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The use of a louvered redistributing electrode in a plasma electron emitter based on a low-pressure arc

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The paper presents the results on the generation of a pulsed electron beam using a special louver-shaped redistributing electrode in a source with a plasma emitter based on a low-pressure arc with grid stabilization of the cathode plasma boundary and a plasma anode with an open plasma boundary. The configuration of the electrode makes it possible to realize its geometric transparency close to zero for the flow of ions entering the space of the plasma emitter from the anode/beam plasma, but, at the same time, non-zero and, meanwhile, variable transparency for plasma discharge electrons, which makes it possible to ensure efficient electron selection through the grid with the ability to control the density of the emission current to generate an intense (tens to hundreds of amperes) wide (ones to tens of cm^2) electron beam of submillisecond duration, at accelerating voltages up to 15 kV.

Keywords: arc discharge, grid plasma emitter, electron source, redistributing electrode, plasma emission boundary, open plasma boundary, distribution of emission current density.

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Electron sources with a plasma cathode [1] based on a low-pressure arc are efficient devices used widely in the field of heat treatment of materials, beam polishing processes, application of functional coatings, and other technological processes where a controlled input of energy into a material is required for modification of its structure and properties [2]. The key advantages of electron sources with a plasma cathode are their high energy density, the capacity for independent adjustment of the main source parameters (electron energy, currents, and beam duration) within a wide range, and the potential for effective modification of a variety of materials (including metals, ceramics, and polymers). Such modification leads to a significant improvement of the surface properties of materials, which translates into an increase in service life of products made from these materials [3].

However, with all the above advantages, such sources also have a drawback in that the electron beam diameter is small, which makes it difficult to process large surface areas and necessitates scanning the beam over the product. In addition, the energy density distribution over the beam cross section is often Gaussian, which also leads to uneven material surface processing, limiting the scope of possible applications of the electron beam.

The use of an emission grid with a larger diameter (and, consequently, larger area) [4], the introduction of multi-arc systems [5], and the use of redistributing electrodes of a special shape enhancing the beam uniformity [6] rank among the most common methods for solving the above problems. Each of these methods has its own advantages and disadvantages.

Increasing the diameter of the emission grid (and, accordingly, the electron beam) to a certain limit, one may increase the area of electron emission, but this is often accompanied by a reduction in density of the emission current. This approach has an advantage in that it may be implemented without any significant changes to the design of the electron source. However, the emission area increases together with the non-uniformity of emission current density. This necessitates the implementation of additional measures to reduce it, lest the stability of operation of the electron source should deteriorate significantly [7].

Multi-arc systems involve the use of multiple cathodes within a single grid plasma emitter, which are often arranged in a circular pattern to form overlapping plasma flows. The result is that a relatively homogeneous emission plasma bounded by the emission grid is formed [5]. This provides an opportunity to increase significantly the beam diameter and establish a uniform distribution of current density through independent adjustment of current at each cathode [8]. The disadvantage of this method is the complexity of the design of the plasma emitter and its power supply systems.

The use of an electrode redistributing plasma in the emitter allows the emitted electrons to be distributed over a larger area. This approach provides significant beam expansion and is relatively easy to integrate into existing setups. However, if the emitter and the emission grid are large in size, the approach becomes impractical, since it may lead to a reduction in emission current density on the system axis.

The aim of the present study is to increase the electron beam diameter with a simultaneous suppression of non-

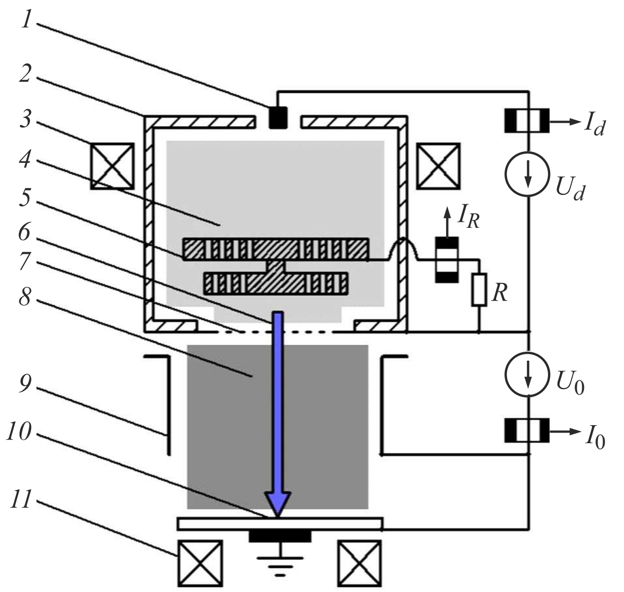

Figure 1. Diagram of the electron source. *1* — cathode, *2* — anode, *3* — solenoid in the emission region, *4* — cathode plasma, *5* — louvered redistributing electrode, *6* — electron beam, *7* — emission grid, *8* — beam plasma, *9* — grounded extraction electrode, *10* — collector, *11* — solenoid in the collector region.

uniformity of the current density (and, accordingly, the energy density) over its cross section and to increase the stability of its generation in a source with a plasma emitter based on a pulsed single low-pressure arc through the use of a special louvered redistributing electrode.

Experiments were carried out using an electron source with a plasma emitter based on a low-pressure arc [9,10]. Its diagram is shown in Fig. 1. When voltage is applied by source U_d, a cathode spot is initiated on the surface of cathode *1*, which ignites a low-pressure arc discharge between cathode *1* and anode *2* and triggers the production of emission plasma *4* in the guiding magnetic field of solenoid *3*. Redistributing electrode *5* (see its design in Fig. 2) has a variable geometric transparency for plasma electrons, which increases along the electrode radius and is inversely proportional to the emission current density measured without this electrode in the plasma emitter system. When an accelerating voltage is applied by source U_0 between anode *2* and extraction electrode *9*, electrons are extracted from emission plasma *4*, pass through the apertures of redistributing electrode *5*, form electron beam *6*, and are accelerated and transported in the guiding magnetic field of solenoid *11* to collector *10*. Anode plasma *8* is produced by ionizing the working gas with electron beam *6* in the drift tube. The generation of beam *6* is accompanied by the formation of a flow of accelerated ions from anode plasma *8* directed toward the plasma emitter. Electrode *5* is louver-shaped. This allows for zero geometric transparency for the accelerated ion flow and raises the stability of electron beam generation due to enhancement of the negative feedback with respect to ion flow [11], which is achieved through its complete interception by electrode *5*.

Figure 3 shows the oscilloscope records obtained with the use of a redistributing electrode in the form of a stainless steel cylinder with a diameter of 65 mm and a thickness of 5 mm (*a*) and a louvered redistributing electrode (*b*). Accelerating voltage U_0, current in the accelerating gap I_0, current in the redistributing electrode circuit I_R, and current in the arc discharge circuit I_d are plotted in this figure. Scale: U_0 — 5 kV/div, I_0 — 40 A/div, I_R — 4 A/div, I_d — 40 A/div, and τ — 20 μs/div. The magnetic field produced by the solenoid in the emission and collector regions is 50 and 60 mT, respectively. The pulse duration is $\sim 150\,\mu$s. When a cylindrical redistributing electrode is used, the oscilloscope records of the front of a current I_R pulse at the redistribution electrode reveal characteristic spikes, which lead to current I_0 spikes in the accelerating gap (Fig. 3, *a*); when a louvered electrode is used, the amplitude of current pulsations in the process of electron beam generation is lower (Fig. 3, *b*) and the current flow is more stable with a somewhat higher current amplitude and, accordingly, a larger integral electron beam energy per pulse.

Figure 4 shows the distributions of energy density of the electron beam over its cross section measured with a sectioned calorimeter. Curve *1* corresponds to the energy density distribution obtained with a redistributing electrode in the form of a cylinder. It has a significant non-uniformity in the center of the system, which is associated with the inhomogeneity of plasma in the emission region. The corresponding diameter of the electron beam at half the energy density is 30 mm. Curve *2* corresponds to the energy density distribution with the proposed louvered electrode with self-consistent negative feedback; the beam diameter at half the energy density here is 40 mm. Curve *3* corresponds to the energy density distribution recorded without a redistributing electrode.

It follows from the presented figures that the proposed method of electron beam generation with the discussed redistributing electrode with a non-zero geometric transparency for fast and plasma electrons allows for a more uniform distribution of the electron beam power density at the collector. The redistribution mechanism is driven by the fact that, unlike ions, fast and plasma electrons may pass through apertures in the electrode in crossed electric and magnetic fields.

This provides an opportunity to switch to higher arc discharge currents without provoking an electrical breakdown of the accelerating gap, which is typically caused by disruption of layer/grid stabilization of the emission plasma boundary due to the existing non-uniformity of the emission current density. The presence of a louvered electrode, which is connected via a resistance and introduces a negative feedback mechanism, allows one to reduce the emission current at the moment of a sharp and uncontrolled increase in current in the accelerating gap.

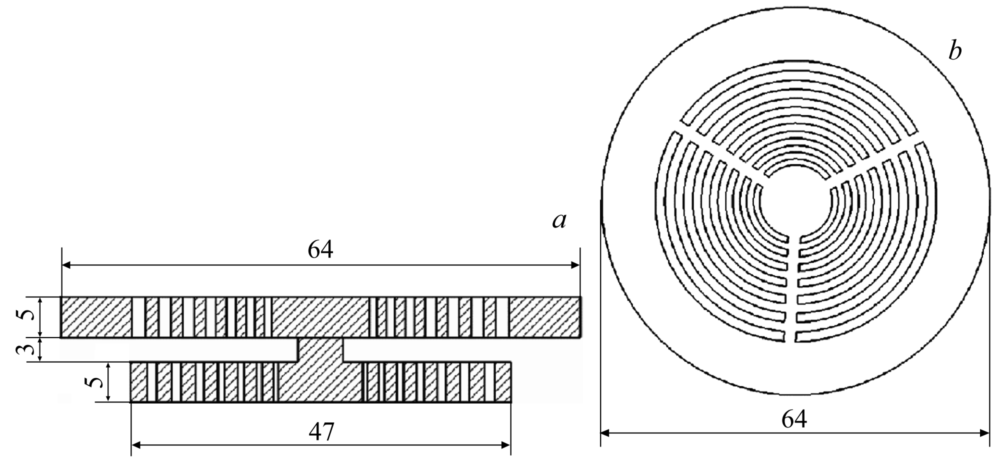

Figure 2. Redistributing electrode: *a* — side view, *b* — top view.

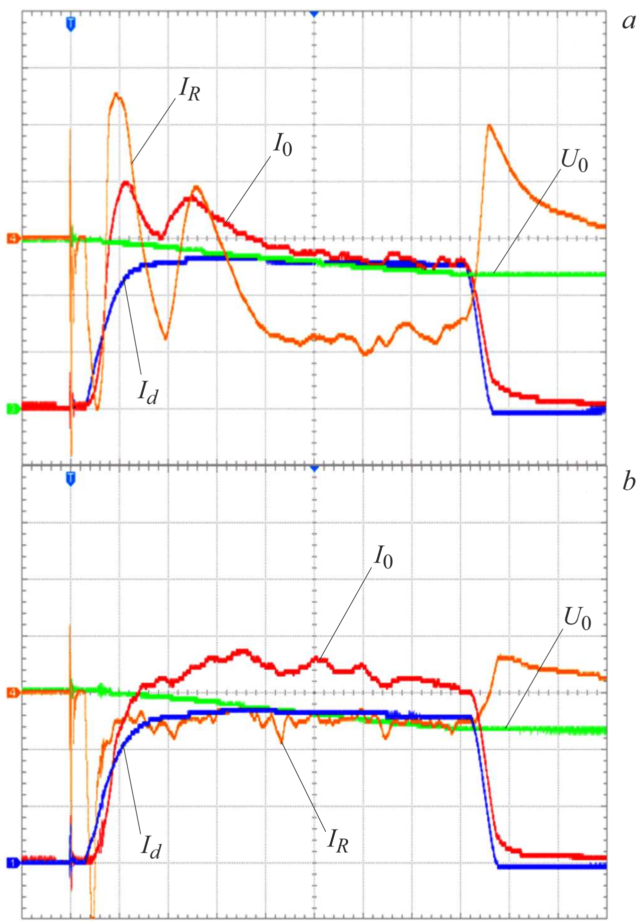

Figure 3. Oscilloscope records of accelerating voltage U_0, current in the accelerating gap I_0, current in the redistributing electrode circuit I_R, and current in the arc discharge circuit I_d.

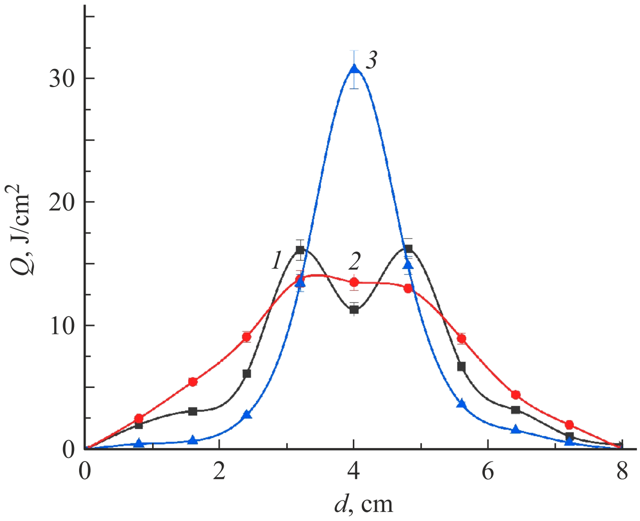

Figure 4. Distributions of energy density of the electron beam over its cross section measured using a sectioned calorimeter.

The proposed louvered redistributing electrode made it possible to increase the electron beam size from 20 to 40 mm by increasing the size of the emission window while maintaining the mode of complete interception of the ion flow by this electrode. Non-zero variable transparency is established in this case for plasma electrons, which are extracted upon reaching the boundary of emission plasma stabilized by a fine-structured grid and form an intense beam with a satisfactory distribution of current density over the cross section. The produced electron beam was used in experiments on modification of the surface of metal materials, including those intended for medical use, to form layers with increased hardness and wear resistance.

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Conflict of interest

The authors declare that they have no conflict of interest.

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