HIGH-FREQUENCY SURFACE WAVES IN DUST-CONTAINING PLASMAS

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The comprehensive studies of collective processes in bounded plasmas are stimulated by significant success achieved in recent years by new low-temperature plasma technologies [1]. Many low-temperature technological plasma are contaminated by highly charged impurities or dust. The presence of the latter is naturally caused by erosion of the processed surfaces or polymerization in the gaseous phase [2]. Therefore, the modelling of dust-contaminated gas discharges is actual. The massive (in comparison with the plasma ions) particles significantly affect the charge balance in plasmas, accumulating the considerable amount of negative charge and producing the specific dust-charge fluctuations [3]. The problem of influence of dust on dispersion characteristics of plasma waves needs detailed examination, and there are many important factors significantly affecting the process. Specifically, we would like to emphazise the open character of plasma-dust system demanding rigorous account of collision mechanisms specific to dust-contaminated plasmas, especially those leading to plasma recombination (“sinks"). The account of the latter is natural for open systems like most of gas discharges.

Here we address the problem of electrostatic high-frequency surface waves propagation at the interface between a dusty plasma and a dielectric. The variable charge of immobile heavy dust particles is taken into account because the the balance between the ionization and recombination processes maintainig the equilibrium plasma density in a discharge is perturbed. Under these conditions we consider perturbations of the stationary plasma currents onto the dust grains’ surfaces due to the difference between the values of the electrostatic potential at the grain surface and of the local plasma, the additional sink of electrons to the grains induced by the high-frequency wave fields, and the corresponding viscosity effects. The latter are connected with the electron-neutral collisions which usually dominate in a wide range of operating gas pressures, the Coulomb elastic electron-dust collisions and the effective frequency of electrons momentum variation due to the charging collisions of plasma electrons with dust grains. It is shown here that all the above factors lead to a significant damping of SWs.

Consider the high-frequency surface waves propagating at the interface between the cold and isotropic plasma $x > 0$ and a dielectric with a dielectric permeability $\epsilon_0(x < 0)$. The size of dust particles is supposed to be significantly less than the interparticle distance, electron Debye radius as well as the wavelength and the skin depth of the SW. Under the assumptions the dust grains can be considered as heavy (compared with the plasma ions) point masses. Since the high-frequency SWs are considered, the time scale of the grains charge variation can be several orders of magnitude less than the characteristic time scales for dust particles motions. Thus, the dust grains are treated as an immobile background. Equations describing the propagation of high-frequency (ion motions are also neglected for the studied perturbations) surface waves are

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = -\nu_{ed} n_e + \nu_i n_e - \beta n_e^2 + \beta_{si} n_e^2 + \nabla \cdot (D_a \nabla n_e), \tag{1}$$

$$\frac{\partial \mathbf{v}_e}{\partial t} + \nu_{eff} \mathbf{v}_e = -\frac{e}{m_e}\mathbf{E}, \tag{2}$$

$$\nabla \cdot \mathbf{E} = 4\pi \sum_j Z_j e n_j, \tag{3}$$

where $\mathbf{E}$ is the electric field of the SW, m_j, n_j, $\mathbf{v}_j$, and $q = Z_j e$ are the mass, density, fluid velocity, and charge of the species $j = e, i, d$, respectively. In Eq. (1), ν_{ed} is the collection rate of plasma electrons by dust grains, ν_i is the ionization frequency, β is the volume recombination rate, β_{si} is the step-wise ionisation rate, and D_a is the ambipolar diffusion coefficient. In Equation (2) we have $\nu_{eff} = \nu_{en} + \nu_e^{el} + \nu_e^{ch}$, which is the effective electron collision frequency incorporating the electron-neutral collision frequency ν_{en}, the frequency of Coulomb elastic electron-dust collisions ν_{el} and the effective frequency of charging collisions (collection of plasma particles by dust) ν_e^{ch}.

We consider the electrostatic limit ($\mathbf{E} = -\nabla\varphi$, where φ is the electrostatic potential of the SW). It is assumed that the SW's of interest propagate along the interface $x = 0$ in z direction. In the absence of the electrostatic perturbations, the quasi-neutrality condition of a plasma containing charged dust is $Z_i n_{i0} = n_{e0} + Z_d n_{d0}$. The dust-charge relaxation process is described by the following charge balance equation [3]:

$$d_t q_d = I_e(q_d) + I_i(q_d), \tag{4}$$

where q_d is the average charge on the dust grain, and $I_e(q_d)$ and $I_i(q_d)$ are the electron and ion grain currents flowing into the grain surface. The dust quantities q_d, I_e and I_i contain the steady-state and perturbed components so that $q_d = q_{d0} + q_{d1}$, $I_e = I_{e0} + I_{e1}$, $I_i = I_{i0} + I_{i1}$. Here I_{e0} and I_{i0} are the steady-state electron and ion currents at the grain surface and the stationary charge of the grain, respectively.

Note that for high-frequency perturbations we can neglect perturbations of the microscopic ion current in comparison with those of the electron one: $I_{i1} \ll I_{e1}$. Therefore, the equation for the perturbed dust charge is

$$d_t q_{d1} + \nu_{\rm ch} q_{d1} = -|I_{e0}| n_{e1}/n_{e0}, \tag{5}$$

where $\nu_{\rm ch}$ is the charging rate of the dust particle [3], defined by the equilibrium electron and ion microscopic currents. The effective charging frequency ν_e^{ch}, the electron capture rate onto the grain surface ν_{ed} as well as the frequency of Coulomb elastic electron-dust collisions ν_{el} can be found in Ref. [3, 4]. The expressions for the electron-neutral collisional frequency ν_{en} as well as for the quantities ν_i, β, β_{si} and D_a incorporated in Eq. (1) are given in Ref. [5]. The set of equations (1), (2), (3), and (5) describes the coupling process between the high-frequency electrostatic SW and the dust-charge relaxation process (DCRP).

Electron continuity equation (1) allows us to determine the stationary electron plasma density in a discharge in the absence of perturbations such as high-frequency SWs. Here, we assume that the pressure is not very low so that the recombination losses in a plasma volume prevail over diffusion ones and do not take into account the last term in Eq. (1). In the zeroth approximation, we obtain from Eq. (1) the equilibrium electron density $n_{e0} = (\nu_i - \nu_{ed})/\beta_{eff}$, where $\beta_{eff} = \beta - \beta_{si}$. It is instructive to notice that the equilibrium electron density in dust-contaminated discharge is smaller than that in the dust-free discharge by the factor proportional to the capture rate of plasma electrons by dust ν_{ed}. Moreover, the ionization degree in the discharge chamber must be relatively high ensuring the realization of the inequality $\nu_i > \nu_{ed}$, otherwise the stationary state does not exist.

After linearization with respect to the wave perturbations, Eq. (1) is reduced to

$$\frac{\partial n_{e1}}{\partial t} + n_{e0}\nabla\cdot\mathbf{v}_e = -\nu_{ed}(Z_{d0})n_{e1} + n_{e0}\frac{\partial\nu_{ed}}{\partial Z_d}|_{Z_{d0}}Z_{d1} - 2\beta_{eff}n_{e0}n_{e1} + \xi_1\nu_i n_{e1} \qquad (6)$$

where n_{e1} and Z_{d1} are the perturbations of the electron density and dust charge, respectively, and the coefficient ξ_1 depends on the used model of the direct ionization. Below, we consider two cases, namely, the constant ionization rate model, $\xi_1 = 0$, as well as the density-dependent ionization rate model $\xi_1 = 1$. For the electrostatic high-frequency wave perturbations from Poisson's equation (3) one can easily obtain the perturbed electron density $n_{e1} = (1/4\pi e)\nabla^2\varphi + Z_{d1}n_{d0}$. The equation describing the DCRP is then

$$d_t q_{d1} + \nu^*_{\text{ch}} q_{d1} = -\frac{|I_{e0}|}{4\pi e n_{e0}}\nabla^2\varphi, \qquad (7)$$

where $\nu^*_{\text{ch}} = \nu_{\text{ch}} + \tilde{\nu}$, $\tilde{\nu} = |I_{e0}|n_{d0}/en_{e0}$ is the correction of the dust-charge relaxation frequency arising from the perturbation of the electron density.

From Eqs. (2),(3), (6) and (7) for the SW electrostatic potential we easily find

$$\nabla\cdot(\tilde{\epsilon}(\omega)\nabla\varphi) = 0 \qquad (8)$$

where

$$\tilde{\epsilon}(\omega) = 1 - \frac{\omega_{pe}^2}{\eta(\omega + i\nu_{eff})} - \frac{i\tilde{\nu}}{\omega + i\nu^*_{\text{ch}}}\left(1 - \frac{i}{\eta}\frac{n_{e0}}{n_{d0}}\frac{\partial\nu_{ed}}{\partial Z_d}|_{Z_{d0}}\right), \eta = \omega - i\nu_{ed} + \xi_2\nu_i, \xi_2 = 2 - \xi_1.$$

Matching the solutions of Eq. (8) with corresponding boundary conditions at the dusty plasma-dielectric interface we obtain the dispersion relation for high-frequency electrostatic surface oscillations

$$D(\omega)(\omega + i\nu^*_{\text{ch}}) = i\tilde{\nu}\left(\eta + \frac{\omega_{pi}^2 r^3 n_{i0}}{\nu_{\text{ch}}}(1 + \tau + \mathcal{Z})\right), \qquad (9)$$

where $D(\omega) = (\epsilon_0 + 1)\eta - \frac{\omega_{pe}^2}{\omega + i\nu_{eff}}$, $\tau = T_i/T_e$, T_e and T_i are the electron and ion temperatures, $\mathcal{Z} = Z_d e^2/aT_e$. This is the coupling equation connecting the high-frequency surface oscillations and the dust-charging damped mode $\omega = -i\nu'_{\text{ch}}$. In the absence of dust, (9) is reduced to the standard dispersion equation for electrostatic surface waves at the plasma-dielectric interface, which yields the well-known frequency of high-frequency surface electrostatic oscillations $\omega = \omega_{pe}/\sqrt{1 + \epsilon_0}$. Corrections associated with electron thermal motions can be included in (9) straightforwardly.

To follow the influence of variable-charge dust grains on the surface oscillations we assume that the frequency ω exceeds any of quantities $\nu_{eff}, \nu_{ed}, \nu^*_{\text{ch}}$ which characterize the dissipative processes in the system. The validity of this assumption is checked below for typical parameters of gas discharge plasmas. In this case, we suppose $\omega = \omega_L + \delta_1' + i\delta_1''$, where $\omega_L = \omega_{pe}/\sqrt{\epsilon_0 + 1}$. From the coupling equation (9) for δ_1' and δ_1'' we find

$$\delta_1' = -\frac{\tilde{\nu}}{2(1+\epsilon_0)\omega_L}\{\frac{\tilde{\nu}}{1+\epsilon_0} + \frac{\omega_{pi}^2 r^3 n_{i0}}{\nu_{\rm ch}}(1+\tau+\mathcal{Z})\} \quad (10)$$

$$\delta_1'' = \frac{1}{2}\{\frac{\tilde{\nu}}{1+\epsilon_0} - \nu_{eff} - (\xi_2\nu_i - \nu_{ed})\} \quad (11)$$

It follows from Eq. (10) that the frequency downshift takes place for the case considered. Comparing the values $\nu_{eff}, \nu_{ed}, \nu_{\rm ch}^*$ and $\tilde{\nu}$ in Eq. (11) one can easily obtain that accounting of the dust charging dissipative processes leads to increasing of damping of surface oscillations compared with the dust-free case. For the DCRP, assuming $\omega = -i\nu_{\rm ch}^* + i\delta_2$, from Eq. (9) one can show that in most cases the charging rate of dust grains is slightly decreased under the influence of the high-frequency SWs.

The applicability range of the obtained results is illustrated by performing numerical estimations for $\nu_{eff}, \nu_{ed}, \nu_{\rm ch}^*$ and $\tilde{\nu}$ using typical parameters of gas discharges. First, we obtain the ratio $e\Delta\varphi_g/T_e$, which defines the average charge on a dust grain, and, therefore, significantly affects through the quasineutrality condition the ratio n_{d0}/n_{e0}. This ratio can be found from the condition of zero total (i.e., electron plus ion) current flowing onto the grain surface in the absence of high-frequency perturbations. And since the results depend significantly on the type of the operating gas, we perform the numerics for Hydrogen (H_2), Nitrogen (N_2) and Argon (Ar) plasmas. For the given set of parameters characterising the dusty plasma, viz. $T_e \sim 10$ eV, $T_i \sim 1$eV, $r \sim 5\mu$m, $n_{e0} \sim 5 \times 10^{10}$ cm^{-3}, $n_{i0}/n_{e0} = 10$, one can obtain $e\Delta\varphi_g/T_e$: -0.77 (in H_2 plasmas), -1.5 (in N_2 plasmas), -1.71 (in Ar plasmas), the average dust charge Z_{d0}(H_2)= -2.52$\times 10^4$, Z_{d0}(N_2)= -5.37$\times 10^4$, Z_{d0}(Ar)= -6.12$\times 10^4$. For the relative concentrations of dust particles n_{d0}/n_{e0} we thus find 3.6$\times 10^{-4}$ (H_2); 1.68$\times 10^{-4}$ (N_2); 1.74 $\times 10^{-4}$ (Ar), respectively. For all the above cases the estimations show that the inequality $\bar{\nu} \ll \omega$ (the validity condition of our results), where $\bar{\nu}$ represents the dissipative parameters $\nu_{eff}, \nu_{ed}, \nu_{\rm ch}^*$ and $\tilde{\nu}$, is observed. Namely, $\bar{\nu} \sim 3 \times 10^7 - 5 \times 10^8$ sec^{-1}, while $\omega \sim 8 \times 10^9$ sec^{-1}.

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