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Study of Dust Grain Charging in Helium at Elevated Pressures by Nonlocal Moment Method

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Paper [1] was devoted to the study of non-self-sustained atmospheric pressure discharge in helium with the use of dusty particles injected into the discharge area, the diameter of the particles being about 25 μm. In that paper in simulating the charging process of dusty particles it was supposed that there was negligible influence of the dusty field upon electron transport coefficients. The present work was devoted to studying the applicability of this approach. Used in [1], the diffusion-drift approach was also applied for describing the processes of charged particle transfer. At middle and elevated (about atmospheric) pressures the electron energy relaxation length is comparable with the characteristic size of the task, therefore, the electron distribution function becomes a non-local function of coordinates, which considerably complicates the problem of calculating the processes in dusty plasma.

Widely used for calculating the radial profile of potential and densities of charged particles in glow discharges, the so called non-local moment method [2] was applied for taking into consideration the non-locality of the electron distribution function (EDF). The results produced according to this model well agree with the simulation results based on more precise kinetic methods.

In this method it is supposed that transport coefficients and the energy loss rate of electrons are only defined by electron mean energy that is dependent on coordinates and is determined by the electron balance equation. This approximation is valid if electron-electron collisions are dominant, these collisions resulting in maxwellization of the EDF. In the non-local method the self-consistent system of equations for determining the charge of dust particles and the densities of electrons and ions in the vicinity of the dusty particle is as follows:

$$\frac{\partial n_e}{\partial t} + \nabla \mathbf{j}_e = Q_{ion} + \nu_{ion} n_e - \beta_{ei} n_e n_i$$

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$$\frac{\partial n_e \langle \varepsilon_e \rangle}{\partial t} + \nabla \mathbf{h}_e + e \mathbf{j}_e \mathbf{E} = (\eta - I) Q_{ion} - n_e W_S ,$$

$$\nabla \mathbf{E} = 4\pi e \, (n_i - n_e) ,$$

$$\mathbf{j}_e = -\nabla (D_T n_e) - k_e n_e \mathbf{E} , \ \mathbf{j}_i = n_i k_i \mathbf{E} - D_i \nabla n_i , \ \mathbf{h}_e = -\nabla (G n_e) - \beta n_e \mathbf{E} ,$$

where n_e, n_i, $\mathbf{j}_e$, $\mathbf{j}_i$, k_e, k_i, D , D_i are the densities, the fluxes, the mobilities, and the diffusion coefficients of electrons and ions, respectively, Q_{ion} is the rate of the gas ionization by an external source, ν_{ion} is the frequency of ionization by plasma electrons, β_{ei} is the electron-ion recombination coefficient, $\langle \varepsilon_e \rangle$ is the mean energy of electrons, $\mathbf{h}_e$ is the electron energy flux, G is the electron energy diffusion coefficient, β is the thermoelectricity coefficient, η is the energetic cost of the electron-ion pair production, in a first approximation η is equal to the doubled ionization potential, W_S is the rate of the energy loss for elastic and inelastic collisions, **E** is the electrical field strength. In [1] there was a supposition that under the influence of beam fast electrons the secondary electron emission (SEE) can result in the essential change in the dusty particle charge. Therefore, the model takes into account the SEE process with the coefficient in the range of 0.0÷1.0.

In fig.1,2 there are simulation results for the process of charging the isolated dusty particle with the radius of 10 μm in He under atmospheric pressure for different j_b - the *e*-beam current density with the energy of 120 keV. These figures show that the SEE has a weak effect upon the charge of the dusty particle. Analyzing the simulation result showed that the temperature of electrons near the dusty particle weakly differs from the temperature of electrons far from the dusty particle. Therefore, to calculate the charge of dusty particles, particularly, for not very great beam current densities (fig.1,2), it is possible to use the value of the electron diffusion coefficient and the electron mobility resulting from the parameters of plasma far from the dusty particle.

Studying the stationary radial distribution of electrons and ions showed that the Boltzmann distribution could describe the behavior of electrons and could not describe that of ions (fig.3). Fig.3 also shows that the growth in the ionization rate, proportional to the *e*-beam current density, leads to the decrease of the plasma sheath. That results from the decrease in the Debye shielding length of plasma with the growth in ionization rate, though, according to fig.4 the potential of the dusty particle does not follow the Debye potential.

Fig.3 shows an interesting feature of the helium beam plasma: the region of plasma disturbance by a dusty particle is much greater than the region of the plasma quasi-neutrality violation. That results from high mobility of He_2^+ ions and low recombination rate of these ions. Therefore, in helium the dusty particles make a considerable effect upon the mean density of electrons in plasma when the dust particle density is within 10^3 cm^{-3}. That effect leads to the decrease in non-self-sustained discharge current density in helium, which was experimentally observed in [3]. For comparison, in fig.5 there are radial distributions of electrons and ions near a dust particle in xenon under atmospheric pressure [4]. There, owing to high recombination rate and low mobility of Xe_2^+ the ion distribution has a maximum.

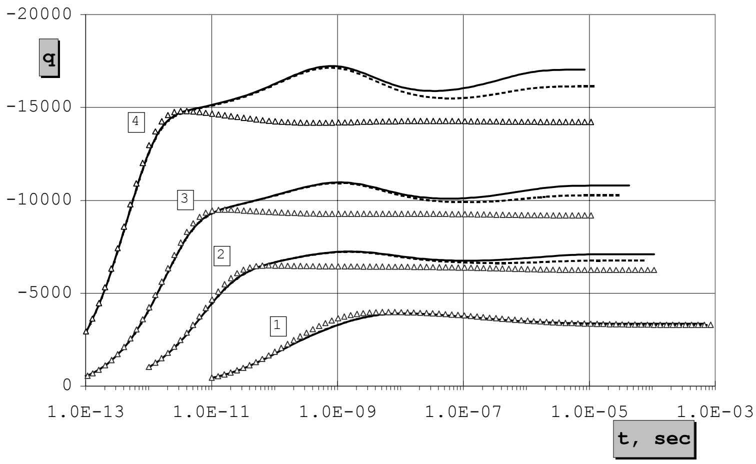


Fig.1. Time evolution of the dust particle charge in the atmospheric helium *e*-beam plasma.
1 – j_b=100 µA/cm^2;
2 – j_b=10^4 µA/cm^2;
3 – j_b=10^5 µA/cm^2;
4 – j_b=10^6 µA/cm^2.
Solid curves: the SEE coefficient is $\theta = 0.1$, dashed curves: $\theta = 1$; triangles is the calculation for T_e = const.

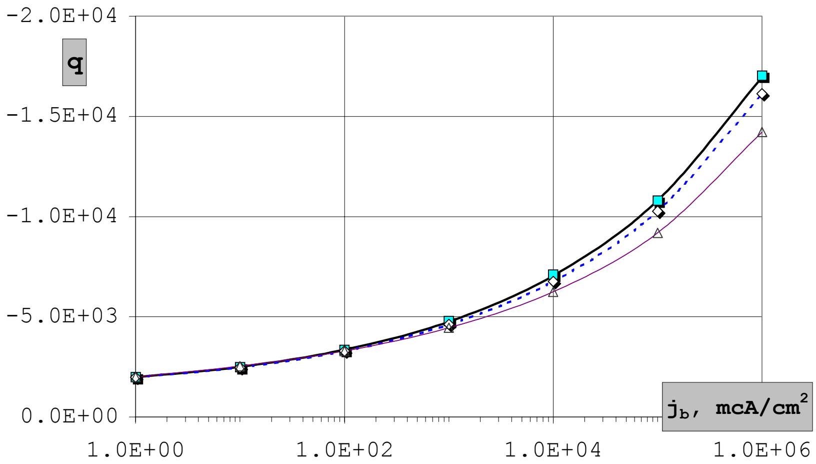
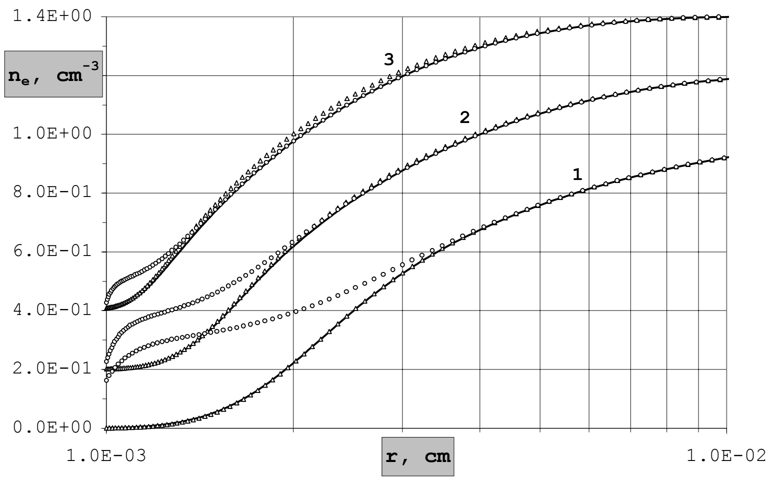


Fig.2. Dependence of the dusty particle charge in the atmospheric helium *e*-beam plasma on the *e*-beam current density: squares - θ = 0.1, rhombs - $\theta = 1$; triangles - T_e = const.

Fig. 3. Steady-state radial distributions of electrons (the solid curve) and ions (circles), the Boltzmann distribution of electrons (triangles).
1 - j_b =1 µA/cm^2,
2 - 10^2 µA/cm^2,
3 - 10^4 µA/cm^2.



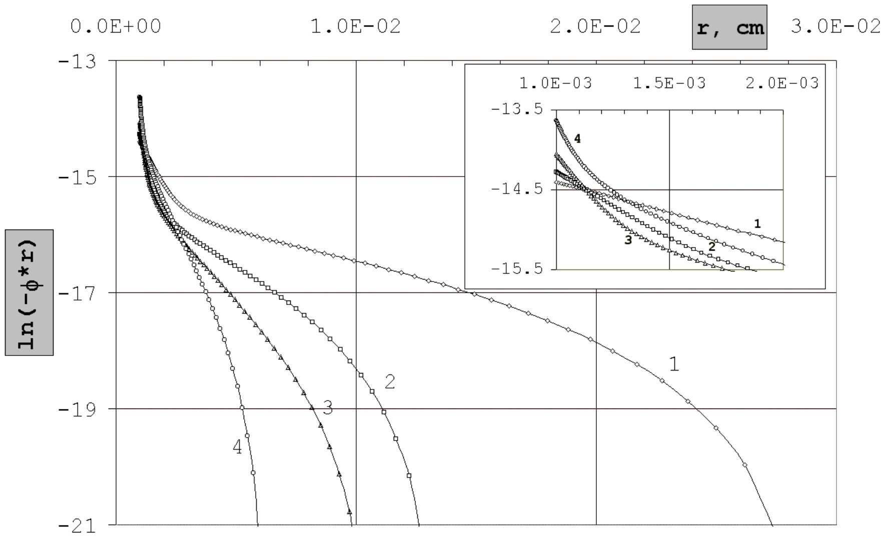
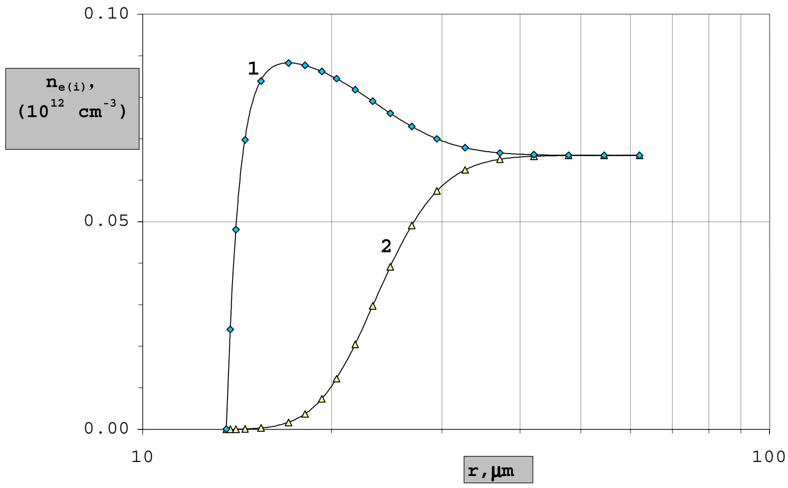


Fig.4. The steady-state radial distribution of the potential of the single dust particle with radius of 10 μm. 1: j_b=1 μA/cm^2, 2: 10^2 μA/cm^2, 3: 10^4 μA/cm^2, 4: 10^6 μA/cm^2.

Fig. 5. The steady-state radial distribution of electrons (1) and ions (2) in Xe when Q_{ion} = 10^{16} cm^{-3}s^{-1} and the radius of particle is 13.6 μm [4].



Conclusions

- In describing the charging of dusty particles in the helium beam plasma it is possible to use transport coefficients for undisturbed plasma;
- The process of the secondary electron emission weakly effects upon the charge of dust particles;
- In helium the region of plasma disturbance by a dusty particle is much greater than the region of the plasma sheath.

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