Efficiency of Ion Generation and Ion Extraction in an Ion Source with a Gridded Plasma Cathode and a Magnetic Multipole

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Abstract – Dependences of the ion current extracted from the anode plasma on the working gas (argon) pressure were measured for variants of a two-stage electrode system, which had different surface areas of the gridded plasma cathode and configurations of the multipole magnetic system. It was shown that the current of ions extracted from the anode plasma depended on conditions used for injection of fast electrons to the second stage. These conditions were considerably different for linear and ring magnetic multipole systems. The maximum energy efficiency of the ion generation, which was calculated from the ratio of the ion current to the screen electrode of the ion optics to the total discharge power, was as large as 1.6–1.9 A/kW at the discharge current in the first stage equal to 0.2–2 A and the second stage voltage equal to 150 V. The energy efficiency of the ion source was 0.5 A/kW when an argon ion beam having the energy of 4.5 keV, the cross-section of 50 cm^2 and the total current of 0.4 A was generated.

1. Introduction

A non-self-sustained gas discharge confined by a peripheral magnetic field is used in sources of broad gas-ion beams [1]. Usually this discharge is sustained by the thermoionic emission from cathodes located in the magnetic-field-free space. Electrons, which are accelerated in the cathode layer of the space charge, are reflected repeatedly from regions of a strong transverse magnetic field between unlike poles of the magnetic system. This ensures an efficient energy relaxation of the electrons and generation of spatially uniform plasma. It was proposed [2] to outfit this gas-discharge system with a gridded plasma cathode (GPC) based on a hollow-cathode glow discharge. Main factors responsible for the electron emission of the GPC in the ion source were determined too. In addition to the dependence of the electron emission current on the grid mesh size, which is typical of plasma sources of electrons [3], researchers observed a sharp increase in the electron current with growing pressure of the gas. This increase was due to an intensive reverse ion flux leading to the rise of the cathode plasma potential [4].

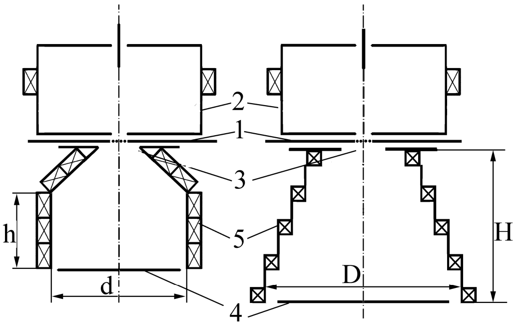
The flux of ions towards the screen electrode of the ion optics depends not only on the electron emission current from the plasma cathode, the gas pressure and the energy of electrons injected to the anode stage, but also on the level of their energy relaxation and the distribution of the ion current between the electrodes. A distinctive feature of GPC systems as compared to thermal cathode systems is that fast electrons are injected to the magnetic-field-free region from the outside. Therefore, dimensions of the GPC surface and the topography of the uncompensated magnetic field in the electron injection region may have a considerable effect on the character of movement of peripheral fast electrons, conditions of ion generation and going away from the plasma.

This study deals with the influence of the GPC surface and conditions of injection of fast electrons to the anode stage of the discharge confined by a multipole magnetic field with linear and ring geometry of the poles, on the anode plasma parameters and the distribution of the ion current between electrodes of the anode stage over a broad interval of gas pressures. The efficiency of ion generation and their extraction from the anode plasma of the discharge with the GPC was determined too.

2. Experimental Technique

The experiments were performed using an ion source with GPC (Fig. 1, *a*, *b*), which was described in detail elsewhere [4]. The diameter of the plasma cathode grid 1 was 10 and 30 mm. The stainless-steel wire grid had meshes 0.6×0.6 mm in size and its geometrical transparency was 67 %. The cathode aperture diameter changed according to the size of the plasma cathode grid. The surface area of the hollow cathode 2 was 1000 cm^2. The inlet aperture of the hollow anode 3 was 60 mm. Ions were extracted to the ion collector 4, which was installed instead of the screen electrode of the beam forming ion-optical system.

The peripheral magnetic field was produced using either a linear or ring configuration of magnetic poles, which were formed by permanent magnets installed in rows on the anode of the cylindrical or conical shape. The linear multipole was created by permanent magnets 5 made of the samarium-cobalt alloy, which were installed in twelve linear rows on the surface of the cylindrical anode (d=130 mm, h=100 mm), and a conical branch pipe (Fig. 1, *a*). The diameter of the branch pipe at the end of the magnetic poles was 80 mm. A variable-diameter anode of the length H=160 mm was used in the system with ring poles. The anode comprised round cylinders 36 mm long whose diameters increased in the direction from the grid to the ion collector 4 from d=110 mm to D=180 mm (Fig. 1, *b*). Further in the text the anode of this shape will be referred to as the conical anode. Five ring rows of permanent magnets were installed on the surface of the cylinders. The magnetic pole, which was next to the grid, had the diameter d_p of 90 mm. Thanks to the conical shape of the anode, it was possible to make the total length of the magnetic poles shorter and, hence, decrease the area of the loss of fast electrons [2], and increase the surface area of the ion collector. These features should improve the efficiency of the ion generation in the anode stage and lead to the increase in the current of ions extracted to the collector.



a) b)

Fig. 1. Schematic diagram of the electrode systems

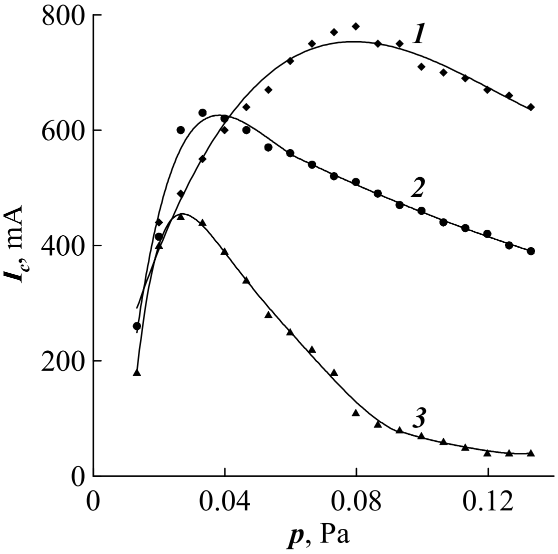


Fig. 2. Ion current vs. argon pressure. The diameters of the cathode aperture: 10 (1), 20 (2), 30 mm (3). (d_p=90 mm). Ring multipole. I_1=0.4 A

The current in the glow-discharge cathode circuit I_1 was preset within 0.2–2 A by changing the voltage U_1 between the hollow cathode and the grid from 350 to 500 V. The voltage U_2 between the anode and the electrically connected grid 1 and the collector 4 was maintained at 150 V using a separate power supply. Currents in the hollow cathode circuit, the grid unit, the anode and the ion collector were measured in the experiments. The argon was leaked directly into the hollow cathode. Values of the gas pressure $(2.6–13)\cdot 10^{-2}$ Pa were measured in the vacuum chamber. The cathode plasma potential was measured using a collecting cylindrical Langmuir probe.

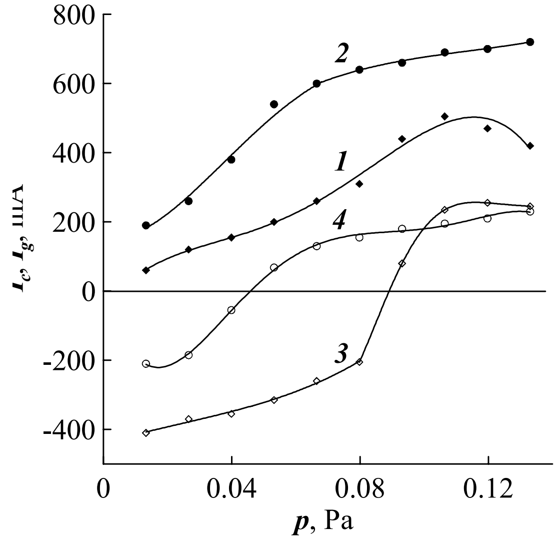


Fig. 3. Collector ion current (1, 2) and grid current (3, 4) vs. argon pressure. The diameters of the cathode aperture: 10 (1, 3); 30 mm (2, 4). Linear multipole

3. Results

Figure 2 presents gas pressure dependences of the ion current to the collector Ic, which were obtained for d_p=90 mm. The ion current changed non-monotonically. The current maximum shifted towards higher pressures as the GPC size diminished. The current decreased at a maximum rate when the grid size was the largest. This behavior of the ion current differed fundamentally from dependences, which were measured in the system with a linear multipole (Fig. 3). The last dependences were characterized by a monotonic growth of the current up to pressures when the bipolar diode between the cathode and anode plasma became unstable [4].

Pressure dependences of Ic and the current in the grid unit circuit Ig in the system with large d_p=110 are shown in Fig. 4. These dependences changed most as compared to those in Fig. 2. The surface area of the plasma-contacting surfaces of the grid unit was determined by the size of the anode and cathode apertures. The cathode plasma potential measured with Langmuir probe increased with growing GPC size and reversed sign after the second stage is turn-on. The distributions of the axial component of the magnetic field on the length H in the anode stage (Fig. 5) demonstrate that the maximum longitudinal component of the field were much larger when the pole diameter was small, d_p=90 mm.

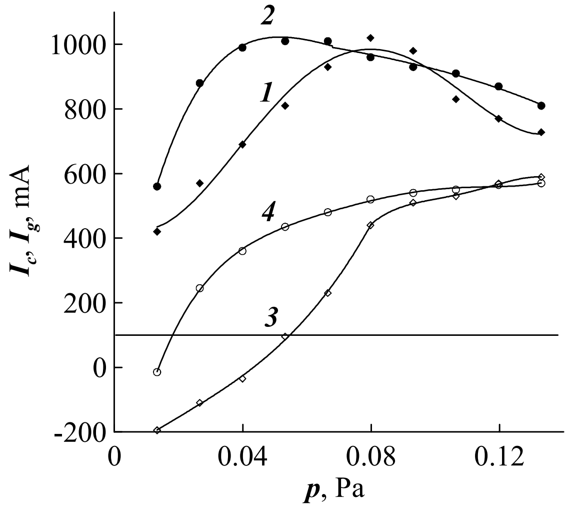


Fig. 4. Collector ion current (1, 2) and grid current (3, 4) vs. argon pressure. The conical anode. Cathode aperture: 10 (1, 3), 30 mm (2, 4), (d_p=110 mm)

Figures 6 and 7 present gas pressure dependences of the power consumed in the first and second stages of the gas discharge systems with linear and ring multipoles, which were calculated from the relationships $W_1=U_1\cdot I_1$ and $W_2=U_2\cdot I_a$, where I_a is the current in the second stage anode circuit. The energy efficiency of generation of ions coming to the collector з, which is defined by the relationship $I_c/(W_1+W_2)$, is also shown in these figures. Irrespective of the type of the magnetic system, the W_1 value decreased with growing pressure due to decrease of the discharge operating voltage. The W_2 value for the system with the linear multipole increased monotonically with the pressure. The power consumption W_2 in the ring multipole system increased quickly and then decreased due to the reduction of ion generation rate. Correspondingly, the value of з for the linear system increased monotonically, while in the ring system it reached a maximum and decreased smoothly because of the decrease in the ion current to the collector. The maximum з value was equal to 1.6–1.9 A/kW. The energy efficiency of the ion source with the linear multipole was 0.5 A/kW during generation of an argon ion beam having the energy of 4.5 keV, the cross-section of 50 cm^2 and the total current of 0.4 A.

4. Discussion

Irrespective of the type of the magnetic system, the GPC area influences parameters of the anode plasma because the cathode plasma potential grows with increasing effective surface area of the anode in the glow discharge and the current of electrons extracted from the cathode plasma. A similar effect was observed in studies concerned with the effect of the mesh size of the GPC on parameters of the anode plasma [4]. The fast growth of the ion current to the collector with increasing gas pressure, which begins after the direction of the grid current is reversed, is explained by the sign reversal of the plasma potential relative to the anode and transition of the plasma cathode from emission through a potential barrier to emission from open plasma boundary. In this regime the electron emission current approached the glow-discharge current. When the grid diameter was 10 mm, this transition was observed at the largest pressure and was accompanied by switchover of the discharge to the constricted operation regime [4].

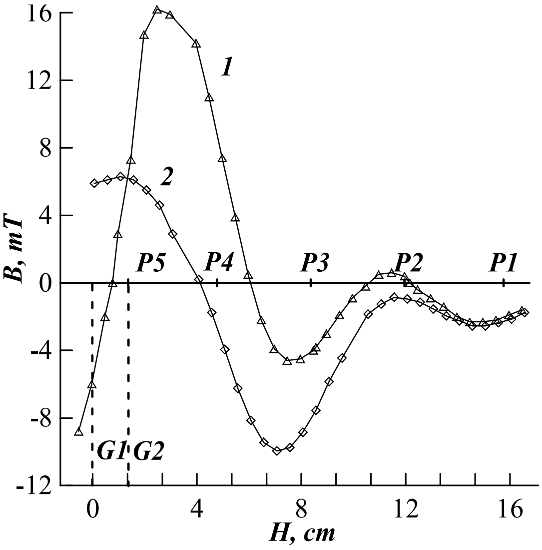


Fig. 5. Axial component of the magnetic field of the conical anode: for 5 poles (1), for 4 poles (2). P1-P5 are ring points. G1, G2 – position of the grids for the systems with 5 and 4 rings, respectively

As soon as the electron extraction efficiency reached a maximum, the growth of the total ion current to the grid and the collector with increasing pressure decelerated. In the system with the ring multipole ion currents were redistributed such that the ion current to the collector began decreasing as the gas pressure built up. This was due to the enhancement of the diffusion of peripheral fast electrons, which were confined near GPC, across the magnetic field. It is known [5] that the coefficient of the classical diffusion across a magnetic field is proportional to the frequency of the interaction between electrons and molecules of a neutral gas.

Unlike gas-discharge systems with the thermal emission cathode located in the magnetic-field-free region, the use of the GPC suggests injection of fast electrons to this region from the outside. The main distinction between the injection of electrons to the magnetic systems with ring and linear poles consisted in different directions of initial velocities of fast electrons and the magnetic field lines. While in the system with the linear magnetic multipole electrons were injected transversely to the field lines, in the system with ring poles electrons were injected along the axis of diverging magnetic field.

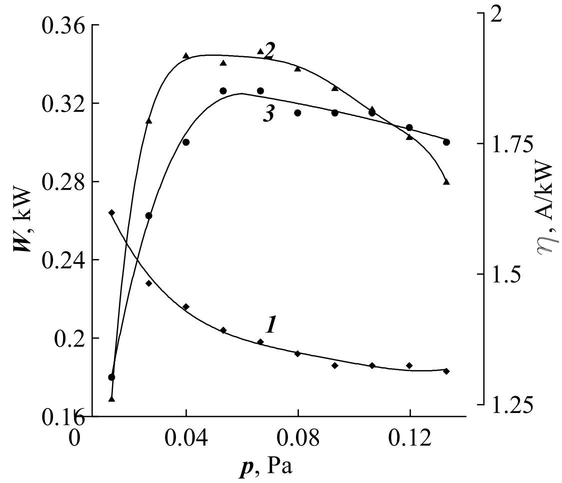


Fig. 6. Discharge power: W_1 (1); W_2 (3) and the energy efficiency η (2) vs. argon pressure for the ring multipole system. I_1=0.6 A, U_2=150 V. The diameter of the cathode aperture is 30 mm

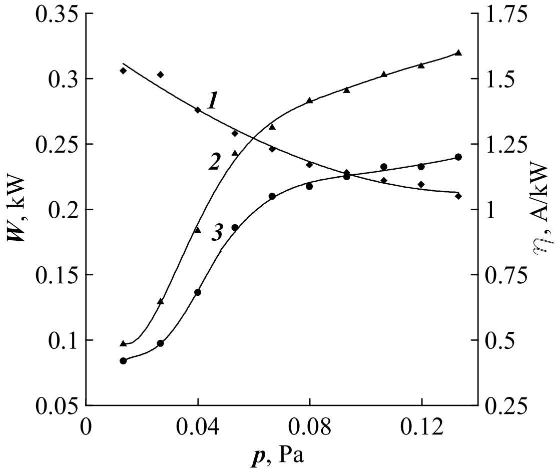


Fig. 7. Discharge power W_1 (1); W_2 (3) and the energy efficiency η (2) vs. argon pressure for the linear multipole system. I_1=0.6 A, U_2=150 V. The diameter of the cathode aperture is 30 mm

If injected across the magnetic field, electrons at the beam periphery hit the region of a stronger field, were reflected by this field, and followed trochoidal trajectories towards the screen electrode. In the system with the ring multipole the movement of electrons at the beam periphery, which were injected along lines of the nonuniform magnetic field, represented a combination of the Larmor gyration and the azimuthal drift in the magnetic field [6]. As a result, peripheral electrons were decelerated in the direction to the screen electrode and stayed most of the time near the grid. The probability of their capture by the magnetic field and the diffusion drift across the magnetic field to the anode increased with growing pressure. Since ions, which were generated near GPC, moved to the grid, the ion current to the collector decreased.

The energy efficiency of the ion source at hand, which depended on the ratio of current of ions extracted through orifices in the screen electrode of the ion-optical system to the current in the ion collector circuit, which accounts nearly 1/3–1/4. The difference in the fractions of extracted ions was due to the influence of the ion layer between the plasma and the screen electrode [7]. Thus, if regimes of the plasma generation and the ion extraction from plasma were optimal, the energy efficiency of the two-stage ion source might be as high as 0.5 A/kW.

5. Conclusions

1. If surface areas of the GPC and the outlet aperture of the hollow cathode were equal, the effect of GPC area on the value of extracted ion current is determined by the change of the anode-cathode surface area ratio and, correspondingly, the change of the potential of the hollow-cathode glow-discharge plasma, and, finally, the change of electron extraction efficiency from the cathode plasma.
2. The main reason for different characteristics of the plasma generation systems with linear and ring magnetic multipoles was different directions of the injection of fast electrons relative to the magnetic field. As a result, electron trajectories and the distribution of the ion current over electrodes of the anode stage were different.
3. The maximum current of ions, which were generated in the gas-discharge system with a conical anode and a ring magnetic multipole, was approximately 1.5 times higher than the current in the cylindrical system with a linear multipole when the values of the current in the first stage and the voltage of the second stage were equal. However, the maximum energy efficiency of these generation systems was nearly the same. This fact was due to the large loss of ions to the grid in the ring multipole system.

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