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Kinetics of low-pressure discharge plasmas containing dust grains

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A spatially averaged model for low-pressure argon discharge plasmas containing dust grains is presented. Using the model we investigate the effects of the dust on the electron and ion number densities, the electron energy distribution, the dust charge, the effective electron temperature, as well as the power losses in the discharge.

An rf 13.56 MHz argon discharge of radius *R* and of length *L* (with *L*<<*R*) containing dust grains is considered. The plasma is composed of electrons, singly charged positive ions Ar^+, and negatively charged dust grains. We assume that the dust particles are all of the same size and are uniformly distributed over the plasma slab and are absent near the plasma boundaries. We consider relatively small dust particles with the radius a_d (50- 200 nm), and the plasma conditions when the distance *d* between the dust grains is much larger than the Debye length. For the present problem the Debye-Hückel potential can be taken as the shielding potential of a dust grain [1]: $\phi(r) \approx \phi_s (a_d / r) \exp[-(r - a_d)/\lambda_D]$, where $\lambda_D = [4\pi e(n_e / T_{eff} + n_i / 2E_0)]^{-1/2}$ is the Debye length, ϕ_s is the potential at the dust surface, n_e and n_i are the electron and ion densities, E_0 (=0.06 eV) and $T_{\rm eff}$ are the average ion energy and the effective electron temperature, respectively. To find the dust charge accumulated on the dust particles the orbit motion limited (OML) approximation is used. We also assume that the electron energy distribution function (EEDF) is essentially isotropic and stationary, and to find the isotropic part of the EEDF $F_0(u)$ (where *u* is the electron energy) the Lorentz approximation is used [2].

For relatively high neutral gas pressures and plasma sizes considered here one can obtain the EEDF from the homogeneous Boltzmann equation[2]:

$$-\frac{2e}{3m_e}\frac{d}{du}\left(\frac{u^{3/2}}{\nu_m(u)}E_{eff}^2(u)\frac{dF_0}{du}\right) = S_{ea}(F) + S_{ee}(F) + S_{ed}(F), \qquad (1)$$

where $E_{eff} = E_p \nu_m(u) / [2(\nu_m^2(u) + \omega^2)]^{1/2}$, ν_m is the collision frequency for momentum transfer, $\omega = 2\pi \times 13.56 MHz$, $E_{\rm p}$ is the electric field sustaining the plasma, and $S_{ea}(F), S_{ee}(F), S_{ed}(F)$ describe the electron atom, electron-electron, and electron-dust collisions, respectively. The electron-dust collision term can be modeled by [3] $S_{ed}(F_0) = \frac{d}{du}\left[\frac{2m_e}{m_d} u^{3/2} \nu_{ed}^e (F_0 + T_d \frac{dF_0}{du})\right] - \nu_{ed}^c F_0 u^{1/2}$, where $\nu_{ed}^e(u)$ and $\nu_{ed}^c(u)$ are the rates of momentum transfer and electron collection in electron-dust collisions, m_e and m_d are the electron and dust grain masses, T_d (=0.026 eV) is the dust temperature (here it is equal to the neutral gas temperature). Here, $\nu_{ed}^e(u) = n_d \sqrt{2eu/m_e}\sigma_{ed}^e$, $\Lambda \approx -\lambda_D T_{eff} / a_d \phi_s$, and $\sigma_{ed}^e = \pi a_d^2 (-\phi_s / u)^2 \exp(2a_d / \lambda_d) \ln \Lambda$. Furthermore, $\nu_{ed}^c(u) = n_d \sqrt{2eu/m_e}\sigma_{ed}^c$, where the electron-dust collection cross-section is $\sigma_{ed}^c = \pi a_d^2 (1 + \phi_s / u)$ for $u \geq -\phi_s$ and 0 for $u < -\phi_s$.

For a given EEDF, the electron current collected by a dust grain in the OML approximation is $I_e = -\pi a_d^2 e n_e \int_{-\phi_s}^{\infty} (1 + \phi_s / \varepsilon)\sqrt{2eu/m_e} F_0(u) \sqrt{u} du$. The ion current is $I_i = \pi a_d^2 e n_i \sqrt{2eE_0 / m_i} (1 - \phi_s / E_0)$. Here it is assumed that the ions are Maxwellian distributed. The dust surface potential is related to the dust charge Z_d by $\phi_s = eZ_d / a_d$. The model assumes that the electron and ion grain currents balance each other, or

$$I_e + I_i = 0, \tag{2}$$

and that the quasineutrality condition

$$n_e + n_d |Z_d| = n_i \tag{3}$$

is satisfied.

To find the averaged electron density, it is necessary to consider the particle and power balance in the discharge. The balance equation for the electrons can be written as

$$D_a \pi^2 / L^2 \approx <\nu^i> - <\nu^c{}_{ed}>, \tag{4}$$

where D_a is the ambipolar diffusion coefficient, ν^i is the ionization frequency. The symbol < > denotes the energy-averaged value.

Multiplying both sides of the Eq. (1) by the electron energy and then integrating over the entire energy range one can obtain the electron power balance equation:

$$\mathrm{Re}(\sigma) E_p^2 / 2en_e \approx 2m_e / m_i < u\nu_m^e > + \sum_j V_j < \nu_j > + 2m_e / m_d < u\nu_{ed}^e > + < u\nu_{ed}^c >, \tag{5}$$

where $\mathrm{Re}(\sigma)$ is the real component of the plasma conductivity, ν_m^e is the electron-neutral momentum transfer collision frequency, $<\nu_j>$ and V_j are the averaged frequency and threshold energy for the j-th nonelastic process. In our study it is assumed that the power absorbed per unit area $P_{in} \approx L\,\mathrm{Re}(\sigma)E_p^2/2$ is fixed.

From Eqs. (1) — (5) the plasma properties were studied for different dust sizes a_d and densities n_d. First, we compare the EEDFs in a dust-free plasma with that in a dust discharge. In Fig. 1 (a) the EEDFs are shown for the dust-free plasma (solid curve) and dust plasma (dashed curve) obtained at the same n_e= 3.2×10^{10} cm^{-3} and E_p=200 V/m as in the dust-free plasma case.

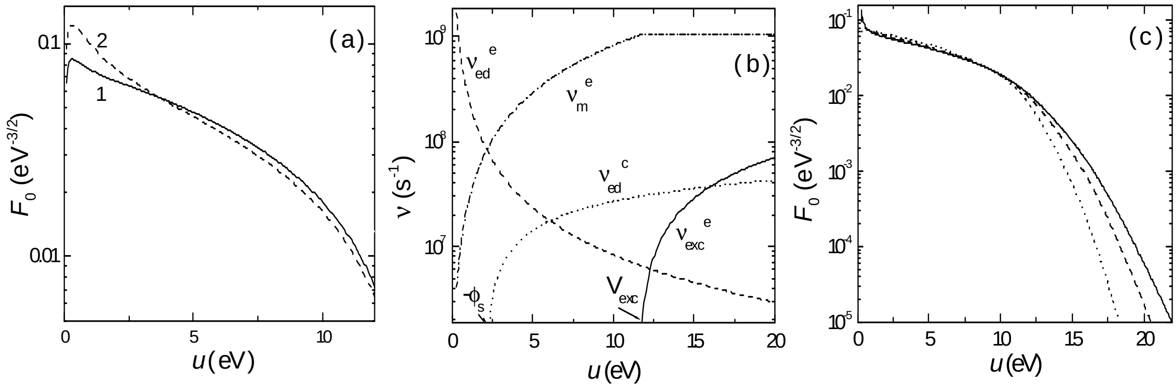

Fig.1. (a): the EEDFs in dust-free (1) and dust (2) plasmas (at n_d=1.5×10^8 cm^{-3}, a_d=200 nm) for the same E_p and n_e ; (b) the collision frequencies in dependence on the electron energy for n_d = 10^8 cm^{-3}, a_d=200 nm at P_{in}=1 W/cm^2; (c) the EEDFs for different dust radii: a_d=200 nm (solid line), a_d=150 nm (dashed line) and a_d=50 nm (dotted line) at P_{in}=0.3 W/cm^2 and n_d=10^7 cm^{-3}. In all the cases p_0=0.1 Torr.

One can see from Fig. 1 (a) that in the dust contaminated plasma (at the same electric field sustained the plasma as in the dust-free discharge) the number of electrons with $u > -\phi_s$ is smaller than that in the pristine (dust-free) discharge. It is due to collection of the electrons by dusty particles. Compared with the pristine plasma in dusty plasmas there appears an additional region of inelastic collisions ($-\phi_s < u <$ V$_{exc}$, where V$_{exc}$ is the excitation threshold energy) [Fig. 1 (b)]. To balance the enhanced electron loss, the electric field sustaining the plasma grows with n_d and/or a_d. At the conditions corresponding to Fig. 1 (c) E_p = 220, 359, and 459 V/m for n_d = 50, 150 and 200 nm, respectively. The rise of E_p increases the number of high-energy electrons in the EEDF tail (see, for example, Fig. 1 (c), where the EEDFs for different dust radii are presented). Due to an increase of the number of high energy electrons the averaged ionization frequency and the effective electron temperature grow with a_d or/and n_d. For parameters of Fig. 1 (c) T_{eff} = 3.87, 4.03 and 4.17 eV for a_d=50, 150, and 200 nm, respectively. The electron density decreases and power deposited on the dust particles increases with a_d and/or n_d (see, for example, Fig.2, where the charged particle densities and power losses as a function of n_d are presented).

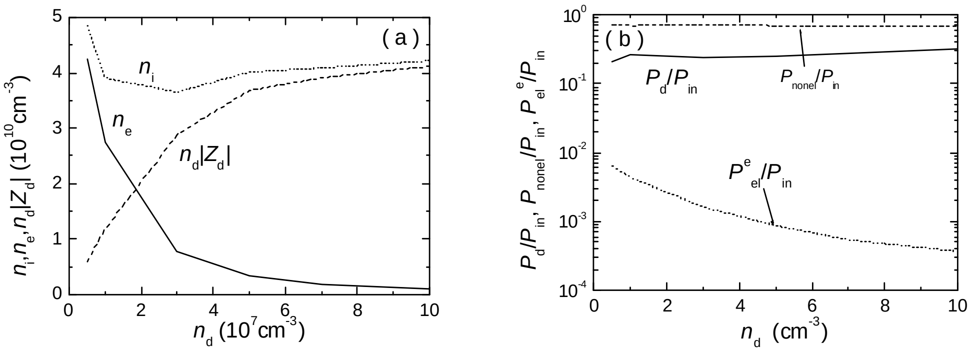

Fig.2. The charged particle densities (a) and power losses (b) in dependence on n_d at P_{in} =1.0 W/cm^2, p_0=0.1 Torr, and a_d= 200 nm. P_d, P_{nonel}, and P_{el}^e are power loss in the nonelastic electron-dust, nonelastic electron-neutral and elastic electron-neutral collisions, respectively.

At high dust densities the power deposited on dust particles can be about 30% of the input power. The decrease of the number of electrons with $u > -\phi_s$ may be also accompanied by changes of the EEDF shape. The Druyvesteyn-like electron energy distribution normally found in pristine plasmas (or at low dust densities and/or sizes) becomes nearly Maxwellian for sufficiently high grain density and/or size (Fig.3).

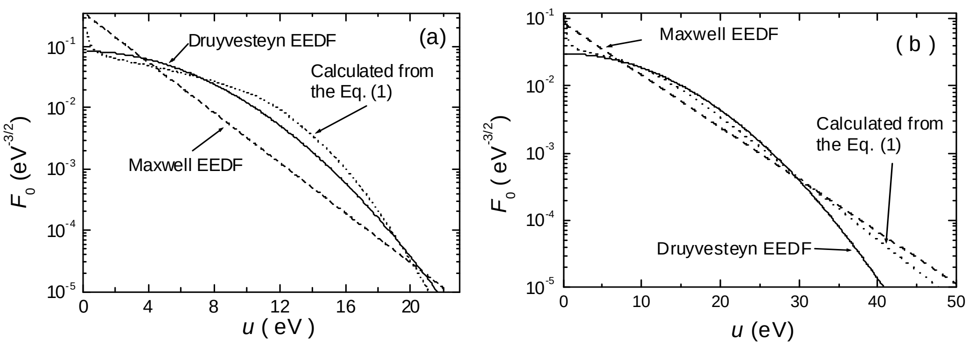

Fig.3. The EEDFs at n_d = 10^7 cm^{-3} (a) and n_d = 10^8 cm^{-3} (b). The other parameters are the same as in Fig. 2. The EEDF calculated from (1) is compared with Maxwell and Druyvesteyn distributions.

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