EXCITATION OF SURFACE WAVES AND ELECTROSTATIC FIELDS BY A RF WAVE IN A PLASMA SHEATH WITH CURRENT

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Abstract

It is shown in a one-dimension model that when a current in a plasma sheath is present, the excitation of surface waves and electrostatic fields by a RF wave is possible in the sheath. This phenomena depends strongly on the joint action of Miller's and driven forces. It is also shown that the action of these forces are carried out at different characteristic times when the wave front travels through the plasma sheath. The influence of the current, in the steady limit, is taken into account by a small functional variation of the density perturbations and generated electrostatic field.

1 Introduction

The electrostatic fields generation by electromagnetic radiation injected in a plasma, is mainly related with the acceleration of charged particles. This is a topic of very active interest [1,2].

When an EM wave impinges on a plasma, the electrons are influenced by oscillating and averaged forces, where the latter ones vary slowly in space and time. The better known force of this type is the Miller force [3].

The Miller force arises when the amplitude of a high frequency field varies in space. However, there are other forces acting on the electrons, besides Miller's. For instance, there exists an averaged force due to collisions, acting on the electrons, when a transverse EM wave propagates through the plasma.

These collision originated forces play an important role in the current drive processes. Unlike Miller force, the driven forces remain when the field amplitude does not vary in space.

In a real situation, the EM field amplitude depends on the coordinates, thus both kind of forces act on the electrons.

This work purports to investigate the effects on a current plasma sheath when a EM wave propagates through it. Gorbunov et. al. [4] investigated the current-free case.

Transient effects on the current plasma sheath during the EM wave propagation are studied as well. These effects show a strong dependence on boundary conditions, which excites surface waves and electrostatic fields. It is also shown that these phenomena appear at different characteristic times during the wave front propagation.

2 Basic equations

Let us consider a linearly polarized transverse EM wave, propagating along the X-axis. The electric field is of the form,

$$\tilde{E}(x,t) = \frac{1}{2}\left\{E(x,t)e^{-i\omega t+ikx} + E^{*}(x,t)e^{i\omega t-ikx}\right\} \quad (1)$$

where ω, k, E are the frequency, the wave number and the slowly-varying in space-time complex wave amplitude respectively.

Neglecting the wave dispersion by assuming $(\omega_p/\omega)^2 \ll kL_0$, where ω_p is the plasma frequency, and a sufficiently large characteristic length for the amplitude, L_0, allows us to describe the wave amplitude variation as,

$$\frac{\partial E}{\partial t} + v_g\frac{\partial E}{\partial x} + \gamma E = 0 \quad (2)$$

where $v_g = (\partial\omega/\partial k)$ is the group velocity and γ is the damping rate.

For the description of the plasma electron motion we use a hydrodynamic model [5]. After linearizing with respect to the electric field, we obtain a set of equations for the slowly varying magnitudes,

$$\frac{\partial n}{\partial t} + n_0\frac{\partial v}{\partial x} = 0 \quad (3)$$

$$\frac{\partial v}{\partial t} + \nu v = \frac{1}{m}J + \frac{e}{m}E - \frac{T}{n_0 m}\frac{\partial n}{\partial x} \quad (4)$$

$$\frac{\partial E}{\partial x} = 4\pi e n \quad (5)$$

where E, n, v are the electrostatic field, the density perturbation and the electron velocity respectively. T is the electron temperature and J the average Lorentz force $J = \frac{e}{c}\overline{\tilde{v}\tilde{B}}$. $\tilde{B}$ is the magnetic field induced by the electric field $\tilde{E}$.

From the equation for the electron oscillating velocity $\tilde{v}$, and Ampere's law (after averaging in time the rapidly oscillating part, in linear approximation with respect to $\partial/\partial x$ and effective collision frequency ν), we obtain

$$J = -\frac{e^2}{4m\omega^2}\left(\partial|E|^2/\partial x - 2\frac{\nu k}{\omega}|E|^2\right) \quad (6)$$

The first term on the right-hand side in (6) is the Miller force [3] and the second one the driven force [6]. When a transverse EM wave impinges perpendicularly on a homogeneous plasma we consider that the amplitude variation is given in the boundary $x = 0$ by $E(0,t) = E_0(t)\Theta(t)$, where $\Theta(t)$ is the Heaviside function.

Let us now consider the resulting electrostatic fields generated by the interaction, wave-plasma. The electric field equation obtained from equations (3)-(5) becomes

$$\frac{\partial^2 E}{\partial t^2} + \omega_p^2 E + \nu\frac{\partial E}{\partial t} - v_T^2\frac{\partial^2 E}{\partial x^2} = -\frac{\omega_p^2}{e}J \quad (7)$$

When the current is present in the plasma sheath, the boundaries can be matched by a conductor [4]. In the one-dimensional model it corresponds to an adequate choice of the boundary conditions. In our case we have

$$n(L,t)=0; \qquad \int_0^L dx\, n(x,t)=0. \tag{8}$$

3 Stationary case

From the solution of Eq. (7), with the boundary conditions (8) and considering that $|E_0(t)|^2 = \mathcal{E}_0^2(1-e^{-\alpha t})$, (where $\mathcal{E}_0$ is a constant in time amplitude), there results that when the current is present, the electrostatic field depends on the damping of the wave alone. The influence of the current is taken into account by a small functional variation of the density perturbations and the generated electrostatic fields.

4 Non-stationary case

From the analysis of the expression for the electrostatic field obtained in this case, in the limit $r_D \ll 1/G, L$ and $\omega_p \gg \alpha, \nu$ (r_D and $G = 2\gamma/v_g$ are the Debye radius and the damping coefficient respectively), we have that when an EM wave travels through the current plasma sheath, there appears electrostatic fields in different regions. In the first region, the electrostatic field is proportional to $\Theta(t - x/v_g)$ and it is related with the wave front. In this region when $\omega_p \gg \nu$ excites a plasma wave with wave number ω_p/ν and with a damping rate $\nu/2$. The amplitude for this wave can be sufficiently large if the wave front is small ($\alpha > \omega_p$). After the plasma wave is damped a space damped electrostatic field is established. The second region is located near the boundary, where the perturbations travel at the electron thermal speed v_T (terms proportional to $\Theta(t - x/v_T)$). The origin of this perturbations is embedded in the boundary condition $E(0,t) = E(L,t)$. To satisfy the last condition, it is necessary to compensate in the boundaries the excited field by the wave front. If the field varies in time with a frequency ω_p, then some perturbations traveling with frequency ω_p are originated at the boundary. However, these perturbations don't have a wave shape and can't propagate. It occurs as if the excited field by the impinging wave in the boundary $x = 0$, had been reflected. These kind of waves are known as surface waves [7].

When $t < L/v_g$, the wave front have not arrived to the boundary $x = L$. For this elapsed time, we obtain the expression for the case of a semi-bounded plasma without current [4]. When $2L/v_T > t > L/v_g$, from the equation for the field we keep terms proportional to $\Theta(t - L/v_g - (L-x)/v_T)$, which determine the perturbations traveling from the boundary $x = L$ at the electron thermal speed. The terms proportional to $\Theta(t - L/v_g - (L+x)/v_T)$ determine the perturbations in the boundary $x = 0$ after the perturbations from the boundary $x = L$ have arrived.

Other terms proportional to $\Theta(t - L/v_g - x/v_T)$ show similar effects to those caused by terms proportional to $\Theta(t - (2L-x)/v_T - L/v_g)$, with characteristic times $t > 2L/v_T$. This case is not further discussed in this work.

5 Conclusions

When a transverse linearly polarized EM wave propagates through a current plasma sheath, there arises different phenomena depending on the characteristic times.

When $t < L/v_g$ the observed processes are similar to the semi- infinite current-free plasma sheath.

In the steady case the electrostatic field depends on the damping rate alone. The influence of the current is taken into account by a small functional variation of the density perturbations and generated electrostatic fields.

It is shown that in the non-steady case, the wave front propagation process in the plasma sheath creates surface waves near its boundaries and space damped electrostatic fields. These phenomena depend on the characteristic times considered.

References

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