Simulations of the glow discharge positive column parameters in helium

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Abstract. The self-consistent model for the positive column of a glow discharge is presented. The model is based on the simultaneous solution of the nonlocal Boltzmann equation for electron energy distribution function, continuity equation for ions and Poisson equation for electric field. Calculations were performed for a discharge tube similar to the Plasma Kristall-4 experiments for plasma forming gas helium for the range of pressures of 20-70 Pa and the range of discharge currents of 0.5-2.5 mA. Axial electric field strength, electron temperature and electron density dependences on the discharge current and the gas pressure are obtained. The results show a good correlation with the data obtained by the other authors.

1. Introduction
Glow discharge is one of the most popular types of discharges for industrial applications and fundamental researches [1]. A series of works on this topic showed that the electron energy distribution function (EEDF) in such discharges differs significantly from Maxwellian one [2,3]. The high-energy part of the EEDF is significantly depleted due to losses in active elastic and inelastic electron collisions with neutral atoms and molecules. Therefore the Boltzmann equation is necessary to use for the correct determination of EEDF.

A complex, or dusty, plasma takes a special place in the physics of low-temperature plasma. It is an ionized gas containing micron-sized solid particles. Dusty plasma can form dust structures of various sizes and shapes. It can be found both in space (in planetary rings, planetary magnetosphere, near-wall areas of spacecraft) and in various plasma industrial installations for etching and deposition of thin films [4]. Currently, the complex plasma of a positive glow discharge column is actively studied in the experiments of the Plasma Kristall-4 project (PK-4) [5].

Plasma-forming gas is one the most important characteristic of the low-temperature plasma, as it affects all the main plasma parameters. Despite the fact that a series of recent experiments of the PK-4 project was carried out in neon, helium, along with other noble gases, is also of great interest as a plasma-forming gas for basic and applied research in both complex and pure plasma. This paper presents numerical calculations of the parameters of a glow discharge plasma in helium in the absence of dust particles using a non-local self-consistent model for the tube, similar to the PK-4 experiment tube.

2. Model
For the description of the glow discharge positive column a nonlocal self-consistent model, recently developed in [6], is performed for the case of dust free plasma. To describe the spatial and temporal
evolution of plasma electrons of a glow discharge the nonlocal non-stationary Boltzmann equation for the velocity distribution function of electrons \( F(t,r,v) \) was used:

\[
\frac{\partial F(t,\vec{r},\vec{v})}{\partial t} + \vec{v} \cdot \nabla F(t,\vec{r},\vec{v}) - \frac{e_v E(\vec{r},t)}{m} \frac{\partial F(t,\vec{r},\vec{v})}{\partial \vec{v}} = S^{el}(F) + \sum_k S^{in}_k(F),
\]

where \( S^{el}(F) \) - integral of electron elastic collisions, \( S^{in}_k(F) \) - integral of electron inelastic collisions with excitation of the \( k \)-th state of an atom by electron impact (for helium 1-st excited level with energy of 19.8 eV and ionization threshold of 24.6 eV were taken into account [7]). Assuming weak anisotropy, electron distribution function was decomposed by Legendre polynomials with two first terms left, isotropic \( f_0(t,r,v) \) and anisotropic \( f_1(t,r,v) \). The transition from variable \( v \) to the full kinetic electron energy variable \( \epsilon \) was also realized.

Current electric radial field distribution \( E(r,t) \) was calculated by Poisson equation:

\[
-\frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \frac{\partial \phi(r,t)}{\partial r} \right] = 4\pi e \left[ n_i(r,t) - n_e(r,t) \right],
\]

where \( \phi(r,t) \) - electric radial potential distribution. The radial ions density distribution \( n_i(r,t) \) was obtained with help of non-stationary drift-diffusion equation:

\[
\frac{\partial n_i(r,t)}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \left( \mu_i n_i(r,t) E(r,t) - D_i \frac{\partial n_i(r,t)}{\partial r} \right) \right] = v_i(r,t) N_i.
\]

Here \( \mu_i \) - ion mobility coefficient, \( D_i \) - ion diffusion coefficient, \( v_i(r,t) \) - radial distribution of ionization frequency. The equations were solved by the relaxation method from some initial distribution function. It was shown that the form of the initial distribution function did not affect the steady-state solution.

The radial electron density dependence \( n_e(r,t) \) was obtained by integrating of the isotropic part of EEDF \( f_0(\epsilon,r,t) \):

\[
n_e(r,t) = \int_0^\infty \epsilon^{3/2} f_0(\epsilon,r,t)
\]

The radial temperature dependence \( T_e(r,t) \) was calculated as:

\[
T_e(r,t) = \frac{2}{3} \left( \frac{1}{n_e(r,t)} \right) \int_0^\infty \epsilon^{3/2} f_0(\epsilon,r,t)
\]

Below the axial values of \( n_e(r,t) \) and \( T_e(r,t) \) are presented, i.e. the values at \( r=0 \).

Axial electric field \( E_z \) was calculated by a feedback of the discharge current \( I_d \), that was set for each calculation regime.

3. Results and discussion

For the discharge tube with diameter \( d = 3 \) cm calculations of the positive column plasma parameters were conducted for the pressures of plasma forming gas helium in the range of 20-70 Pa and discharge currents of 0.5-2.5 mA. Figure 1a illustrates discharge current dependences of axial electric field \( E_z \) for different gas pressures.

It is seen that axial electric field decreases with discharge current for the whole range of pressures, which is a characteristic relation for low temperature glow discharge plasma. Presented dependences are in good qualitative agreement with works [5,8,9] for neon, while electric field absolute values for helium are much higher (2-3 V/cm for neon) due to the greater ionization threshold 24.6 eV versus 21.6 eV for neon and greater excitation thresholds.
The pressure dependences of axial electric field for different discharge currents are presented in figure 1b. It is seen that with decreasing gas pressure to 20 Pa, the electric field, necessary for discharge burning, increases substantially. Moreover, it was obtained that the axial electric field dependence on pressure has minimum at every discharge current.

In figure 2 electron temperature dependences versus discharge current and gas pressure are presented.

It is seen that in low pressure modes the electron temperature changes significantly with variation of discharge current, while at high pressure it changes slightly (less than 4 % with alter of discharge current from maximum to minimum value). As for electric field, the values of electron temperature for 20 Pa are substantially higher than in other regimes. All dependences are also in good qualitative agreement with experimental and numerical results from work [5,8].
In figure 3 electron density dependences are presented versus discharge current (a) and versus plasma forming gas pressure (b).

![Figure 3](image)

**Figure 3.** Electron density $n_e$ at the discharge axis versus discharge current $I_d$ (a) and gas pressure $p$ (b).

Figure 3 illustrates that electron density at discharge axis increases approximately linearly with an increase of discharge current at every gas pressure value. With an increase in pressure at fixed current value the electron density at discharge axis likewise increases, which is also the common feature of glow discharges. Shapes of presented dependences of electron densities are consistent with results in neon [5].

**Conclusion**

The nonlocal self-consistent model for glow discharge positive column simulations was presented. The calculations of plasma parameters in helium were performed for the wide range of plasma forming gas pressures and discharge currents. The distributions of a number of characteristics were obtained, such as axial electric field, electron temperature and electron density. Most of calculated dependences are in a good agreement with similar works in this subject for other gases and other models. The peculiar pressure dependence of axial electric field was revealed. Obtained results have a substantial importance for subsequent experiments and simulations as in complex plasma in helium as in dust free plasma.

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