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A method for combined control of an electron beam in a source with a multi-arc grid plasma emitter

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The paper proposes and implements the principle of operation of an electron source with a multi-arc grid plasma emitter, which makes it possible to modulate the electron beam current during a submillisecond pulse by simultaneously modulating the amplitude of the arc discharge current and modulating the inter-grid voltage by introducing an additional grid that overlaps the end of the hollow anode and regulates the potential barrier for plasma electrons. The proposed control method makes it possible to expand the range of adjustment of the electron beam current by four orders of magnitude.

Keywords: arc discharge, low pressure arc, plasma cathode, electron beam, grid control, electron source.

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The problem of expanding the range of parameters of generated electron beams remains relevant to applications involving the surface modification of various materials through continuous or pulsed surface heating [1,2]. Pulsed electron beams are the most effective tool for such applications, providing both short-term high-energy impact (melting, alloying) and modes with preliminary heating of the sample surface or maintenance of its temperature, which are aimed at adjusting the morphology or eliminating internal stresses without destroying the surface structure [3–5]. However, the capabilities of pulsed electron beams at low operating residual gas pressures (10−50 mPa) with a constant current amplitude (beam power) are limited to a significant degree by certain physical properties of modified materials (thermal conductivity, heat resistance, electrical properties, etc.).

It was demonstrated in [5,6] that the high-energy impact needed for modifying the surface of various materials using sources with a plasma cathode based on an arc discharge may be achieved by controlling the power of an electron beam during its generation within a submillisecond range of pulse durations via modulated control of the arc discharge current. However, this approach does not allow one to generate low-current electron beams needed for preliminary gradual heating and cleaning of the material surface, since the minimum arc current is normally on the order of a few amperes.

The electron beam current and power may be reduced through the use of an additional grid electrode that forms a potential barrier for plasma electrons, the height of which is determined self-consistently by the flowing current [7,8]. In the present study, we consider a two-grid system where the potential difference (intergrid voltage) may be varied during a single pulse.

It was demonstrated in [9] that an electron source with a plasma cathode based on a single low-pressure arc allows one to implement the so-called combined method of electron beam power control, which integrates the two mentioned methods of adjusting the beam current. This combination makes it possible to modulate the electron beam current over a wide range within a single pulse, opening up the opportunities for modifying the surface of various solid materials with a controlled rate of energy input. The aim of the present study is to expand further the range of electron beam power in a source with a multi-arc plasma cathode and combined beam current adjustment.

Figure 1 shows the diagram of an electron source with a multi-arc plasma emitter and grid control of the electron beam current. The electron source includes a multi-cathode unit, a power supply system, an additional fine-structure grid, and a source of reference and modulated voltage. The operation of the main units of this multi-arc electron source was discussed in detail in [10]. Electrons are extracted from the plasma emitter under the influence of a constant accelerating voltage from source E_0 through the cells of emission grid *6* and the cells of control grid *8* positioned on anode electrode *10.* The accelerating voltage is applied between electrode *11* and grounded electrodes *12* (extraction electrode combined with the drift tube) and *16* (collector). The extraction and acceleration of electrons lead to the formation of anode plasma *13.* Its boundary is open, mobile, and is positioned self-consistently near control grid *8.* Electron beam *14* is transported to the collector over a distance of approximately 600 mm in the field of solenoids.

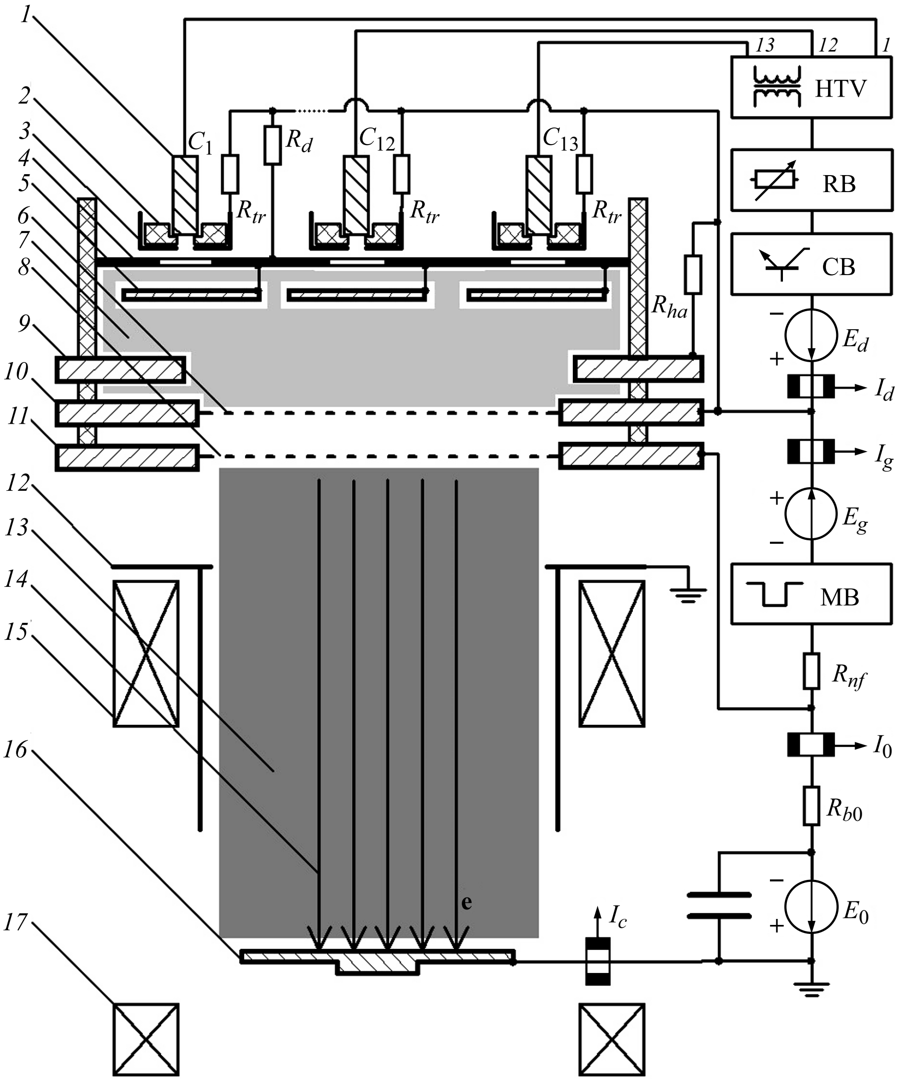

Figure 1. Diagram of the multi-arc electron source with grid control. *1* — Cathode, *2* — insulator, *3*— ignition electrode, *4* — diaphragm, *5* — redistribution electrode, *6* — emission grid, *7* — emission (cathode) plasma, *8* — control grid, *9* — intermediate anode, *10* — anode, *11* — additional anode, *12* — extraction electrode, *13* — anode (beam) plasma, *14* — electron beam, *15* and *17* — magnetic coils, and *16* — collector.

When current flows, the capacitor bank is discharged in the electron source, generating an accelerating voltage.

In order to ensure the possibility of adjustment of the current of electron beam *14* both through modulation of the arc discharge and by grid control, additional coverage of the end of hollow anode *10* with control grid *8* was arranged. The diameters of the emission and control grids are 85 mm, and the cells are 0.14×0.14 mm in size. Both grids are made of stainless steel. The arc 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. Two sources are connected in series between the grids: reference voltage source E_g and control voltage source MB. The reference voltage source is a block of capacitor banks charged through a voltage multiplier from an adjustable autotransformer, which provides smooth adjustment of the output voltage within the range from 0 to -60 V. Modulated voltage source MB is a set of storage capacitors, each of which is connected to an IGBT- module. As in the case of amplitude and width modulation of the arc discharge current, the modulated voltage source allows for amplitude modulation of voltage between emission grid *6* and control grid *8*. This power supply contains four switch–capacitor pairs, thus providing 16 bias voltage variations. The amplitude step is 5 V, and the minimum time step is 10 μs.

As the negative bias voltage at the control grid increases, a potential barrier preventing electrons from passing through the grid cells into the accelerating gap is established [11,12]. The modulated bias voltage source is operated in pulsed mode with reverse polarity relative to the reference voltage source. Control of the MB block transistors allows one

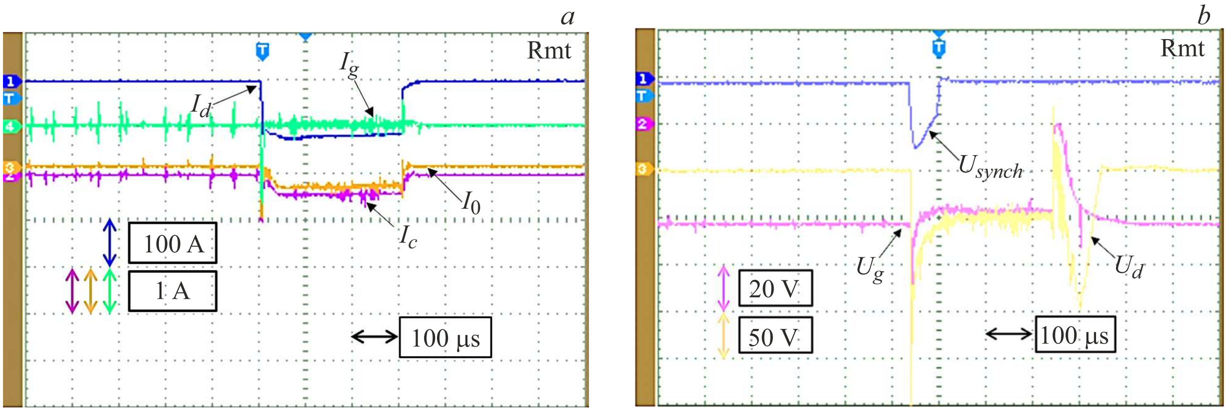

Figure 2. Typical oscilloscope records of currents (inverted signal) (*a*) and voltages in the cutoff mode at a constant current amplitude I_d (*b*). A color version of the figure is provided in the online version of the paper.

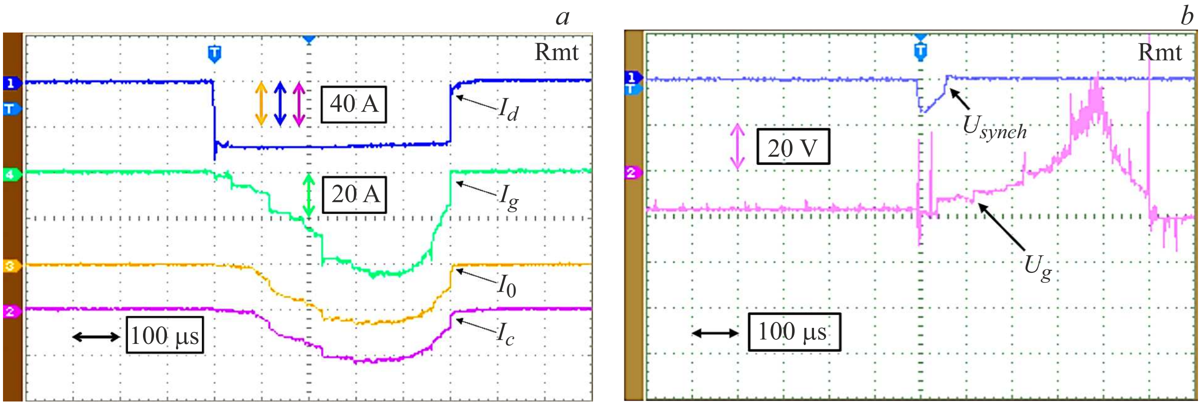

Figure 3. Typical oscilloscope records of currents (inverted signal) (*a*) and voltages in the increasing power mode at a constant current amplitude I_d (*b*). A color version of the figure is provided in the online version of the paper.

to generate voltage pulses compensating for the potential difference between the emission and control grids. Thus, the potential barrier at the control grid is reduced temporarily, and the number of emitting electrons increases. Depending on the magnitude of reference voltage and the bias pulse amplitude, one may expand the adjustment range of current in the accelerating gap to hundreds of milliamperes during a single pulse of a submillisecond duration.

Figure 2 shows the oscilloscope records of currents (inverted signal) and voltages that illustrate the possibility of generating an electron beam with current $I_0 = 400$ mA at an arc discharge current $I_d = 120$ A. The experimental parameters are as follows: residual gas pressure $p(\mathrm{Ar}) = 20$ mPa; accelerating voltage $U_0 = 15$ kV; the magnetic field amplitudes in the emitter, accelerating gap, and collector regions are $B_e = 30$ mT, $B_g = 22$ mT, and $B_c = 110$ mT, respectively; and pulse duration $\tau = 300\,\mu$s. Rogowski coils were used to measure arc discharge currents, control grid currents, collector currents, and currents in the accelerating gap. The voltage between the emission and control grids was measured across a shunt resistor with an oscilloscope. Voltage is U_{synch} is needed for synchronization of electrical signals of the electron source when two oscilloscopes are used.

As the negative voltage between the emission and control grids increases, the potential barrier for plasma electrons grows higher. Owing to this, current I_0 in the accelerating gap decreases to the point of almost complete cessation of emission at $U_g \approx -(40{-}50)$ V (Fig. 2, *b*). This U_g value corresponds to the maximum energy of electrons extracted from emission plasma and is consistent with the results of measurements of arc discharge voltage U_d at one of the cathodes ($U_d \approx 40{-}50$ V). Following the start of an arc discharge current pulse, voltage U_g is varied from -45 to -35 V using control voltage source MB, while current I_0 in the accelerating gap is 0.4 A.

Figure 3 shows typical oscilloscope records of currents (inverted signal) and voltages illustrating the capacity to control the current in the accelerating gap at a constant arc discharge current $I_d = 60$ A, residual gas pressure $p(\mathrm{Ar}) = 20$ mPa, accelerating voltage $U_0 = 15$ kV, pulse duration $\tau = 500\,\mu$s, and similar magnetic field values.

Following the start of an arc discharge current pulse, the modulated voltage source changes voltage U_g between the control and emission grids from -20 to $+40$ V, which is accompanied by a gradual increase in current in the accelerating gap I_0. These oscilloscope records verify the

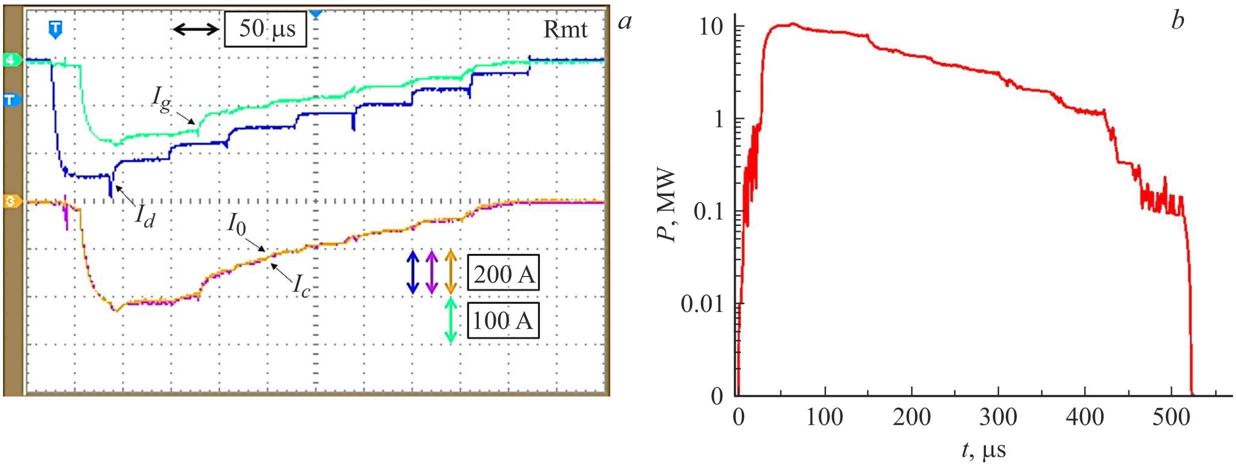

Figure 4. Typical oscilloscope record of currents (inverted signal) (*a*) in the decreasing power mode (*a*) and instantaneous power plot (*b*). A color version of the figure is provided in the online version of the paper.

possibility of modulating the current in the accelerating gap by adjusting the voltage between the emission and control grids, which determines the height of the potential barrier during a submillisecond pulse.

Figure 4 shows the oscilloscope records of the falling electron beam current in the accelerating gap (*a*) and the plot of its instantaneous power (*b*) during a pulse. Reference voltage $U_g = -10\,\text{V}$, $U_0 = 25\,\text{kV}$, $p(\text{Ar}) = 30\,\text{mPa}$, $\tau = 500\,\mu\text{s}$, and the magnitude of magnetic fields is similar to that in previous experiments. With the combined use of arc discharge current sources and voltage modulation, beam current adjustment through variation of both the concentration of emission plasma and the potential barrier height was implemented. Thus, the possibility of changing the instantaneous power from 0.1 to 10 MW during a single pulse of submillisecond duration was demonstrated.

The implemented new modes of generation of a modulated electron beam with its current amplitude possibly varying by four orders of magnitude (0.4–400 A) within a single submillisecond pulse open up opportunities for application of such beams in materials science (specifically, in surface modification of ceramic materials).

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Conflict of interest

The authors declare that they have no conflict of interest.

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