Sources of Ribbon Ion Beams with Coarse-Structure Gridded Plasma Cathode[1]

N.V. Gavrilov, O.A. Bureev, D.R. Emlin, A.S. Kamenetskikh, and A.I. Menshakov

Institute of Electrophysics, Ural Branch RAS, 106, Amundsen str., Ekaterinburg, 620016, Russia
Phone: (343) 267-87-78, Fax: (343) 267-87-94, E-mail: gavrilov@iep.uran.ru

Abstract – A nonself-sustained hollow-cathode discharge maintained by emission of a grid-stabilized plasma cathode is studied in an effort to develop high-voltage sources of ribbon ion beams operating in continuous and pulsed-repetitive regimes. The conditions necessary for stable emission from the plasma cathode with a coarse-structure grid over a wide interval of discharge currents, generation of extended spatially homogeneous plasma in the hollow cathode is determined, and the dimensions of the rod anode of the nonself-sustained discharge in order to improve the ion generation efficiency is optimized. Specific features of the formation of ribbon ion beams by a multi-slit ion optics system with a high geometrical transparency are analyzed. The design and parameters of an ion source operating in the continuous regime and generating a ribbon beam of argon ions with an energy of 40 keV, a cross-sectional area of 450×40 mm and a current of 50 mA are described.

1. Introduction

A source of ribbon ion beams, whose operation based on the use of a nonself-sustained plasma cathode discharge and in which the direction of injection of fast electrons coincides with the direction of ion extraction from the plasma, is described in [1]. Close to uniform distribution of the current density over the cross-sectional area of the ion beam was achieved due to the use of an extended plasma emitter of electrons. For this electron emitter to form in a hollow-cathode glow discharge, the exit aperture of the cathode should be shaped as a slit whose length is comparable with the length of the ion beam. However, instabilities, which are characteristic of the slit-contracted discharge, limit the maximum length and the maximum current of the ribbon beam. As the discharge current decreases and the cathode layer becomes thicker, the column of the discharge along the slit shrinks [2] and starts moving under the action of the electron pumping of the gas atoms [3]. The discharge instability and the inhomogeneous electron emission lead to a nonuniform distribution of the current density in the ion beam. The decrease in the minimum value of the beam current is achieved by increasing the width of the slit aperture. In this case, to maintain the discharge operating conditions, it is necessary to increase the flow rate of the working gas, but this increase is not always acceptable.

The system, in which fast electrons are injected to the plasma of a nonself-sustained hollow-cathode discharge transversely to the ion extraction direction [4], does not require the match between the shape and the size of the hollow cathode aperture and those of the electron and ion plasma emitters. Therefore, a hollow-cathode glow discharge constricted by a small-size aperture can be used in the plasma cathode. The expansion of the anode region of the discharge and the increase in the surface area of the plasma cathode to ~100 cm^2 allow increasing the lifetime of the anode grids, which are perforated electrodes with large-diameter apertures [5]. However, to make the ribbon beam longer without rise in its non-homogeneity, we need to find optimal conditions for leak of the gas and injection of fast electrons to the nonself-sustained discharge plasma; while to improve the ion generation efficiency, it is necessary to optimize the surface area and the dimensions of the apertures of the plasma cathode grid and match the areas of the rod anode and the hollow cathode of the nonself-sustained discharge.

This paper presents results of optimization of the electrode system of a ribbon ion source, describes the design and parameters of an ion source operating in a continuous regime, and gives results of tests of a pulse-periodic ion source prototype with the mean ion emission current of up to 200 mA.

2. Experimental technique

The experiments dealing with properties of a nonself-sustained discharge and the ion emission of the plasma were performed using prototypes whose electrode scheme is shown in Fig. 1. The electrode scheme includes the extended hollow cathode of the nonself-sustained discharge *1* (the plasma chamber) with the rod anode *2* mounted on the inside and the emission window *3* on the side surface of the chamber and one or two plasma cathodes *4* installed on the end faces of the plasma chamber. A hole-constricted hollow-cathode glow discharge (HCGD) with an expanded anode region was used in the plasma cathodes. The HCGD current was up to 0.5 A in the continuous regime and up

[1] The work was partially supported by RFBR (Project No. 07-08-00128) and the RF President Grant for young Russian scientists (No. MK-1373.2008.8).

to 10 A in the pulse-periodic regime. The grid electrodes *5* of the plasma cathode had the surface area of 70 cm^2 with holes 4 mm in diameter. The igniting electrode *6* initiated the discharge in the cathode cavity.

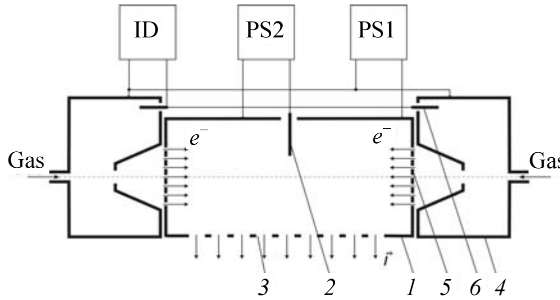

Fig. 1. Electrode scheme of the gas-discharge system: *1* – plasma chamber; *2* – anode; *3* – emission window; *4* – hollow cathode; *5* – grid; *6* – igniting electrode; ID – ignitor device; PS1, PS2 – power supplies of the discharge in the first and the second stage

Dimensions of the HCGD cathode and the diameter of its exit aperture were determined on condition of a stable operation of the glow discharge at the gas (argon) flow rate of 10^3 cm^3/h and the minimum current of 0.3 A. The diameter of the hollow cathode was 120 mm and that of the exit aperture was 10 mm. The choice of the surface area of the plasma cathode grid, the diameter and the length of channels in the grid apertures ensured the plasma cathode emission with a current accounting for 0.5–1 of the glow discharge current without a considerable increase in the plasma potential relative to the grid [6]. The plasma chamber length (0.6–0.7 m) was 0.1 m longer than the beam length so as to exclude the edge effects in the distribution of the ion emission current density, while the radius of the chamber was taken approximately equal to the width of the plasma emitter of ions. The anode was made of a tungsten rod 4 mm in diameter, while the anode length was varied within 120–220 mm. The plasma density distribution in the plane of the emission window was measured using a system of flat near-wall probes, while the distribution profile in the ion beam was measured by a mobile wire collector (1 mm in dia).

3. Results

The glow discharge in the electrode system of the plasma cathode was ignited by an auxiliary pulsed discharge between the hollow cathode and the igniting electrode mounted in the cathode cavity. The appearing plasma ensured the subsequent ignition of the glow discharge through the hollow cathode aperture to the grid. Two ignition methods were tested: 1) the use of an auxiliary pulsed discharge with a current of up to 10 A, the duration of 100 μs and a high voltage (up to 3 kV) at the plasma cathode grid, providing the rupture of the cathode layer in the aperture and the initial ionization in the anode region of the discharge; 2) ignition by quenching of the auxiliary discharge [7] when the cathode layer in the cathode aperture is ruptured due to the decrease in the potential of the decaying plasma. In the last case the transistor device disconnected the auxiliary discharge circuit at the droop of the current pulse. Fig. 2 presents the gas pressure dependences of the minimum voltage between the cathode and the grid ensuring a stable ignition of the glow discharge.

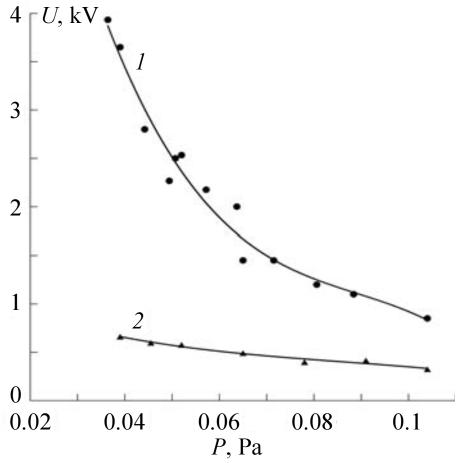

Fig. 2. Gas pressure dependences of the minimum voltage between the anode and the grid necessary for ignition of the main discharge: *1* – ignition at high voltages; *2* – ignition by forced quenching of the auxiliary discharge

The method of ignition by forced quenching of the auxiliary discharge provided the decrease in the energy consumption to ~0.2 J. This is especially important for operation of the source with a high pulse repetition rate.

Figure 3 shows the average number n of ions, which are generated by a primary electron at different lengths of the anode, as estimated from the experimental measurements of the currents to the anode I_a and cathode I_c electrodes of the plasma chamber: $I_a/I_c =$ $= (1 + 1/n)$. In a nonself-sustained discharge, the optimal length of the anode at a given surface area

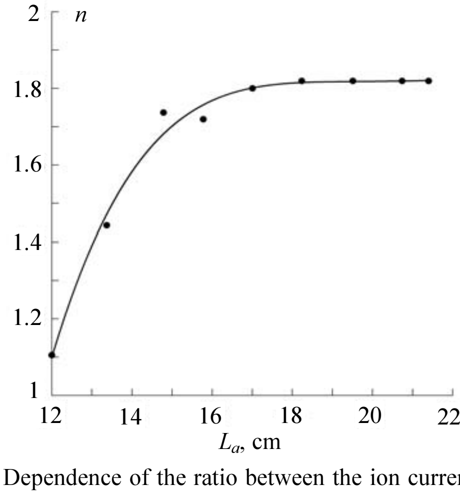

Fig. 3. Dependence of the ratio between the ion current and the current of injected electrons on the anode length. The gas pressure is 0.04 Pa. The voltage between the anode and the grid is 200 V. The discharge current is 5 A

of the hollow cathode depends not only on the kind of the gas [8], but also on the gas pressure and the voltage between the electrodes of the nonself-sustained discharge [9].

A non-uniformity of plasma density distribution along the axis of the plasma emitter does not depend on the number (one or two) of operating plasma cathodes. The way of the gas dispensing in the plasma cathode is the main factor governing the plasma density distribution (Fig. 4). The non-uniformity equal to 15–17% of the maximum value is the case for one-sided gas input. A close to uniform plasma density distribution (8% at the 60 cm length) is ensured by two-sided gas input through the openings on the both end faces of the plasma chamber.

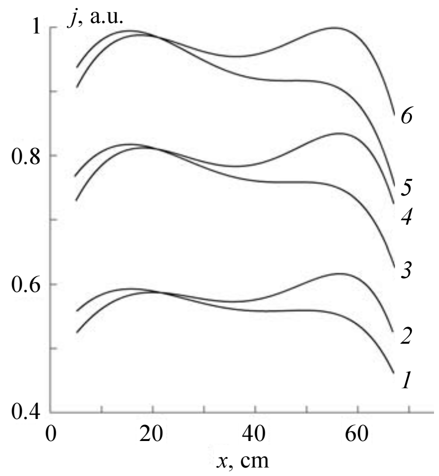

Fig. 4. Plasma density distribution along the plasma emitter when the gas is leaked into the plasma chamber on one (*1*, *3*, and *5*) and two (*2*, *4*, and *6*) end faces. The voltage between the anode and the grid is 150 V (*1* and *2*); 200 V (*3* and *4*); 250 V (*5* and *6*)

In the prototype tests the direct current of the argon ion emission equal to 50 mA from the surface area of 500×50 cm was achieved at the current of a glow discharge in the plasma cathode equal to 0.4 A, the voltage across the electrodes of the nonself-sustained discharge equal to 100 V and the total argon flow rate of 30 cm^3/min. The ion emission current of over 2 A from the surface area of 600×100 cm was ensured in the pulsed regime at the nonself-sustained discharge current of 15 A. The plasma cathodes with large-aperture grids provided a stable plasma generation in both continuous low-current and pulsed high-current regimes of the nonself-sustained discharge.

4. Design and parameters of the continuous operation ion source

The electrode system of the ion source (Fig. 5) is mounted in the rectangular casing *1* (1036×320×349 mm) on the high-voltage ceramic insulator *2*. The insulator chamber, which is filled with transformer oil, houses the high-voltage cable bushings *3* and the gas feed pipe *4*. Two plasma cathodes *5* are installed on the end faces of the plasma chamber *6*. The rod anode *7* is mounted in the symmetry plane of the system. The plasma chamber is 120 mm in diameter and 600 mm long; the emission window is 50×500 mm in size. The working gas is leaked in through the two plasma cathodes.

To ensure the constant value of the plasma ion emission current (50 mA), the self-sustained discharge current in the plasma cathodes is maintained constant (0.3 A) and the nonself-sustained discharge current also is stabilized at a level of 0.47 A by changing the upplied PS2 voltage, while the electron extraction efficiency accounts for ~0.7 of the discharge current.

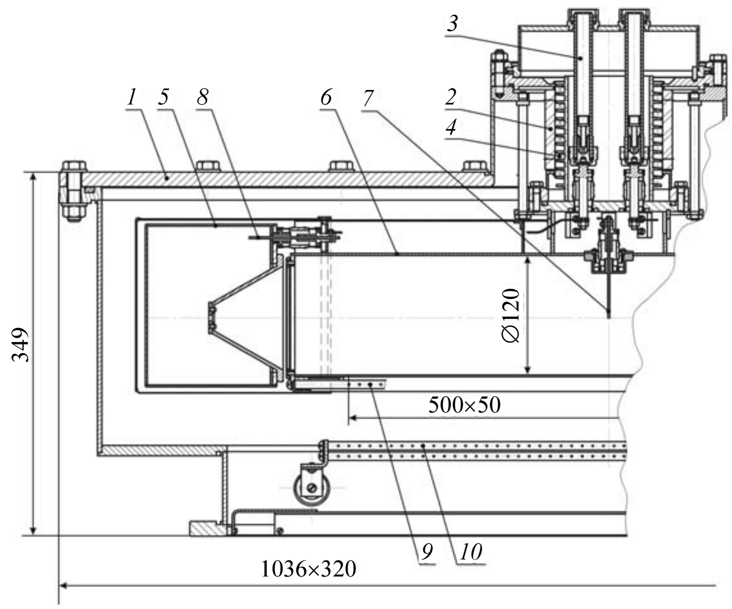

Fig. 5. Design of the ion source: *1* – casing; *2* – high-voltage insulator; *3* – cable bushings; *4* – gas feed pipe; *5* – plasma cathode; *6* – plasma chamber; *7* – anode; *8* – ignitor electrode; *9* – screen electrode; *10* – accelerating electrode

The supply circuit maintains the discharge operation in one of the plasma cathodes only. If the discharge is quenched by chance, the cathodes are turned on spontaneously, facilitating the equalization of the current density distribution and improving the temperature conditions of the gridded plasma cathode.

The ribbon ion beam is formed with a two-electrode multi-slit ion-optics system. By design, the screen electrode *9*, which is 500 mm long, includes a set of 2-mm tungsten rods spaced 10 mm each. To decrease the cutoff voltage of secondary electrons, the accelerating electrode *10* is made up of two similar sets of the rods spaced 10 mm each. With the accelerating gap 40 mm long, this plane-parallel system formed a converging ribbon beam having the current of 50 mA at the voltage of 40 kV. FWHM of the beam was 2–3 mm at a distance of ~250 mm from the optics. A screen electrode with rods having the curvature radius of 150 mm was used to increase the width of the ribbon beam to 40 mm.

Figure 6 shows the current density distributions on the beam length for operation with one and two plasma cathodes. The maximum nonuniformity of the distributions was not over 20%. The ion source operates stably at the working gas (Ar) pressures of 0.03–0.07 Pa.

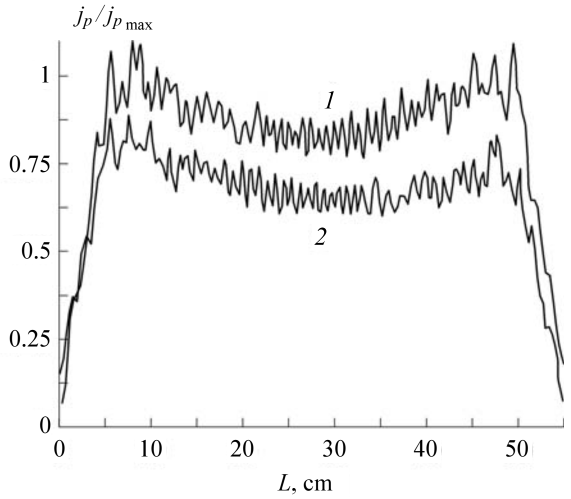

Fig. 6. Current density distribution on the length of the ion beam with the emission of electrons from one (*1*) and two (*2*) end faces of the chamber. The accelerating voltage is 40 kV. The beam current is 48 (*1*) and 36 mA (*2*)

5. Conclusion

The plasma cathode with a coarse-structure grid provides a stable operation at the electron extraction efficiency approaching 1 over a wide interval of currents (0.2–10 A) in the hollow-cathode glow discharge with an expanded anode region. The spatial homogeneity of the plasma generated in a nonself-sustained hollow-cathode discharge 600 mm long depends on the working gas density distribution and accounts for ~20% when one plasma cathode operates. To increase the ion generation efficiency it is necessary to optimize the surface area of the rod anode, which depends on the average number of ions generated by a primary electron in the nonself-sustained discharge plasma.

A converging ribbon ion beam with the focal line ~1 mm in size and a ribbon beam 40 mm wide and 450 mm long with the current of 50 mA at the argon ion energy of 40 keV were formed by varying the curvature radius of the screen electrode in a multi-slit ion optics system with a high geometrical transparency. An advantage of the newly designed source is its high reliability, long lifetime and a stable operation in the working gas pressure range 0.03–0.07 Pa.

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