Generation of Broad Electron Beams with the Use of High-Current Glow Discharge Constricted with an Extended Slit

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Abstract – **This study deals with the problem of extending the working interval of amplitudes and durations of the current pulse of broad electron beams generated in the source having a gridded plasma cathode based on the slit-constricted glow discharge in the electrode system comprising a hollow cathode and a hollow anode. The minimum current pulse duration, which is limited by the time of discharge transition to a steady state, was shortened from hundreds to tens of μs due to measures taken to curtail the time of the ion withdrawal from the plasma to the cathode. The grid control method was used to decrease the rise time of the beam current pulse to several μs.**

It was shown that the minimum current of a broad electron beam was limited by the value of the discharge current, at which the double thickness of the cathode space charge layer approached the width of the slit aperture of the hollow cathode. If the current decreased further, the surface area of the discharge channel in the slit diminished, leading to the increase in the spatial inhomogeneity of the anode plasma. If the amplitude of the discharge current increased up to 100 A, the uniform distribution of the current density over the cathode surface and along the cathode slit was not disturbed.

At the accelerating voltage of 4 kV the electron source with the plasma cathode grid 200×350 mm in size generated broad electron beams both in the direct current mode with the current of up to 1 A and in the pulsed mode with the current of up to 80 A. The beam current pulse duration was adjusted between 25 and 100 μs using grid control methods.

1. Introduction

The pulsed glow discharge with electrons oscillating in the cathode cavity is used for generation of electrons beams with a high current density [1]. The high-current low-voltage regime of operation of the hollow-cathode glow discharge (HCGD) at a low gas pressure is realized if the ratio of the cathode and anode surface areas is $S_c/S_a \sim (2M_i/m_e)^{1/2}$, which ensures the withdrawal of plasma electrons to the anode without the positive anodic drop of the potential and on condition that the path of fast electrons till they leave the cath-

ode cavity is sufficient for their energy relaxation [2]. Broad electron beams can be formed without the corresponding increase of the cathode size by the following means: the use of multi-rod labyrinth cathodes [1] or constriction of the discharge in a hole having the area $\sim S_a$ and extraction of electrons from the anode plasma through a metal grid whose surface area $S_e > S_a$ [3]. A slit cathode aperture can be used most reasonably for generation of beams having a nonequiaxial rectangular or ribbon shape of cross section. It was shown [4] that at a current of 1 to 10 A the discharge is uniformly distributed over the slit aperture provided the geometrical width of the slit is larger than the double thickness of the cathode layer. This principle underlied the development of a plasma cathode for an electron accelerator producing beams 1000×200 mm^2 across with the current of 1-2 A and the pulse length of 0.5-1 ms. The electron accelerator with HCGD plasma cathode had highly stable properties at the working gas pressure of up to 10^{-1} Pa, lived long, and was simple to operate [5].

The objective of this study was to expand the working interval of parameters of broad electron beams, which are generated in systems based on HCGD with a long constriction slit. The generation of short current pulses is hampered since transition of HCGD to a steady state under normal conditions at a low gas pressure takes hundreds of μs. Systems, which initiate a high-current HCGD in a time of about several μs using injection of a dense plasma and striking of short-time arcs, do not provide reproducible ignition and have a short lifetime [6]. We propose to accelerate the HCGD transition to a steady state by decrease the ion drift time.

In addition to the control of the beam current duration by changing the discharge operation time, we analyzed the possibility of the grid potential control of the emission from the HCGD-based plasma cathode. Properties of the slit-constricted discharge over the interval of currents from 1 to 100 A were studied. Conditions of a stable uniform emission from the grid-stabilized HCGD plasma cathode in pulsed and direct current operating regimes were determined.

2. Experimental technique

The experiments were performed using an electrode system comprising the hollow cathode 1
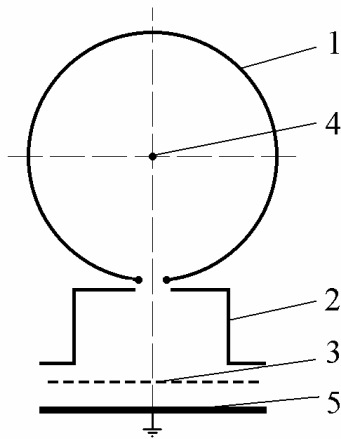
Fig. 1. Schematic of the plasma cathode electrode system: 1 – hollow cathode, 2 – hollow anode, 3 - metal grid, 4 – ignition electrode, 5 – collector

(400×⌀200 mm), whose aperture was 20×325 mm in size, and the hollow anode 2 of the rectangular cross-section (215 × 380 × 85 mm) (Fig. 1). Electrons were extracted through the stainless-steel mesh grid 3 measuring 200 by 350 mm with meshes 0.6×0.6 mm in size. The igniting electrode 4 was stretched along the axis of the hollow cathode. The gas (argon) was leaked into the cathode cavity. The discharge ignition voltage was 2-3 kV at the gas pressures of 0.01-0.04 Pa, which were measured in the vacuum chamber. The dc discharge of up to 1 A was maintained by a power supply with current regulation. Discharge current pulses (100 A, 100 μs) were formed with an artificial line. Current-voltage curves of dc and pulsed HCGD are shown in Fig. 2.
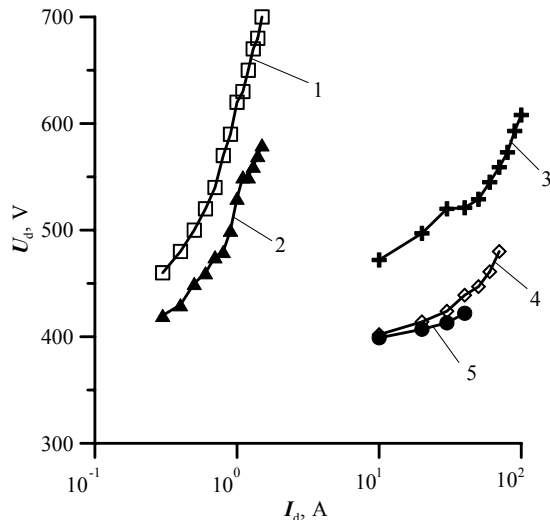
The current distribution along the cathode aperture

Fig. 2. Current-voltage characteristics for the discharges in continuous (1, 2) and pulsed (3, 4, 5) operation modes. 1 – P = 0.053 Pa; 2 – 0.087 Pa; 3 – 0.013 Pa; 4 – 0.027 Pa; 5 – 0.04 Pa
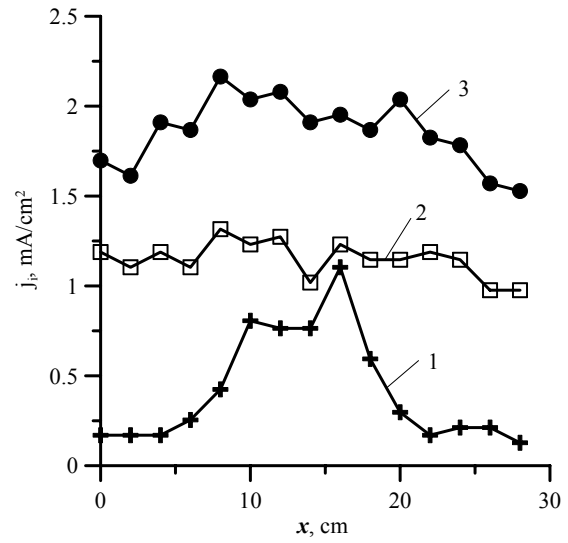

Fig. 3. Ion current density distribution along outlet aperture; P = 0.027 Pa; 1 – I_d= 0.5 A; 2 – 2 A; 3 – 4 A

was measured by wire electrodes, stretched across the slit in 20-mm steps. It is seen from Fig. 3 that the discharge is uniformly distributed over 20 mm slit at currents above 2 A, ensuring breakage of the cathode layer on the whole length of the slit. Otherwise, the discharge current passed in a limited region of the slit. The discharge to the anode was delayed and this delay time depended on the time required to reach the value of auxiliary discharge current onto wire, ensuring breakage of the cathode layer.

Probe measurements demonstrated that in the continuous operation regime of HCGD at the discharge current of 0.5 A and the argon pressure of 0.04 Pa the cathode plasma potential was negative (−10 V) relative to the anode, while the anode plasma potential was positive (about +20 V). Thus, electrons, which were extracted from the cathode plasma to the anode plasma, were accelerated in the double layer up to the energy of 30 eV. The current density was almost uniformly distributed over the hollow cathode surface (Fig. 4) independently of the value of the discharge current and the character of its distribution in the plane of the outlet aperture of the cathode.

The distribution of the electron current density was measured along the long and short axes of the plasma cathode grid. The dependence of the longitudinal distribution of the current density in the grid plane on the ratio between the slit length and the longitudinal axis of the grid is shown in Fig. 5. The use of a long slit is a mandatory condition for a uniform electron emission along the long axis of the plasma cathode. The nearly Gaussian transverse distribution of the electron current density becomes less inhomogeneous if a variable-transparency grid is used [4].
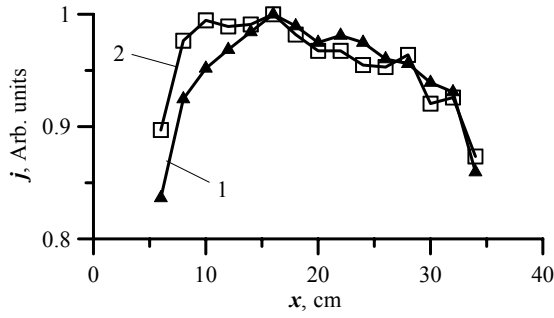
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Fig. 4. Ion current density distribution along hollow cathode surface; $P = 0.02$ Pa. $1 - I_d = 1$ A; $2 - 25$ A

The electron beam was formed in a plane-parallel gap 10 mm long between the grid and the collector, which received a constant voltage (4 kV). The pulsed electron beam was measured using the Rogowski coil. The negative potential of the grid (0-110 V) was preset by galvanic cells and a storage capacitor. The potential barrier in the grid plane was removed by applying ~110 V voltage pulses having the rise time of ~1 μs and the length adjustable within 25-100 μs.

3. Control of the plasma cathode emission

Similarly to arc plasma cathodes with grid stabilization, the length of the beam current pulse can be controlled either by changing the discharge operation time or by applying a constant negative cutoff potential to the grid relative to the anode. The duration of the electron emission from the plasma cathode can be controlled by removing the cutoff potential for a certain period of time [7].
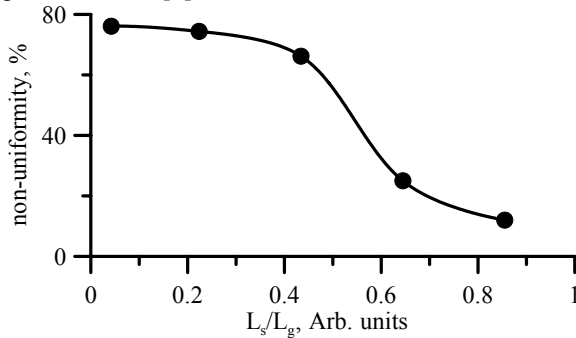

Fig. 5. Non-uniformity of electron emission current density distribution as a function of slot-hole cathode aperture and longitudinal grid axis lengths ratio; $L_a = 38$ cm, $P = 0.03$ Pa, $I_d = 80$ A

Figure 6 presents discharge current oscillograms, which were recorded for a discharge in the cathode cavity 200 mm across without additional elements (1), with eight tubular electrodes 25 mm across installed parallel to the axis of the hollow cathode on the diameter 135 mm (2), and with additional four tubes installed on the diameter 75 mm (3). The rise time

from 0.1 to 0.9 of the maximum discharge current value (50 A) at the argon pressure of 0.013 Pa was 60, 30 and 20 μs, respectively. When the volume of the cathode cavity decreased by 8% due to the installation of additional elements, the full path of fast electrons shortened and the gap voltage had to be raised for ~50 V to maintain the constant discharge current.

It should be noted that in a known device with a multi-rod labyrinth cathode [1] the discharge setup time at the current of less than 500 A is ~200 μs. This is explained by a short path of fast electrons because of a small volume between the cores and a large surface area of the hole S_e.

Fig. 7 presents wave forms of the discharge current and the beam current, and an oscillogram of a beam current pulse, which was formed by control of plasma cathode grid potential. A characteristic feature of these oscillograms is the increase in the beam current during the pulse, while the discharge current remains constant. The characteristic of the grid control, which is shown in Fig. 8, suggests that the electron extraction efficiency depends on the gas pressure.

4. Discussion

In the case of glow discharges maintained by the ion-electron emission from the cathode, the time scale of the current buildup is $\tau_o = \tau_i /(\gamma N - 1)$ [8], where γ is the ion-electron emissivity of the cathode material, N is the average number of ionization collisions of a fast electron during its lifetime, and τ_i is the lifetime of ions in plasma. According to [7], the time of HCGD transition to a steady state in the normal regime without the intermediate microscopic arc stage is determined by the ratio between the relaxation length of primary electrons $\Delta \sim (eU/w) \lambda_e$ and their average path in the cathode cavity $l = 4V/S_a$. Here w is the energetic cost of ion, λ_e is the average ionization path of an electron, e is the electron charge, V is the cathode cavity volume, and S_a is the surface area of the outlet aperture of the cathode. Thus, the installation of additional elements in the cathode cavity, which causes the decrease in its volume and, hence, shortening of the path of fast electrons, should lead not only to the growth of the discharge operation voltage, but also to the increase in the discharge setup time.
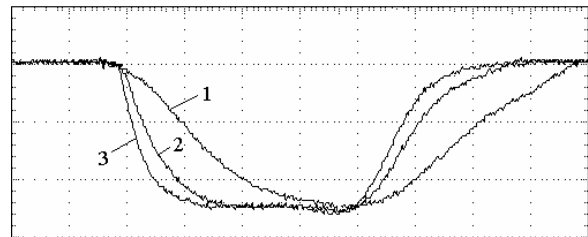

Fig. 6. Discharge current waveforms: 1 – hollow cylinder, 2 – cylinder with eight tubes ∅ 2.5 cm, 3– cylinder with twelve tubes; $P = 0.013$ Pa, $I_d = 50$A; current – 20 A/div., time – 25 μs/div
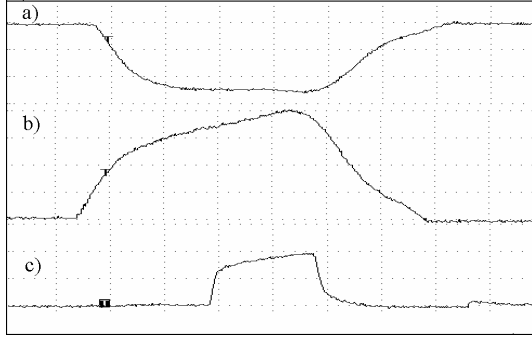
Fig. 7. Oscillograms of the discharge current (a), beam current (b) and grid controlled beam current (c); $P = 0.02$ Pa; $I_d = 50$ A; a) current - 20 A/div.; b) 10 A/div.; c) 20 A/div.; time - 25 μs/div

However, the installation of additional cathode elements in the cavity also leads to shortening of the average path of ions in the plasma and the decrease in their lifetime. Since the cavity volume decreases by ~8% and the average distance between cathode surfaces is several times smaller after the installation of the elements, the τ_0 value diminishes and the discharge progresses faster.
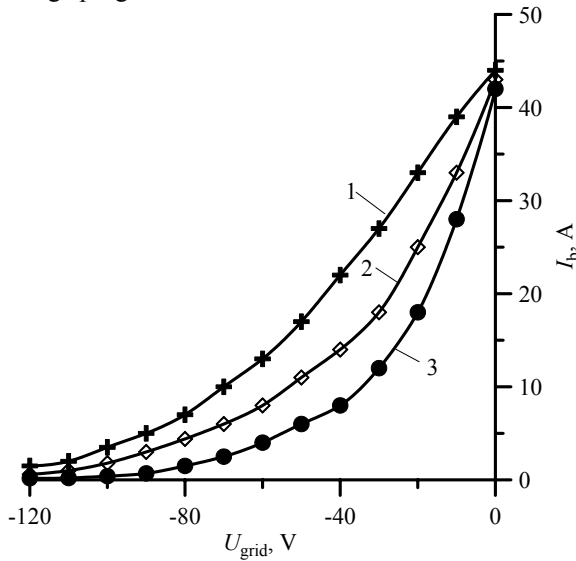

Fig. 8. Beam current versus grid bias voltage: $I_d = 50$A: 1 – $P = 0.013$ Pa, 2 – 0.02 Pa, 3 – 0.04 Pa

The grid control characteristics (Fig. 8) suggest that the gas pressure has a considerable effect on the efficiency of the electron extraction from the plasma. It is known that the plasma potential in the anode cavity decreases with growing gas pressure. The experimentally observed growth of the beam current during a pulse at a constant amplitude of the discharge current (Fig. 7) can also be explained by the rise of the

anode plasma potential due to the reverse ion flux from the accelerating gap [9].

5. Conclusion

The grid plasma cathode based on the slit-constricted glow discharge between the hollow anode and the hollow cathode provides electron beams having a large cross-section (~1000 cm^2) or extended (~1 m) ribbon beams whose duration varies between the direct current regime with the current of about 1 A and the microsecond-long pulsed regime with the current of up to 100 A.

The surface area of the HCGD plasma cathode may be increased due to the extraction of electrons from the anode plasma through the grid. The slit cathode aperture provides a uniform distribution of the anode plasma density along the slit axis, while the variable-transparency grid equalizes the electron emission current density in the transverse direction. The discharge progresses faster and the minimum length of the discharge current pulse becomes shorter when additional elements are installed in the cathode cavity decreasing the path of ions in the plasma.

Highly stable emission properties, a long lifetime, low sensitivity to the composition and pressure of the gas, and a wide variational range of the beam parameters make this type of the plasma cathode promising for generation of electron beams with a large cross-section.

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