A Source of Extended (1.4 m) Ribbon Ion Beams with a Grid-Bounded Plasma Cathode

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Abstract – The design and characteristics of a source for generation of gas ion beams with a ribbon-like cross-section 1.4 m long were described. The source was developed for treatment of metal sheets with the aim of improving their mechanical properties. The ribbon gridded plasma cathode (1400×20 mm in size) was formed by means of a glow discharge in the cathode stage. Permanent magnets produced a linear cusped magnetic field in the anode stage. The energy of the electrons, which were injected to the anode plasma, was preset by the adjustable potential difference (as large as 200 V) between the cathode and anode plasmas. The electrons were confined by the magnetic field and generated an extended plasma body with a nearly uniform lengthwise distribution of the ion emission current density. The ion beam was formed with a multi-aperture two-electrode ion optical system.

A pulsed periodic regime with a large discharge current (3–10 A, 1 ms) provided a stable operation of the discharge with the uniform current density distribution through the whole length of the slotted aperture at a limited gas flow rate. The ratio between the average values of the beam and discharge currents in the first stage increased from 8 to 15 % with growing pressure. It was shown that the wider variation range of this parameter as compared to the case of the DC regime was due to the change of the delay time of the pulsed discharge and the corresponding change of the current pulse length.

The argon ion beam with the average current of 0.14 A and the pulse current of 0.7 A was generated at the accelerating voltage of up to 25 kV and the pulse length of 1 ms. The inhomogeneity of the lengthwise current density in the ion beam was not over 15 % along the length of 1.3 m in optimal conditions.

1. Introduction

The authors [1] proposed and studied a method for formation of a ribbon plasma emitter of ions using a ribbon-shaped gridded plasma cathode and a linear cusped magnetic field, which is produced in the anode cavity of the gas-discharge stage. The highly homogeneous ion emission of the plasma and the large current of ions extracted from the plasma gave grounds to develop an ion source producing beams with the cross axis 1.4 m long. The source was developed for metal sheets treatment to improve their mechanical properties. Since the electrode system was extended many times as compared to the system used in ref. [1], it was necessary to optimize dimensions of the hollow cathode and its exit aperture so as to ensure a stable operation of the discharge through the long slot and a uniform current density distribution across the slot considering that the working gas flow rate was limited by the vacuum pump speed. A pulsed periodic regime with a large discharge current was used to rupture the cathodic layer in the narrow aperture of the hollow cathode. A considerable delay of the glow discharge ignition in a large-size cathode cavity changed gas dependences of the ion source as compared to those in the DC regime. The measures to ensure a stable operation of the ion optical system, which formed an extended ribbon beam under considerable thermal loads, and to prevent the destroying of the plasma cathode grid with the reverse electron beam when the accelerating gap was broken down were tested.

2. The ion source design

The first stage of the gas-discharge system of the ion source (Fig. 1) consisted of the hollow cathode 1 and the anode grid 2, which was installed several millimeters from and opposite to the exit aperture of the hollow cathode. The molybdenum filament 3, which facilitated striking of the glow discharge, was stretched along the cathode axis. The working gas (argon) was leaked into the cathode cavity. Unlike in ref. [1], the hollow cathode was rectangular. This shape was chosen for the maximum utilization of the magnetic field so as to reduce the discharge operation voltage in the first stage. The hollow cathode was 20×20×160 cm in size, while the exit aperture was 140 cm long and 2 cm wide.

The second stage of the gas-discharge system was bounded by the electrically connected anode 2 and screen 4 grids. The anode 5 of the second stage was placed between the grids. Permanent Sm-Co magnets 6, which produced a linear cusped magnetic field in the second stage cavity, were mounted on the anode exterior. The like poles of the magnets were oriented towards the anode. The magnetic field on the anode surface was ~0.1 T.

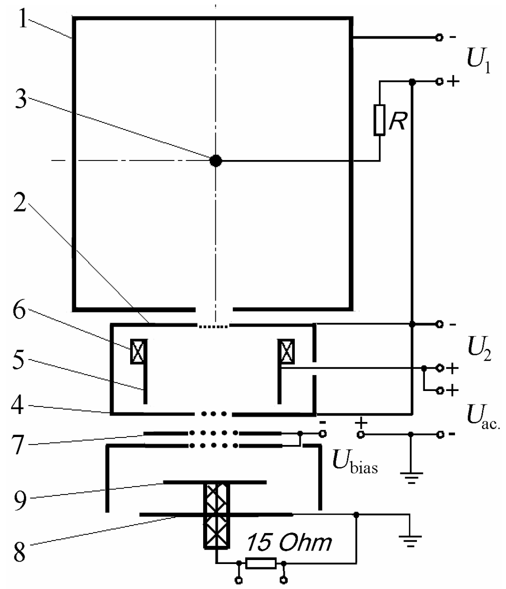

Fig. 1. Schematic diagram of the electrode system

The ribbon beam formation system comprised the screen electrode 4 and the two-row accelerating electrode 7, which were spaced d=15–25 mm from one the other. Slots 20 mm and 50 mm wide were made in the screen and accelerating electrodes respectively. Rods of diameter 2 mm were flexibly fixed in slot recesses every 12 mm perpendicularly to the long axis of the slots. This embodiment excluded any mechanical deformation of the rods during heating that could alter focusing of the ion beam in apertures of the ion optical system. By design, the accelerating electrode included two rows of rods that were spaced at 10 mm. The beam hit the flat collector 8. The lengthwise distribution of the beam current density was measured by the probes 9.

3. The choice of the working parameters of the discharge

The estimates were based on results of the experiments with a plasma ion emitter [1] that provided the ion emission current with the linear density of up to 6 mA/cm through the length of 200 mm. The power capacity of the available high-voltage source limited the maximum beam current and, hence, the emission current density at 1 mA/cm through the length of 1400 mm. In the approximation of the Child-Langmuir law, the cathodic layer of the space charge becomes ~2.5 times thicker as the emission current density decreases. Therefore, the puncture of the cathodic layer throughout the hollow cathode aperture and the discharge operation with a uniform distribution of the current density in the hollow cathode aperture require a nearly proportional increase in the gap width [2]. In this case, the cathode aperture and the discharge operation with a uniform distribution of the current density in the hollow cathode aperture require a nearly proportional increase in the gap width [2]. In this case, the cathode cavity pressure is reduced correspondingly. Thus, if the ribbon beam should be longer, especially without the corresponding rise of the beam current, then a more efficient vacuum pumping need be used, making the installation and its maintenance more costly. This situation can be avoided if the discharge operates and the beam is formed in the pulsed periodic regime.

The average beam current in the pulsed periodic regime is defined by the relationship $I_a=I_m{\cdot}f{\cdot}t$, where I_m is the pulse current, f is the pulse repetition rate, and t is the pulse length. If the ion extraction efficiency is predicted at 10 % of the glow discharge current, the average discharge current should be about 1.4 A at the average beam current of 0.14 A. If the current pulse generator produces pulses 1 ms long and provides the pulse repetition rate of 200 s^{-1}, the required amplitude of the discharge current is I_m~7 A. According to the data of ref. [2], the cathodic layer is punctured through the whole length of the aperture up to 15 mm wide at the appropriate plasma density.

A constant voltage of up to 200 V was applied between the electrodes of the second stage. The constant accelerating voltage was adjusted at 5 to 25 kV. The constant cutoff voltage of secondary electrons was 2–3 kV. The two-row arrangement of the accelerating electrode rods decreased the potential drop in the electrode apertures. As a result, the minimum cutoff voltage of secondary electrons was 1.5–2 times lower.

4. Characteristics of the ion source

Fig. 2 shows dependences of the average current of the ion beam on the average discharge current in the first stage of the ion source. These dependences are almost linear over a wide interval of gas pressures. The discharge/beam current proportionality factor increases from 8 to 15 % as the gas pressure grows (Fig. 2, *a*). Fig. 2, *b* presents dependences of the relative difference of the currents in the first and second stages on the discharge current. The anode current in the second stage was larger than the cathode current in the first stage because secondary particles appeared due to the gas ionization. It follows from Fig. 2, *b* that the total current of ions, which were generated in the second stage, accounted for 0.4–0.7 of the current in the first stage. Thus, the beam current accounted for ~1/5 of the total current of ions produced in the second stage.

The discharge/beam current proportionality factor also depended on the efficiency of the electrons extraction from the plasma, the energy of electrons, and the degree of their energy relaxation in the second stage. Figure 3 presents dependences of the amplitude current to the anode in the second stage on the voltage U_2 in the second stage. At U_2>150 V the current variation rate sharply decreased. As the voltage increased further, the rise of the ion current was insignificant, because the average time of confinement of fast electrons became shorter than the time of their energy relaxation. The pressure buildup was followed by the increase in the ionization frequency and, hence, the rise of the current. The current pulse amplitude increased to a much smaller extent (20–30 %) than the average beam current changed with growing pressure (see Fig. 2).

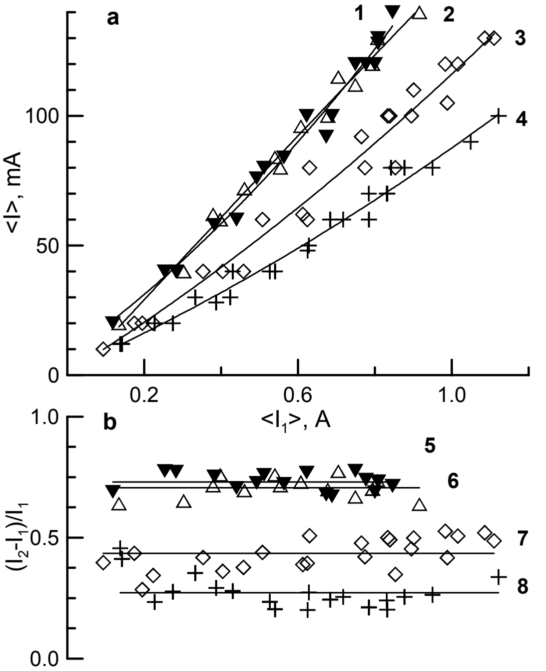

Fig. 2. Dependences of the average beam current (a) and relative difference between second and firstst stage currents (b) on the discharge current I_1. P=0.12 (1, 5); 0.1 (2, 6); 0.09 (3, 7); 0.08 Pa (4, 8); t=1 ms, d=19 mm

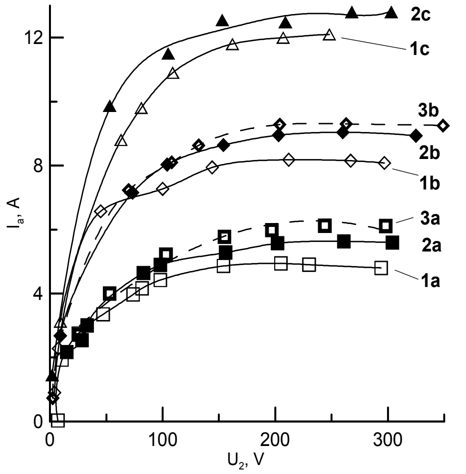

Fig. 3. Anode current I_2 versus second stage voltage U_2. I_1=4 (a), 6(b), 8 A (c). P=0.08 (1); 0.09 (2); 0.1 Pa (3)

The gas pressure dependences of the average and pulse characteristics of the discharge were different because the delay time of the discharge in the first stage increased as the gas pressure was reduced (Fig. 4). When the argon pressure decreased from 0.05 to 0.075 Pa, the delay time was 0.4 to 0.1 ms shorter on the average. Since the discharge current was controlled by the voltage across the discharge gap, the decrease in the discharge current also led to the increase in the delay time. Thus, if the gas pressure in the discharge gap was reduced and the discharge current decreased, the average beam current dropped because the discharge current pulse became shorter.

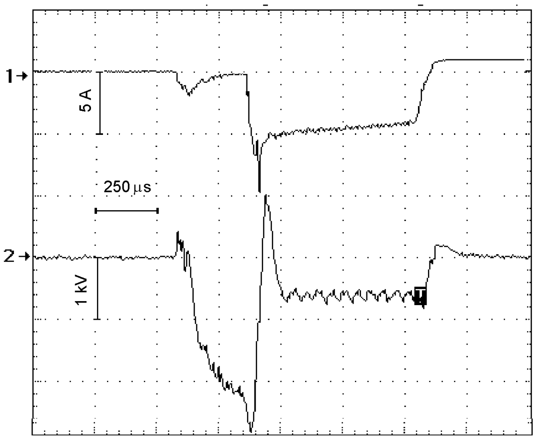

Fig. 4. Oscillograms of the first stage discharge current I_1 (1) and voltage U_1 (2). P=8·10^{-2} Pa

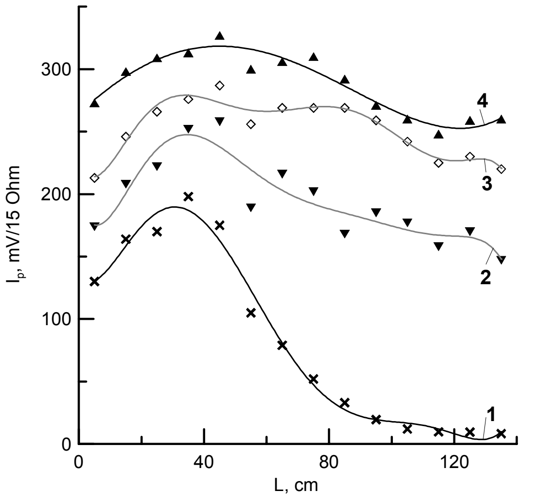

Fig. 5. The lengthwise distributions of the ion beam. U_{hv}=15 kV. P=8·10^{-2} Pa, d=19 mm; (1) I_d=2A, (2) 4 A, (3) 6 A, (4) 8 A

The lengthwise distributions of the current density over the beam collector at different values of the discharge current are shown in Fig. 5. The distribution, which was inhomogeneous to not more than 25 %, was achieved at discharge currents higher than 6 A.

Fig. 6 shows dependences of the current in the circuit of the accelerating electrode of the ion optics on the value of the accelerating voltage at a fixed current of the high-voltage source. The considerable current at the minimum of the curves is not due to the loss of the beam current, but is explained mostly by the current of slow ions, which appeared due to the charge exchange of fast ions and the gas ionization [3]. The beam formation conditions are optimal and the beam current equals the high-voltage source current at the minimum points of the dependences.

Fig. 7 shows dependences of the average currents in the circuits of the high-voltage source and the accelerating electrode on the value of the accelerating voltage U_{hv} at fixed values of the pulse discharge current I_1. When the accelerating gap was 19 mm long and the I_1 value was 3 A and 4.4 A, the beam formation conditions were optimal at the voltage U_{hv} of 15 kV and 20 kV respectively. In this case, the average beam current, which was determined by the pulse repetition rate f, could be of any value. Thus, an advantage of the pulsed periodic regime of the plasma generation is the possibility to control the average beam current by changing the f value without violating the optimal conditions of the discharge operation and the beam formation.

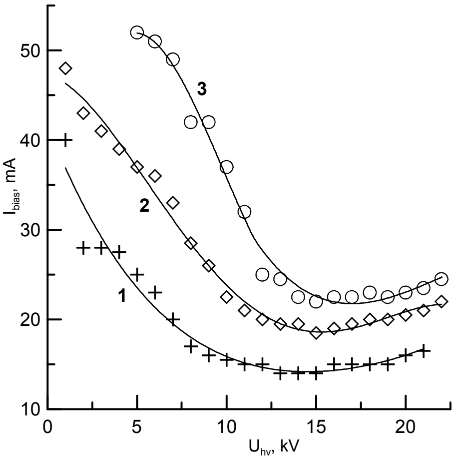

Fig. 6. Current in the circuit of the accelerating electrode Ibias versus accelerating voltage U_{hv}. Beam current $<i>$=40 (1); 60 (2); 80 (3) mA (t=1 ms, p=0.12 Pa, d=19 mm)

5. Conclusion

The increase in the length of the ribbon beam, especially if the increase is realized without the corresponding rise of the beam current in the source of extended ribbon ion beams, which is based on a hollow-cathode glow discharge constricted by a slot aperture, requires that a high-speed vacuum pump is used. If the cathode aperture is made wider for the rupture of the cathodic layer, the gas pressure in the hollow cathode drops and operation of the glow discharge in the high-current low-voltage form is hampered. The gap width may be decreased in the high-current pulsed periodic regime of the discharge operation. Simultaneously, the average beam current can be controlled by changing the pulse repetition rate without disturbing the optimal conditions of the beam formation in the ion optical system.

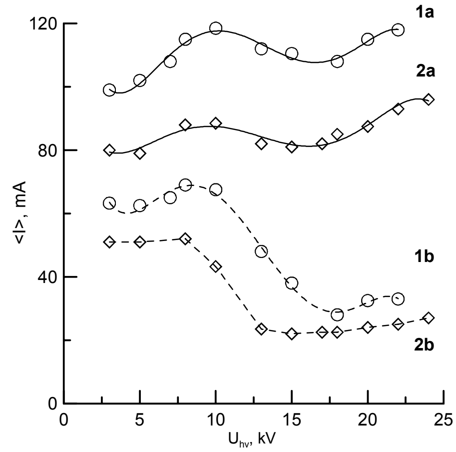

Fig. 7. Average beam current (a) and current in the circuit of the accelerating electrode I_{bias} (b) versus accelerating voltage. d=19 mm, t=0.92 ms. I_1=4.4 A (1), 3.2 A (2)

The gas discharge system with the hollow cathode 0.2×0.2×1.6 m^3 in size and the exit aperture 1.4×0.02 m^2 in size provided the pulsed periodic operation of the glow discharge at the amplitude current of up to 10 A and the current pulse length of up to 1 ms. An argon ion beam with the pulse current of up to 0.7 A and the average current of up to 0.14 A was generated at the ion energy of up to 25 keV. The beam length, through which the current density inhomogeneity was not over 25 %, was 1.3 m. The energy efficiency of the source, which was estimated as the ratio between the beam current and the total discharge power, was 0.17 A/kW at the pressure of 0.12 Pa and the discharge pulse current of 5 A.

References

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