Processes in the Ion Beam Transport Region and Their Influence on Electrically Measured Value of Ion Beam Current

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Abstract – A method was proposed for separate measurements of the current of slow charge-exchange ions and the current of ions formed due to ionization of the gas by beam ions and fast secondary electrons in the region of the beam propagation. The method is also used for determination of the coefficient of the ion-electron emission of the ion beam collector and the charge-exchange cross-section of accelerated ions. For this purpose, the distribution of currents over electrodes of a modified Faraday cup with non-equipotential electrodes is analyzed. The application of the method to the control of the current of argon ion beams with the ion energy of units to tens of keV and the study of processes in the region of the beam propagation at pressures from 0.03 to 0.15 Pa was considered.

1. Introduction

The interaction of an ion beam with a gas and electrodes leads to formation of secondary charged particles, which increase the error of measurements of the beam current by electrical methods [1]. If the gas pressure is low, the difference between the current of the accelerating voltage source and the current measured in the beam collector circuit is due mainly to the ion-electron emission of the collector. If the gas pressure is high, processes of the resonance charge-exchange of accelerated ions on gas atoms and ionization of the gas by secondary electrons and beam ions become more intensive. An additional source of the measurement error appears as a result of the separation of flows of secondary charged particles on the surface, which have different potentials. The withdrawal of slow ions from the beam plasma to the accelerating electrode of the ion optics, which is negatively biased relative to the beam collector, and the rise of considerable currents in the electrode circuit make it impossible to control the loss of the beam current at the ion optics electrodes and assess correctly the beam current from the current measurements in the high-voltage source circuit.

This study deals with a measurement method based on an analog of the Faraday cup where the input electrode is the accelerating electrode of the ion source, which receives the cutoff voltage of secondary electrons, while a low voltage (tens of volts) of different polarities is applied to the walls relative to the grounded collector. With the current balance at the electrodes of this device, we studied how charge-exchange processes, ionization by fast secondary electrons and beam ions, the secondary electron emission from the beam collector and the accelerating electrode influence on the measurements of the beam current and determined characteristics of these elementary processes.

2. Experimental Technique

Wide beams of argon ions with largely different energies were generated in the experiments using glow-discharge ion sources, namely a high-energy (30 keV) ion source with the electrode system of the inverted magnetron type [2] and a low-energy (5 keV) ion source with a gridded plasma cathode having a magnetic multipole in the anode stage [3]. The plasma and the screen electrode of the ion-optical system in these sources are separated by a layer of a space charge with the voltage drop U_s, which has a considerable effect on the extraction of ions and formation of the beam [4]. Mathematical modeling and measurements of the beam profile helped determine regimes, in which the beam loss at the accelerating electrode was nearly absent. In the low-energy ion source with U_s=150 V the optimal current of the beam was 6 mA. In the case of the argon ion beam having the energy of 30 keV the optimal beam current at U_s=500 V was 30 mA.

The experimental scheme is shown in Fig. 1. The size of holes in the screen electrode 1 and the accelerating electrode 2 of the ion-optical system for formation of 30-keV beams was d=12 mm. The accelerating gap length was l=40 mm. The beam had the initial diameter of 120 mm. The distance between the accelerating electrode and the beam collector was L=120 mm. The walls 3 had the diameter D=220 mm. The accelerating voltage U_b was applied between the screen electrode 1 and the grounded beam collector 4. The negative cutoff voltage of secondary electrons U_a was applied between the electrode 2 and the collector 3. It was equal to 0.5 kV and 1 kV for the low- and high-energy sources respectively. The size of holes in electrodes of the low-voltage optics was d=4 mm. The accelerating gap had the length l=3 mm. The diameter of the 5-keV ion beam at the ion optics outlet was 30 mm. The distance to the collector was L=40 mm. The electrode 4 had the diameter D=90 mm. All the electrodes were made of a stainless steel. Geometrical dimensions of the Faraday cup electrodes were chosen so as to exclude bombardment of walls by accelerated ions.

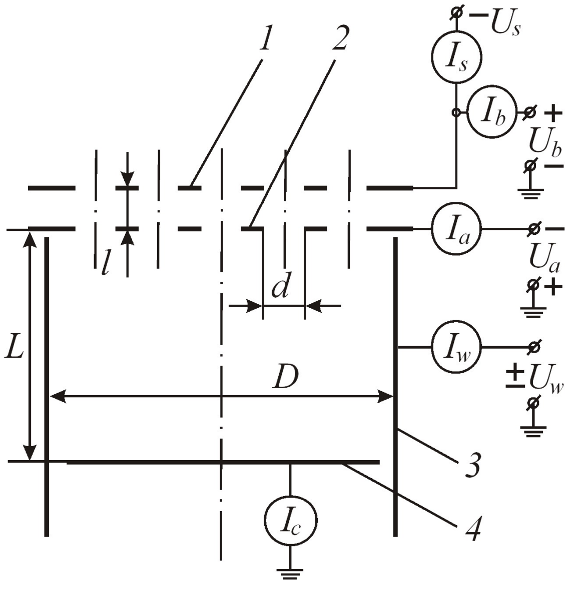

Fig. 1. Experimental scheme: 1 – screen electrode; 2 – accelerating electrode; 3 – walls; 4 – collector

The potential of the walls was selected on condition that it should be low in order to minimize changes in regimes of the gas ionization by secondary electrons when the walls reverse their polarity, but sufficient for reliable cutoff of plasma electrons or ions. The potential of the walls was U_w=+30 V, 0 and 30 V relative to the grounded collector. Currents to the screen electrode I_s, the high-voltage source current I_b, the current in the accelerating electrode circuit I_a, the current to the beam collector I_c, and the current to the walls I_w were measured in the experiments. The gas pressure in the region of the beam drift changed from 0.04 to 0.15 Pa in the high-voltage system and 0.03 to 0.06 Pa in the low-voltage system.

The change of the pressure influenced not only processes in the beam propagation region, but also the intensity of ionization processes in the ion source plasma. This influence showed up as the pressure dependence of the ion beam current at a constant discharge current and a constant accelerating voltage [3]. The current of the accelerating voltage source I_b was stabilized in the experiments in order to keep the ion beam current constant when the pressure changed.

The beam plasma potential was measured using a Langmuir collecting probe, which was screened from direct hitting by accelerated ions. In all the experiments the plasma potential was several volts higher than the potential at the positive electrode (the collector or the walls).

3. Processes in the Region of the Beam Propagation

The total current to the Faraday cup electrodes should be equal to the ion current I_{io} at the entrance to the beam propagation region. As a result of the resonance charge exchange, the current of accelerated ions decreases according to the relationship

$$I_{ic}=I_{io}\exp(-\sigma_{ce}n_o x), \qquad (1)$$

with the distance to the ion-optical system. Here σ_{ce} is the resonance charge exchange cross-section, n_o is the concentration of neutrals, x is the distance from the measurement point to the ion optics. The ion bombardment of the collector causes formation of secondary electrons whose current is proportional to the ion-electron emission coefficient γ. The γ value depends on the collector material, the collector surface condition, and the type and energy of ions [5]. If it is assumed that the resonance charge exchange does not alter the flow of fast particles to the collector and the average value of the ion-electron emission coefficient of fast ions and neutrals is taken equal to γ_L, we obtain a relationship for the current of secondary electrons from the collector in the form $\gamma_1 I_{io}$. Plasma ions, which are withdrawn from the plasma to the accelerating electrode, acquire some energy in the space charge layer. The ion-electron emission causes appearance of secondary electrons, which are also accelerated in the layer to the energy eU_a determined by the cutoff voltage. These electrons, along with the beam ions, ionize the gas. The current of slow ions, which appear in the beam propagation region, comprises the current of slow charge-exchange ions I_{ic} and the current of ions I_{ii} formed by the gas ionization. Since particles, which appear during ionization, are paired, the current of plasma electrons equals the current of ions, $I_{ei}=I_{ii}$.

If the potential of the walls is positive, the relationship for the collector current is

$$I_c^+=I_{io}-I_{ic}+\gamma_1 I_{io}+k_1 I_{ic}+k_2 I_{ii}, \qquad (2)$$

where k_1 and k_2 are constants independent of the gas pressure.

The rest of slow ions go to the accelerating electrode. The relationship for the current to this electrode can be written as

$$I_a^+=[(1-k_1)I_{ic}+(1-k_2)I_{ii}](1+\gamma_2). \qquad (3)$$

The coefficient $(1+\gamma_2)$ takes into account the ion-electron emission current from the electrode.

The electron current to the positive-potential walls, I_w^+, includes the current of secondary electrons from the collector and the accelerating electrode and the total current of plasma electrons:

$$-I_w^+=\gamma_1 I_{io}+\gamma_2/(1+\gamma_2)I_a^+ + I_{ei}. \qquad (4)$$

Using the sum of the current (2) and the ion component of the current (3), it is possible to determine the current of ions I_{ii}, which appear due to the gas ionization:

$$I_{ii}=I_c^+ + I_a^+/(1+\gamma_2)-I_{io}(1+\gamma_1). \qquad (5)$$

The sum of the currents (2), (3) and (4) gives the current of the ion beam I_{io} at the exit from the ion-optical system.

If the potential of the walls is negative, all electrons go to the collector. The relationship for the current to the collector will have the form

$$I_c^- = I_{io} - I_{ic} - I_{ei} - [\gamma_2/(1+\gamma_2)]I_a^-. \quad (6)$$

The current to the walls comprises fractions of the currents of slow charge-exchange ions, $k_3 I_{ic}$, and ions resulting from the gas ionization, $k_4 I_{ii}$:

$$I_w^- = k_3 I_{ic} + k_4 I_{ii}. \quad (7)$$

Here k_3 and k_4 are constants.

By analogy with (3), the current to the accelerating electrode can be written as

$$I_a^- = [(1-k_3)I_{ic} + (1-k_4)I_{ii}](1+\gamma_2). \quad (8)$$

Then the sum of the current of ions to the walls (7) and the ion component of the current to the accelerating electrode (8) is equal to the total current of slow ions from the plasma:

$$I_{ic} + I_{ii} = I_w^- + I_a^-/(1+\gamma_2). \quad (9)$$

Similarly to the case of the positive potential of the walls, the sum of the currents (6–8) is I_{io}.

If we assume that the change of the walls potential influences little the ionization intensity, from (9) and (5) it is possible to deduce a relationship for the current of slow charge-exchange ions:

$$I_{ic} = I_{io}(1+\gamma_1) + I_w^- - I_c^+ + (I_a^- - I_a^+)/(1+\gamma_2). \quad (10)$$

Combining (1) and (10), we obtain an equation describing the relationship between measurement results and characteristics of elementary processes:

$$\gamma_1 + \exp(-\sigma_{ce} n_o L) = [I_c^+ - I_w^- + (I_a^- - I_a^+)/(1+\gamma_2)]/I_{io}. \quad (11)$$

Extrapolating the right side of the relationship (11), which is a function of the pressure in the experiment, until it crosses the ordinate axis, we obtain the value of the coefficient γ_1. The approximation of this function by the exponent gives the σ_{ce} value.

4. Experimental Results and Discussion

The gas pressure dependences of currents to the collector, the accelerating electrode and the walls bearing different potentials (Fig. 2), which were obtained for the high-energy ion beam, showed that secondary particles made a considerable contribution to the measured currents.

The linear extrapolation of the curve 1, which corresponds to the relationship (5), until it crossed the ordinate axis (Fig. 3) allowed determining the $I_{io}(1+\gamma_1)$ value and calculating the coefficient γ_1~1.5. The curve 2 (Fig. 3), which was plotted by summing up currents to all the electrodes at a positive potential of the walls, gave the value of the initial beam current I_{io}~31±1 mA.

The curve 3 (Fig. 3) represents the ratio of the current of slow charge-exchange ions and the initial current of the ion beam, I_{ic}/I_{io}, as a function of the pressure in accordance with (10).

The curve 4 (Fig. 3), which was plotted according to (5), is the ratio between the current of ionized ions and the initial beam current, I_{ii}/I_{io}. It follows from these dependences that the process of charge exchange had the decisive effect on the current of slow ions under the experimental conditions.

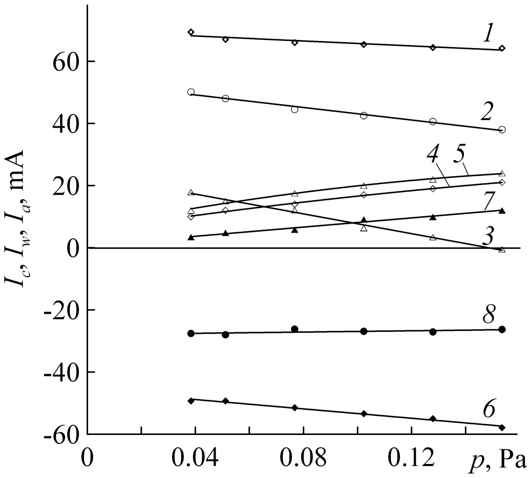

Fig. 2. Currents to the collector I_c (1, 2, 3), the accelerating electrode I_a (4, 5) and the walls I_w (6, 7, 8) versus the argon pressure. The walls potential is +30 (1, 5, 6), 0 (2, 8), −30 V (3, 4, 7)

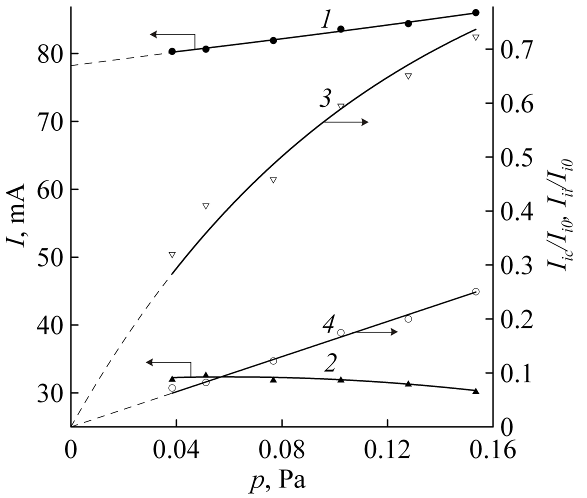

Fig. 3. The sum of the current to the collector and the ion beam current to the accelerating electrode (1), the sum of currents to the electrodes (2), and the ratio of the current of charge-exchange ions I_{ic} (3) and the current of ionized ions I_{ii} (4) to the beam current I_{i0} versus the argon pressure. The walls potential U_w=+30 V

The dependences, which were obtained in the experiment with the low-energy beam, were specific in that the collector current was always smaller than the current in the circuit of the high-voltage source and weakly depended on the potential of the walls, while the ratio between the current to the walls and the ion beam current was nearly one order of magnitude smaller than the ratio in the case of high-energy ions.

The curves 1 and 2 in Fig. 4 are relative currents of charge-exchange ions and ions resulting from the gas ionization as a function of the pressure in the low-voltage system. The comparison with Fig. 3 shows that the share of charge-exchange ions increased in the total current of slow ions, but the ratio between the current of charge-exchange ions and the beam

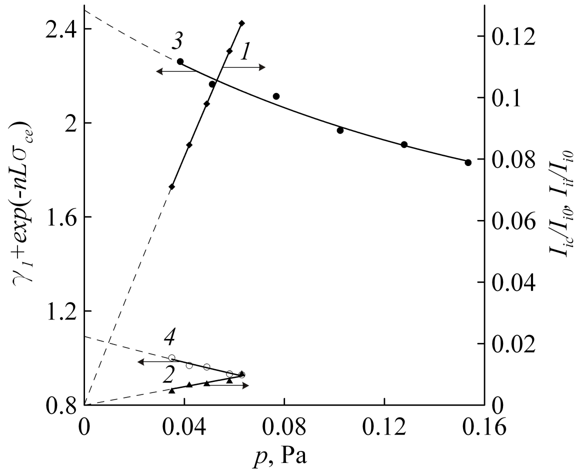

Fig. 4. The ratio of the current of charge-exchange ions I_{ic} (1) and the current of ionized ions I_{ii} (2) to the beam current I_{i0} versus the gas pressure and $\gamma_1+\exp(-\sigma_{ce}n_0L)$ as a function of the gas pressure. The energy of argon ions is 5 (1, 2, 4), 30 keV (3)

current decreased. This was due to the corresponding changes in the charge-exchange and ionization cross-sections, which followed the decrease in the ion beam energy, and a smaller extent of the region of the low-energy beam propagation. The curves 3 and 4 (Fig. 4) were plotted in accordance with the relationship (11) for low-voltage (curve 4) and high-voltage (curve 3) ion beams. The approximation of these curves by the exponent gives σ_{ce}~$1.8\cdot10^{-15}$ cm^2 for high-energy argon ions and σ_{ce}~$2.2\cdot10^{-15}$ cm^2 for low-energy ions. These values are in agreement with known literature data [6, 7]. The extrapolation of the curves 3 and 4 until they crossed the ordinate axis gave the coefficient γ_1~1.5 for the high-voltage system and γ_1~0.1 for the low-voltage system. This is in agreement with the data of [5].

5. Conclusion

The Faraday cup with non-equipotential electrodes was used for determination of characteristics of elementary processes of the interaction of accelerated argon ions with the gas atoms and the material of the ion beam collector. The relative contribution of the charge exchange and ionization processes to the current of slow ions, which were generated in the beam propagation region ~10 cm long at the gas pressure of ~0.1 Pa and the ion energy of units to tens of keV, was evaluated.

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