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VLASOV-MAXWELL SIMULATIONS OF A FINITE AMPLITUDE, HIGH FREQUENCY LONGITUDINAL WAVE IN A MAGNETIZED PLASMA

F. Califano [1,2], M. Lontano [1]

[1] Istituto di Fisica del Plasma, C.N.R., EURATOM-ENEA-CNR Ass., Milano, Italy

[2] Istituto Nazionale di Fisica della Materia, Universita' di Pisa, Pisa, Italy

Abstract

The plasma response to the injection of a purely electrostatic (es) wave of finite amplitude with frequency in the range of the upper hybrid $\omega_0 = (\omega_{pe}^2 + \omega_{ce}^2)^{1/2}$ is investigated by means of a 1D-2V Vlasov-Maxwell numerical code. In the early stage of the wave-plasma interaction, the electron distribution function (edf) takes an almost ring-like shape in the plane normal to the magnetic field. Then, a sort of instability occurs leading to its broadening and flattening. The spectral densities in wave-vectors and frequencies of the electric field and of the fluid variables are also investigated.

Introduction

The physics of the propagation of the electron Bernstein waves (ebw) have been investigated for a long time in connection with their potentialities in the heating and the current drive processes of a magnetically confined plasma, for fusion energy production purposes. They are high frequency, almost electrostatic kinetic modes of a hot magnetised plasma, which are excited by wave transformation of an extraordinary mode in the region of the cold upper hybrid resonance. Recently, a renewed interest for the use of ebw has arisen in connection with their application to reversed field pinches and spherical tori [1-3]. Generally speaking, since ebw frequencies are in the range of the electron cyclotron frequency, their propagation and absorption properties can be well described in the frame of the linear and the quasilinear theory. However, due to the increasing demand of radiofrequency input power in large fusion machines, bearing in mind that ebw are excited in the region of a plasma resonance, the local wave electric field can achieve large values which may trigger a non linear plasma response. In this work, we describe the results of Vlasov-Maxwell numerical simulations of the interaction of a driven electrostatic wave with frequency $\omega_0 = \omega_{uh}$, and $k_0\rho_{Le} = 1$, where ω_{uh} and ρ_{Le} are the cold upper hybrid frequency and the Larmor radius of thermal electrons, respectively.

The numerical analysis

With reference to a physical system characterized by one spatial coordinate (x) and two velocity degrees of freedom (v_x, v_y), the Vlasov-Maxwell system of equations write:

$$\frac{\partial f_a}{\partial t} + v_x \frac{\partial f_a}{\partial x} - \Lambda_a \left\{ \left[E_x(x,t) + E_{dr}(x,t) + B_z v_y \right] \frac{\partial f_a}{\partial v_x} + \left[E_y - B_z v_x \right] \frac{\partial f_a}{\partial v_y} \right\} = 0 \tag{1}$$

$$\frac{\partial E_x}{\partial x} = \iint dv_x dv_y \; f_i(x, v_x, v_y, t) - \iint dv_x dv_y \; f_e(x, v_x, v_y, t) \tag{2}$$

$$\frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t} \tag{3}$$

$$\frac{\partial B_z}{\partial x} = -\frac{\partial E_y}{\partial t} - \iint dv_x dv_y \; v_y f_i(x, v_x, v_y, t) + \iint dv_x dv_y \; v_y f_e(x, v_x, v_y, t) \tag{4}$$

where the following dimensionless variables have been introduced: $\omega_{pi}t \rightarrow t$, $\mathbf{v}/c \rightarrow \mathbf{v}$, $\omega_{pi}x/c \rightarrow x$, $f_a c/n_{0a} \rightarrow f_a$, $eE(B)/m_i c\omega_{pi} \rightarrow E(B)$. Moreover, $\Lambda_i = -1$, $\Lambda_e = 1836$, $E_{dr}(x,t) = a \sin(k_0 x - \omega_0 t)$ is the externally applied es wave, q_a, m_a, and T_a are the electric charge, the mass and the temperature of the a-species, respectively, c is the speed of light, e is the modulus of the electron charge, $\beta_a = v_{ta}^2/c^2$, and $v_{ta} = (T_a/m_a)^{1/2}$. Eqs.(1-4) are numerically integrated with periodic boundary conditions, in the interval $x \in [0, 6\lambda_0]$, where $\lambda_0 = 2\pi/k_0$ is the normalised wavelength of the pump [4]. Initially both electrons and ions are at the equilibrium and no field is present. The analysis has been performed for $n_e=10^{11}$ cm^{-3}, $T_e=T_i=10$ eV, $B_0=1$ kG, which lead to the following dimensionless plasma parameters: $\lambda_{De} \approx 1.03\times10^{-4}$, $\rho_{Le} \approx 1.05\times10^{-4}$, $\rho_{Li} \approx 4.48\times10^{-3}$, $\beta_e = 3.9\times10^{-5}$, $\beta_i = 2.3\times10^{-8}$, $\omega_{ce} \approx 42.2$, $\omega_{ci} \approx 0.023$. The frequency of the pump, ω_0, has been chosen close to the cold upper hybrid frequency, $\omega_{uh} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}$ ($\approx$ 60, in dimensionless units), the wave-vector $k_0 \approx 9.5\times10^3$ is such that $k_0\rho_{Le} \approx 1$, and consequently $\omega_0/k_0 \approx 6.3\times10^{-3}$. Finally, the electric field amplitude of the driven wave has been taken 2 kV/cm, so that the ratio of the electrostatic to the electron thermal energies is of the order of unity. It corresponds to $a = 3\times 10^{-4}$. The numerical integration has been carried out in the interval $x \in [0, 6\lambda_0]$, where $\lambda_0 = 2\pi/k_0 \approx 6.61\times10^{-4}$ is the normalised wavelength of the pump, and for t = 2.3, that is for about 15 electron Larmor periods ($t_{ec} = 2\pi/\omega_{ce} \approx 0.15$). In Fig.1 the level lines of the edf $f_e(v_x,v_y)$ are shown at four times, t = 0, 0.1, 0.42, 2.3, at the spatial position $x = 2.5\times10^{-3}$. The horizontal and vertical axis refer to v_x and v_y (in units of the speed of light). respectively. It is seen that the initial isotropic Maxwellian edf is strongly distorted by the driven wave, and develops a ring-shaped structure during the first cyclotron orbit ($t = 0.1 < t_{ec}$). The ring-like character of the edf is clearly seen in Fig.2 where the contour plots of $f_e(x,v_x, v_y)$ are shown in the phase space x-v_x, for $v_y = 0$, at t = 0 and t = 0.1. The region around $v_x = v_y = 0$ is almost completely depleted during the initial ($t < t_{ec}$) regular acceleration of the electrons. A typical value of the velocity of accelerated electrons is ≈ 0.02.

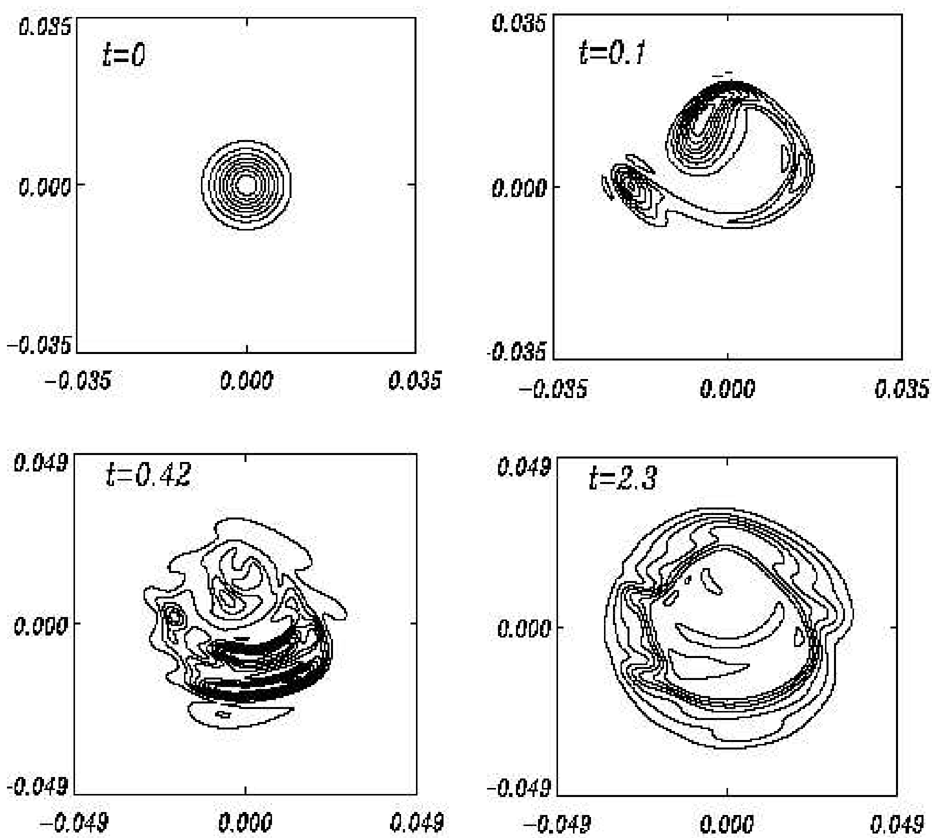

Fig.1

At later times (t = 0.42 in Fig.1) $f_e(v_x,v_y)$ goes through a phase characterised by the formation of several peaks. Different parts of the velocity space v_x-v_y mix up leading to an increase of the typical width of the edf. After several gyrations (t = 2.3), a quasistationary state is achieved with an almost isotropic and flat edf, with an average energy of 6×10^{-4}, to be compared with the initial thermal energy $3T_e/2 \approx 6\times10^{-5}$. In the course of the wave-plasma interaction, electron density oscillations up to ± 20 % of the unperturbed value are generated. The wave-vector spectral distributions of the self-consistent electrostatic field, electron and ion density fluctuations develop several peaks at the harmonics of the pump k_0.

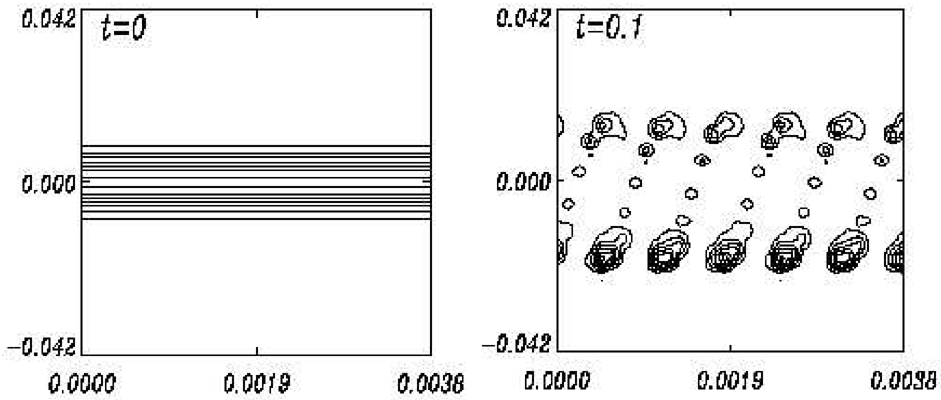

Fig.2

Concluding remarks

The non linear interaction between a driven electrostatic wave, propagating normally to the external uniform magnetic field, and a collisionless plasma has been investigated by means of a Vlasov-Maxwell code. The aim has been to model the propagation of a finite amplitude eBw close to the upper hybrid resonant layer. It is shown that a high frequency electrostatic wave is able to produce a ring-like edf during the early phase of the interaction. Later on, the strong perturbations induced by the wave on the edf result in the collisionless heating of the electrons over few cyclotron periods.

References

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