Negative potential barrier effects in a collisional ion-beam dusty plasma

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Recibido el 15 de enero de 2002; aceptado el 10 de mayo de 2002

In this paper, several effects observed in the ion-acoustic instability induced by a negative dusty particle barrier, are described. We derive the dispersion relation in a one dimensional ion-beam plasma system using our fluid-kinetic-algebraic treatment taking into account forces due to the large negative charge of the dust particles in a stationary regime. That means that fluctuations of charge of dust particles are neglected. Considering a simple model where dust particles can be considered as immobile and the presence of collisions is taken into account, we calculate modes and instabilities to analyze this new effect.

Keywords: Dusty plasma; particle beam interaction in plasma.

En este trabajo, se describen varios efectos que se generan en la inestabilidad iónica-acústica en presencia de un chorro inducidas por una barrera de gránulos negativos. Se deduce una relación de dispersión unidimensional en el sistema chorro-plasma usando nuestro tratamiento algebraico fluído-cinético, tomando en cuenta las fuerzas de interacción debido a la barrera granular negativa en su estado estacionario. Esto significa que no tomamos en cuenta fluctuaciones de carga en la misma. Considerando ahora, un modelo sencillo, en donde los gránulos están quietos y tomando en cuenta las colisiones, calculamos los modos y la inestabilidad para analizar estos nuevos efectos.

Descriptores: Plasmas granulares; interacción chorro-plasma.

PACS: 52.25.Zb; 52.40.Mj

1. Introduction

The study of dusty plasma systems is now in vigorous growing and therefore many experiments and theoretical approaches has been developed in order to observe different modes of propagation through the plasma. Recent laboratory experiments show ion-acoustic waves and dust-acoustic waves. Due to the applications in space-plasmas, industrial-plasma, etc, the study of nonlinear physics and instabilities in dusty plasmas systems are of great importance today. The focus of the present work is mainly dedicated to analyze the ion-acoustic instability in the presence of an ion beam of relative low ion concentration against the electron density. Considering the dust particle as immobile and negatively charged in the equilibrium state, this negative barrier create a potential that accelerate the beam. In order to treat our multicomponent system we use a hybrid model, where electrons and dusty are treated as fluid and ions and beam kinetically, that is in our knowledge, a simpler form to treat this multicomponent system. The self-consistent electric field is obtained from an ambipolar field equations together with the momentum and continuity equations. Now the relations here obtained could be inserted in the Vlasov relations to obtain the dispersion relation. This can be solved using our multicomponent numerical procedure, described in earlier papers [1-3].

\[ m_\beta n_\beta \{ \frac{\partial \vec{v}_\beta}{\partial t} + (\vec{v}_\beta \cdot \vec{\nabla}) \vec{v}_\beta \} = -e n_\beta \vec{E}, \]
\[ \frac{\partial n_\beta}{\partial t} + \vec{\nabla} \cdot (n_\beta \vec{v}_\beta) = 0, \]

where \( m_\beta, n_\beta, \vec{v}_\beta, \vec{E} \) are the mass, the particle density, fluid velocity and electric field, with \( \beta = e \) (electron) and \( d \) (dust).

Using now the Vlasov equation linearized, we get

\[ \frac{\partial f^{(1)}_\alpha}{\partial t} + \vec{v} \frac{\partial f^{(1)}_\alpha}{\partial \vec{v}} + \frac{Z_\alpha e E^{(1)}}{m_\alpha} \frac{\partial f^{(0)}_\alpha}{\partial \vec{v}} = -\nu_\alpha f^{(1)}_\alpha, \]

where \( \alpha = i \) (ion) and \( b \) (beam). In order to determine \( f^{(1)}_\alpha \) we use the plane wave approach \( \exp[i(kz - \omega t)] \), obtaining

\[ f^{(1)}_\alpha = -\frac{Z_\alpha e E^{(1)} f^{(0)}_\alpha}{im_\alpha (kv - \omega + iv)}. \]

We assume that ion and beam follows a Maxwellian distribution function in the

\[ f^{(0)}_\alpha(v) = n^{(0)}_\alpha \frac{m_\alpha}{2\pi K_B T_\alpha} \frac{1}{2} \exp \left\{ -\frac{m_\alpha (v - v_\alpha)^2}{2K_B T_\alpha} \right\}. \]

The electric field \( \vec{E} \) could be determined from the ambipolar equation,

\[ Z_\alpha e \vec{E} = \frac{1}{n_\alpha} \vec{\nabla} p_\alpha + \nu_\alpha n_\alpha \vec{v}_\alpha + \vec{F}_{ad}, \]

here \( \vec{F}_{ad} \) is the coulomb force between beam particles and dust, \( \nu_\alpha \) is the collision frequency.

2. Theoretical model

Using the momentum and fluid equations together with ambipolar field equation allows us to write down,
We can write the linearized quasineutrality equation assuming that dust particles are at rest and its mass is very high compared with the mass of electrons and we neglect charge fluctuations \((Z_d = Z_d^{(0)})\),
\[
n_e^{(1)} + Z_d^{(0)} n_d^{(0)} \cong n_e^{(1)} + n_{ba}^{(1)}.
\]

3. Derivation of the dispersion relation

Using the fluid model and the kinetic model, with the previous simplification, we can write the dispersion relation in the following form:
\[
0 = 1 + \frac{N_i \theta_i \Omega^2 (1 + \zeta_d Z_d^{(0)})}{M_i N_i K^2} + \frac{N_i \Omega^2 (1 + \zeta_d Z_d^{(0)})}{M_i N_i K^2} - 4 \pi i N_d \theta_e \lambda_{De}^3 \left\{ \frac{(2 + 2 N_i Z_d^{(0)}) - N_d(2 + \theta_d) \theta_i \Omega^2}{(M_i N_1 K(NZ_i \theta_i - 4 \pi i N_i n_e^{(0)} K \lambda_{De}^3))} \right\} - \frac{(-N + N_i \theta_i) \Omega^2 \zeta_d Z_d^{(0)}}{(M_i N_1 K(NZ_i \theta_i - 4 \pi i N_i n_e^{(0)} K \lambda_{De}^3))}
\]
where
\[
\begin{align*}
N1 &\equiv N_b + N_i - N_d Z_d^{(0)}, &\theta_i &\equiv \frac{T_e}{T_i}, &\theta_b &\equiv \frac{T_i}{T_b}, \\
N_b &\equiv -1 + N_b + N_i - N_d Z_d^{(0)}, &N_{i,d} &\equiv \frac{n_{i,d}(0)}{n_e}, \\
M_i &\equiv \frac{m_i}{m_e}, &\nu &\equiv \frac{v_{id}}{\omega_{pi}}, &\Omega &\equiv \omega_{pi}, &\omega_{ps} &\equiv \sqrt{\frac{\epsilon_i^2 n_i}{m_i \epsilon_0 e}}, \\
\kappa &\equiv \frac{\kappa}{\kappa_{De}} \equiv \kappa \lambda_{De}, &\lambda_{De} &\equiv \frac{\sqrt{\epsilon_i^2 n_i}}{\epsilon_0 K_B T_e}, \\
Z(\zeta_a) &\equiv \Sigma_i \frac{b_i}{\zeta_a - a_i}, &\zeta_a &\equiv \frac{\omega^*/\kappa - \nu_a}{\nu_{th,a}}, &\omega^* &\equiv \omega - i \nu.
\end{align*}
\]

with: \(n_{i,d}\) is the particle density, \(T_i, T_b\) and \(T_e\) are the ion, beam and electron temperature, \(m_i\) and \(m_e\) are the masses of ion and electron, \(v_{id}\) is the collision frequency between ion and dust particles, \(\omega_{pi}\) is the ionic frequency, \(\kappa_{De}\) and \(\lambda_{De}\) are the Debye number and length, \(Z(\zeta_a)\) is the multipole approximation for the plasma dispersion function \(Z\) and \(\nu_{th,a}\) is thermal velocity.

4. Results and conclusion

The numerical computation method for an Argon (Ar) dusty plasma system with a beam was carried out in 1D, finding good agreement with the experiments (Figs. 1 and 2, with \(\theta_i = 20, \theta_b = 10, K = 0.1\), and \(Z_d^{(0)} = 4 \times 10^2\)). For this dusty plasma, the ion-acoustic instability increases considerably if the particle concentration of the beam \(n_b\) and dust \(N_d\) are low with respect to \(n_e\). We introduce a new algebraic and fast theoretical model for the analysis of the time instability of the ion-acoustic waves. On the other hand, the negative barrier formed by particles of dust affects the ion-acoustic instability, observing a decreasing of the time growth rate in the beam-dusty plasma system. We define this model as a hybrid model, due to the application of the fluid-kinetic model in or-
Figure 2. Propagation of modes in the Ar plasma system.

Figure 3. Dispersion relation in the Ar dusty plasma system. $T_e/T_i = 10$ and $Z_d \approx 10^3$. Where P1, P2 and P3 are experimental points.


