radiation whose frequency is less than the plasma frequency of the surrounding plasma (hence they may be also appropriately named as ‘electromagnetic cavitons’). We notice that we do not observe a drift of such structures towards the low-density region. This difference from the observations of [11] might be ascribed to the smoother electron gradient in our case.

The regular structures, forming an axially symmetrical row, observed in the low-density region near the plasma boundary (far left side in figure 1) have indeed features which are similar to both electromagnetic cavitons and magnetic vortices. This ‘dual’ nature can be observed in figure 4, which shows the components of the fields E_z and B_z perpendicular to the simulation plane as a contour plot and the components in the (x, y) plane as a vector plot. By analyzing the frequency spectrum of the fields inside the density depression, we find that the fields E_z , B_x and B_y are oscillating at a frequency of approximately 0.1ω , lower than the local value

Figure 4. (Anti-)symmetrical row of slowly varying structures in the low-density region of the plasma at $t = 625T_L$. The left column shows the fields E_z (contour plot) and $B_x + B_y$ (vector plot) oscillating at a frequency $\simeq 0.1\omega$. The right column shows the quasi-static fields B_z (contour plot) and $E_x + E_y$ (vector plot). The laser pulse parameters are $a_L = 2.7$, $r_L = 8\lambda$ and $\tau_L = 150T_L$.

of the plasma frequency (for unperturbed plasma) $\omega_p \simeq 0.15\omega$. Qualitatively, the oscillating fields are similar to those of the lowest TM resonant mode in a cylindrical cavity.

The frequency analysis of E_x , E_y and B_z shows that these field components are quasi-static, their spectrum being peaked around zero frequency. The electric field components E_x and E_y are in the radial direction with respect to the axis of the structure, as it is expected for a cavity expanding under the action of the radiation pressure of the trapped radiation. The static magnetic field component B_z is associated with current rings flowing around the axis of the structure.

Apart from being associated with ‘post-soliton’-like structures, the fact that the magnetic vortices form a symmetrical row and are localized near the boundary of the channel makes them different from those observed in the wake of a much shorter laser pulse, for which the creation of a low-density channel does not occur, and which seem to form an antisymmetrical row [1, 26]. It is nevertheless possible that the current filamentation instability discussed in [26] plays a role in vortex formation also in the present case. In the early stage we observe a strong electron current in the main channel and two narrow return current sheets just outside the channel boundaries; later, the current layers seem to bend locally forming vortices around magnetic field maxima.

The axial symmetry of these particular structures suggests that in ‘realistic’ 3D geometry they may have a toroidal or ‘donut’ shape. To get an impression of such a 3D structure one should imagine the field patterns of the 2D simulations rotating around the x -axis. This particular type of coherent structure would be characterized by azimuthal components of $\mathbf{E}$ (oscillating) and $\mathbf{B}$ (quasi-static) directed along the torus circumference, a solenoidal and oscillating magnetic field coiled up round the torus and by an electrostatic field component perpendicular to the torus surface. The 3D soliton discussed in [13] has a toroidal magnetic field and a poloidal magnetic field; however, in our case we have no clear indication of the charge oscillations inside the solitons observed in [13].

Inside the main and secondary low-density channels generated in the denser region of the plasma, the growth of field patterns which are less regular than those of figure 4, but

Figure 5. Details of the evolution of field structures in the denser region of the plasma, from the simulation of figure 1. The laser pulse parameters are $a_L = 2.7$, $r_L = 8\lambda$ and $\tau_L = 300T_L$.

qualitatively similar, can be observed. Figure 5 gives details of their evolution. We observe a tendency of this type of structures to grow inside the channels and to be correlated with rippling and bending of the channel walls. Theoretical work will be required to address the physics of formation of such structure patterns.

4. Conclusions

The main results emerging from the series of 2D PIC simulations reported in this paper may be summarized as follows. Ion acceleration due to the space-charge field in the channel drilled by the laser pulse leads to hydrodynamical breaking of the plasma profile at the channel walls. Two side effects of the ion-driven ‘breaking’ have been identified: a change in the radial profile of the electrostatic field (including a sort of ‘echo’ effect for pulses shorter than the breaking time) and a breakup of ‘long’ laser pulses due to the sudden ‘leak’ generated in the channel walls. The evolution of coherent, slowly varying field structures has been monitored in time up to thousands of laser cycles, corresponding to several picoseconds in ‘real’ experiments. Patterns of multi-peak structures appear inside low-density channels, and the formation of structures having both oscillating and static field components with a hybrid soliton-vortex nature has been observed. These results, and the perspective of experimental investigations of such field patterns, support the view of relativistic ‘laser plasmas’ as environments showing a high degree of self-organization and a wealth of coherent structures, which are thus of great interest for the physics of nonlinear systems.

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