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A ionization instability in weakly ionized unmagnetized plasmas with negatively charged dust grains

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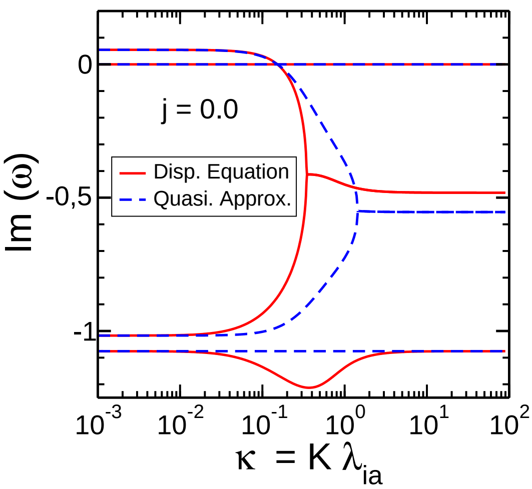
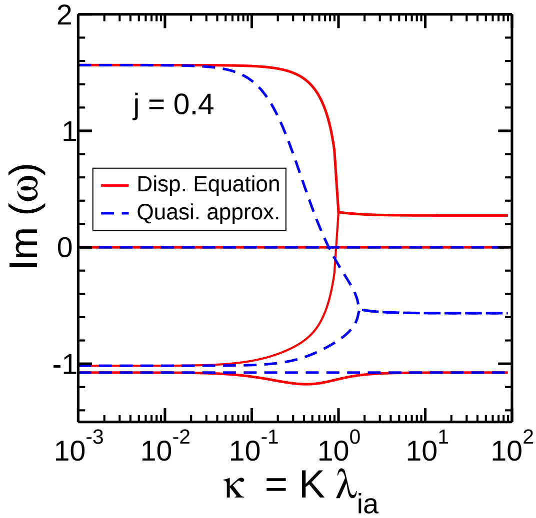


The investigation of ionization instabilities in weakly ionized dusty plasmas using multifluid formulations is a subject current interest [1, 2, 4]. Small carbon particles in fusion devices have been also detected at the edge of tokamaks by Thomson scattering where additionally high energy electrons are present [3]. In dust free plasmas the injection of a suprathermal electron current density $J_{eb} = -e\Gamma_{eb}(E_b)$ with energy over the ionization threshold $E_I < E_b$ of the neutral gas may unstabilize the equilibrium state. The charge production by thermal $\nu_I n_{eo}$ electron population and by energized electrons $G_o = \nu_I n_{eo} + n_a \sigma_{eb} \Gamma_{eb}$ is balanced by loss rate $R_o = \nu_L n_{io}$ [5].

$$n_a \Gamma_{eb}(E_b)\, \sigma_{Ib} + \nu_I n_{eo} = \nu_L n_{io} \qquad (1)$$



In present model the equations are essentially those of Ref. [4] with an additional charge source term for the high energy electron beam. The electron impact ionization cross section is approximated by $\sigma_I(E) \cong \sigma_{eb} + C\,(E - E_b)$ and the cross section σ_{ia} for elastic collisions between ions and neutrals is considered as constant, as well as the corresponding frequency $\nu_{ia} = \sigma_{ia} n_{io}$.

The plasma potential fluctuations are related with charged particle densities by means of the more involved Poisson equation instead of the currently used quasineutral approximation.

The dimensionless multifluid equations [2a-f] are obtained using the characteristic time $\tau = 1/\nu_{ia}$ and length $s = z/\lambda_{ia}$ scales for elastic collisions between ions and neutral atoms. The electric potential φ is scaled as $\phi = e\varphi/K_B T_e$ and the charged particle densities are normalized with respect to their equilibrium values $N_\alpha = n_\alpha/n_{\alpha o}$ ($\alpha = i, e, d$). Finally, the ion and dust speeds are scaled with respect to ion sound speed $V_i = u_i/c_{is}$, $V_d = u_d/c_{is}$ in order to preserve the same time scale and is introduced the ratio $\rho = \lambda_D/\lambda_{ia}$.

Thus, in these scaled transport equations the relevance of the different terms could be calculated according to the values of collision frequencies ($\nu_{ia}, \nu_{id}, \nu_{di}, \nu_{da}$ and ν_{ad}) between all heavy species in the plasma.

The dimensionless equations respectively for dust grains, ions and thermal electrons are,

$$\frac{\partial N_d}{\partial \tau} + \frac{\partial}{\partial s}(N_d V_d) = 0 \tag{2a}$$

$$N_d\left(\frac{\partial V_d}{\partial \tau} + V_d\frac{\partial V_d}{\partial s}\right) - Z_d\left(\frac{m_i}{m_d}\right)N_d\frac{\partial \phi}{\partial s} + \left(\frac{\nu_{da}}{\nu_{ia}}\right)V_d N_d + \left(\frac{\nu_{di}}{\nu_{ia}}\right)N_d(V_d - V_i) = 0 \tag{2b}$$

$$\frac{\partial N_i}{\partial \tau} + \frac{\partial}{\partial s}(N_i V_i) = F_o \tag{2c}$$

$$N_i\left(\frac{\partial V_i}{\partial \tau} + V_i\frac{\partial V_i}{\partial s}\right) + N_i\frac{\partial \phi}{\partial s} + \left(\frac{T_i}{T_e}\right)\frac{\partial N_i}{\partial s} + N_i V_i + F_o V_i + \left(\frac{\nu_{id}}{\nu_{ia}}\right)N_i(V_i - V_d) = 0 \tag{2d}$$

$$N_e = \exp(\phi) \tag{2e}$$

$$\rho^2\frac{\partial^2\phi}{\partial s^2} = N_e + Z_d\frac{n_{do}}{n_{eo}}N_d - \frac{n_{io}}{n_{eo}}N_i \tag{2f}$$

where the right term in Eq. [2c] $F_o = (G - R_o)/\nu_{ia} n_{io}$ is,

$$F_o = \frac{n_{eo}}{n_{io}}\left(\frac{\nu_I}{\nu_{ia}}N_e + h_o(j) + h_1(j)\,\phi\right) - \frac{\nu_L}{\nu_{ia}}N_i \tag{3}$$

The following dimensionless parameters are related with the ionizations produced by the electron beam,

$$h_o(j) = \frac{\sigma_{Ib}}{\sigma_{ia}}\sqrt{\frac{2m_i}{m_e}}\frac{J_{eb}}{J_{eT}} \qquad h_1(j) = \frac{CK_B T_e}{\sigma_{ia}}\sqrt{\frac{2m_i}{m_e}}\frac{J_{eb}}{J_{eT}}$$

where J_{eT} is the electron thermal current density.

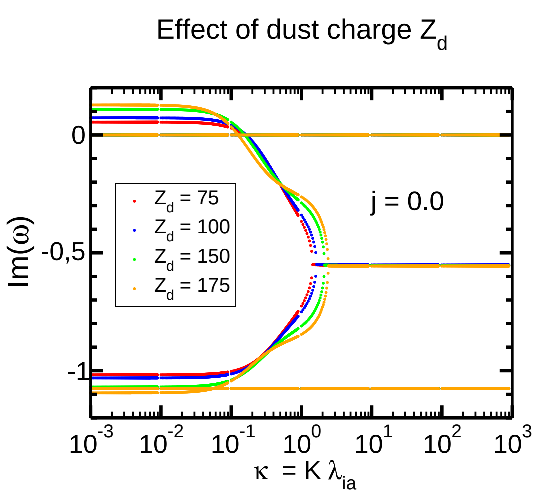
The dimensionless equilibrium equation equivalent to Eq.[1] is,

$$\frac{n_{eo}}{n_{io}}\left(h_o(j)+\frac{\nu_I}{\nu_{ia}}\right)=\frac{\nu_L}{\nu_{ia}}. \tag{4}$$

and the different equilibrium states depend on j and Eq. [4] permits to eliminate the ion losses ν_L which rely on particular experimental details.

The general dispersion relation resulting from the linearized equations deduced from Eqs. [2a-f] depends on the dimensionless wave number $\kappa = K\lambda_{ia}$ and growth rate $\omega = \Omega/\nu_{ia}$. In the long wave length limit ($K\lambda_D \simeq 0$) is recovered the dispersion relation obtained using the quasineutral approximation and setting also $j_{eb} = 0$ the so called *ionization continuum model* [4, 6].

The numerical solutions of both dispersion equations are compared in Figures 1 and 2 for two values of the ratio $j = J_{eb}/J_{eT}$ and in these calculations are used the experimental data of Ref. [4]. Then, the smallness of the dimensionless ratios $\nu_{id}/\nu_{ia} \simeq 10^{-7}$ and $\nu_{di}/\nu_{ia} \simeq 10^{-2}$ compared with $(\nu_{da}+\nu_{di})/\nu_{ia} \simeq 1$ and $(\nu_{ia}+\nu_{id})/\nu_{ia} \simeq 1$ lead to an approximate dispersion relation where only three roots are different from zero.Thus, the more important friction forces are those between dust grains and ions and neutral gas background with dust particles.



Contrary to dust free plasmas the ionization instability is triggered even for $J_{eb} = 0$ as shown in Figure 1. This fact is caused because of the imbalance between the equilibrium electron and ion densities ($n_{io} > n_{eo}$) originated by the negative charge of dust grains, which unstabilizes all equilibrium states from $\kappa = 0$, even in the absence of the ionizing electron beam. The electric field fluctuations become amplified by the negative charge of dust particles contrary to dust free plasmas [5].

The unstable root with ($Im(\omega) > 0$) of the dispersion equation present an exponential aperiodic ($Re(\omega) = 0$) growth rate and is compared in Figures 1 and 2 with those obtained by using the quasineutral approximation. The unstable positive branch starts at $\kappa = 0$ and joins in a bifurcation point the stable roots. A maximum unstable wave number is obtained related with the minimum allowed length for space charge fluctuations. This is not the case of the solutions of the dispersion equation obtained using the quasineutral approximation where for

$J_{eb} > 0$ an unstable growing amplitude wave is found for large wavenumbers.

In Figure 3 it may be appreciated the effect of the dust charge Z_d in the cutoff unstable wavenumbers holding the equilibrium ion n_{io} and dust n_{do} densities constant. The increments in the negative charge of dust increases the instability growth rates and reduce maximum unstable wavenumber.

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