STUDY OF PROPAGATION OF ULTRA-INTENSE ELECTROMAGNETIC WAVE THROUGH PLASMA USING SEMI-LAGRANGIAN VLASOV CODES

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INTRODUCTION : Here, the interaction of relativistically strong laser pulses with underdense and overdense plasmas is investigated by a Semi-Lagrangian Vlasov code. These simulations revealed a rich variety of phenomena associated with the fast particle dynamics induced by wavebreaking. Investigating these interactions highlights new physical processes. But describing the population of trapped and accelerated particles will require very detailed analysis of kinetics and time history of plasma wave evolution. The S-L V code allows us to handle the interaction of ultrashort electromagnetic pulse with plasma at strongly relativistic intensities with a great deal of resolution in phase space.
We developed a new Semi-Lagrangian scheme for simulating the interaction of an ultra-intense electromagnetic wave with plasma. We have begun to investigate the relativistic parametric instability induced by a strongly relativistic pump wave in periodic plasma. Then, we submitted similar analysis techniques to the simulations of inhomogeneous plasma where spatial periodicity no longer applies : in this more realistic case, propagation of a relativically strong laser pulse in moderately overdense plasma is studied using 1D and 1D1/2 S-L V codes.

I. NUMERICAL 1D PERIODIC S-L V SIMULATION OF THE RELATIVISTIC PLASMA INSTABILITY INDUCED BY AN ULTRA-INTENSE LASER PUMP WAVE :

We start from the 1D relativistic Vlasov model :

$$\frac{\partial f}{\partial t}+\frac{p_x}{m\gamma}\frac{\partial f}{\partial x}+e\left(E_x-\frac{mc^2}{2\gamma}\frac{\partial}{\partial x}\left(a^2\right)\right)\frac{\partial f}{\partial p_x}=0 \qquad (1)$$

where : $\gamma=\left(1+\frac{p_x^{\,2}}{m^2c^2}+a^2\right)^{1/2}$ is the Lorentz factor and $a(x,t)=\frac{eA(x,t)}{mc}$ is the normalised amplitude of the potential vector $\mathbf{A}=(0,A_y,A_z)$, coupled with the Maxwell's equations :

$$\frac{\partial E_y}{\partial t}=-c^2\frac{\partial B_z}{\partial x}+\omega_p^{\,2}A_y\rho(x,t) \qquad (2)$$

$$\frac{\partial E_z}{\partial t}=c^2\frac{\partial B_y}{\partial x}+\omega_p^{\,2}A_z\rho(x,t) \qquad (3)$$

$$\frac{\partial B_y}{\partial t}=\frac{\partial E_z}{\partial x} \qquad (4)$$

$$\frac{\partial B_z}{\partial t}=-\frac{\partial E_y}{\partial x} \qquad (5)$$

where : $\rho(x,t)=\frac{1}{n_0}\int\frac{f}{\gamma}dp_x$

The longitudinal component of the electric field is obtained by solving Poisson's equation :

$$\frac{\partial E_x}{\partial x}=\frac{e}{\varepsilon_0}\left(n_e(x,t)-n_i\right) \qquad (6)$$

In this first simulation, we have an initial homogeneous maxwellian distribution function with a temperature T_e = 3 keV. The electromagnetic wave is assumed to be circularly polarised, the initial pump wave is : $\mathbf{E}=(0,E_0\cos k_0x,E_0\sin k_0x)$, where (ω_0,k_0) satisfy the relativistic dispersion of circularly polarised waves : $\omega_0^2=\omega_p^2/\gamma_0+k_0^2c^2$ with the Lorentz factor given by : $\gamma_0^2=1+a_{osc}^2$. Choosing : $k_0c/\omega_p=1/\sqrt{2}$ and $a_{osc}=\sqrt{3}$, we obtain for the ratio of the electron plasma density to the critical density : $n_e/n_c=1$, or $n_e/\gamma_0n_c=0.50$. Moreover, the box length is : $L_x=2\pi/\Delta k=2\pi/k_0$.

In Fig. 1, we have plotted the growth rate of the relativistic parametric instability, induced by the high intensity pump wave, obtained by solving the dispersion relation in the case of a cold plasma. The maximum of the growth rate $\gamma/\omega_p\approx0.409$ correspond to the most unstable mode located at $kc/\omega_p=1.40$. In Fig. 2, we show the time evolution of the most unstable plasma mode (mode 2) on a logarithmic scale. The curve indicates a growth rate around $\gamma_{num}/\omega_p\approx0.406$. It is found in good agreement with the theoritical value predicted by the model of S. Guérin et al [1]. Finally, Fig. 3 presents the phase space with separatrix (limit between trapped and detrapped electrons).

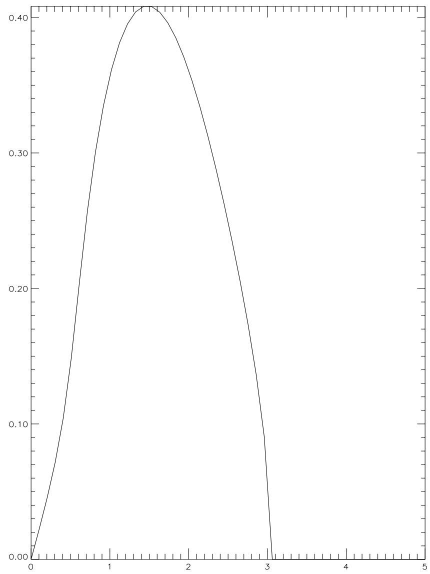

Fig. 1

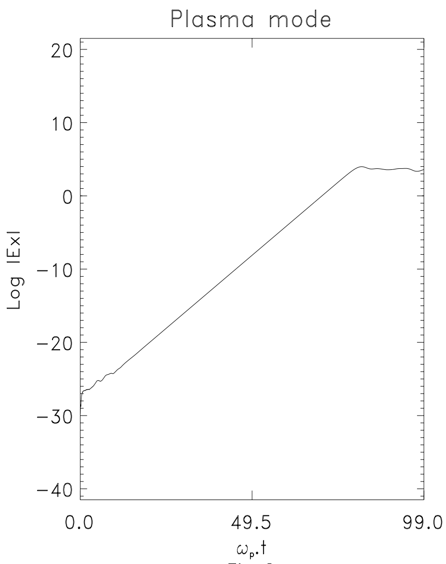

Fig 2

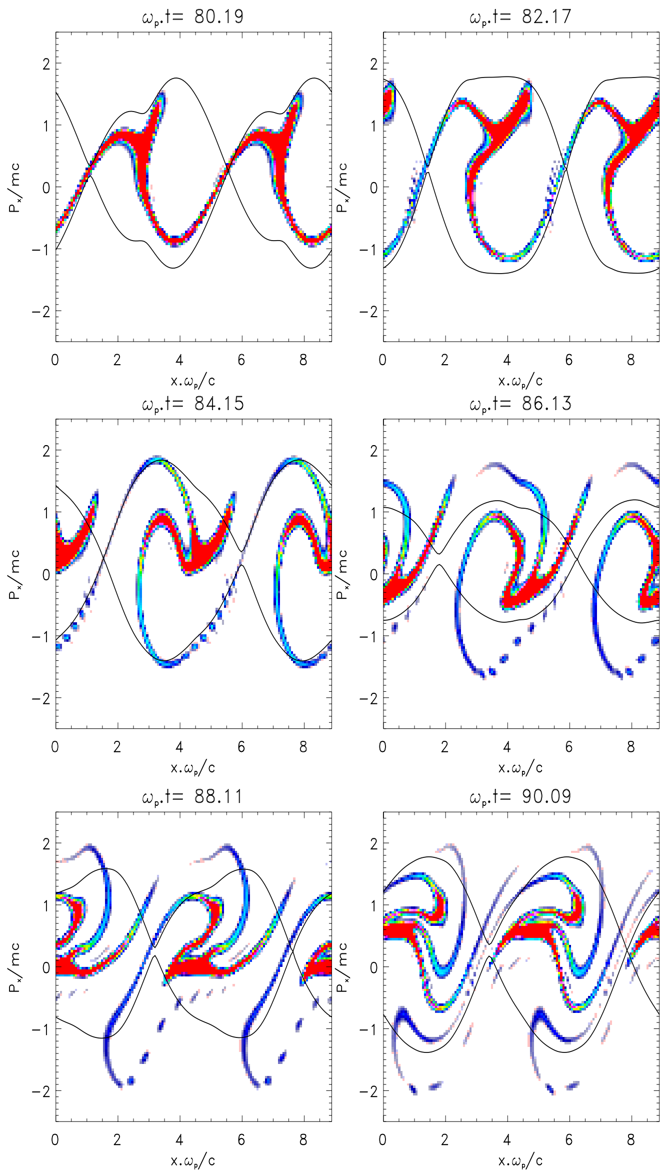

Fig. 3

II. STUDY OF LASER PENETRATION IN OVERDENSE AND UNDERDENSE PLASMA :

The plasma can be described by the Vlasov equation for the electron distribution function $f(x,p_x,t)$:

$$\frac{\partial f}{\partial t}+\frac{p_x}{m\gamma}\frac{\partial f}{\partial x}+e\left(E_x-\frac{P_y(x,t)B_z}{m\gamma}\right)\frac{\partial f}{\partial p_x}=0 \qquad (7)$$

with : $\gamma=\left(1+\frac{p_x^{\,2}}{m^2c^2}+\frac{P_y^{\,2}(x,t)}{m^2c^2}\right)^{1/2}$ the Lorentz factor.

P_y is the fluid transverse momentum, defined as : $\frac{\partial P_y}{\partial t}=eE_y$. Thus, we have a cold description in the perpendicular momentum direction.

The electromagnetic value : $E^+(x,t)=E_y+cB_z$ describes the wave part propagating in the forward direction +x, while the quantity : $E^-(x,t)=E_y-cB_z$ propagates in the backward direction. Thus, we can obtain the reflection rate as $R=\frac{S_r}{S_0}$, where S_0 is the incident Poynting vector flux and S_r the reflected vector flux.

This second simulation is obtained with an initial maxwellian distribution function between $x_a\omega_p/c=40$ and $x_b\omega_p/c=80$ with a ratio of the electron plasma density to the critical density : $n_e/n_c=1.2$. The electromagnetic wave is assumed to be circularly polarised, $a_{osc}=\sqrt{2}$. Fig. 4 displays the time evolution of the reflection rate at position $x = x_a$ and the transmission rate at position $x = x_b$. Fig. 5 shows phase space representation of the electron distribution function at time $t\omega_p\approx 224$ (the wave goes through the plasma : self-induced transparency).

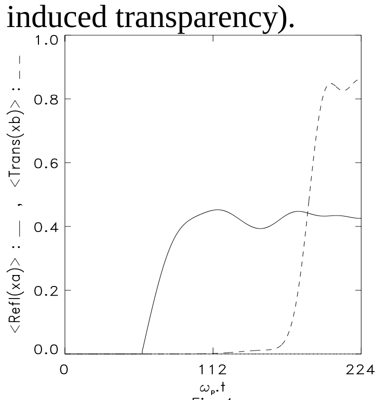

Fig 4

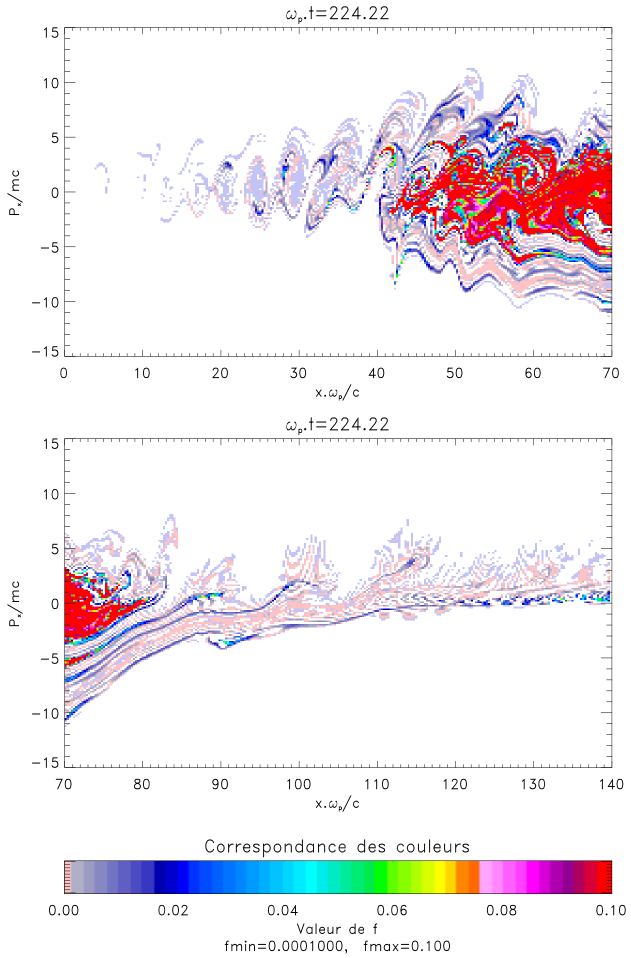

Fig. 5

In this last simulation, the ration of the electron plasma density to the critical density is : $n_e/n_c = 0.1$. The laser gaussian profile pulse duration is $\tau = \frac{4\pi}{\omega_p}$, the wave is circularly polarised, with $a_{osc} = \sqrt{3/2}$. Fig. 6 displays the phase space at time $t\omega_p = 150$, with acceleration mechanism due to laser wake field.

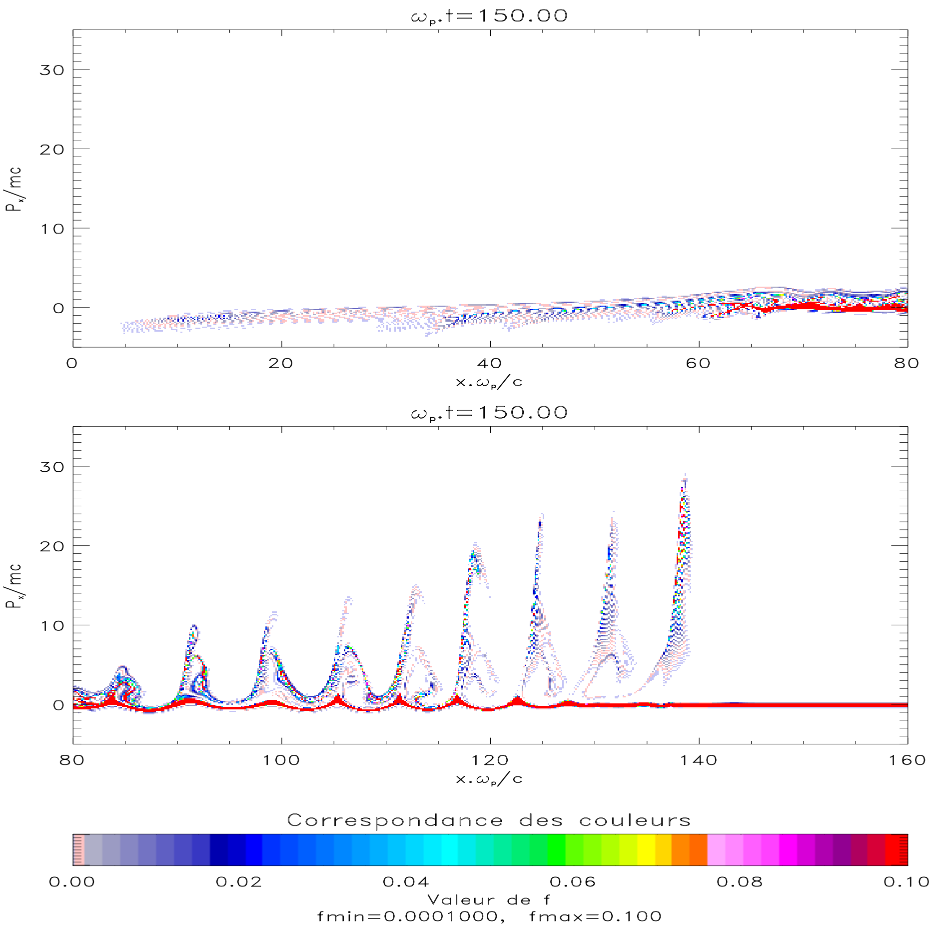

Fig. 6

CONCLUSION : A new semi-lagrangian scheme has been assembled for simulate the interaction of an ultra-intense electromagnetic wave with a plasma. The S-L V code may be a good candidate to explore and understand these processes with a very detailed analysis of the rich variety of phenomena associated with the fast particle dynamics induced by the electromagnetic wave.

This work on a one-dimensional system is intended as preparation for the application of similar analysis techniques to the simulations of two dimensional systems case where filamentation takes place. In the latter case, one cannot use an one-dimensional plasma but must consider transverse spatial effects.

[1] S. Guérin, P. Mora, J.C. Adam, A. Héron, G.Laval, Propagation of ultra intense laser pulses through overdense plasma layers, Physics of Plasmas, 2693-2701, 3(7), 1996.