35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.165 (2008)

Propagation Modes of the Ionization Instability in a Dusty Plasma under Electron Beam Injection

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The interaction of an electron beam with a weakly ionized and complex dusty plasma is a subject of interest for different fields, ranging from material science up to cometary complex plasmas [1] - [9]. When the energy of these fast electrons with current density $J_{eb}(E_b)$ lies over the first ionization energy $E > E_I$ of the background neutral gas, ionization instabilities could be developed [4]-[8]. We deal with the multi-fluid description of a weakly ionized plasma composed of populations of ions, negatively charged dust grains and thermal electrons inmersed into a uniform background of neutral atoms with density n_a at rest. The one-dimensional continuity and momentum transfer transport equations for each plasma species, α using the standard notation, are

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial z}(n_\alpha u_\alpha) = S_\alpha \qquad (1)$$

$$\frac{\partial u_\alpha}{\partial t} + u_\alpha \frac{\partial}{\partial z} u_\alpha + \frac{q_\alpha}{m_\alpha}\frac{\partial \varphi}{\partial z} + \frac{T_\alpha}{m_\alpha n_\alpha}\frac{\partial n_\alpha}{\partial z} = -\sum_\beta \nu_{\alpha\beta}(u_\alpha - u_\beta) - \frac{S_\alpha}{n_\alpha} u_\alpha \qquad (2)$$

The index α stands for positive ions and identical dust grains, $(\alpha = d, i)$ with charges $q_i = e$ and $q_d = -eZ_d$ while β runs for (d, i) and a with $\nu_{\alpha\, e} \simeq 0$. The isothermal electron population with temperature $T_e \gg T_i \gg T_d$ is $n_e = n_{eo}\exp(e\varphi/T_e)$ and $u_e = 0$. Both, the source and sink terms and drag friction forces in Eqs. (1) and (2) are considered by the corresponding collision frequencies $\nu_{\alpha\beta}$. The plasma potential fluctuations are related to the charged particle densities by means of the Poisson equation for the electrostatic plasma potential

$$\frac{\partial^2 \varphi}{\partial z^2} = -4\pi e\,(n_i - n_e - Z\,n_d) \qquad (3)$$

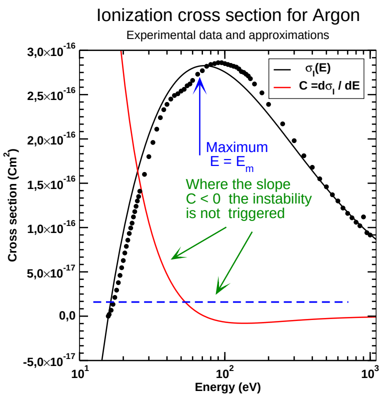

Figure 1: Ionzation cross section for Argon.

The ionizations caused by the electron beam with particle flux $\Gamma(E)$ (current density $J_{eb} = -e\Gamma$) and ion losses $\nu_L\, n_i$ are considered in the ion source - sink term $S_i = \nu_I\, n_e + n_a\, \sigma_I(E)\,\Gamma(E) - \nu_L\, n_i$, while the almost point grain charging equations are neglected, $S_d = 0$ [6, 7, 8, 9].

The ionization frequency ν_I and the electron impact ionization cross-section of neutrals $\sigma_I(E)$ account for the ion production by both ionizing thermal and injected non-thermal electrons. Note that the ionization cross section and beam current density J_{eb} depend on the electron beam energy $E_b > E_I$, consequently, the effects of the beam source term strongly depends on E_b and $\sigma_I(E_b)$ variations.

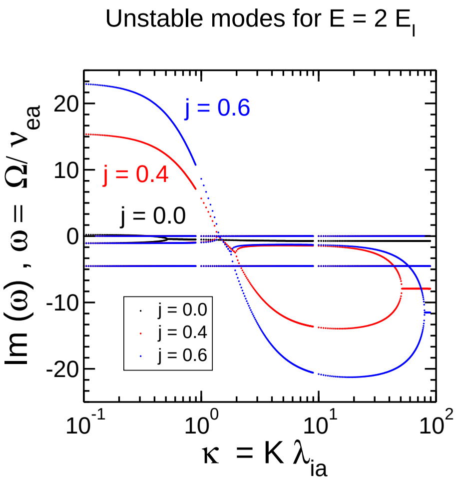

Figure 2: Imaginary part of normalized frequency versus wave number. For $E_b > E_m$ (positive χ) the instability growth rate increases for $j \geq 0$.

We follow the previous work [9] in the stability analysis and Eqs. (1), (2) and (3) are linearized and Fourier transformed using the phasor $\exp(-i\omega t + kz)$. In the equilibrium state, the temperatures T_α and densities $n_{\alpha o}$ are uniform whereas all particle populations ($u_{\alpha o} = 0$) remain at rest. Thus, with $\nu_\alpha = \sum_\beta \nu_{\alpha,\beta}$ and on taking $x = x_{eq} + \delta x$ for any variable, and we will obtain the following linearized equations,

$$-i\,\omega\,\tilde{n}_\alpha + i\,k\,n_{\alpha o}\,\tilde{u}_\alpha = \tilde{S}_\alpha \tag{4}$$

$$(\nu_\alpha - i\,\omega)\,\tilde{u}_\alpha + i\,k\left(\frac{T_e\,q_\alpha\,\tilde{n}_e}{e\,n_{eo}\,m_\alpha} + \frac{\tilde{n}_\alpha T_\alpha}{m_\alpha\,n_{eo}}\right) = \sum_{\alpha\neq\beta} \nu_{\alpha\beta}\,\tilde{u}_\beta \tag{5}$$

where tilded variables are the Fourier transformed perturbation amplitudes δx. The ion source term $\tilde{S}_i$ is currently calculated under the assumption of a uniform incident flux,

$$\Gamma(E_b) = n_b\,u_b = n_b\,(2e\varphi_b/m)^{1/2}$$

of ionizing electrons, where n_b is the beam density with energy $E_b = e\varphi_b$ greater than the ionization energy I of the neutral background atoms [4, 5, 9]. Alternatively, because of the beam energy fluctuations, $E_b + e\delta\varphi$, the non-thermal electron population n_{eb} also varies, thus, assuming Γ as divergence-free inside the plasma, we have $\delta\Gamma = u_{eb}\,\delta n_{eb} + n_{eb}\,\delta u_{eb} = 0$ at first approximation. Therefore, $\delta n_{eb} = -n_{eb}\,(\delta\varphi/2\varphi_b)$ modifies the global electron density and also contributes to charge space effects in Eq. (3). In addition, for the electron impact cross section we have, $\delta\sigma_I = (d\sigma_I(E_b)/dE_b)\,\delta E_b$ with $\delta E_b = e\delta\varphi$. This leads us to a more involved linearized ion source term,

$$\tilde{S}_i = \nu_I\left(1 + \frac{n_b\,\sigma_I(E_b)\,\Gamma}{n_{eo}\,\nu_I}\,\chi\right)\tilde{n}_e - \nu_L\,\tilde{n}_i = \nu_I\,(\,1 + j\,\chi) - \nu_L\,\tilde{n}_i = \nu_I^*(j)\,\tilde{n}_e - \nu_L\,\tilde{n}_i \tag{6}$$

where $j = \tilde{n}_{eb}\,\sigma_I(E_b)\,\Gamma/\nu_I$ is the dimensionless electron beam current density where the function $\nu_I^*(j)$ works as an effective ionization collision frequency and the dimensionless factor

$$\chi = \left(\frac{T_e}{\sigma_I(E_b)}\right)\frac{d\sigma_I}{dE_b}$$

accounts for the slope of $\sigma_I(E_b)$ which strongly depends on the value of the electron beam energy E_b as shown in Fig. 1. Therefore, the current $J_{eb} = -e\Gamma(E_b)$ contributes to or hinders the ionization instability through S_i in accordance with the sign of χ. Using the linearized Poisson equation and the Boltzmann relation for thermal electrons $e\tilde{\varphi} = T_e\tilde{n}_e/n_{eo}$ we obtain $\tilde{n}_e\zeta = (\tilde{n}_i - Z_p\tilde{n}_d)$, where the dimensionless correction factor ζ is related to charge fluctuations induced by n_{eb}, being $\zeta \simeq 1 + k^2\lambda_{De}^2 - n_b T_e/(n_{eo}e\varphi_b)$.

The dimensionless dispersion equation for $\omega(\kappa)$ is calculated from Eqs. (4) and (5) using the ion source term of Eq.(6). The collision frequency ν_{ea} is used which leads to the frequency $\omega = \Omega/\nu_{ea}$, and the corresponding mean free path λ_{ea} is used for the lengths leading to the scaled wavenumer $\kappa = K\lambda_{ea}$. The results are similar to those of Ref. [9], but with $\nu_I^*(j)$ instead of a constant ionization frequency ν_I only related with ionizations by thermal electrons.

In the linear analysis the ionization instability is triggered for $\operatorname{Im}\omega(\kappa) > 0$ and both, the incident beam energy E_b and $d\sigma_I/dE$ critically control the unstable modes through $\nu_I^*(j)$ in Eq.(6).

Fig. 2 shows that significant departures from the equilibrium (unstable modes) are observed for $E_b = 2E_I$ with positive χ, the larger values of $j \geq 0$ increase the scaled instability growth rate $\operatorname{Im}\omega(\kappa)$. On the contrary, the unstable positive branch is only found in Fig. 3 for $j = 0$ when $E_b = 5E_I$ where χ is negative. Therefore, for electron beam energies $E_b > E_m$ the system is stabilized by increments in the current density $j > 0$ as suggested by Eq.(6). Moreover, the effect of this ionizing electron current would disappears for $E_b = E_m$.

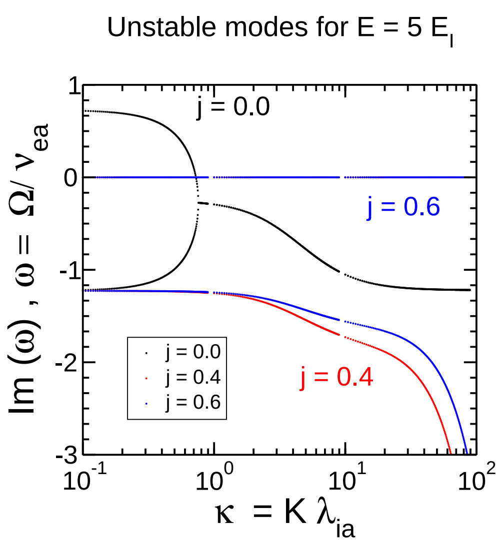

Figure 3: Contrary to Fig. 2 for $E_b > E_m$ (negative χ) the roots of $\omega(\kappa)$ lead to stable branches for $j > 0$.

We conclude that the decreasing dependence of the electron impact ionization cross section with energy leads to an stabilizing effect, and restricts the energy range and amplitude rate for the ionization instability.

In addition, χ also controls the dust frequency modes. The resonant destabilization for growing of dust acoustic (DA) modes [8, 9] coupled to dust ion acoustic modes (DIA) can be enhanced or reduced since the asymtotic condition,

$$K^2\left(C_{DIA}^2+\frac{T_i}{m_i}\right)=\left(\frac{n_{io}}{n_{eo}}-1\right)\nu_i\,\nu_L$$

where C_{DIA}, is the dust ion acoustic speed, changes into a more challenging non-conclusive one,

$$K^2\left(\frac{C_{IA}^2}{\zeta}+\frac{T_i}{m_i}\right)=\left(\frac{1+j\,\chi}{(1+j)\,\zeta}\,\frac{n_{io}}{n_{eo}}-1\right)\nu_i\,\nu_L$$

which is reduced to the former expression for $j=0$ and $\zeta=1$. Finally, although the energy of the electron beam is controlled in the experiments, the accelerated electrons at the high potential side of a double layer also excite ionization instabilities [3, 4, 5]. We stress here that the current J_{eb} can also originate from the jump in plasma potential and most of the previous conclusions would be also valid for anodic double layers [10].

Acknowledgements: This paper is supported by the Spanish Government under Grants HU2005-0022, ENE2007-67406-C01 and ENE2007-67406-C02.. The support by the Austrian Academy Exchange Service and the exchange programme is also gratefully acknowledged.

References

[1] L. Lamelle, L. Beaunier, S. Borensztajn, M. Fialin and F. Guyot, Geochimica et Cosmochimica Acta, **67**, (10), 191–201 (2003). M.N. Vasiliev and A.H. Mahir, Surface & Coatings Technology, **180-181**, 132 (2004). V.N. Babichev, A.F. Pal', A.N. Starostin, A.V. Filippov and V.E. Fortov, JETP Letters, **80**, 241 (2004).

[2] G. E. Morfill and V. N. Tsytovich and H. Thomas, Plasma Phys. Rep. **26**, pp. 690 (2000).

[3] J.C. Johnson, N. D'Angelo and R.L. Merlino, J. Phys. D **23**, 682 (1990).

[4] L. Conde, Phys. Plasmas, **11**, 1955 (2004).

[5] A. Aanesland, C. Charles, M.A. Lieberman and R.W. Boswell, Phys. Rev. Letters, **97**, 075003 (2006).

[6] P. K. Shukla and G. Morfill, Phys. Letters A, **216**, pp. 153-156 (1996).

[7] N. D'Angelo, Phys. Plasmas, **4**, (9), 3422 (1997)

[8] X. Wang, A. Bhattachragee, S. K. Gou and J. Goree, Phys. Plasmas, **8**, 5018 (2001).

[9] L. Conde, Phys. Plasmas, **13**, 032104 (2006).

[10] R. Stenzel, C. Ionita and R. Schrittwieser, Plasma Sources Sci. Technol., **17**, 035006 (2008).