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Propagation of finite amplitude disturbances in an inhomogeneous magnetized plasma

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Abstract

The evolution of electromagnetic waves injected from the boundary in a inhomogeneous magnetized collisionless plasma is investigated by means of a kinetic numerical code. The Harris pinch magnetic configuration as the background equilibrium configuration for wave propagation is used. The numerical code solves the Vlasov equation for ions and electrons in the 1D - 2V phase space, self consistently coupled to the Ampere and to the Faraday equations. The external magnetic field is transverse to the wave propagation direction. Open boundary conditions are used to inject the waves from outside at a given frequency, while the wavelength is selected self-consistently by the system.

Introduction

Self-consistent electromagnetic (ES) fields in spatially non-uniform plasmas represent one of the fundamental aspects of plasma physics with several implications in both radiofrequency driven and laser produced plasma experiments. The availability of fully non-linear kinetic codes [1] allows one to investigate several aspects of the wave-plasma interaction which go beyond the limits of a WKB theory: the effects of a finite amplitude of the excited waves, the propagation of wavelengths of the same order, and even smaller, than the typical spatial scale-lengths of the plasma gradients, the interplay between kinetic and fluid properties of the interaction. The investigation of the propagation of driven electrostatic waves in an unmagnetized plasma has been carried out in [2, 3]. The physical picture which comes out is very rich, and it is far richer if a magnetized plasma is considered.

In this paper we present the results of a kinetic study of the propagation of an externally driven electromagnetic wave in a magnetized non-uniform plasma. The unperturbed equilibrium configuration is that of the Harris pinch [4]. It is the result of the one-dimensional equilibrium (in x) between a localized plasma layer and a transverse (with respect to the direction of the plasma gradients, for example in z) non uniform magnetic field, which changes sign in correspondence of the maximum plasma density ($x = 0$). All physical quantities are uniform in the plane y,z.

This equilibrium geometry represents a useful model to investigate wave propagation in a non uniform magnetized plasma, since cut-off and resonance are met from a wave excited far from plasma layer (that is at $x = -\infty$).

The physical model

We solve the 1D - 2V Vlasov equation with open boundary conditions

$$\frac{\partial f_\alpha}{\partial t} + v_\alpha \frac{\partial f_\alpha}{\partial x} + Z_\alpha \frac{m_e}{m_\alpha}(E + v \times B)\frac{\partial f_\alpha}{\partial v} = 0, \tag{1}$$

where $\alpha = e, i$, coupled with the Maxwell equations. The basic physical quantities are then normalized to $\bar{t} = \omega_{pe}^{-1}$, $\bar{l} = d_e$, $\bar{v} = c$, $\bar{E}(\bar{B}) = m_e c \omega_{pe}/e$, where d_e is the electron skin depth, and ω_{pe} the electron plasma frequency. The equilibrium Harris configuration at $t = 0$ for a neutral plasma layer (electrostatic potential $\phi(t = 0) = 0$), composed by Maxwellian electrons and ions, is described by the distribution functions

$$f_e = (\frac{\beta_e}{2\pi})N_1 exp[-\beta_e(v_x^2 + (v_y - V_e)^2 + 2V_e A_y)] + N_0 exp[-\beta_e(v_x^2 + v_y^2)], \tag{2}$$

$$f_i = (\frac{\beta_i}{2\pi})N exp[-\beta_i(v_x^2 + (v_y - V_i)^2 - 2V_i A_y)]; \quad \beta_{ei} = N\,(\beta_i + \beta_e)/\beta_i \tag{3}$$

The static magnetic field and the vector potential are given by:

$$B_z = -\sqrt{\beta_{ei}/\beta_e}\ \tanh(xV\sqrt{\beta_e\beta_{ei}}); \quad A_y = -(1/\beta_e)V\ \log\cosh(xV\sqrt{\beta_e\beta_{ei}}) \tag{4}$$

Moreover, in Eqs.(2-4) $N_1 = 0.9$, $N_0 = 0.1$, $v_{th,e} = 0.1$, $v_{th,i} = 0.00023$, $V_e = -0.05$, $V_i = 0.0005$, $\beta_e = 100$, $R_T = T_i/T_e = 0.06$, $R_m = m_i/m_e = 1836$, $\beta_i = \beta_e R_m/R_T$

Numerical results

We have studied the propagation of an extraordinary-mode (a transverse wave with the electric field $E_{y,dr}$ and the magnetic field $B_{z,dr}$) at two frequencies, $\omega_0 = 0.7$ and 0.35. In the former case the excited wave propagates initially in a transparent magnetized plasma, which becomes inaccesible at $x = 17.4$, the position of the linear cut-off. Very close to the cut-off, there is the upper-hybrid cold resonance. The case at $\omega_0 = 0.35$ refers to the excitation of an electromagnetic disturbance at the boundary of an overdense plasma, which becomes more and more overdense approaching $x = 20$, where the magnetic field vanishes. The plasma response has also been sampled at two different driver amplitudes, $E_{y,dr} = 0.01$ and 0.05. The different combinations of parameters correspond to values of the normalized quiver velocity $\tilde{v}/v_{th,e}$ ranging approximately between 0.15 and 1.5.

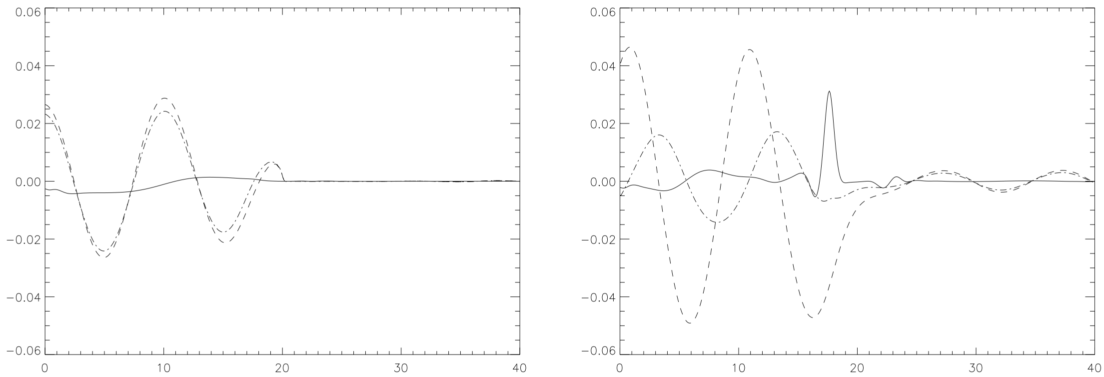

Figure 1: E_x, E_y and B_z (full, dashed and dot-dashed line) *vs.* x for $E_{y,dr} = 0.05$, $\omega = 0.7$ at $t = 20$ and $t = 75$, left and right frame, respectively.

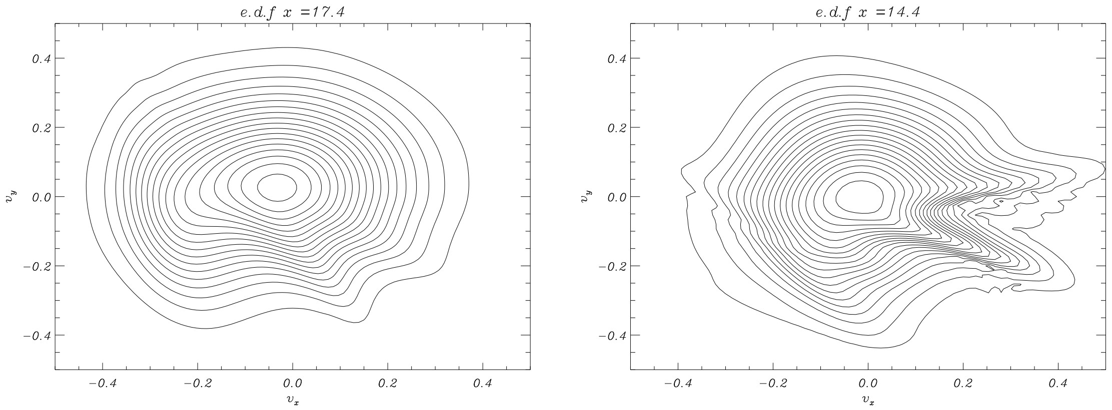

Figure 2: Left frame: The isocontours of the e.d.f. in the (v_x, v_y) plane at $t = 50$, $x = 17.4$. Other parameters are the same as in Fig. 1. Right frame: The isocontours of the e.d.f. in the (v_x, v_y) plane a t $t = 90$, $x = 14.4$. Other parameters are the same as in Fig. 3.

Let's consider first the underdense plasma case ($\omega_0 = 0.7$) for the higher amplitude value $E_{y,dr} = 0.05$. In Fig.1 the longitudinal component of the electric field E_x (continuous line), the transverse components of the electric field E_y (dashed lines) and of the magnetic field B_z (dot-dashed lines) are plotted as functions of x at $t = 20$ (a) and at $t = 75$ (b). In Fig. 1, left frame, it is seen that E_y and B_z are in phase and the corresponding wave-vector $k_x \approx 0.63$ satisfies the linear dispersion, as expected. With elapsing time, the front of the perturbation reaches the plasma layer, and several effects take place. The electromagnetic part of the disturbance is reflected at the cut-off, while the electrostatic part is enhanced at the upper-hybrid resonance. A small portion of the electromagnetic energy tunnels across the overdense plasma and appears at the side $x > 20$, as a pure X-mode. In Fig. 1, right frame, the same quantities as in Fig. 1, left frame, are plotted at a later time. It is seen that the reflected electromagnetic wave has suffered a half-π

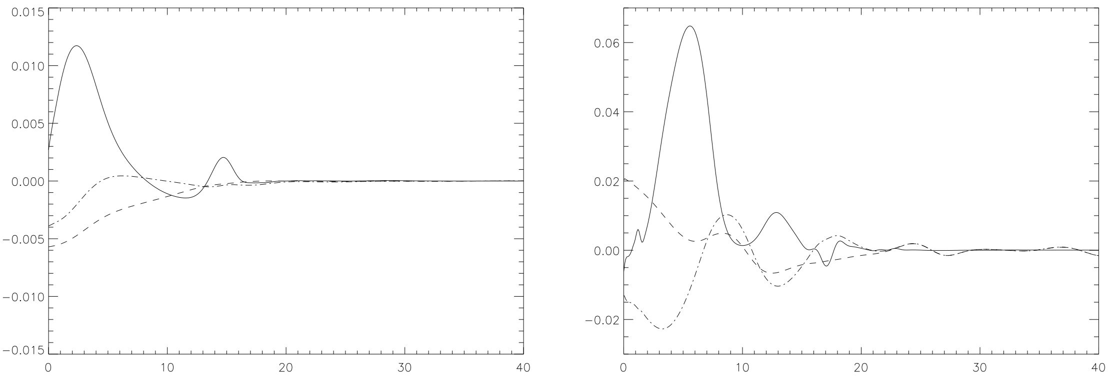

Figure 3: E_x, E_y and B_z (full, dashed and dot-dashed line) *vs.* x for $E_{y,dr} = 0.05$, $\omega = 0.35$ at $t = 68$, $E_{y,dr} = 0.01$ and $t = 198$, $E_{y,dr} = 0.05$, left and right frame, respectively.

dephasing between the E_y and B_z, the E_x is strongly peaked at the resonance, and the tunneled electromagnetic wave shows fully phased E_y and B_z, propagating towards the right boundary of the simulation interval. In Fig. 2, left frame, the contour plot of the e.d..f at $x = 17.4$ (close to the plasma resonance) in the v_x, v_y plane is shown at $t = 50$. The main distortion of the initial Maxwellian are observed for $v_x > 0$ and $v_y < 0$.

A lower frequency case has been also considered ($\omega = 0.35$), which corresponds to the excitation of an electromagnetic disturbance which is in cut-off. In Fig. 3, left frame, E_x (continuous line), E_y (dashed lines), and B_z (dot-dashed lines) are plotted as functions of x for $E_{y,dr} = 0.01$ at $t = 68$ (left frame) and for $E_{y,dr} = 0.05$ at $t = 198$ (right frame). For both excitation amplitudes it is seen that the electromagnetic field is evanescent over approximately 200 λ_{De}. Moreover quite strong electrostatic field fluctuations for $0 < x < 10$ take place. In this case, the e.d.f. is heavily distorted from the initial Maxwellian, as it can be seen in Fig. 2, right frame, which shows the isocontours in the plane v_x, v_y, at $x = 14.4$ and for $t = 90$.

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