Non-linear Behaviours in Ablation Plasma via Non-Differentiability

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Assuming that the plasma ablation particles move on continue but non-differentiable curve, some non-linear effects in the dissipative approximation of motions are analysed. Thus, through numerical simulations using the fractal hydrodynamic model, both the splitting of a plasma plume, and a multi-peak structure of the current density result. The theoretical model was validated by experimental data.

1. Introduction

Laser ablation involves complex phenomena, from the interaction of laser radiation with the solid target [1], to laser beam absorption in the ablation plume [2], to hydrodynamics and electrical processes in the generated transient plasma, etc [3 - 6].

The theoretical models that describe these global dynamics are sophisticated and ambiguous [3, 4, 6, 7]. However the situation can be standardized taking into account that the elementary processes induced by laser-matter interaction impose various temporal resolution scales, and the pattern evolution imposes different degrees of freedom e.g.: from one, at the initial stages, to three at the final stages of the patterns induced by the laser-produced plasma [8, 9].

In order to develop new physical models we must admit that the plasma ablation implies both chaotic behaviors and self-similarity at all possible space-time scales. Then, for temporal scales that are large with respect to the inverse of the highest Lyapunov exponent, the deterministic trajectories are replaced by a collection of potential trajectories and the concept of definite positions by that of probability density. All of these imply the functionality of the Scale Relativity Theory (SRT) in the study of ablation plasma dynamics [10, 11].

In the present paper, using the hydrodynamic version of SRT, which we will refer to from now on as the fractal hydrodynamic model [12, 13], some non – linear effects in ablation plasma dynamics are obtained by numerical simulations. The theoretical results are compared with the experimental data.

2. Theoretical model

In the following, using the fractal hydrodynamic equations in an axial symmetry (the *z*-axis coincides with the laser beam axis and is directed along the outer normal to the target surface), we analyse the dynamics of the plasma plume, assuming that this can be assimilated with a isentropic fluid type [14]. The presence of an external perturbation is specified only by adequate initial and boundary conditions (e.g. spatio-temporal Gaussian). In this situation, let us introduce the normalized coordinates

$$\omega t = \tau\,,\ kr = \xi\,,\ kz = \eta\,,$$
$$\frac{V_{Dr}k}{\omega} = V_\xi\,,\ \frac{V_{Dz}k}{\omega} = V_\eta\,,\ \frac{n}{n_0} = N \qquad \text{(1a-f)}$$

and by admitting the adiabatic expansion, the states density and the specific momentum conservation laws become [12, 13]:

$$\frac{\partial N}{\partial \tau} + \frac{1}{\xi}\frac{\partial}{\partial \xi}\left(\xi N V_\xi\right) + \frac{\partial}{\partial \eta}\left(N V_\eta\right) = 0$$
$$\frac{\partial}{\partial \tau}\left(N V_\xi\right) + \frac{1}{\xi}\frac{\partial}{\partial \xi}\left(\xi N V_\xi^2\right) +$$
$$+\frac{\partial}{\partial \eta}\left(N V_\xi V_\eta\right) = -N^{\gamma-1}\frac{\partial N}{\partial \xi} \qquad \text{(2a-c)}$$
$$\frac{\partial}{\partial \tau}\left(N V_\eta\right) + \frac{1}{\xi}\frac{\partial}{\partial \xi}\left(\xi N V_\xi V_\eta\right) +$$
$$+\frac{\partial}{\partial \eta}\left(N V_\eta^2\right) = -N^{\gamma-1}\frac{\partial N}{\partial \eta}$$

For numerical integration we shall impose the initial conditions:

$$V_\xi\left(0,\xi,\eta\right) = 0$$
$$V_\eta\left(0,\xi,\eta\right) = 0$$
$$N\left(0,\xi,\eta\right) = \frac{1}{5}\,;\ 1 \le \xi \le 2\,; \qquad \text{(3a-e)}$$
$$0 \le \eta \le 1$$

and the boundary ones:

$$V_\xi\left(\tau,1,\eta\right) = 0\,,\ V_\xi\left(\tau,2,\eta\right) = 0\,,$$

$$V_\eta(\tau,1,\eta)=0,\ V_\eta(\tau,2,\eta)=0,$$
$$N(\tau,1,\eta)=\frac{1}{5},\ N(\tau,2,\eta)=\frac{1}{5},$$
$$V_\xi(\tau,\xi,0)=0,\ V_\xi(\tau,\xi,1)=0,$$
$$V_\eta(\tau,\xi,0)=0,\ V_\eta(\tau,\xi,1)=0, \quad \text{(4a-l)}$$
$$N(\tau,\xi,0)=\frac{1}{10\mu}\exp\left[-\left(\frac{\tau-\frac{1}{5}}{\frac{1}{5}}\right)^2\right]\cdot$$
$$\cdot\exp\left[-\left(\frac{\xi-\frac{3}{2}}{\mu}\right)^2\right]$$
$$N(\tau,\xi,1)=\frac{1}{5}$$

where ω is the plasma pulsation, k is the inverse of Debye length and n_0 is the plasma equilibrium density.

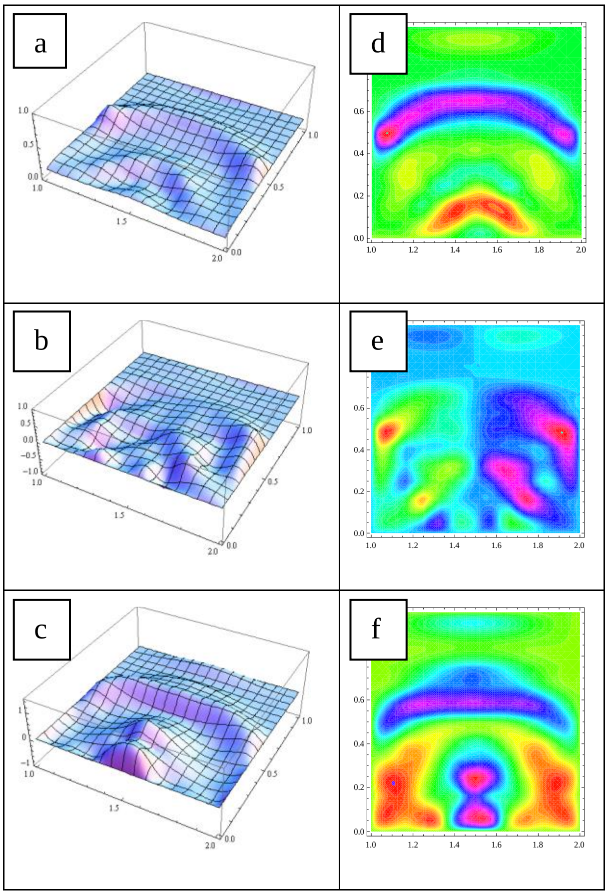
In the boundary conditions (4k) we assumed that the laser pulse which "hits" the target induces a plasma source that has a spatial-temporal Gaussian profile, similarly with the laser beam. Therefore, the control parameter μ (space width) is proportional with the beam diameter. The system (2a-c) with the initial conditions (3a-e) and the boundary conditions (4a-l) was numerically integrated using finite differences [15].

In Figures 1a-f the dynamics of the normalized density field N and normalized velocities fields V_ξ and V_η , respectively, are plotted for the normalized times τ = 0.75 and μ = 0.17 (three dimensional and contour plot evolutions). The followings features of the expansion process result: i) the generation of two plasma structures (see the dynamics from Figures 1a,d); ii) the symmetry of the normalized speed field V_ξ with respect to the symmetry axis of the spatial-temporal Gaussian (see the dynamics from Figures 1b,e); iii) shock waves and vortices at the plume periphery for the normalized speed field V_η (see the dynamics from Figures 1c,f). Moreover, on the symmetry axis (ξ = 1.5), plotting the current density (Figures 2a-c) for various distances from the target, a multi-peak structure can be observed. Increasing the value of the control parameter, μ, we conclude the followings: i) the arrival time of the fast peak is increasing; ii) the ratio between the first and the second maximum is decreasing; iii) the magnitude of the first maximum is decreasing as a consequence of lateral expansion. Therefore we conclude that the plume splitting is a hydrodynamic process, being similar with the propagation of a Gaussian perturbation.

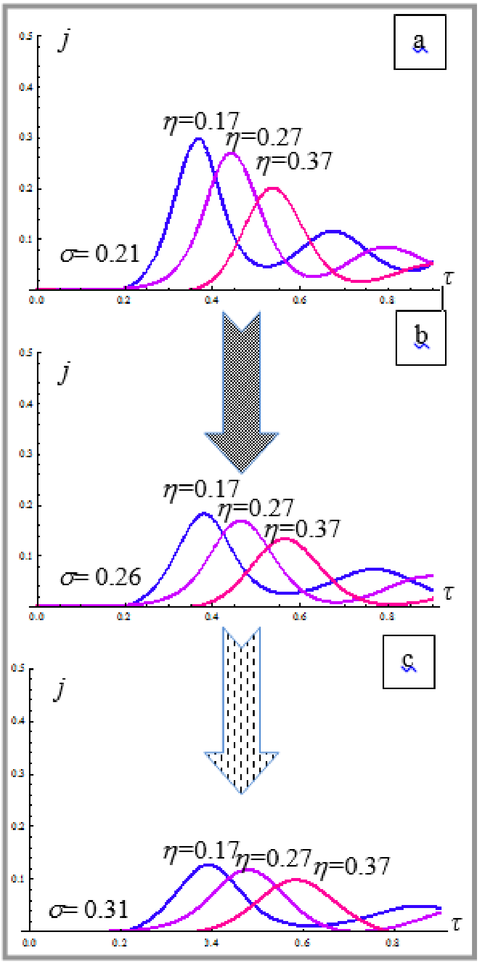
3. Conclusions

The main conclusions of the present paper are the following:

i) using the fractal hydrodynamic model (based on states density and specific momentum conservation laws), the plasma ablation dynamics has been analysed using numerical simulations;
ii) as a result of the numerical simulations the generation of two plasma structures, the symmetry of the normalized speed field V_ξ with respect to the symmetry axis of the spatial-temporal Gaussian, shock waves and vortices at the plume periphery for the normalized speed field V_η are obtained;
iii) in the frame of the same numerical simulation, multi-peak structures with specific characteristics (the arrival time of the fast peak is increasing, the ratio between the first and the second maximum is decreasing, the magnitude of the first maximum is decreasing as a consequence of lateral expansion) are obtained;
iv) in order to validate our theoretical model with the experimental data we used the experimental setup from [3,4,16,17]. The experimental data obtained [3,4] (transient ionic currents recorded by a Langmuir probe located at different distances on the normal to the target for a given laser pulse energy, transient ionic currents recorded by a Langmuir probe placed at a given distance normal to the target for different laser pulse energies, the visible emission from the aluminum plasma plume recorded using an ICCD PI MAX camera at a specific moment of time and for a given laser pulse energy) is in accordance with our model by means of Figs. 1,2).



Figures 1a-f Three dimensional dependences of the normalized density N, normalized velocitys, V_ξ and V_η, on the normalized coordinates, ξ and η for the normalized time $\tau = 0.75$ and $\mu = 0.17$ (a, b, c); two dimensional contour of the normalized density N, normalized velocitys, V_ξ and V_η, for the same τ and μ (d, e, f).



Figures 2a-c Normalized time-dependence of the numerical normalized current density on the symmetry axis ($\xi = 1.5$) for various normalized distances from the target and normalized space-widths of the initial Gaussian distribution: $\mu = 0.21$ (Figure 2a); $\mu = 0.26$ (Figure 2b); $\mu = 0.31$ (Figure 4c).

4. References

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