Charged particles density distribution in the cathode fall region of the glow discharge in helium

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Abstract. In the present work, the mechanism of formation and propagation of the group of high energy electrons in the cathode regions of a glow discharge in helium is discussed. Using the method of the Monte Carlo collisions simulation, the beam electron energy distribution function in the cathode fall region of a glow discharge has been determined in the gas pressure range of 30−70 Pa. It is shown that the electron distribution function at the end of the cathode fall region contains a lot of electrons which have no any collisions and have energies close to the cathode fall potential. On the basis of the obtained results the distribution of the ion density was simulated using the Poisson equation. It is shown that the ion density distribution stays almost constant in the cathode fall region. The beam and ion density increased with the pressure growth.

1. Introduction
In this work, using a Monte Carlo collision method the model of charged particle density distribution in the cathode fall (CF) region of a glow discharge is proposed. A positive space charge in the CF region of a glow discharge (GD) forms a strong electric field near the cathode surface, which promotes the formation and further propagation of a small group of high-energy electrons (a beam) along the discharge length. As a result of beam propagation, an electron avalanche is formed at the end of the CF region, and the density of charged particles necessary to maintain a stable discharge is established. At the start of the negative glow (NG) region the space charge and strong electric field are disappeared and plasma of a NG can be assumed in a quasi-neutrality state. Measurements of the longitudinal electric field in a wide range of glow discharge generation modes, carried out by the probe [1] and optical [2] methods established the linear nature of the distribution of the longitudinal electric field in the sheath. The maximum value of electric field achieved on the cathode surface is linearly decreased to the end of the cathode fall. The boundary between the CF and the NG regions is clearly distinguished by plasma luminosity so that the length of the sheath can be quite accurately measured. This circumstance allows for each specific discharge generation mode to find (to estimate) the distribution of the longitudinal electric field quite accurately without a complicated and time-consuming process of measuring, using only experimental data on the voltage drop across the GD and the width of the cathode sheath region. Using the distribution of the longitudinal electric field in the CF region set in this way, one-dimensional calculation of the energy distribution function of the beam electrons was performed depending on the axial coordinate of the GD. For this purpose, the mechanisms of the formation and propagation of an electron beam along the discharge axe is considered by the method of direct statistical modeling.
2. Model description

2.1. Distribution of the longitudinal electric field

In accordance with experimental data about a distribution of the longitudinal electric field $E$ in the cathode regions of the GD, the computational domain is constructed from two parts. The linearly falling longitudinal electric field in the CF region and the zero electric field in the NG region are determined as:

$$
E = \begin{cases} 
- \frac{2U_{\text{fall}}}{d_c} \left( 1 - \frac{x}{d_c} \right), & x \leq d_c \\
0, & x > d_c
\end{cases}
$$

where $U_{\text{fall}}$ is the voltage drop across the CF region, and $d_c$ is the width of the sheath. The values of $U_{\text{fall}}$ and $d_c$ are measured experimentally for the corresponding generation conditions of the GD. The perpendicular component of the electric field is assumed to be absent.

2.2. Electron energy distribution function

For finding the electron energy distribution function (EEDF) the trajectories of the movement of the electrons launched from the cathode surface (plane $(y, z)$ with $x = 0$) were calculated many times taking into account the collisions. The electrons were equiprobably launched from all electrode surface with initial energy of $1$ eV. The trajectory of the movement was calculated in 3D space with the limits, corresponding to the walls of the experimentally used discharge tube. The EEDF, $f(\varepsilon, x)$, was determined during the electron trajectories calculations. The method consisted in finding the number $J$ of crossings of the plane $(y, z)$ by electrons having energy within the interval $(\varepsilon, \varepsilon + \Delta \varepsilon)$ [3]:

$$
J = \int_{s_0}^{s_{\text{tot}}} N \sigma_{\text{tot}}(\varepsilon(s)) ds = -\ln(1 - R_{\text{tot}}),
$$

where, $\phi_{\text{in}}$ is the electron flux rate on the cathode, $N_i$ is the initial number of electrons emitted from the cathode and $\Theta_i$ is the angle between the electron velocity and the axis $x$. The evaluation of the trajectory of the movement was stopped if electron crossed the wall or the sum of its potential and kinetic energy became less than the potential of excitation of the $1s2p \, ^1P$ level: $I_{\text{exc}} = 21.21$ eV. More detailed description of the used method for EEDF determination can be found in [3, 4].

2.3. Electron collisions

For the given distribution (1), trajectory $s$ of electron motion between the collisions was evaluated using the second Newton law. The moment of collision occurrence was chosen randomly in the following way:

$$
\lambda_{\text{tot}} = \int_{s_0}^{s_{\text{tot}}} N \sigma_{\text{tot}}(\varepsilon(s)) ds = -\ln(1 - R_{\text{tot}}). 
$$

where $\lambda_{\text{tot}}$ is the free path length, $s_0$ is the initial coordinates of the electron, $N$ is the gas density, $\sigma_{\text{tot}}$ is the total collision electron-neutral cross section and $R_{\text{tot}}$ is the random number between $(0, 1)$. The type of collision was defined in accordance with the contribution of the corresponding cross section to all investigated processes. The following processes were taken into account in the trajectory evaluation: elastic collisions of an electron with neutral gas, ionization from the ground state, and excitation of the $1s2p \, ^1P$ level. Cross sections of elastic, ionization, and excitation collisions were taken from [5–8].

In an elastic collision, an electron is scattered on angle $\Theta$ and decreases its energy on value $2m/M(1-\cos \Theta)$, where $M$ is the helium atom mass. The experimental data on elastic differential cross section were taken from [9–11]. When the ionization collision occurred, the energy of the primary
electron was decreased by the sum of the ionization potential and the energy of the secondary electron, determined randomly. The differential ionization cross section was taken from [12]. Since ionization collisions are also anisotropic and the experimental data on the ionization double differential cross section of scattering are insufficient, the procedure of the determination of the scattering angle of the incident electron and the ejected angle of the secondary electron is taken from [3, 13]. The trajectories of movement of the secondary electrons are also evaluated if the kinetic and potential energy is more than \( I_{\text{ext}} \). The energy of the electron is decreased by the excitation potential \( I_{\text{ext}} \) if the excitation collision takes place, anisotropy of the angular scattering is not taken into account. The initial number of electrons launched from the cathode surface \( N_{\text{it}} \) was \( 10^5 \). More detailed the using Monte Carlo collision model description can be found in [14].

2.4. Ion density
Let us suppose that the electron beam is the main electron carrier at the end of cathode fall region [15], the beam density \( n_b \) can be evaluated through the discharge current \( I_d \) and the cathode drop potential:

\[
n_b \approx \frac{j}{e \cdot <v>} = \frac{I_d}{\pi R^2 \cdot e \cdot \sqrt{2U_{\text{fall}}}} \cdot m,
\]

where \( j \) is a current density. The simulated EEDF \( f(\varepsilon, x) \) was normalized using equation (4). Knowing the electron beam distribution through the CF region and the electric field distribution (1) the ion density \( n_i \) was calculated using Poisson equation:

\[
\Delta E = -4\pi(n_i - n_b).
\]

Since the EEDF does not contain information about the electrons with energy less than \( I_{\text{ext}} \) at the end of sheath and Eq. (5) cannot be used, the ion density is evaluated for \( x \) within the range \( (0, d_c - \Delta x) \), where:

\[
\Delta x = d_c \sqrt{1 - \frac{U_{\text{fall}} - I_{\text{ext}}}{U_{\text{fall}}}}.
\]

3. Experimental setup
The GD was generated in a cylindrical quartz tube with the inner diameter of 44 mm. The distance between the aluminum electrodes was 45 cm. The tube was pumped out to a vacuum of 0.3 Pa by a rotary pump and then filled out by a helium gas with a constant flow rate. In all investigated cases the GD occupied the entire cross section of the tube. Since the electric field in the NG region was negligible with the cathode fall, the total discharge drop \( U_d \) was presumed to be equal \( U_{\text{fall}} \). For the measurements of the CF region width \( d_c \) the discharge photos were taken and then processed by the PC with an accuracy of \( \pm 0.5 \) mm. The discharge photo is shown in fig. 1.

![Figure 1](image-url) The GD photo. Pressure 30 Pa, \( I_d = 5 \) mA, \( U_d = 1400 \) V, \( d_c = 2.16 \) cm.

4. Results and discussion
The discharge conditions, for which simulations have been performed, are presented in Table 1. The results of the evaluation of the EEDF distribution in cathode fall region of GD are plotted in fig.2. It is
seen that the EEDF has the distinct core body of the electrons which have no inelastic collisions on the way. The energy of the beam electrons is increased with the distance from the cathode $x$ and reached its maximum value at the end of the CF region $x = d_c$. The rare secondary electrons generated at the beginning of the CF region are also accelerated in electric field and form the middle part of the EEDF. Towards the negative glow region the number of secondary electrons is dramatically increased and at the end of the CF region the EEDF has a significant number of the secondary electrons with the energy close to the ionization potential.

Table 1. The GD parameters and the electrons beam density.

| $P$, Pa | $U_{dc}$, V | $d_c$, cm | $n_b(d_c)$, $10^6$cm$^{-3}$ |
|---------|-------------|-----------|-------------------|
| 30      | 1400        | 2.16      | 1.48              |
| 40      | 1140        | 1.61      | 1.49              |
| 50      | 1080        | 1.46      | 1.52              |
| 60      | 920         | 1.21      | 1.54              |
| 70      | 800         | 1.02      | 1.57              |

Figure 2. The EEDF distribution in CF region for the pressure 70 Pa and $I_d = 5$ mA.

The charged particle density distribution along the CF region for the constant discharge current is shown in fig. 3. It is seen that the beam densities increase linearly from the cathode. Then the linear dependence is changed and the beam densities start to grow rapidly. The electron avalanche is formed. The ion density stays practically constant along the entire cathode fall region path. The beam and ion densities increase with the pressure $P$ growth.
Figure 3. The charged particle density distribution in the CF region for different pressures: \( P = 30, 40, 50, 60 \) and 70 Pa. Discharge current is 5 mA. The beam densities are normalized on their maximum values.

5. Conclusions
The simulation of the beam electron energy distribution function with allowance of elastic and inelastic collisions in the cathode fall region of a GD has been performed for the gas pressure of 30–70 Pa. The charged particle distribution has been obtained. The proposed model can be used for the further construction of hybrid model of the direct current glow discharge.

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