Electron parameters in a hollow cathode discharge plasma in He and He:H₂O mixture

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Abstract. The electron energy distribution functions (EEDFs) were measured in the discharge plasma in pure helium and in helium with the addition of water vapor He:H₂O (2:1). The studies were carried out in the discharge gap between the rectangular hollow cathode and the mesh anode using the original probe measurement system. It was established, in particular, that the EEDF in He had pronounced maxima in the regions of ~4 eV and ~15 eV, while in the He:H₂O mixture there was no local maximum in the high-energy region. The EEDF calculations in the local approximation for experimental conditions were performed. It turned out that the calculated distribution functions differ noticeably from the measured ones. The possible physical causes leading to the discrepancy between the measured and calculated EEDFs were discussed.

1. Introduction

In recent years, new methods of quantitative spectroscopy have been developed [1-5]. In the future, they can be used at various facilities, including tokamaks [4-5] to search for water leaks from the cooling system [6]. However, to increase the measurement sensitivity by some of the proposed methods, it is necessary to carry out calibration probe measurements to establish the electron energy distribution function (EEDF) [5]. The focus of this work was to study the plasma parameters in discharge with a hollow cathode in helium and a mixture of helium with water vapor.

2. Experimental setup

The studies were carried out on the "Leak" experimental set-up [1-5, 7-8]. The discharge device (Figure 1) had the form of a 100×50×10 mm³ hollow rectangular tungsten cathode with a 100×10 mm² open side of facing the tungsten mesh anode (100×10 mm²) located at a distance of 10 mm from the edge of the cathode. Except for the open side facing the anode, ceramic plates were fixed outside on all cathode faces. The UIP-1 unit was used as a voltage source, a ballast resistance of 1.3 kΩ was included in the electric circuit.
Figure 1. Schematic of the discharge system with a placed probe.

Probe measurements are widely used in plasma diagnostics, however, the correct determination of plasma parameters from the measured current-voltage characteristics (IVCs) in practice is not an easy task. The parameters determined by the probe method — the plasma potential $U_p$, electron concentration $n_e$, and electron energy spectrum were obtained by differentiating the IVCs and were sensitive to the accuracy of measuring of the IVCs and the method of its formation. Among the best data published today, the results of [9, 10] can be noted, where in some cases it was possible to achieve a range of 3-4 orders of magnitude for EEDF, however, the details of the procedures and methods are not described there.

In [7, 8], we proposed to form a current-voltage characteristic with a voltage on the probe in the form of a combination of periodic and noise signals. The signal fractions were varied for different parts of the IVC to reduce the error in determining the plasma parameters. Such a measuring system was used in this work.

The probe was a tungsten wire with a diameter of 0.1 mm, emerging from the ceramic insulator by 2 mm. The probe was placed in the center of the open part of the cathode at a distance of 5 mm from its edge (see Figure 1).

3. Experimental results

The measurements were carried out at a pressure of 2.2 Torr in He and a mixture of He:H$_2$O (2:1). Figure 2 shows the results of measurements of the distribution function. For the convenience of analysis, they are presented in two versions: EEDF, $f(u)$, and electron energy probability function (EEPF) – $F(u)$=u$^{-1/2}$. The figure also shows the measurement errors.

Figure 2. Measurement results in the form of EEDF (a) and EEPF (b). The pressure is 2.2 Torr. 1 – discharge in He; 2 – discharge in He + H$_2$O (2:1). 1', 2' – Maxwell distribution functions with mean energies corresponding to 1 and 2.

The following parameter values were obtained in the He discharge: the mean electron energy was $<u>=7.4\pm0.5$ eV, $n_e=(7.2\pm0.2)\times10^{10}$ cm$^{-3}$, $U_p=-1.0\pm0.2$ V (in this case, the discharge voltage was $U_d=445$ V , the discharge current was $I_d=115$ mA). In the discharge in the He:H$_2$O mixture (2:1):
<u> = 4.5 ± 0.7 eV, \( n_e = (1.2 ± 0.05) \times 10^{10} \) cm\(^{-3}\), \( U_p = -20.0 ± 0.3 \) V (\( U_d = 283 \) V, \( I_d = 234 \) mA). The mean electron energy \(<\mathbf{u}>\) was calculated by integrating the measured EEDF.

As can be seen from Figure 2, when water vapor was added to helium, the fraction of fast electrons in the steady-state EEDF decreased. This occurred, probably, due to the loss of electron energy upon the dissociative excitation of \( \text{H}_2\text{O} \) molecules (cross-section value \( \sigma \sim 10^{-17} \text{ cm}^2 \) [1]), ionization (\( \sigma \sim 10^{-16} \text{ cm}^2 \) [1]), etc. The thresholds of these processes are in the region of 10 eV [11].

4. Discussion

Using the measured potential values, it is possible to estimate the magnitude of the reduced electric field \( E/N \) (\( E \) is the electric field strength, \( N \) is the number of atoms and molecules per unit volume) at the location of the probe: \( E/N \approx 3 \) Td (in the case of helium) and \( E/N \approx 57 \) Td (in the case of a mixture of helium with water vapor). For the indicated \( E/N \) values, we calculated the EEDF in He and the \( \text{He}:\text{H}_2\text{O} = 2:1 \) mixture within the framework of the local Boltzmann equation [11]. The sets of cross-sections for the electron scattering from He atoms and \( \text{H}_2\text{O} \) molecules were taken from [13] and [14, 15], respectively. The calculated EEDFs are shown in Figure 3a. As can be seen from a comparison of the graphs in Figure 2 and 3a, the calculated distribution functions differ significantly from the measured ones. Let’s consider the possible reasons for this difference.

![Figure 3](image_url)

**Figure 3.** Results of the calculations:

(a) The EEPFs (EEDFs) in He and \( \text{He}:\text{H}_2\text{O} = 2:1 \) mixture calculated for the experimental data of \( E/N \) values within the framework of the local Boltzmann equation;

(b) Spatial relaxation of the EEDF in He under uniform electric field applied. \( P = 2.2 \) Torr, \( T = 300 \) K, \( E = 10 \) V/cm. The numbers on the curves indicate the distance from the electron source at which the EEDF was calculated. The dashed line is the established EEDF. He, \( P = 2.2 \) Torr, \( T = 300 \) K, \( E = 10 \) V/cm.

As for the measurements of the EEDF in a gas mixture, the following should be borne in mind. The indicated ratio of helium and water vapor was set before the ignition of the discharge. In a discharge, molecules of water sufficiently dissociate [2], so the question remains about the actual composition of the mixture under the discharge conditions. More detailed studies of this issue are needed.

A characteristic feature of the EEDF measured in helium is the presence of a local maximum in the energy region of \(~15\) eV, and the distribution function in the region of this maximum is only 5 times smaller than the values in the region of the main maximum (Figure 2). In a discharge in inert gases, there are several processes in which electrons with high energies appear: collisions of the second kind of electrons with excited He* atoms (for definiteness, we will assume that this atom is in the lowest metastable state)
and chemioionization processes

\[ \text{He}^* + \text{e} \rightarrow \text{He} + \text{e} \left( +19.8 \text{ eV} \right) \]  
\[ \text{He}^* + \text{He}^* \rightarrow \text{He}^* + \text{He} + \text{e} \left( +15 \text{ eV} \right) \]  
\[ \text{He}^* + \text{He}^* \rightarrow \text{He}^*_2 + \text{e} \left( +17.5 \text{ eV} \right) \]  

These processes can lead to the formation of a local EEDF maximum in the high energy region, but only in the afterglow of the discharge [16] when there is no heating of electrons by the electric field.

In [17], the EEDF was measured inside a hollow cathode in a discharge in helium. In particular, it was shown that under certain conditions (gas pressure, discharge current, the position of the probe inside the hollow cathode), the EEDF has a two-maxima form. Although in these works the reasons for the formation of the second maximum were not discussed in detail, it can be assumed that its formation is due to the nonlocal nature of the formation of the EEDF under the conditions of a hollow cathode. In several theoretical papers (see [13, 18-19] and references therein), it was shown that the spatial relaxation of EEDF in inert gases (in particular, in helium) in an electric field can have a substantially nonlocal character. In this case, the EEDF with two maxima can form. To illustrate this effect, we calculated the spatial relaxation of the EEDF in helium in a uniform electric field for the following conditions: gas pressure \( P=2.2 \) Torr, gas temperature \( T=300 \) K, electric field strength \( E=10 \) V/cm. The calculations were carried out using the Monte Carlo method, similar to that used in [13]. Electrons were launched at the point \( z=0 \). It was assumed that the electric field was directed along the negative direction of the Z-axis, so the electron drift occurs in a positive direction. The energy spectrum of the electron source was specified in the form of \( \exp(-(u-u_0)^2/\Delta^2) \), \( u_0=10 \) eV, \( \Delta=4 \) eV, the angular distribution of the starting electrons was assumed to be isotropic. The cross-sections for electron scattering by helium atoms (the cross-section for elastic scattering, the cross-sections for the excitation of electronic levels, and the cross-section for ionization) were taken to be the same as in [13]. The ionization process was taken into account similar to the processes of excitation of electronic levels, i.e. the electron energy decreased by the value of the ionization potential, and secondary electrons were not considered.

Fig. 3b shows the EEDFs calculated at various distances from the source. As can be seen from Figure 3b, at small distances from the source (0.2 cm), the distribution function has a maximum in the energy region of \( \sim 7 \) eV. When moving along the Z-axis, electrons receive energy from the field and the position of the maximum shifts to the region of higher energies (\( \sim 9 \) eV at \( z=0.6 \) cm). Note that under these conditions, the energy accumulation by electrons in an electric field occurs faster than the energy loss in elastic collisions. With further movement along the Z-axis, the right “wing” of the distribution function shifts to the energy region of \( \sim 19.8 \) eV (excitation energy of the lower electronic level of the helium atom). The electrons of this “wing” lose energy in the processes of excitation of electronic levels and “jump” to the low-energy region so that in the low-energy region one more EEDF maximum is formed (graph \( z=1 \), Figure 3b). At distances \( z=(1.6–1.8) \) cm, the right maximum becomes weakly pronounced. According to the calculations, with increasing \( z \), the maximum formed in the low-energy region gradually shifts to the high-energy region, and the scenario described above is qualitatively repeated. But at the same time (due to the loss of electron energy in elastic collisions and due to the excitation of electronic levels), the maximum width gradually increases, its amplitude decreases, and ultimately the distribution function takes on a steady-state form (dashed line in Figure 3b).

Thus, under conditions of spatial relaxation, EEDFs with two maxima close in amplitude can form. However, the following must be kept in mind. The described scenario of spatial relaxation occurs in a situation where the loss of electron energy in inelastic collisions predominates. At low electric field strengths, when electrons lose energy mainly in elastic collisions, the spatial relaxation of the EEDFs is aperiodic and a local maximum does not form in the high-energy region [19].

In pure helium, the electric field in the gap between the cathode and the anode (in the probe position) is quite small, \( E=2 \) V/cm. According to our preliminary calculations performed for \( E=2 \) V/cm, it is impossible to explain the measured EEDF only in the framework of spatial relaxation of the
EEDF in the gap between the cathode and the anode. Further experimental and theoretical calculations are needed.

5. Conclusion

The probe method was used to study the EEDFs in a hollow-cathode discharge plasma in pure He and a He:H$_2$O mixture (2:1) at a pressure of 2.2 Torr. The measurements were carried out in the discharge gap between the rectangular hollow cathode and the mesh anode using the original probe measurement system. In experiments with He, the discharge current was 115 mA at a discharge voltage of 445 V, and in experiments with He:H$_2$O, the discharge current was 234 mA at a discharge voltage of 283 V. It was found that the EEDF in He has a well-pronounced double-hump structure with maxima in regions of 4 eV and 15 eV. When water vapor was added to helium, the EEDFs transformed into single-hump one with a maximum in the region of 4 eV. According to estimates (assuming that the gas temperature was 300 K), the reduced electric field at the position of the probe was $\approx 3$ Td (for He) and $\approx 57$ Td (for the mixture).

For the indicated $E/N$ values, the EEDFs in He and the He:H$_2$O mixture were calculated within the framework of the local Boltzmann equation. As it turned out, the calculated EEDFs differ significantly from the measured ones. The difference between the calculated and measured EEDFs in a gas mixture may be because the actual composition of the gas mixture under the discharge conditions noticeably differs from the initial one due to the dissociation of water molecules. In the case of pure helium, the difference may be due to the nonlocal nature of the formation of the EEDFs under discharge conditions. It was shown that, under certain conditions, the nonlocal nature of spatial relaxation can lead to the formation of EEDFs with two maxima. But at the moment, it cannot be claimed that it is the effect that can explain the form of the EEDFs measured in helium. Further experimental research as well as the theoretical studies are needed.

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