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Electron source with a multi-arc plasma cathode for generating a modulated beam of submillisecond duration

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The paper presents the design of a multi-arc discharge system and the principle of creating its multichannel power supply for a SOLO-type electron source with a multi-arc grid plasma emitter. The cathode assembly is based on an open (noncounteracting) arc discharge initiated by an electric breakdown along the surface of a dielectric. Compared to a single-channel system with a large distributing electrode, a multi-arc setup allows not only for increased beam diameter, but also for effective control of beam power during submillisecond pulses, as well as control over energy density distribution. The results of generating a modulated electron beam with a diameter of 30–60 mm, which is transported to the collector in a longitudinal magnetic field at a distance of about 600 mm, with a satisfactory level of homogeneity for technological applications, are presented. This approach to generating intense modulated electron beams in electron source systems with plasma cathodes significantly expands the possibilities of such unique equipment, both for scientific research and for solving industrial problems..

Keywords: Electron source, plasma cathode, arc discharge, plasma anode with an open boundary, electron extraction coefficient.

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Low-pressure arc discharges are used widely to generate intense (with subkiloampere currents) electron beams and produce emission plasma for this purpose in plasma cathodes (PCs) of electron sources [1–3]. They allow for generation of emission plasma in a PC discharge system within a wide range of working gas pressures and discharge current amplitudes, which may reach hundreds of amperes even with a single cathode [4–7] and a level of several kiloamperes with multicathode discharge systems [8–11]. Stable initiation of a cathode spot (or spots) is one of the conditions for using a high-current arc discharge in a PC discharge system. Cathode spots in the designed plasma emitter are initiated on 13 cathodes via dielectric surface breakdown. Twelve of them are arranged in a circle with a diameter of 84 mm, and one additional cathode is positioned at the center of the emitter. No pressure difference in the discharge system is needed in this case, and simultaneous spot initiation may be achieved with a relatively simple single-channel working gas feed system, enabling the construction of scalable PC discharge systems with a large number of independent cathode assemblies (multi-arc discharge systems). Independent operation of several cathode assemblies requires a more sophisticated power supply of the PC discharge system; however, the use of modern components and optimization of power supply circuits may simplify the design of a multichannel arc discharge system that has good potential in terms of both constructing a PC with a large emission surface area and exercising operational control over the distribution of the current density of a beam over its cross section.

A PC with a multi-arc discharge system is part of the electron source shown schematically in Fig. 1. A cathode spot is initiated on each cathode *1* as a result of dielectric *2* surface breakdown between cathode *1* and ignition electrode *3*. Electrodes *3*, current-distributing electrodes *5*, and intermediate anode *9* are connected to anode electrode *10*, which is the common anode of arc discharges, through resistances R_{tr}, R_d, and R_{ha}, respectively, that ensure switching of the main discharge current to anode electrode *9*. Additional electrode *4* together with electrode *5* do not only redistribute the discharge current, but also provide partial stabilization of current in the accelerating gap by introducing negative feedback with respect to the ion component of current flowing from the accelerating gap to the emitter through the emission grid cells [12]. The typical PC dimensions are as follows: inner diameter of insulator *8* — 125 mm; distance from the cathodes to emission grid *6* — 80 mm; emission grid diameter — 85 mm; size of the grid cells (in the clear) — 0.12×0.12 mm; and grid wire thickness — 0.09 mm. Electrons are extracted from the PC through the cells of emission grid *6*, which is positioned at anode electrode *10*, under the influence of a constant accelerating voltage from source E_0 with a high-voltage capacitor bank with a capacitance of 6 μF. The accelerating voltage is applied between emission electrode *10* and the grounded electrodes (extraction electrode *11*, which is combined with the drift tube, and collector *15*). Extraction and acceleration of electrons at working gas pressure $p(\mathrm{Ar}) = (1-5) \cdot 10^{-2}$ Pa lead to the production of plasma in the electron beam transport space and the

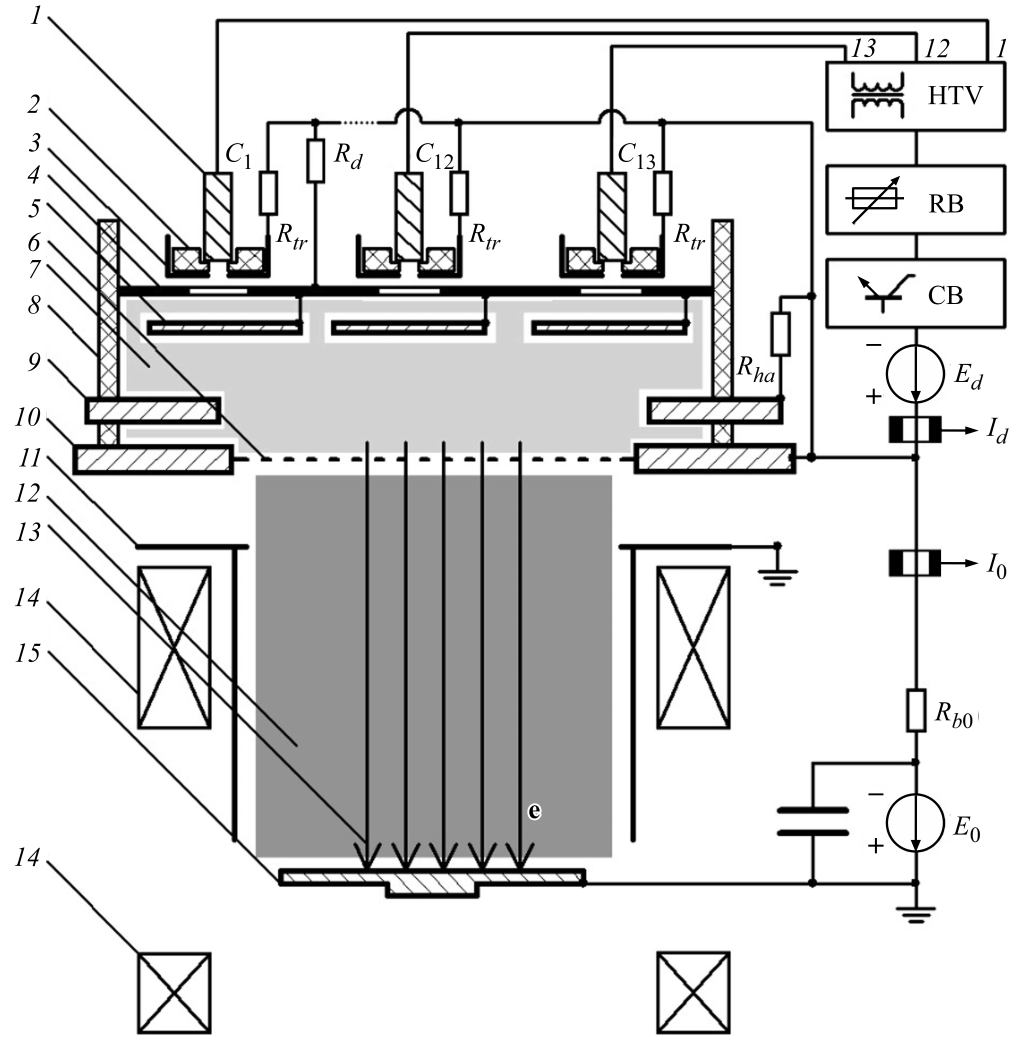

Figure 1. Diagram of the modernized „SOLO“ source with a multi-arc discharge system. *1* — Cathode, *2* — insulator, *3*— ignition electrode, *4* — additional electrode, *5* — redistribution electrode, *6* — emission grid, *7* — cathode plasma, *8* — insulator, *9* — intermediate anode, *10* — anode, *11* — grounded extraction electrode, *12* — anode (beam) plasma, *13* — electron beam, *14* — solenoid, and *15* — collector.

formation of so-called anode beam plasma with a boundary that is open, mobile, and established self-consistently near the emission grid. The beam is transported to collector *15* over a distance of approximately 600 mm in the field of solenoids *14*. In order to implement control over the electron beam power, which is needed to maintain a controlled rate of energy input into the workpiece and form the needed temperature field in its surface [13], the designed power supply system of the multi-arc PC provides an opportunity to generate amplitude- and width-modulated arc discharge current, which may be adjusted directly within a submillisecond current pulse. The discharge power supply system is equivalent to a charged capacitor that is discharged through resistor box RB. The values of these resistors may be altered dynamically within a discharge current pulse by switching on the corresponding power transistors in commutation box CB. The arc discharge is initiated by ignition unit HTV. Figure 2 shows the typical oscilloscope records of modulated discharge current and current in the accelerating gap that illustrate the possibility of controlling the electron beam power in such a system within the duration of a submillisecond pulse. One specific feature of beam generation in this system is the need to operate within a relatively narrow range of working gas pressures where, on the one hand, plasma is produced rapidly in the beam transport space, ensuring compensation of the beam spatial charge and the formation of a plasma anode, and, on the other hand, a sufficient electrical strength of the accelerating gap is maintained. Operation in the plasma-filled mode affects a significant proportion of ions in the total current of the accelerating gap, which varies in the course of a pulse and specifies, along with discharge current I_d, the amplitude of total beam current I_0.

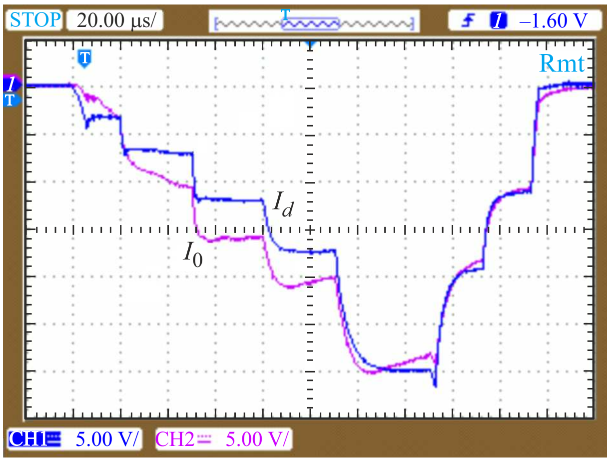

Figure 2. Typical oscilloscope records of modulated arc discharge current I_d and current I_0 in the accelerating gap at an initial accelerating voltage of 15 kV and pressure $p(\mathrm{Ar}) = 4 \cdot 10^{-4}$ Torr. Scale: 100 A/div, 20 μs/div.

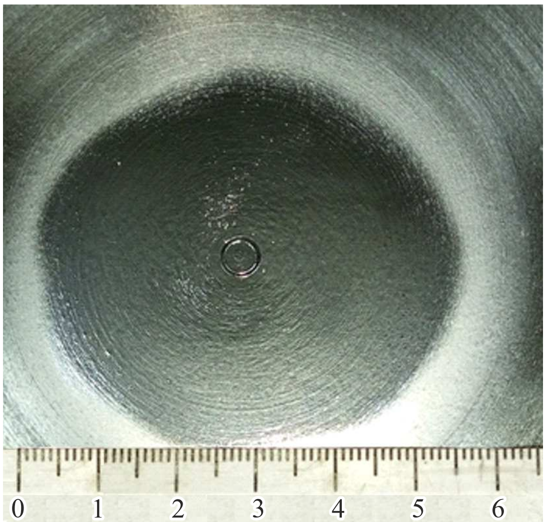

Figure 3. Beam signature formed in the process of titanium collector surface melting at a beam energy density of $\sim$ 18 J/cm^2.

It was demonstrated in experiments [14,15] that a certain profile of the emission current density, which depends on the magnitude of the guiding magnetic field, the beam current amplitude, the working gas pressure, the accelerating voltage, etc., needs to be formed to obtain a uniform distribution of energy density over the beam cross section on the collector. A multiparameter dependence of this kind often necessitates minimization of the concentration at the center of the emission region. In the discharge system under consideration, this is achieved by correcting the plasma density in the near-axis PC region by an additional central current channel. When generating a beam without the central cathode in a sufficiently strong magnetic field ($>$ 0.05 mT), a beam leaving circular signatures on the collector may be shaped. With the plasma density corrected by the central cathode, a fairly uniform beam signature with a diameter up to 50 mm was obtained in the process of titanium collector surface melting. The region of visible beam impact with a diameter up to 60 mm is also seen in Fig. 3.

The constructed multi-arc discharge system has lifted a number of limitations of a single-channel system with a discharge constriction channel and demonstrated the scalability of PC discharge systems based on a low-pressure arc discharge. Compared to a single-channel system with a large-size redistribution electrode, a multi-cathode system with redistribution of the arc current between the cathodes allows one not only to increase the diameter of a generated electron beam, but also to control the initial and final (after transport in a longitudinal magnetic field) distributions of energy density over the beam cross section in a more efficient manner due to separate adjustment of cathode currents. New modes of generation of a modulated beam with an electron energy up to 25 keV, a current up to 700 A, and a pulse duration up to 150 μs, which may be increased by reducing the beam power, were demonstrated experimentally. The beam generated by this electron source may be used in experiments on electron-beam modification of materials and products with the aim of altering their functional and operational properties in a controlled manner by pulsed heating of a thin (from several micrometers to tens of micrometers) surface layer to the melting point and subsequent ultrafast ($\sim 10^7$ K/s) cooling driven by the thermal conductivity of the bulk material.

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Conflict of interest

The authors declare that they have no conflict of interest.

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