Plasma Cathode Based on Hollow-Cathode Glow Discharge for Broad-Beam Electron Accelerator[1]

N.V. Gavrilov, A.S. Kamenetskikh, V.V. Osipov, V.A. Shitov

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

Abstract – We have proposed a concept and studied properties of a plasma cathode with a large emitting plasma area. The plasma cathode employed a low-pressure glow discharge with a hollow anode and a hollow cathode having a long slit outlet aperture. Conditions ensuring operation of the discharge with a uniform distribution of the current over the slit length have been determined, providing homogeneous emission along the large axis of the grid plasma cathode. The transverse inhomogeneity of emission depended on the distance between the emission grid and the cathode aperture. It was adjusted by changing transparency of the plasma cathode grid along the short axis. The electron plasma emitter 350×100 mm in size was tested in a pulsed repetitive regime of the discharge operation at a current of 1–10 A, a current pulse length of 1 ms, and a gas pressure of 0.01–0.05 Pa. This principle was used in the development of a plasma cathode having a surface area of 20×100 cm for an electron accelerator with the beam extraction through a foil window. Advantages of the proposed gas-discharge system include high reliability, ease of maintenance, a long lifetime of the cathode, high stability and reproducibility of the pulse shape, and a wide range of control of the beam current amplitude and the pulse length.

1. Introduction

Development of a simple and reliable plasma cathode with a large emitting surface area, which would be capable of running over the interval of pulse lengths from 10^{-5} s to the continuous mode and at emission current amplitudes from 0.1 to 10 A or higher, opens up prospects for further advancement of applications using the irradiation of gas media and solids with powerful electron beams. Since energy efficiency of hot-filament systems is low in pulsed regimes [1] and the minimum current of arc plasma emitters [2] amounts to tens of amperes, it is expedient to use a glow discharge, which is capable of operating both in high-current pulsed and continuous low-current regimes.

A low gas pressure, which is required to maintain the high electric strength of a high-voltage gap, is achieved in a hollow-cathode glow discharge on condition that the ratio of the anode and cathode surfaces is $\geq 10^{-2}$ [3]. This circumstance impedes the use of the proposed principle for development of a plasma cathode having a large emitting surface area. The cathode surface in known systems of this type equals ~100 cm^2 [4]. If the surface ratio is changed with the aim of decreasing overall dimensions of the device, the working voltage of the electron accelerator is limited to ~150 kV [5]. The use of an electron system with a narrow hole between the cathode and anode regions of the glow discharge allows increasing the surface area of the plasma emitter of electrons [6], but the plasma generated in the anode region of the discharge may prove to be considerably inhomogeneous. Several cathode chambers and a common hollow anode [7] are installed to decrease the anodic plasma inhomogeneity. However, the need of individual electric and gas supply units to feed each chamber complicates the servicing and operation of the plasma cathode in high-voltage devices and reduces reliability of the system as a whole. A multichannel regime of the discharge operation with one power supply can be realized only over a limited interval of glow discharge currents [8]. Therefore, this method cannot be used to control the emission current and ensure a uniform distribution of the current density over a large working surface of the plasma cathode.

The approach proposed in this study provides conditions for stable operation of a hollow-cathode glow discharge through a long narrow slit with a uniform distribution of the current over the slit. Therefore, prerequisites are provided for generation of anodic discharge plasma, which is spatially homogeneous along the slit axis, and creation of a homogeneous plasma emitter with a large surface area thanks to the electron flow, which diverges transversely to the slit, in the anodic region.

2. Experiment

Electrode system of the plasma cathode (Fig. 1). consists of a stainless-steel hollow cathode (item 1) 200 mm in diameter and 350 mm long and a hollow anode (item 3), part of whose surface 200×300 mm in size was covered with a metal grid (item 4). The grid was electrically insulated from the anode electrode.

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The trigger electrode 2 was installed in the cathode chamber. The cathode wall had a slit 300 mm long, whose width h was adjustable within 10 to 40 mm. The gas (argon) was fed into the cathode chamber. The minimum pressure of discharge initiation depended on the design of the trigger electrode. It proved to be the lowest when a thin (0.3 mm) tungsten filament, which was connected to the positive terminal of the discharge power supply, was stretched along the cathode axis.

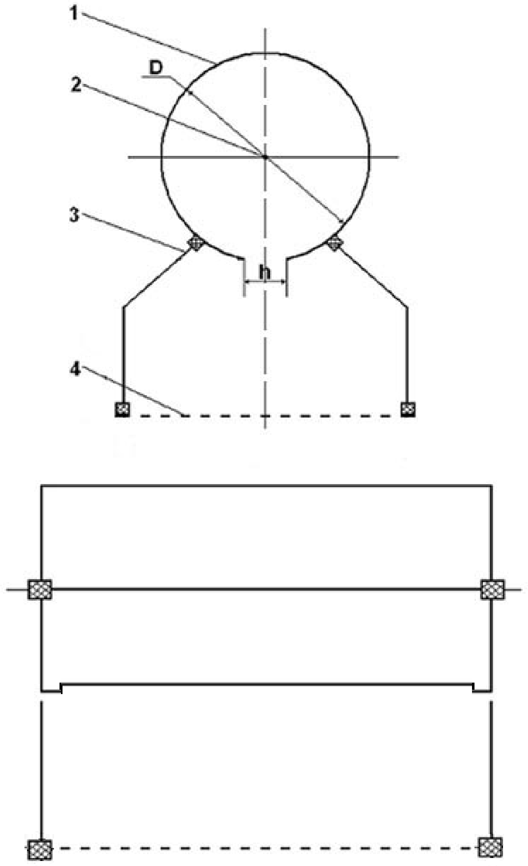

Fig. 1. A cross-sectional view of the plasma cathode

A glow discharge was initiated when a voltage pulse of 3.5 kV was applied to the gap. The operation voltage of the discharge at a current of 1–10 A and a pulse length of 1 ms was 350–700 V under the gas pressure of the vacuum chamber equal to $(1–5)\cdot10^{-2}$ Pa. The filament current was limited first by a resistor. However, the experiments demonstrated that the current in the filament circuit did not exceed 10% of the discharge current because of the small surface area of the filament. When electrons were extracted from the plasma, the current to the filament reversed its polarity and turned to the ion current as a result of the increase in the plasma potential.

The experiments on determination of the optimal shape and dimensions of the slit revealed that a stable operation of the discharge with a nearly uniform distribution of the current along the slit was ensured when the slit had some optimal width, whose surface area was much larger (by one order of magnitude) than the area corresponding to an optimal ratio of the anode and cathode surfaces, $S_c/S_a \sim (M_i / m_e)^{1/2}$ (M_i and m_e being the ion and electron mass respectively) [3]. The discharge was constricted if the slit width narrowed and the minimum working pressure of the gas increased if the slit widened. If an attempt was made to realize multi-channel operation, the discharge operated only through one orifice. In this case, the discharge current was localized in the adjacent portion of the hollow cathode surface.

Inhomogeneity of the longitudinal distribution of the electron current over a length of 15 cm, which was measured in the plane of the emitter grid, accounted for ~15–20% of the average current. FWHM transverse distribution was about 75 mm at the distance between the grid and the slit equal to 100 mm (Fig. 2). The transverse distribution inhomogeneity diminished as the grid-to-slit distance and the slit width increased. The use of a grid with variable transparency along the transverse axis represented the most efficient method for redistribution of the current over the grid surface and reduction of inhomogeneity (see the curve 3 in Fig. 2).

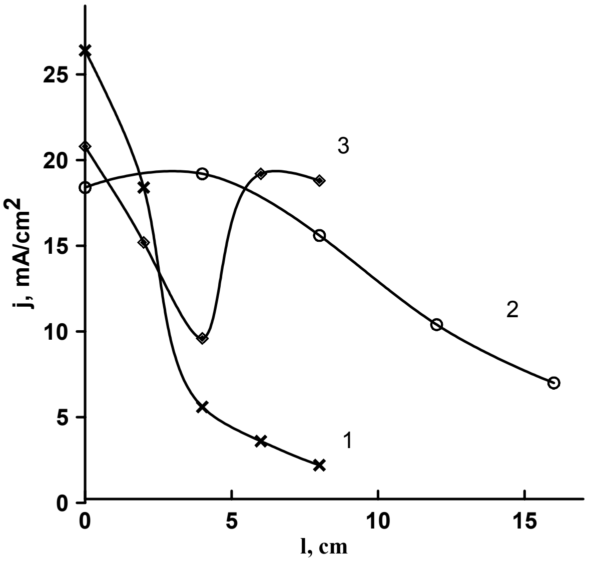

Fig. 2. A longitudinal (2) and transverse (1, 3) electron current density distributions over the plasma emission surface. Discharge current 10 A

Efficiency of electron extraction from the plasma, which was determined as the ratio between the beam and discharge currents, depended on the grid transparency and the accelerating field strength and was equal to 0.5–0.9. Similarly to arc plasma cathodes, the system under study allowed the grid control of the plasma cathode emission [9]. Therefore it was possible to expand the working range of the pulse length for the plasma cathode at hand to units of microseconds or shorter. A positive potential of 150 V, which was applied to the grid relative to the anode, increased the extraction efficiency from 0.5 to 0.9. The extraction efficiency was impaired when negative pulses were applied and the cathode emission stopped at a voltage of –200 V. The rise time of an emission current pulse was several microseconds.

Results of experiments on the model were used for development of a plasma cathode having the surface area 200×1000 mm in size for replacement of the thermo-emission cathode of the electron accelerator with the beam power of up to 20 kW. At present the cathode design has been debugged and the glow discharge operates stably at a pressure of 0.01 Pa.

3. Conclusions

An electrode system with a long hollow cathode provided a stable operation of the glow discharge through a slit aperture at a current of ~10 A and formed a plasma emitter of electrons whose surface area was comparable with the working surface of the cathode. This is impossible in principle when electrons are extracted from cathodic plasma because of a large loss of fast electrons and the increase in the discharge operation voltage.

It was shown that and the grid transparency the grid voltage could efficiently control the emission current density distribution and the length of beam current pulses.

A low working gas pressure of the proposed plasma cathode design (up to $1\cdot10^{-2}$ Pa for nitrogen) provided high working voltages of the electron accelerator.

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