POTENTIAL STRUCTURE FORMATION AND ELECTRON ACCELERATION IN THE SUDDEN CHANGE OF HE DISCHARGE TUBE DIAMETER

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ABSTRACT

It has been measured the axial distributions of the potential, electron number density, and electron energy distribution function (DF) at a constriction of the He discharge. Near by constriction potential increase more steeply, electrons gain additional energies and DF acquires a secondary peak, which is shifted towards higher energies as the potential increases. The regime of excitation of the various systems of levels changes in the axial direction because of the different energy dependence of the cross sections of singlets and triplets. On the basis of the measured distributions and densities the numbers of excitations and ionizations have been calculated. The calculated numbers of excitations are compared to the measured relative intensities. The DF is calculated from the kinetic equation using the measured profile of the potential. The calculated distributions are compared to the measured ones.

Keywords: double layer, positive column. electron energy distribution, collision controlled plasma.

I. INTRODUCTION

An abrupt change in positive column (PC) diameter are known to cause drastic changes in plasma parameters such as the electric field, the charged particle density and the electron energy distribution, resulting in a double sheath, or a kind of double layer (DL) [1, 2]. Double layers are essentially the transition region in a plasma composed of two adjacent layers with opposite sign of the space charge. Existence of a DL in collisionless plasmas is typically accompanied by such phenomena as trapped particles, plasma – wave instabilities, and wave – particle interaction. A great deal of work on DLs have been done for collisionless plasmas with a single species, with the emphasis on the above mentioned phenomena and this problem is well understood [3, 4].

Since the discharge we studied has a sudden change in the PC diameter, it has formal similarity to constricted discharges used to generate DLs. However, significant differences exist. The discharge we studied is a collision controlled discharge in the helium. This discharges are intrinsic interest both from the fundamental as well as the applied points of view [5, 6].

In [7] it was observed that a large plasma potential drop is locally formed at a constriction of an Hg – Ar mixture positive column and insisted that the potential drop is sustained to equalize the random electron current flowing between both sides of constriction. The potential formation even causes a double hump in the DF at a phase of strong electric field. A solution of the Boltzman equation including the spatial derivative under the assumption of a rectangular – shaped electric field has successfully predicted a partial shift of low energy electrons to higher energies. In [8] a grid has been installed in plasmas to excite plasma waves. Such a grid causes a large disturbance in electric field not only in the vicinity of the installation position, but also over a long distance towards the anode through the PC, i. e. towards the downstream direction of electron flow. This disturbance causes a large distortion in the DF, eventually yielding even a double hump similar to the DF at a constriction in the column. It has been detected the spatial plasma variations in both axial and radial directions. The spatial variation of radiation intensity is also detected by image reconstruction using a computerized tomography technique. The downstream variations of the DF is calculated using modified Fourier transform of the spatial derivative included in the Boltzman equation under appropriate boundary conditions.

In the present study we detect the spatial plasma variations in axial direction in the region of sudden change of discharge tube diameter in an He PC. It has been measured the axial distributions of the potential, electron number density, and DF in the region of a DL formed at a constriction of the discharge. Near by constriction potential increase more steeply, electrons gain additional energies and DF acquires a secondary peak, which is shifted towards higher energies as the potential increases. The regime of excitation of the various systems of levels changes in the axial direction because of the presence of the shifting secondary maximum on the DF and different energy dependence of the cross sections of singlets and triplets. On the basis of the measured distributions and densities we calculate the numbers of excitations and ionizations in the DL region. The calculated numbers of excitations are compared to the measured relative intensities. The DF is calculated from the kinetic equation using the measured profile of the potential. The calculated distributions are compared to the measured ones.

II. EXPERIMENTAL APPARATUS AND THE RESULTS OF THE MEASUREMENTS

The discharge was produced in a cylindrical glass chamber 55 mm in diameter and 700 mm long. The anode was placed in a movable narrow glass tube with an inner diameter of 22 mm. In the anode part the discharge narrowed, and at the transition region of the PC on the cathode side an electrical double layer of space charges formed. A movable cylindrical probe oriented at right angle to the tube permitted performing radial measurements in the region of the constriction of the column. By moving the anode together with the narrow part of the tube along the discharge chamber, we could shift the double layer relative to the probe or to the slit of the spectrograph and make measurements of the axial distributions of the electrical and optical parameters of the plasma. Measurements were carried out in spectrally pure helium at pressures 0,1 – 0,5 torr and at discharge currents from 20 to 300 mA in the absence of moving striations.

The DF was measured by using the second derivative method, by superimposing a 100% modulated signal on the probe bias voltage and carrying out the harmonic at the modulation frequency. The plasma potential was determined from the zero of the second derivative. This permitted a more exact determination of the radial and axial profiles of the potential.

Figure 1 shows the region of the constriction of the discharge and a typical example of the measured axial distributions of the plasma potential and electron number density for P = 0,2 torr and J_p = 100 mA. Far from the constriction on the cathode side the potential varies linearly. The DF measured in this part of the tube has the characteristic shape for a uniform positive column under these conditions. In this region the electron density does not change along the axis.

Near the narrowing a transition region forms, consisting of an electrical double layer with an electronic space charge on the cathode side and a space charge of positive ions on the anode side. According to the Poisson equation, in this region the trend of the potential changes, the field increases sharply, and the electrons acquire an additional energy, as a result of which the ionization increases strongly in the boundary region in the narrow part of the tube. Figure 2 shows the DFs measured at distances of 1.4, 1.0 and 0.4 cm from the edge of the narrow part, on the cathode side. The additional peak corresponds to a group of electrons accelerated in the DL. It is seen that as one moves along the steeply ascending branch of the potential the additional peak shifts toward higher energies. Here the secondary maximum decreases, and it rapidly vanishes as a result of elastic and inelastic collisions with atoms.

In the region of the constriction the electron density increases sharply (Fig. 1b) and then falls off almost to the level in the wide part, and in some cases undergoes several such strong changes and them approaches a constant value. This behavior of the electron density is due to electron focusing effects, since the DL in the mouth of the narrow part had the shape of a spherical segment, and therefore the accelerated electrons were focused along the direction toward the narrow part. The radial distribution of the density at the beginning of the narrow part of the tube was substantially narrower than in the regions more remote from the DL.

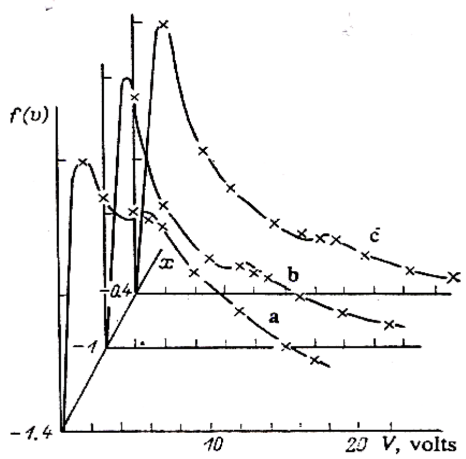

FIG. 2. Electron energy distribution functions measured at various distances from the narrowing, on the cathode side. P = 0.2 torr, J_p = 100 mA. The points show the results of the calculation, a) 1.4; b) 1; c) 0.4 cm.

The numbers of excitations of different groups of levels with principal quantum numbers of 3 and 4 were calculated by using measured distributions. Figure 1c shows the results of a calculation done on the axis of the tube for the levels 3^3P_1 (5) and 3^1P_1 (6). Also shown in this figure are the distributions of the relative intensities of the lines λ = 388.9 (3) and 501.6 nm (4). From the two distributions we see a change in the regime of excitation of the triplet and singlet levels. Some of the disagreement between the calculated and measured results can be attributed to the fact that we ignored the radial distributions of the parameters, with the result that the distributions of the parameters on the axis and integrated over the cross section are different. Analogous changes in the ratios of the populations are also observed for other

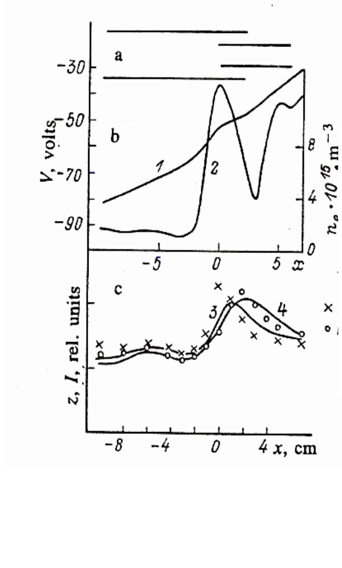

FIG. 1. a: Diagram of the narrowing region of the discharge tube. B: Neasured distributions of the potential (1) and electron density (2) on the axis, c: Measured relative intensities of the lines.

singlets and triplets.

III.CALCULATION OF THE DF

A method was developed for analytical calculation of the electron energy distribution function in electric fields of specified configuration for the case when the field and the plasma density are nonuniform along the direction of current flow in [9]. The problem is solved for the case of small fields, in which the energy balance is governed by quasielastic collisions. All the collisions can be divided into quasielastic and substantially inelastic, in which the energy lost is much higher than the characteristic energy scale for the decay of the distribution function, $\Delta\varepsilon$, and for the latter it is proposed to take into account the excitation of only one level, with energy ε_1. Such a situation is often encountered in inert gases, and it is the case for the conditions of the experiments described above.

If the transport frequency of quasielastic collisions ν is much higher than the frequency of inelastic collisions ν^* and the characteristic scale is the mean free path, then the distribution is nearly isotropic, and the system of equations for it are of the form

$$\frac{\partial f_0}{\partial t} = \frac{\upsilon}{3}\left(\nabla f_1\right) + \frac{1}{3\upsilon^2}\frac{\partial}{\partial \upsilon}\upsilon^2\left(\frac{eE}{m}f_1\right) - \frac{1}{2\upsilon^2}\frac{\partial}{\partial \upsilon}\left(\upsilon^3 \delta \nu f_\upsilon\right) = \nu^*(\upsilon) f_0(\upsilon,r,t) - \frac{\upsilon_1}{\upsilon}\nu^*(\upsilon_1) f_0(\upsilon,r,t), \quad (1)$$

$$f_1 = \frac{eE}{m\nu}\frac{\partial f_0}{\partial \upsilon} - \frac{\upsilon}{\nu}\nabla f_0, \qquad (2)$$

Where E(r, t) is the electric field, $f_1 \ll f_0$ is the directed part of the distribution function, and $v_1 = [v^2 + (2\varepsilon_1/m)]^{1/2}$.

The stationary solution ($\partial f_0/\partial t = 0$) of equation (1) separates into two solution for the two regions $\varepsilon < \varepsilon_1$ and $\varepsilon \geq \varepsilon_1$.

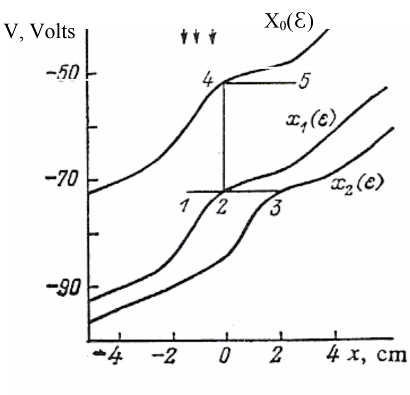

FIG. 3. Diagram for the calculation of the EEDF. The arrows show the points of the calculation.

In the elastic region $\varepsilon < \varepsilon_1$, where the inelastic collisions can be neglected, the formula for calculating the distribution function from a specified profile of the potential reduces to

$$f = A\int_x^{x_3}\frac{\nu(x)dx'}{\upsilon^3(x')},$$

Where x′ is the moving coordinate of the electron along the trajectory in the elastic region (horizontal line 1-2 in Fig. 3), and the limits of integration are from the point at which the distribution function is calculated (point 1) to the point x_3 along the horizontal trajectory 1-2-3. A particle found on the curve $x_0(\varepsilon)$ has zero kinetic energy, and a particle on the curve $x_1(\varepsilon)$ has a kinetic energy of ε_1. For $x > x_1(\varepsilon)$ the electron suffers an inelastic collision and makes a vertical transition from point 2 to point 4 and then continues to gather speed along the horizontal line 4-5. The distance from x_1 to x_3 along the horizontal is determined by the mean free path for elastic collisions. Under the conditions of our experiments in helium $x_3(\varepsilon) - x_1(\varepsilon)$ was equal to 2 cm. The energy dependence of the

frequency of elastic collisions was neglected in the calculations, and a value $\nu(x') = 5.64.108\ s^{-1}$ was adopted.

In the inelastic region $\varepsilon > \varepsilon_1$ the distribution function is exponentially decaying:

$$f(\upsilon) = B\exp\left\{-\sqrt{\frac{\nu^*\nu_1}{\upsilon_1^2}}\left[x - x_1(\varepsilon)\right]\right\},$$

i.e., for a given value of the energy it is determined by the difference $x - x_1(\varepsilon)$. Here

$$A\frac{\nu_1}{\upsilon_1^3} = B\sqrt{\frac{3\nu^*\nu_1}{\upsilon_1^2}}.$$

The calculated EEDFs on the axis at distances of 1.4, 1.0, and 0.4 cm from the end of narrow part, on the cathode side, are shown in Fig. 2. The point at which the distribution function was calculated are indicated by arrows in Fig. 3. It is seen from the figure that the calculated distribution function manifests the presence of a group of fast electrons, which is shifted toward higher energies as the potential increases. The calculated distribution functions are in satisfactory agreement with the measured ones and have a qualitatively similar behavior. However, there are some discrepancies, apparently due to the simplifications made in the calculations.

IV. CONCLUSION

One should note that the change in the regime of excitation of the various systems of energy levels can be used to study the rates of some reactions with the participation of excited atoms.

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