29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-5.076 (2002)*

TRANSVERSE ION FLOW INDUCED BY CHERENKOV ABSORPTION OF A DRIVEN ELECTROSTATIC WAVE IN A MAGNETIZED PLASMA: THE RESULTS OF VLASOV-MAXWELL KINETIC SIMULATIONS

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Abstract

The interaction of a purely electrostatic (es) wave of finite amplitude, propagating normally to the ambient uniform magnetic field $\mathbf{B}_0$, with a collisionless plasma, and the consequent generation of a transverse ion drift are investigated in the frame of a Vlasov-Maxwell numerical code. It is shown that for a pump frequency ω_0 in the range of the 4th ion cyclotron harmonic, the coupling between the wave and the ions relies on the Cherenkov resonant absorption in the plane perpendicular to $\mathbf{B}_0$.

Introduction

Ion Bernstein waves (iBws), that is compressional es waves which can be excited in a hot magnetised plasma, are expected to produce sheared poloidal plasma flows in a tokamak plasma. Consequently, they can be used to shorten the correlation length of turbulent fluctuations and to reduce the energy leakage from the plasma core towards its periphery [1]. Then, the understanding of the physical mechanism of energy and momentum transfer from an es wave, propagating normally to the ambient magnetic field, towards the plasma ions is of basic concern in order to exploit the potentialities of the absorption process. On the basis of the linear analysis of the iBws, it is know that they are generated in a hot plasma, close to the lower hybrid resonant layer, through the conversion of an externally excited electron plasma wave; then they are absorbed *via* the ion cyclotron damping. Here, we present the results of kinetic Vlasov-Maxwell numerical simulations of the interaction between a driven es wave (with the frequency ω_0 equal to the 4th ion cyclotron harmonic, and the wave-vector $\mathbf{k}_0 = k_0\mathbf{e}_x$, such that the corresponding wavelength is of the order of the ion Larmor radius) and a collisionless magnetized plasma, with $\mathbf{B}_0 = B_0\mathbf{e}_z$. Although the wave frequency is only four times the ion cyclotron frequency, the process of energy transfer is so efficient that it occurs before one Larmor orbit is completed. At strictly perpendicular propagation, the ion Landau damping *via* Cherenkov absorption mechanism governs the ion drift generation [2].

The numerical analysis

In 1D-2V (x,v_x,v_y) geometry, the Vlasov-Maxwell system of equations takes the form:

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

$$\frac{\partial E_x}{\partial x} = \iint dv_x dv_y \, f_i(x,v_x,v_y,t) - \iint dv_x dv_y \, f_e(x,v_x,v_y,t) \quad , \quad \frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t} ,$$

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

where the following dimensionless variables have been introduced: $\omega_{pi} t \to t$, $\mathbf{v}/c \to \mathbf{v}$, $\omega_{pi} x/c \to x$, $f_a c/n_{0a} \to f_a$, $eE(B)/m_i c\omega_{pi} \to E(B)$. Moreover, $\Lambda_i = -1$, $\Lambda_e = 50$ (the reduced ion-to-electron mass ratio of 50 has been assumed in order to shorten the computational times), $E_{dr}(x,t) = a \sin(\omega_0 t - k_0 x)$ 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 $v_{ta} = (2T_a/m_a)^{1/2}$. The equations are numerically integrated with periodic boundary conditions, in the interval $x \in [0, 3\lambda_0]$, where $\lambda_0 = 2\pi/k_0$ is the normalised wavelength of the pump [3].

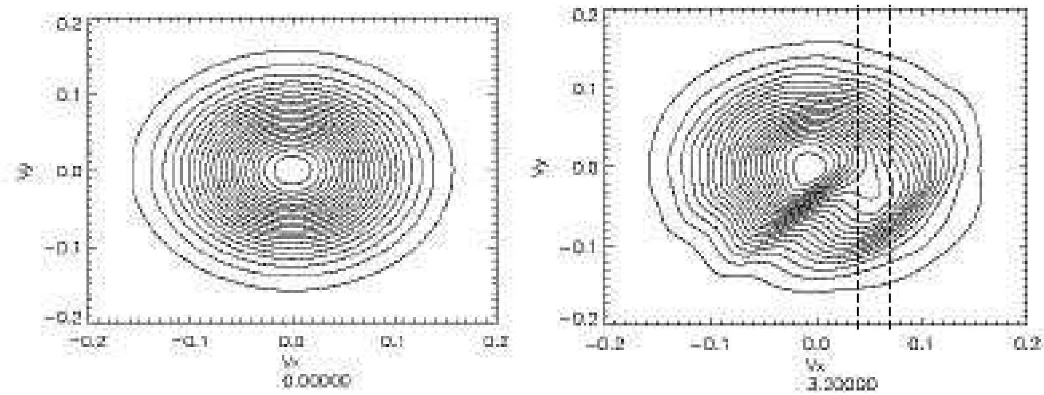

Fig.1

At t=0 both electrons and ions are at the equilibrium and no field is present. The analysis has been performed for a wave frequency varying around the 4th ion cyclotron harmonic, $\omega_0 \approx 4\Omega_{ci}$ ($\omega_0 \approx 1.93$, in dimensionless units), and a wavelength of the order of the thermal ion Larmor radius, that is $k_0\rho_{Li} >> 1$. The reference parameter values are: $n_e=5\times10^{13}$ cm^{-3}, T_e=1 keV, B_0=7.8 T, f=433 MHz, $N_\perp\approx10^3$. A suitable renormalisation of the ion quantities has been required due to the reduced ion-to-electron mass ratio. In dimensionless units, $k_0 \approx 349$ and $\omega_0/k_0 \approx 0.0055$. The present simulations differ from what has been previously presented [4], as high resolution in velocity space has been used ($\Delta v_x = \Delta v_y = 5\times10^{-4}$). In Fig.1 the level lines of the ion distribution function $f_i(v_x,v_y)$ are shown at x = 0.026 and for $\omega_0 \approx 1.93$, $a = 10^{-3}$, at the initial time (t = 0), and after one pump period $2\pi/\omega_0$ (t = 3.2). Note that the coordinate values should be multiplied by 0.1.

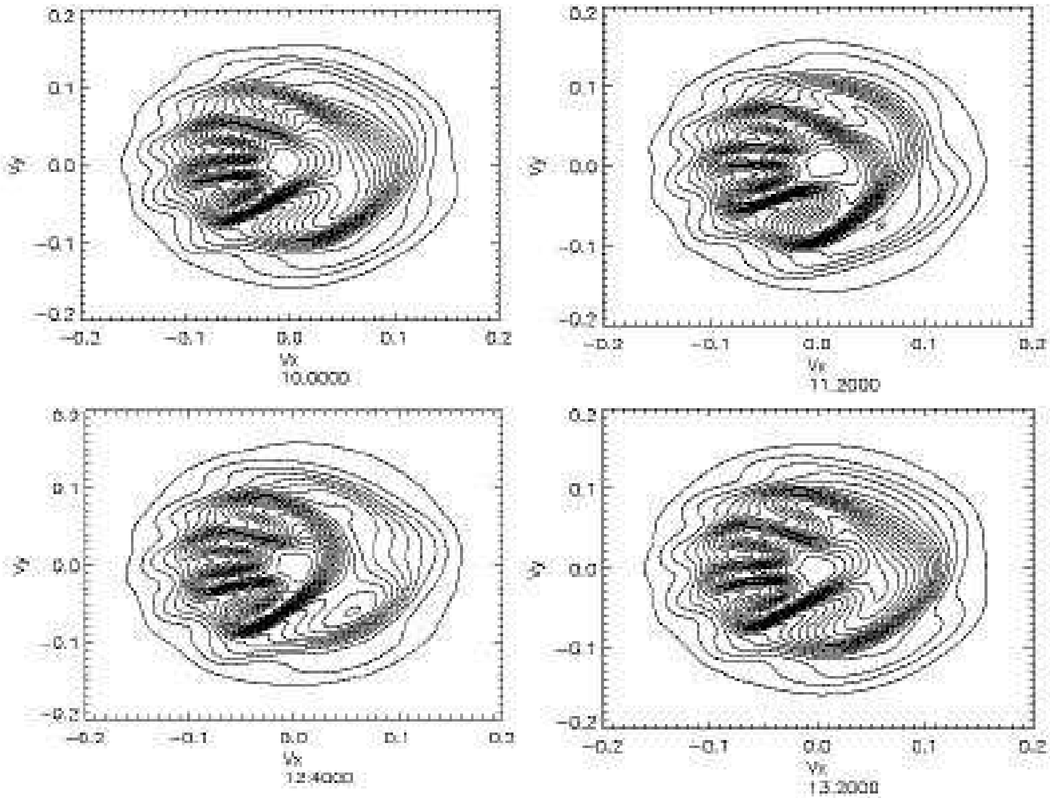

Fig.2

The vertical lines mark the "resonant" region defined by the inequality $|v_x - \omega_0/k_0| < (a/k_0)^{1/2}$ (that is, between 3.8×10^{-3} and 7.2×10^{-3}), where particle trapping is expected to occur. We see that the initially isotropic distribution starts to develop a "plateau" in the v_x-direction well before a complete Larmor orbit is performed ($2\pi/\Omega_{ci} \approx 13$). The effect of the magnetic field is to transfer this perturbation in the other degree of freedom, specifically, first in the negative v_y-direction, and successively according to the (counter-clockwise) ion orbit. At later times the structure of the ion distribution becomes more complicated, as it is seen in Fig.2. The level curves of $f_i(v_x,v_y)$ are shown during the fourth wave cycle at the end of the first ion Larmor gyration: t = 10 (*a*), 11.2 (*b*), 12.4 (*c*), 13.2 (*d*). During the successive evolution (till t =130, not shown here) the whole structure is essentially preserved and appears to "rotate" counter-clockwise, making one full turn in one cyclotron period. The spatially averaged first order moments of the ion distribution function, $\langle U_{ix}(x,t)\rangle$ and $\langle U_{iy}(x,t)\rangle$, oscillate at Ω_{ci}, with almost zero time-average (the former), and negative time-average (the latter). This can be seen in Fig.3, where $\langle U_{ix}(x,t)\rangle$ (dashed line) and $\langle U_{iy}(x,t)\rangle$ (solid line) are shown for $\omega_0 \approx 1.93$ and $a = 10^{-3}$. The negative average ion drift in *y* reaches a quasi-stationary state [4].

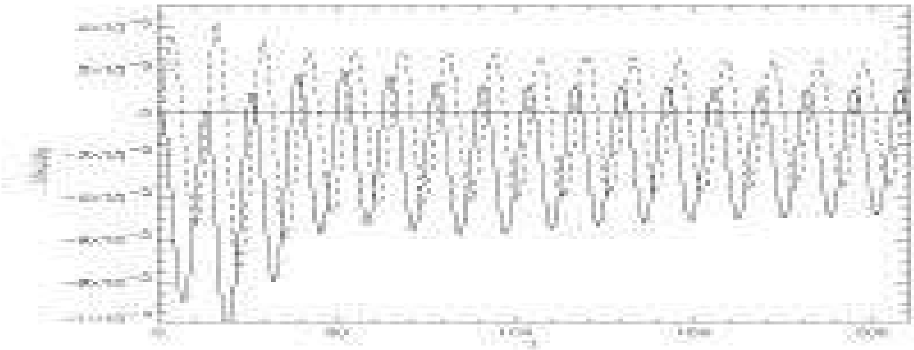

Fig.3

Concluding remarks

The new high-resolution kinetic simulations of the electron-ion plasma response to a driven purely es wave confirm the results of the previous numerical investigations, giving a more detailed description of the time evolution of the ion distribution function. The principal role played by the transverse ion Landau damping in the process of energy and momentum transfer from the wave to the resonant ions has been clearly observed.

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