Formation of Ribbon Plasma Emitter of Ions in Gas Discharge System with Grid-Bounded Plasma Cathode[1]

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Abstract – A method for formation of a plasma emitter of a ribbon ion beam source, which employs a two-stage electrode system of a glow discharge in a single-cusp linear magnetic field, has been proposed and analyzed. Electrons are emitted by a ribbon grid-bounded plasma cathode along magnetic field lines, are accelerated in a bipolar diode between the grid and the anodic plasma, and oscillate between the region of a strong magnetic field at the anode and the bipolar diode. Spatially inhomo-geneous plasma with a uniform distribution of the plasma density maximum over the emission slit is generated in the anodic region. The current of ions extracted from plasma accounts for 0.5–1 of the plasma cathode emission current. A simple design, high energy efficiency of the emitter, a low content of metal ions in the plasma, and the possibility to generate long-length ribbon ion beams having a current equal to hundreds of milliAmps and a uniform lengthwise distribution of the current density for a lengths of ~ 1 m make the proposed emitter promising for technological applications.

1. Introduction

Sources based on lengthy single-chamber [1] and multi-chamber [2] electrode systems of glow discharge in a magnetic field, in which the beam current amounted to 8–15% of the discharge current, were proposed for generation of ribbon ion beams up to 0.5 m long having a current of up to 0.2 A. A cold cathode ensures reliable long-time operation of such sources. However, an increased working gas pressure ($p > 0.02$ Pa) and presence of metal ions (up to several atomic %) in the plasma owing to ion sputtering of the cathode, limit application area of these sources.

The gas pressure was reduced and the contaminant concentration in the plasma was decreased in two-stage electrode systems with a grid-bounded plasma cathode and the anodic plasma. A bipolar diode was formed between the former and the latter. Fast electrons were confined in the second stage by an electrostatic trap with a hollow cathode [3] or a peripheral magnetic field [4]. The magnetic “bucket” provided a highly efficient extraction of ions from the plasma, but a large number of magnetic poles, which were required for compensation of the magnetic field in the plasma-filled trap, increased the ion loss in the region of magnetic slits as the required surface area of the ion emitter shrank. As a result, the emitter efficiency was decreased.

For small-sized emitter the ion loss is reduced by generating sharply inhomogeneous plasma with a maximum density near the plasma emission boundary [5]. A difficulty involved in formation of a linear ion emitter is that the maximum density of transversely inhomogeneous plasma should be constant along the emitter axis. In the present study this objective was achieved thanks to the use of a ribbon grid-bounded plasma cathode and a linear cusp magnetic field where electrons, which were accelerated in the bipolar diode, oscillated and were reflected alternatively by a strong magnetic field near the pole [6] and the electric field of the diode.

The present study deals with the effect of the discharge current (0.1–0.5 A), the gas pressure $(2–4) \cdot 10^{-2}$ Pa and the bipolar diode voltage (50–200 V) on ion emission properties of the plasma generated in a linear cusp magnetic field having induction at the pole of 0.2 T.

2. Experiment

The electrode system of the plasma emitter of ions is shown in Fig. 1. The hollow cathode (item 1) 200 mm across had a slit outlet aperture (item 2) 180 mm long, whose width could be adjusted within 10 to 40 mm. The grid 3 with meshes 0.6 to 1.6 mm in size was installed opposite to the slit. The filament 4, which facilitated striking of the discharge, was stretched along the axis of the cathode chamber. The anode 5 was shaped like a rectangular cylinder 40×50×200 mm in size. The ion collector 6 with dimensions 50×200 mm was fitted at the base of the cylinder. The outside surface of the anode mounted one row of permanent magnets 7 with like poles facing inwards. The magnets produced a linear cusp field. The distribution of the field components are shown in Fig. 1 (b,c). The magnets 5×10×20 mm in size having the pole induction of ~ 0.2 T were made of a KS-37 samarium-cobalt alloy.

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[1] The work was supported by RF Ministry of Industry, Science and Technology, contract No. 40.030.11.1126.

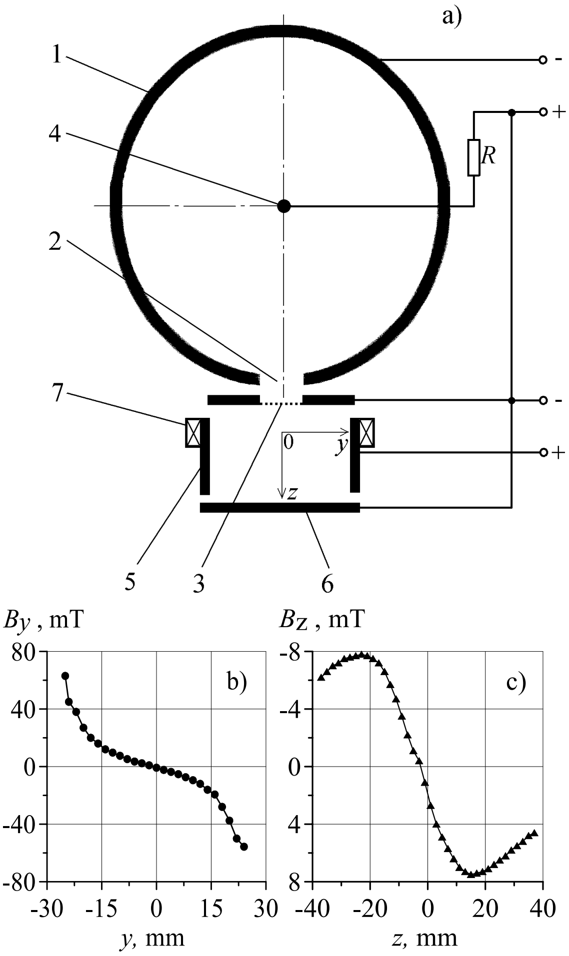

Fig. 1. Schematic diagram of the electrode system (a) and magnetic field distributions (b, c)

A glow discharge having the current I_d = 0.2–0.5 A and the operating voltage U_1 = 280–350 V was initiated after a gas was leaked into the cathode chamber (10–40 cm^3/min) and a voltage (0.4–0.8 kV) was applied between the cathode, the grid and the filament. Application of the voltage U_2 between electrodes of the second stage caused growth of the current in the ion collector circuit. The electron current in the grid circuit dropped with increasing voltage and then turned to the ion current (Fig. 2). The ion current extracted from the plasma increased with pressure (Fig. 3). The anode circuit current was nearly equal to the sum of currents in circuits of the hollow cathode, the collector, and the grid. Figure 4 presents the density distribution of the collected ion current in the direction parallel to the axis of the slit cathode aperture. The distribution was determined using flat probes. Shortening the length of the cathode outlet aperture from 18 cm up to 3 cm resulted in rise of longitudinal distribution non-uniformity of the ion current density from 5–10% up to 20–30%. Also the ion current to the collector was decreased approximately by 15% at high discharge currents.

The grid width (20 mm) was determined by conditions of the discharge operation with a uniform distribution of the current along the cathode aperture. The discharge was constricted if the transverse dimension of the cathode aperture decreased.

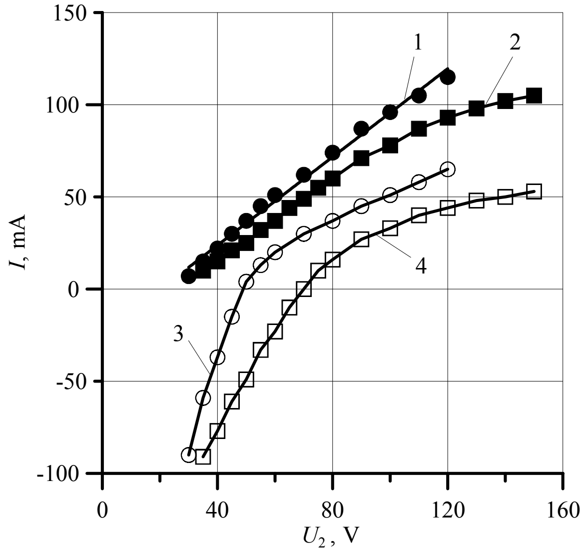

Fig. 2. Collector ion current (1, 2) and grid current (3, 4) as a function of second stage voltage U_2. Discharge current I_d= 0,2 A. Gas pressure (Ar): 1, 3 – 2,7 · 10^{-2} Pa; 2, 4 – 4 · 10^{-2} Pa

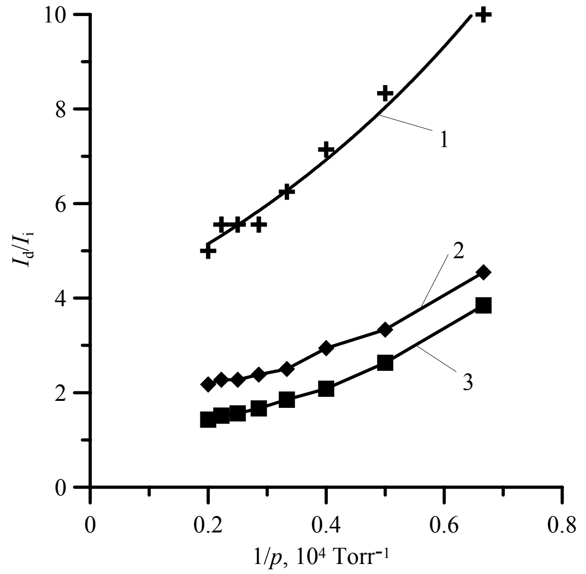

Fig. 3. The ratio of the electron current (I_d= 0,5 A) to the collector ion current as a function of inverse gas pressure. U_2= 50 (1); 100 (2); 150 V (3)

Figure 5 presents density distribution of the current to a probe, which could move in the slit of the ion collector transversely to the cathode slit. The maximum ion current density on the collector axis was 9 mA/cm^2 at the discharge current I_d = 0.5 A, the gas pressure of 4 · 10^{-2} Pa and the voltage U_2 ~ 200 V.

Probe measurements of the cathode plasma parameters in a system with the grid 180×20 mm in size having 1.6-mm meshes demonstrated that the plasma potential relative to the grid was positive and increased by 10–15 V with the voltage of the second stage (Fig. 6).

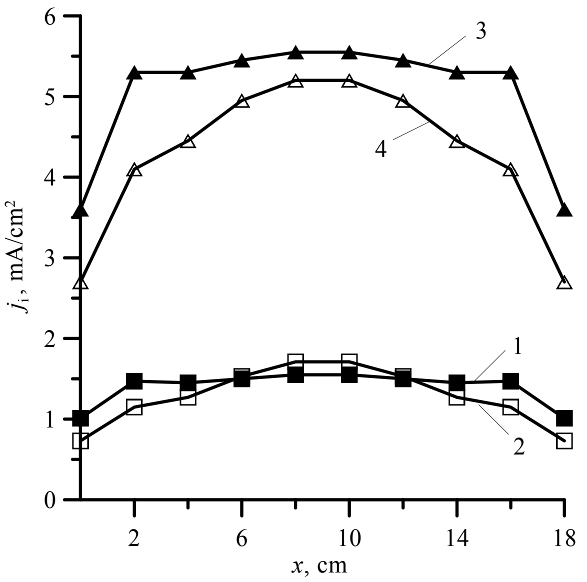

Fig. 4. Longitudinal distributions of the ion current density. Gas pressure (Ar) $4 \cdot 10^{-2}$ Pa. 1, 2 – I_d=0,2 A, U_2= 100 V; 3, 4 – I_d= 0,5 A, U_2= 200 V. Electron emitter lengths: 1, 3 – 18 cm; 2, 4 – 3 cm

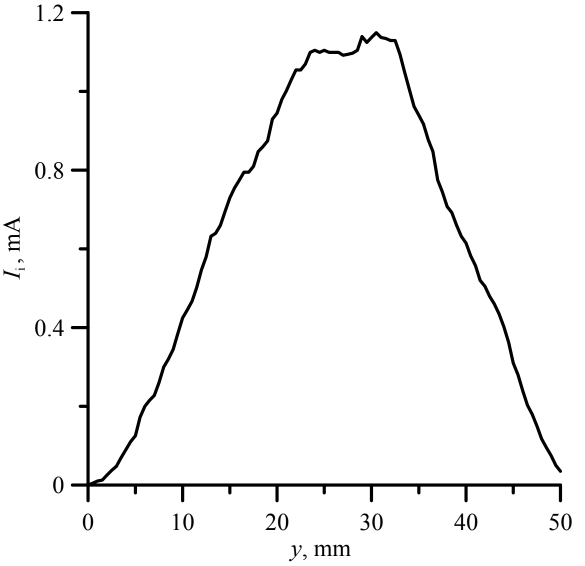

Fig. 5. Profile of the ion current in transversal direction. $P = 4 \cdot 10^{-2}$ Pa; I_d= 200 mA; U_2= 75 V

3. Discussion

A fundamental distinction of the system under study from the two-stage systems described in [3, 4] is the use of a plasma cathode unscreened from the magnetic field. Electrons, which were accelerated in the bipolar diode, passed to a non-uniform magnetic field with curvilinear lines of force closing to the anode of the second stage. Oscillation of electrons along magnetic field lines was accompanied by transformation of the longitudinal component of the electron energy to the transverse component, leading to reflection of electrons from the region of a strong magnetic field near the poles. Since fast electrons, which were accelerated up to the energies of ~ 100–200 eV, had the Larmor radius in the region of a strong magnetic field (0.1 T) nearly two orders of magnitude smaller than the distance between the cathode and the magnetic field poles (~ 3 cm), the magnetic moment invariability condition was fulfilled in the system under study [6].

The length of the electron emitter influenced little homogeneity of the longitudinal distribution of the ion current probably because a weak magnetic field in the paraxial region of the hollow cathode did not impede transverse diffusion of charged particles. Fast electrons could escape to the anode along a field line only if electrons acquired a velocity component towards the anode as a result of their interaction with plasma particles near magnetic poles.

The polarity reversal of the current to the grid with growing voltage across the bipolar diode (Fig. 2) was due to the increase in the ion current from the anodic plasma (a portion of the ion current, which was inversely proportional to the grid transparency, closed to the grid) and a decrease in the loss of electrons from the cathodic plasma on the grid. The last decrease resulted from the growth of the cathodic plasma potential (Fig. 6) and redistribution of the current of extracted electrons and the electron current to the grid.

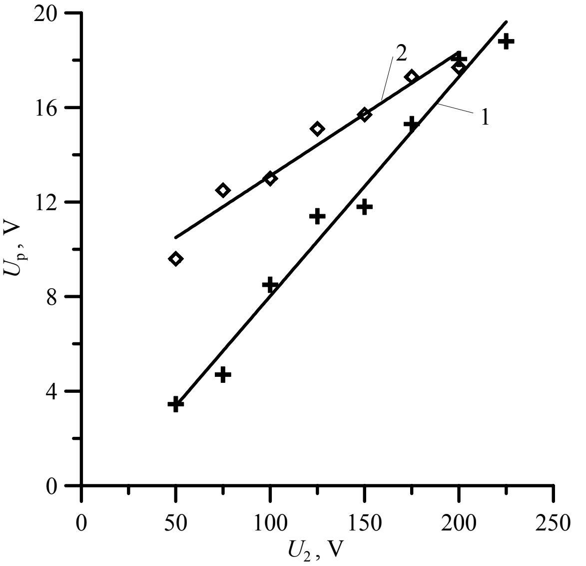

Fig. 6. Potential of the cathode plasma as a function of second stage voltage U_2 at I_d= 0,2 A (1) and I_d= 0,5 A (2). Gas pressure $4 \cdot 10^{-2}$ Pa (Ar)

A specific feature of the two-stage system under study was a large size (36 cm^2) of the grid area, leading to the decrease in the electron emission current density (down to 15 mA/cm^2), a drop of the density of the reverse ion current and, correspondingly, an increase in the accelerating gap of the bipolar diode. As a result, it was possible to use a grid with larger meshes and thicker wires, providing a longer lifetime of the grid. The ion source efficiency can be improved by reducing the loss of the ion current to the grid holder, whose surface area is nearly equal to the surface area of the ion collector. In this connection, it is planned to perform experiments on optimization of the anode design and the magnetic field configuration.

4. Conclusions

1. A grid-bounded plasma cathode in the form of a ribbon has been developed at the basis of a glow discharge with an extended cylindrical hollow cathode having a slit outlet aperture. The emission current density of electrons was distributed almost uniformly over the cathode length (up to 200 mm).

2. Injection of electrons, which were accelerated in a bipolar diode up to energy of several hundred eV, along lines of an inhomogeneous diverging linear magnetic field with a single cusp at the anode ensured efficient generation of plasma in the lengthy anodic stage. The density distribution was close to uniform over the system length.

3. The ratio between the ion current and the plasma cathode electron current increased with growing gas pressure and the bipolar diode voltage and was as large as ~ 0.5–1.

4. The plasma emitter of ions under study can be used in sources of ribbon ion beams with the cross-sectional area 0.1–1 m long and the beam current of 0.1–1 A.

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