Sources of Broad and Ribbon Ion Beams with Grid-Bounded Plasma Cathode and Magnetic Trap

N.V. Gavrilov

Institute of Electrophysics UD RAS, 106 Amundsen Str., Ekaterinburg, 620016, Russia
Phone:(343) 2678778, fax: (343) 2678794, e-mail: gavrilov@iep.uran.ru

Abstract – Designs and characteristics of sources of broad and ribbon ion beams employing a two-stage gas-discharge system have been described. A bipolar diode was formed in the system between the cathode and anode plasmas separated by a fine metal grid. The control of the voltage drop across the diode over a wide interval independently of the gas pressure and the discharge current in combination with efficient confinement of fast electrons in the second stage by magnetic fields provided a high energy efficiency of the ion source and allowed controlling the density and the mass content of the plasma and the charge state of ions. Parameters of the anode and cathode plasmas have been studied in order to minimize the losses of fast electrons and ions in the anode stage and optimize emission of the grid-bounded plasma cathode in the presence of an intensive back ion flow from the anode plasma. The newly designed sources operate at a gas pressure of (0.6–6) · 10^{-2} Pa and provide a beam current density of gas ions 1–10 mA/cm^2. They combine a long lifetime of the cathode and a low content of metal ions in the beam.

1. Introduction

One of the leads in development of gas ion sources is the use of two-stage electrode systems. The plasma cathode is produced in the first stage using a hot filament [1], a high-frequency discharge [2], a cold-cathode arc [3] or glow [4] discharge. Ion emitting plasma having required parameters is generated in the second stage, which represents a trap for injected electrons. By this functional division it is possible not only to optimize operating conditions of the electron and ion plasma emitters separately, but also prolong the lifetime of the cold cathode, reduce the gas pressure in the beam formation and beam drift regions, and decrease the content of metal ions in the beam to fractions of a percent [5]. The grid, which separates the cathode and anode stages, ensures formation of a bipolar diode. The diode voltage and the energy of electrons injected to the second stage can be adjusted over a wide interval independently of the gas pressure and the discharge current [6]. Additional acceleration of plasma electrons in the diode allows increasing the proportion of energy consumed for ion generation, while the consumption for the electron emission of the cold cathode remains unchanged. Therefore, energy efficiency of the ion source is improved and more opportunities are provided for control of the density and mass composition of the plasma, and the charge state of ions.

Systems intended for generation of broad ion beams using a grid-bounded plasma cathode and a multicusp magnetic field in the anode stage [7] ensure more efficient extraction of ions as compared to systems with electrostatic confinement of electrons in the hollow cathode. They do not require, unlike Penning systems, special measures for smoothening of the plasma density in the volume.

A large number of magnetic cusps necessary for compensation of the magnetic field in the volume, increase the ratio of ions gone in the magnetic slits to the extracted ions if the required area of the ion emitter decreases. Therefore, the use of these “magnetic bucket” systems for formation of narrow ribbon beams may be inefficient. When the emitter size is small, the way to reduce ion losses is a formation of sharply inhomogeneous plasma in the discharge with a maximum concentration near the emission boundary of the plasma [8]. Plasma, which is inhomogeneous transversely to the long axis of the ribbon emitter and has a constant maximum density along the axis, can be generated using a ribbon grid-bounded plasma cathode and a linear cusp magnetic field where electrons accelerated in the bipolar diode, oscillate and are repelled alternately by a strong magnetic field near a cusp [9] and the electric field of the diode. However, the presence of a magnetic field near the plasma cathode and in the anode plasma necessitates study of conditions for generation of quiescent low-noise plasma.

If conditions are provided in the anode region for efficient gas ionization and a maximum energy relaxation of fast electrons, the ion component of the bipolar flow in the diode increases and parameters of the cathode plasma change as a result of resonance charge exchange of ions. This may influence the plasma cathode emission.

The present paper describes designs and parameters of sources of broad and ribbon ion beams. It also reports parameters of the anode and cathode plasmas, which were analyzed in order to minimize the loss of fast electrons and ions in the anode stage of the sources and optimize emission regimes of the grid-bounded plasma cathode.

2. Experimental Setup

The electrode system shown in Fig. 1 was used in the study. The plasma cathode was produced by a hollow cathode (item 1) glow discharge, which operated in a high-current vacuum regime. The rod electrode 2 facilitated initiation of the discharge at a low gas pressure. The working pressure of the gas leaked into the cathode cavity was reduced further thanks to a multicusp magnetic field, which was produced near the cathode surface by permanent magnets 3. The grid 4, being the glow-discharge anode, was placed oppositely to the outlet aperture of the cathode, was electrically connected to the screen grid 5 of the ion beam formation system. Grids were installed on end faces of the hollow anode 6, who's outside surface mounted linear rows of permanent magnets 7 with alternating polarities. The magnets formed a multicusp field having the pole induction of up to 0.4 T. The hollow electrodes were 150 mm in diameter, the cathode aperture was adjustable within 0.5–2 cm, while the grid meshes changed in steps of 0.2 to 2 mm. The glow discharge current was 0.1 to 1 A, the second stage voltage was varied between 0–300 V, and the gas (argon) pressure, which was measured in the vacuum chamber, was between 0.05 and 0.5 Pa. Parameters of the cathode and anode plasmas were measured using Langmuir probes and a retarding field electrostatic energy analyzer.

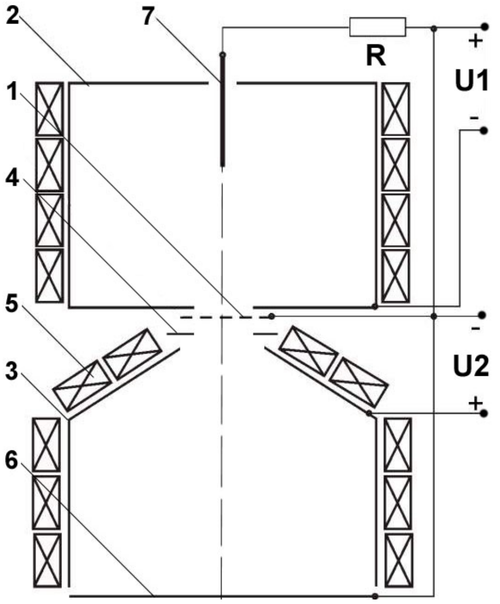

Fig. 1. Schematic of the ion source electrode system

3. Basic Physics

When a voltage was applied to the second stage after initiation of a glow discharge between the hollow cathode and the grid, a bipolar diode was formed between the grid and the anode plasma. Electrons emitted by the cathode plasma and ions from the anode plasma were accelerated at the diode gap. As the first approximation, if the effect of near-anode layers was disregarded, the energy of electrons was determined by the voltage applied between electrodes of the second stage, which might be much higher than the voltage at the double electric layer in constricted discharges [9]. The latter voltage depended on gas conditions in the constriction and usually was equal to 20–50 V. When the energy of fast electrons, which were confined in the magnetic trap, increased, the rate of ion generation in anode stage rises.

If the anodic potential drop in the second stage was positive, electrostatic confinement of ions, which improved efficiency of the ion source, could be realized along with magnetic confinement of fast electrons. The current of ions extracted from plasma was enhanced as the ratio between the full path of a primary electron before it escapes to the anode, l, and the average ionization path λ_i increased. That is, the said current increased with the gas pressure and improvement of fast electron confinement, which was facilitated by the rise of the magnetic field at cusps. If $l/\lambda_i \geq 1$, the ion current increased with growing energy of electrons.

The sign of the potential drop across the anode sheath at the first stage effects the emission of the plasma cathode. If the plasma potential was positive, electrons could be extracted from the open plasma surface [10, 11] and, hence, the emission current could increase up to values approaching the discharge current. Efficient relaxation of fast electrons in the anode plasma of the ion source had a result that, unlike in common plasma electron sources, an average intensity of the field in the bipolar diode could be determined by the space charge of ions. Resonance charge exchange of these ions on gas atoms could affect the density and potential of the cathode plasma and, correspondingly, the electron emission of the plasma cathode.

4. Experimental Results and Discussion

Dependences of the ratio between the glow-discharge current and the ion current to the screen electrode, I_1/I_i, which were measured at different values of the second-stage voltage U_2 and the current I_1, are given in Fig. 2. The ratio I_1/I_i decreased with growing pressure. The increase in the energy of fast electrons also led to the decrease in I_1/I_i. At high pressures the dependence of I_1/I_i had a minimum corresponding to a maximum ion extraction efficiency α. The position of the minimum was determined by the glow-discharge current, the voltage U_2 and the design of the grid unit. In the bucket-type hot-cathode sources the decrease in the ion current at high pressures was explained by a higher rate of ion diffusion to the anode transversely to the field as a result of their collisions with neutrals [12]. The dependence of the ion current on the gas pressure and the voltage U_2 in the two-stage ion source might be due not only to ionization processes in the anode chamber, but also to properties of the plasma cathode.

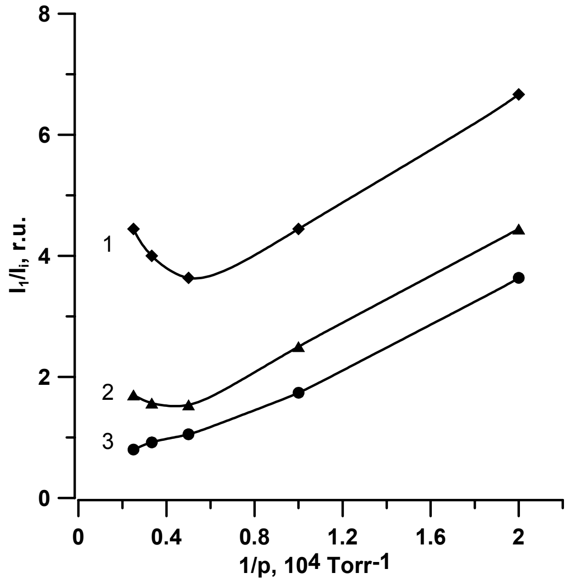

Fig. 2. The ratio of the discharge current to the ion current vs. the inverse value of the gas pressure. $I_1 = 0.4$ A, $U_2 = 50$ (1); 100 (2); 150 V (3)

Figure 3 presents pressure dependences of the ion current to the collector and the current in the grid circuit for with meshes of different sizes. The resulting current to the grid decreased with growing pressure and could reverse its sign. The ion current increased monotonically when a fine grid was installed. In the system with a coarse grid, the current decreased progressively as soon as a certain pressure was reached. The larger was the grid mesh, the lower was the threshold pressure, at which the grid current reversed its sign and the ion current stopped growing.

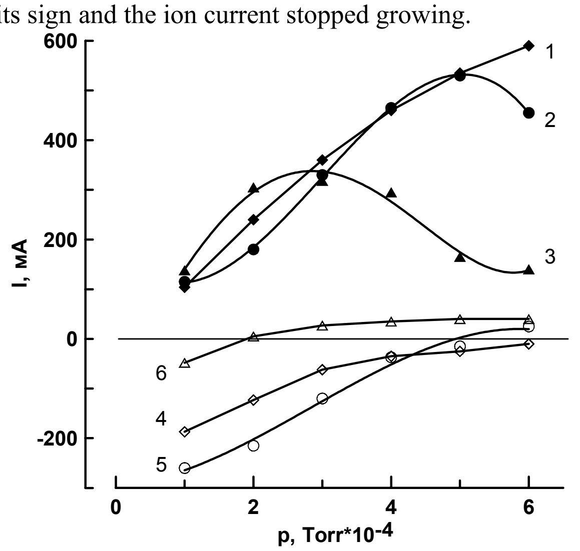

Fig. 3. Collector ion current (1–3) and grid ion current (4–6) vs. argon pressure. $I_1 = 0.6$ A, $U_2 = 200$ V. Mesh length 0.6 (1, 4), 1.4 (2, 5) и 2 mm (3, 6)

The change of the resulting current in the grid circuit could not be attributed only to the increase in the ion current from the anode plasma, because the change of the ion current density with growing pressure was insufficient for compensation of a considerable electron current to the grid. A more probable cause was the change of emission current of the plasma cathode.

Probe measurements of the cathode plasma showed that the plasma potential was negative relative to the anode (−10…−15 V) if voltage was not applied to the second stage. When the second stage was turned on, the cathode plasma potential increased and turned positive. The plasma potential was the higher, the larger the gas pressure, the second-stage voltage and the grid meshes were (Fig. 4). Since the shape of probe characteristics changed with growing pressure in the coarse-grid system, it was difficult to process them and determine the plasma potential. However, the change of the plasma potential could be judged by the shift of its floating potential to the region of positive values for as many as 10–60 V.

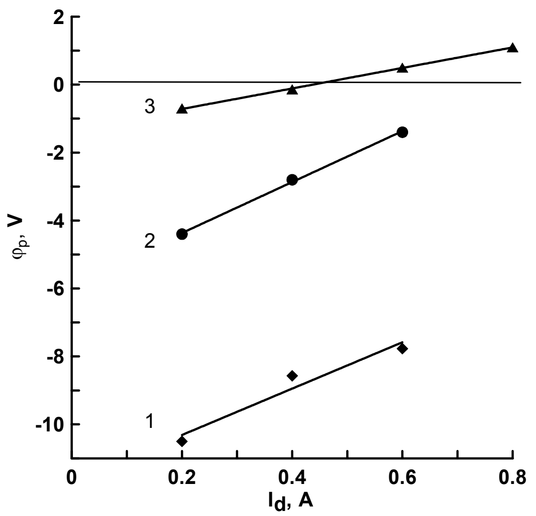

Fig. 4. Potential of the cathode plasma vs. discharge current. Mesh length 0.6 mm. Gas pressure $6 \cdot 10^{-2}$ Pa. $U_2 = 0$ (1), 100 (2), 200 V (3)

The emission regime of the plasma cathode changed due to the growth of the plasma potential. The regime with preliminary acceleration of electrons in the positive anode drop of the potential, when the electron extraction efficiency was nearly proportional to the grid transparency, was replaced by the regime with a potential barrier at the grid, when the electron emission current approached the discharge current. An efficient extraction of electrons in combination with supply of ions from the anode plasma, which charge exchanged on gas atoms, led to a growth of the cathode plasma potential and the drop of the bipolar diode voltage. As a result, the energy of electrons decreased and the rate of ion generation in the anode plasma diminished. It may be inferred therefore that the maximum in the pressure dependence of the ion current was mainly due to processes occurring in the cathode plasma.

Figure 5 presents dependences of the anode plasma potential on the discharge current at different gas pressures. The anode plasma potential remained positive and changed by 2–5 V relative to the anode potential over a wide interval of operation conditions and parameters of the discharge. The electron temperature of the anode plasma was 1–8 eV. The plasma potential and the electron temperature decreased with growing pressure. If the voltage U_2 at the second-stage increased by 100 V, the electron temperature rose by ~ 2 eV and the plasma potential increased by ~ 0.5 V.

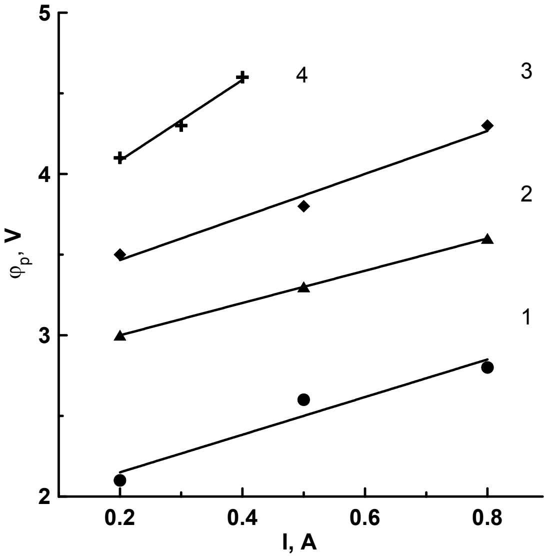

Fig 5. Anode plasma potential as a function of discharge current. Argon pressure $p = 8 \cdot 10^{-2}$ (1); $5.3 \cdot 10^{-2}$ (2); $2.7 \cdot 10^{-2}$ (3); $0.8 \cdot 10^{-2}$ Pa (4)

The positive potential of the anode plasma meant that the anodic stage did not provide conditions for electrostatic confinement of ions, which could escape to the anode along the magnetic lines. The ion current to the anode depended on the area of losses of plasma particles. According to [13], this area is determined by the product of the total length of magnetic poles times the hybrid gyroradius $(r_e\, r_i)^{1/2}$, where r_e and r_i denote gyroradii of plasma electrons and ions respectively. Considering the estimated loss of ions from their escape to the anode, the grid and the grid holder, it may be concluded that the fraction of ions extracted to the screen electrode accounted for about one-half of the full current of ions produced in the anode plasma.

5. Broad Ion Beam Source

A newly developed source [14] generated 100 mA broad ion beams having an energy of up to 5 keV. The source employed a two-electrode ion optical system with apertures 3 mm in size for formation of beams having a surface area of 50 cm^2. The surface area of the grid plasma cathode was 3 cm^2. The source was based on a hollow-cathode glow discharge, whose current was adjustable from 0.2 to 1 A.

Figure 6 shows dependences of the ratio between the ion beam current and the glow-discharge current (a) or screen grid current (b) on the second-stage voltage. Rise of the gas pressure up to $3 \cdot 10^{-2}$ Pa leads to the increase of I_b/I_d, for higher pressures the currents ratio decrease. As it was shown earlier it is due to increase of the plasma cathode current and rise of the ion generation rate at the anode plasma. On the contrary the ratio I_b/I_s decreases with rise of the gas pressure p and voltage U_2. The effect of the U_2 value on the current of ions extracted from plasma one can explain as a result of change of plasma boundary shape and position due to change of the near-electrode sheath thickness [15]. The effect of the gas pressure on the ratio I_b/I_s is not understand well now, but it may be due to the ion current redistribution over the screen electrode surface as a result of non-self-sustained glow discharge in a peripheric magnetic field.

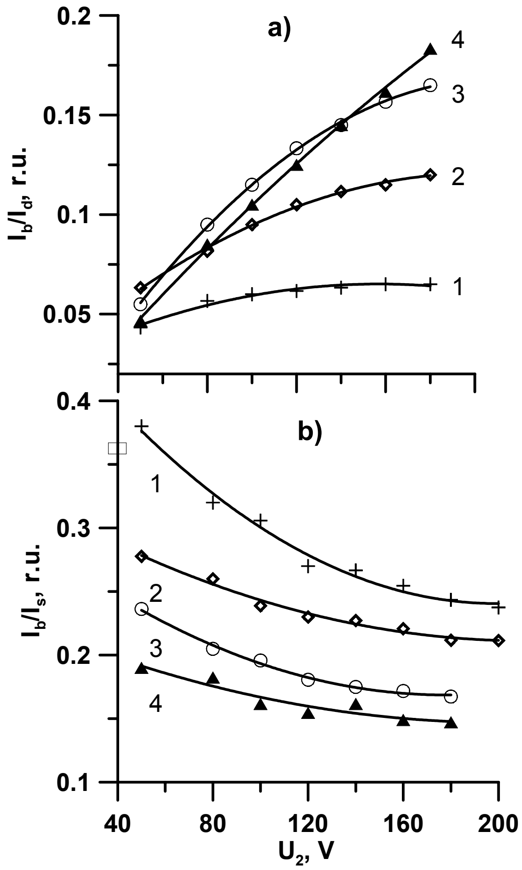

Fig. 6. Ratio of ion beam current to discharge current (a) and ion beam current to screen grid current (b) vs. grid-to-anode voltage. $I_d = 0.4$ A. Gas pressure $0.7 \cdot 10^{-2}$ (1), $1.3 \cdot 10^{-2}$ (2), $2.7 \cdot 10^{-2}$ (3), $4 \cdot 10^{-2}$ Pa (4)

The maximum average density of the beam argon ion current equal to ~ 2.5 mA/cm^2 was obtained at an argon pressure of $1.5 \cdot 10^{-2}$ Pa, an accelerating voltage of 5 kV, a secondary electron cutoff voltage of 2 kV, and an accelerating gap of 2 mm.

The energy efficiency of ion generation in the discharge, which was estimated from the ratio between the ion current to the screen grid and the power consumed in the second stage, $\eta_1 = I_i/(I_1 U_2)$, was about 7.5 A/kW under optimal conditions. This value was smaller than the maximum efficiency (11 A/kW), which was calculated analytically [12] disregarding the loss of energy for the hot cathode emission. If the energy consumption in the first stage was taken into account, the maximum efficiency of the discharge, $з_2 \sim I_i/[I_1(U_1 + U_2)]$, was nearly three times lower. The ion source efficiency is proportional to the ratio between the beam current and the ion current to the screen electrode, I_b/I_i: $з_2 \sim I_b/[I_1(U_1 + U_2)]$. In the experiments the source efficiency was not over 0.33 A/kW, due to decrease of the ion beam current/screen grid current ratio I_b/I_s with growing pressure.

6. Ribbon Beam Source

A fundamental distinction of the gas-discharge system of the ribbon ion emitter from the systems discussed above was the use of a plasma cathode, which was not screened from the magnetic field. Electrons, which were accelerated in the bipolar diode, went to an inhomogeneous magnetic field with curvilinear lines closing to the second-stage anode. Oscillations of electrons along lines of this field were accompanied by transformation of the longitudinal component of the electron energy to the transverse component, leading to reflection of electrons with a strong magnetic field.

The condition of the magnetic moment invariability was fulfilled for the system studied, since the Larmor radius of fast electrons, which were accelerated by the potential difference of ~ 100–200 eV, in the region of a strong magnetic field (0.2 T) was nearly two orders of magnitude smaller than the distance (~ 3 cm) between the cathode and cusps of the magnetic field [16].

The electrode layout of the emitter is shown in Fig. 7 and has been described in detail elsewhere [17]. The hollow cathode (item 1) 200 mm in diameter had a slit outlet aperture (item 2) 180 mm long and 30 mm wide. The grid 3 was installed opposite to the slit. The filament 4 was stretched along the axis of the cathode chamber. The anode 5 was shaped like a rectangular cylinder measuring 40×50×200 mm. The ion collector plate 6 was 50×200 mm in size. The external surface of the anode mounted one row of permanent magnets 7, which formed a linear cusp field.

The current of ions extracted from the plasma increased with growing gas pressure, which was equal to (1–4) · 10^{-4} Torr. The distribution inhomogeneity of the ion current density along the emitter was about 15% at the same length of the ion and electron emitters and increased as the plasma cathode shortened. Probe measurements of cathode plasma in the system with a grid area of 180×20 mm and 1.4-mm meshes showed that the plasma potential relative to the grid was positive and increased by 10–15 V with growing voltage across the second stage. The anode plasma potential approached the anode potential in all modes of the discharge operation.

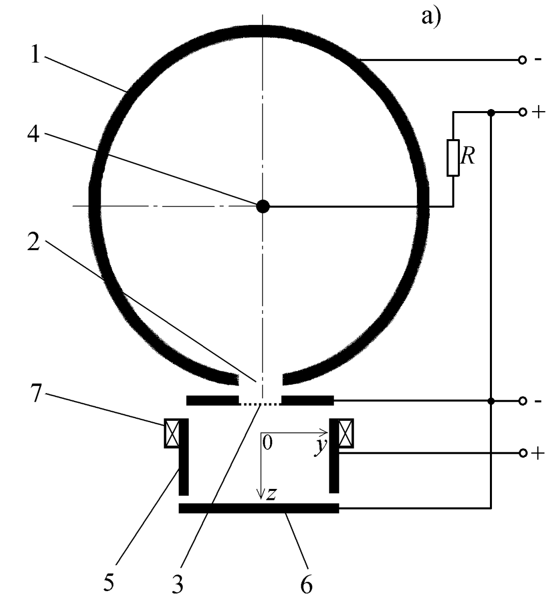

Fig. 7. Schematic diagram of electrode system of the ribbon plasma emitter

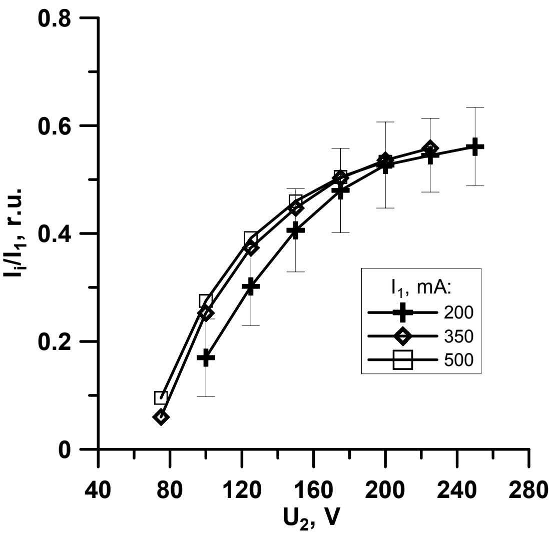

Fig. 7. Ratio of the ion current to the discharge current vs. the voltage U_2. Gas pressure 3 · 10^{-4} Torr. The cathode aperture 18×3 cm, the grid area 18×0.9 cm

A specific feature of the ribbon system was a large surface area of the grid (~ 36 cm^2), which favored the decrease in the electron emission current density and the density of the back ion flow. Therefore, it was possible to use grids with larger meshes and thicker wires, and, hence, to increase a grid lifetime.

7. Conclusions

1. The ratio of the ion current extracted from the plasma to the plasma cathode current increased with growing gas pressure and voltage across the bipolar diode and reached ~ 1 in the gas discharge systems studied.

2. The pressure dependence of the ion current was due not only to variation of the average ionization

path of fast electrons in the anode plasma, but also to alteration of the plasma cathode emission current.

3. The maximum in the gas pressure dependence of the ion current was due to the increase in the cathode plasma potential and the drop of the bipolar diode voltage rather than to the change in the loss rate of charged particles in the anode plasma.

4. Dependence of the ion beam current on gas pressure has a maximum due to decrease of ratio of ion beam current to screen electrode current while screen electrode current rises monotonically with pressure.

5. A ribbon beam source with a ribbon grid plasma cathode in a linear magnetic field formed by a single cusp generated plasma with a nearly uniform density distribution over the length of the system and provided efficient extraction of ions from the plasma.

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