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Current Characteristics of a High-Current Electron Gun with Multi-Gap Initiation of Explosive Emission by Dielectric Surface Flashover

© *V.I. Petrov, P.P. Kiziridi, G.E. Ozur*

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences,
634055 Tomsk, Russia
e-mail: ozur@lve.hcei.tsc.ru

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Current characteristics of a plasma-filled, high-current electron gun at different accelerating voltages and densities of plasma preliminary filling the space between the cahode and collector have been investigated. Multi-gap initiation of explosive emission is performed with the use of parallel operated, resistively decoupled arc plasma sources which electrodes and tube ceramic isolators are built-in to the explosive-emission cathode. Experiments have demonstrated operability of high-current electron gun with a new cathode assembly at accelerating voltage up to 30 kV and its good emissivity (average in area current density) which was approximately 1.4–2.4 times higher than an emissivity of traditional electron gun with plasma anode and multi-wire copper cathode.

Keywords: high-current electron beams, explosive emission, cathode assembly, multi-gap initiation, dielectric surface flashover.

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Introduction

The development of physics and technology for generating low-energy (10–30 keV), high-current electron beams (LEHCEB) is an urgent task from the point of view of their use for modifying the surface layers of metallic materials [1-7]. The formation of such beams is carried out, as a rule, in guns with a plasma anode and an explosive emission cathode [4]. The most actual tasks remain to increase the stability of the LEHCEB parameters from pulse to pulse and to ensure the homogeneity of the distribution of energy density over the beam cross section. The solution of these problems significantly depends on the operating stability of the explosion-emission cathode of the electron gun.

A notable step in improving the operation of a high-current electron gun was our proposed technique of initiating explosive emission by embedding resistively decoupled arc plasma sources into the disk cathode [8]. A distinctive feature of this technique is that the power supply of both arc plasma sources and the accelerating gap of the electron gun is carried out from a single generator of high-voltage pulses. The very first experiments with the new cathode pack showed improved stability of its operation compared to the most commonly used multi-wire copper cathode (usually made from a radio frequency cable braid) and increased (by 1.5–1.7 times) the average density of the emission current. The prospects of this cathode assembly are also due to the possibility of its use in the mode of a vacuum or gas-filled diode, due to the independence of the initiation of explosive emission from the accelerating gap and from its filling. In this paper, which is a continuation of the study of [8], the results obtained after the publication of the latter are presented to study the current characteristics of a plasma-filled high-current electron gun.

1. Experimental procedure

In the experiments, the facility described in [8] was used and its scheme is given in Fig. 1. The cathode assembly includes an explosive emission cathode *1* in the form of a perforated copper disc, into the holes of which ceramic tubes *2* and copper electrodes *3* are inserted flush. The electrodes (69 pieces in total) are grounded through resistors *4* with a total resistance of 3 kΩ (three resistors with a nominal value of 1 kΩ in series; in [8] there were 2 resistors with the same nominal value). The addition of a third resistor to the circuit of each electrode was done to increase the electrical strength of the cathode assembly, which had previously decreased at a voltage above 20 kV. The center-to-center distance between the

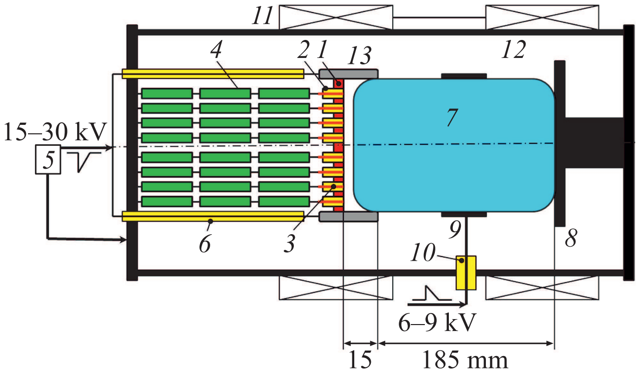

Figure 1. Scheme of the experiment (explanations in the text).

electrodes is 5.5mm. To enhance the electric field and local focusing of the ion flux from the plasma anode, annular grooves of triangular cross section are cut on the working surface of the cathode. The effective diameter of the emitting surface of the cathode was 5 cm, and the corresponding area $S = 19.6\,\text{cm}^2$. To limit the ingress of cathode plasma electrons onto the wall of the gun body *12*, a screen electrode *13* is installed, electrically connected to the cathode.

When a pulse of negative polarity with an amplitude of 15−30 kV is applied to the cathode from a high-voltage pulse generator (HVPG) *5* through through insulators *6*, a breakdown occurs along the surface of the ends of ceramic tubes. This creates a plasma consisting of ionized vapors of cathode materials (cathode spots), ceramic tubes and electrodes, as well as ionized desorbed gas. The formation of cathode spots when current flows through the ignition gaps is ensured by the fact that the current ranges (5−8 A) exceed the threshold arc current through each interval [9], which is a fraction of −units of A for almost all materials (for example, for copper it is about 2 A). The electrons emitted by the initial cathode spots, as well as those generated during the pulse, are accelerated in the double layer between the plasma of the cathode spots and the pre-created plasma anode *7* and transported to the grounded collector *8*. The current growth is provided by both an increase in the number of cathode spots and their expansion, i.e. an increase in the area of the emission surface [4,10,11].

The plasma anode was created using a high-current reflective discharge (RD) when a positive polarity pulse was applied through a pass-through insulator *10* to the annular anode *9*. The guide magnetic field created by the sectioned solenoid *11* provided both ignition and combustion of the high-current reflective discharge, and beam transportation to the collector [4]. The magnitude of the induction of the guide magnetic field was 0.1−0.14 T. In a number of experiments, an annular anode with arc plasma sources embedded in it was used; in this case, the plasma anode was already created using a hybrid discharge [12]. The amplitude of the discharge current was about 500 A, and for the case of a traditional OP (without arc plasma sources) and about 1500 A for the case of a hybrid discharge. To minimize the possible contact of the plasma anode with the screen electrode, the inner diameter of the anode was 3 mm smaller than the inner diameter of this electrode.

The initial density of the anode plasma was adjusted by changing the delay time, τ_d, between the start of the discharge current pulse and the supply of the accelerating voltage pulse to the cathode.

The moments of switching on the power sources of the guide magnetic field, the discharge forming the plasma anode, and the accelerating voltage were controlled using a delayed pulse generator with optical channel isolation. The pulse repetition rate of sending pulses was 1 pulse/10 s.

Pumping of the working volume of the gun was carried out by a turbomolecular pump to a pressure of 0.05 mTorr; after pumping, the working gas (argon) was injected to pressures of 0.3−0.5 mTorr.

The accelerating voltage pulses were recorded using an active divider, the cathode current — by the Rogovsky coil, the beam current — by a low-inductive shunt with a resistance of 0.005 Ω or the Rogovsky coil. The signals from the sensors were fed to the inputs of a 4-channel broadband (200 MHz) digital oscilloscope Tektronix TDS 2024. In each mode, 10 shots were fired.

2. Experimental results and discussion

Figure 2 shows a series of typical pulse waveforms obtained at different values of the HVPG charging voltage, U_{ch}. It can be seen that the beam current to the collector changes slightly with a change in the accelerating voltage. This corresponds to the well-known property of quasi-stationary double layers in plasma: the independence of the current density in the double layer from the applied voltage [13–15].

A similar behavior of the beam current depending on the accelerating voltage was also manifested in the case of the formation of a plasma anode using a hybrid discharge (Figure 3).

A more noticeable increase in the beam current with an increase in U_{ch} than in Figure 2 may be due to the manifestation of the unsteadiness of the double layer with a rapid increase in the accelerating voltage at the pulse front [4], or with a random deviation of the initial density of the anode plasma.

An increase in the beam current was observed, as expected, with an increase in the initial concentration of the anode plasma, which is illustrated by the waveforms shown in Figure 4. It can be seen that with an increase in the delay time τ_d from 15 to 35 μs, the average value of the beam current in the first half of the pulse (with a duration of about 1 μs) decreases approximately three times, which corresponds to the results of measurements of the ion density in the plasma anode obtained by us earlier using double probes (Figure 5) [16].

It should also be noted that with long delay times ($\tau_d > 35\,\mu$s), the instability of the cathode and beam currents from pulse to pulse increased significantly, which is probably due to the low density of anode plasma, and, consequently, the deterioration of conditions for the formation of explosive emission centers on the cathode and the stability of beam transportation to the collector.

The growth of the cathode current, which begins approximately 1 μs after the start of the pulse, is due to the development of a breakdown in the diode with the transition of the discharge into an arc stage with an oscillatory mode of current flow (see waveforms of pulses of accelerating voltage and cathode current). The breakdown of the diode is caused, first of all, by current leaks in the radial direction, which are caused by the anomalous diffusion of electrons emitted from the peripheral region of the cathode

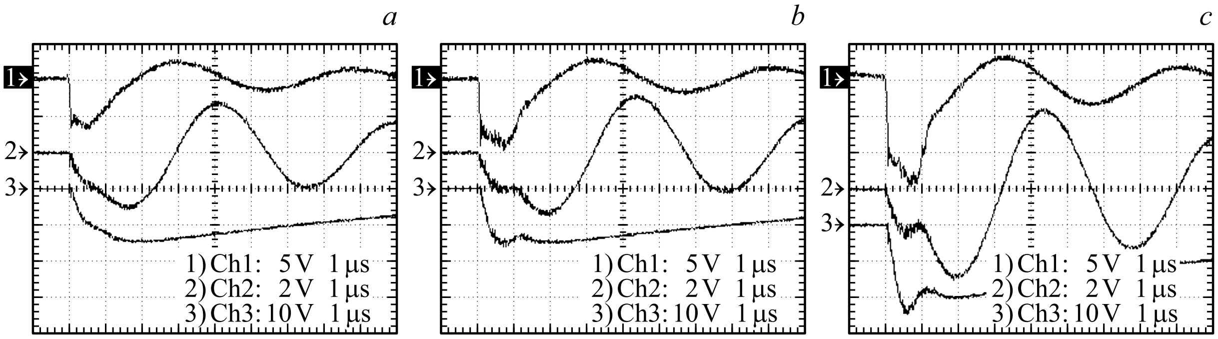

Figure 2. Typical waveforms of accelerating voltage (Ch1, 10 kV/div), total cathode current (Ch2, 24 kA/div) and beam current to collector (Ch3, 10 kA/div); horizontal scale —1 μs/div: $U_{ch} = 15$ kV (*a*), 20 kV (*b*), 30 kV (*c*). Argon pressure — 0.5 mTorr, $\tau_d = 15\,\mu$s, annular anode.

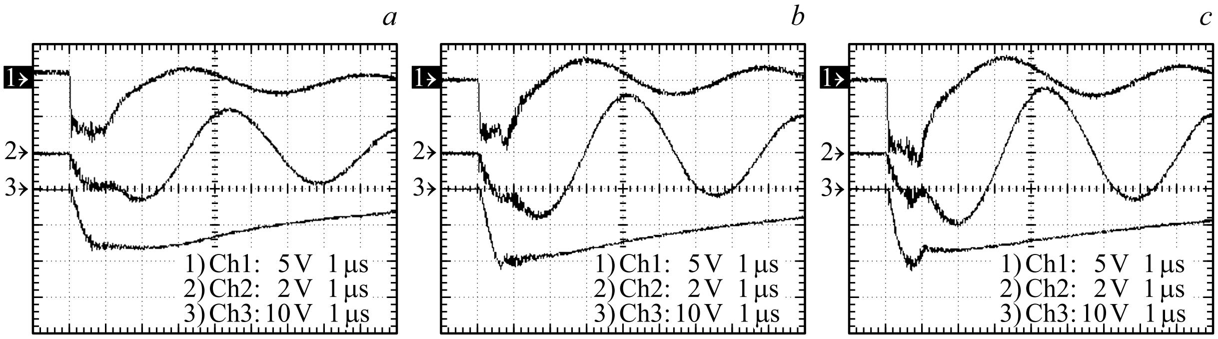

Figure 3. Typical waveforms of accelerating voltage (Ch1, 10 kV/div), total cathode current (Ch2, 24 kA/div) and beam current to collector (Ch3, 10 kA/div); horizontal scale —1 μs/div: $U_{ch} = 15$ kV (*a*), 20 kV (*b*), 25 kV (*c*). Argon pressure — 0.5 mTorr, $\tau_d = 20\,\mu$s, hybrid anode.

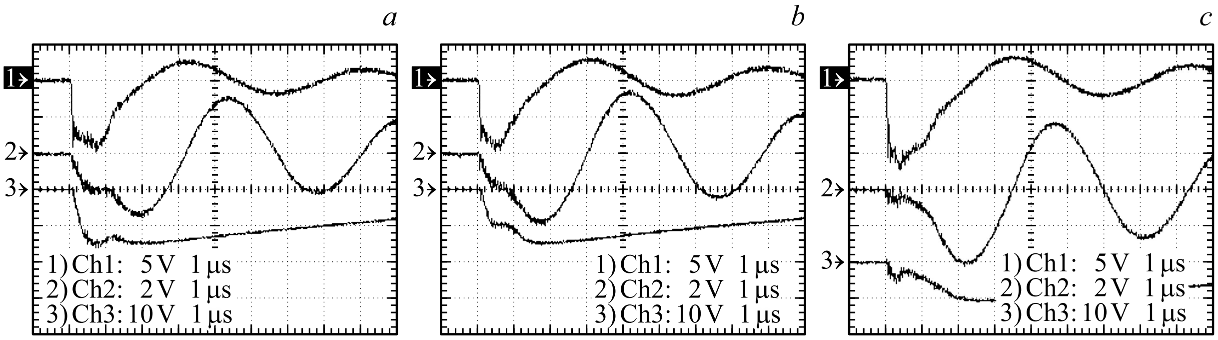

Figure 4. Typical waveforms of accelerating voltage (Ch1, 10 kV/div), total cathode current (Ch2, 24 kA/div) and beam current to collector (Ch3, 10 kA/div); horizontal scale — 1 μs/div: $\tau_d = 15\,\mu$s (*a*); $\tau_d = 25\,\mu$s (*b*); $\tau_d = 35\,\mu$s (*c*). Argon pressure — 0.5 mTorr, $U_{ch} = 20$ kV, annular anode.

plasma across the lines of force of the guide magnetic field [4,17,18]. This behavior of a high-current diode with a plasma anode based on the high-current reflective discharge was repeatedly observed by us earlier [4]. The presence of a screen electrode *13* cannot prevent the breakdown process, since the plasma of the explosive emission centers is quite fast (according to our estimates — for 0.3–0.4 μs at a cathode plasma velocity of about 2 cm/μs [10,11]) will come out on the edge of this electrode, stimulating the appearance of new explosive emission centers on it due to the so-called „pick-up "effect, i.e. the appearance of these centers when charging with ion current from plasma (in this case cathode) non-metallic inclusions and films and their subsequent breakdown [19,20].

A comparison of the current characteristics of a high-current electron gun obtained in this study with similar characteristics obtained earlier for a gun with a traditional multi-wire copper cathode [4] shows an average (by area) cathode current density increased by about 1.4–2.4 times, and the beam current density onto collector — approximately 1.6–2

Comparative characteristics of high-current electron guns with traditional multi-wire copper cathodes and with new cathode assembly

Cathode type	Cathode current, kA	Beam Current on collector, kA	Effective Area emissions, cm^2	Current density cathode/beam, A/cm^2	Source
Multi-wire copper	24	18	28.3	848/636	[4]
Multi-wire copper	30	29	56.7	529/511	[12]
New cathode assembly	25	—	19.6	1276/–	[8]
New Cathode assembly	24	20	19.6	1224/1020	Current work

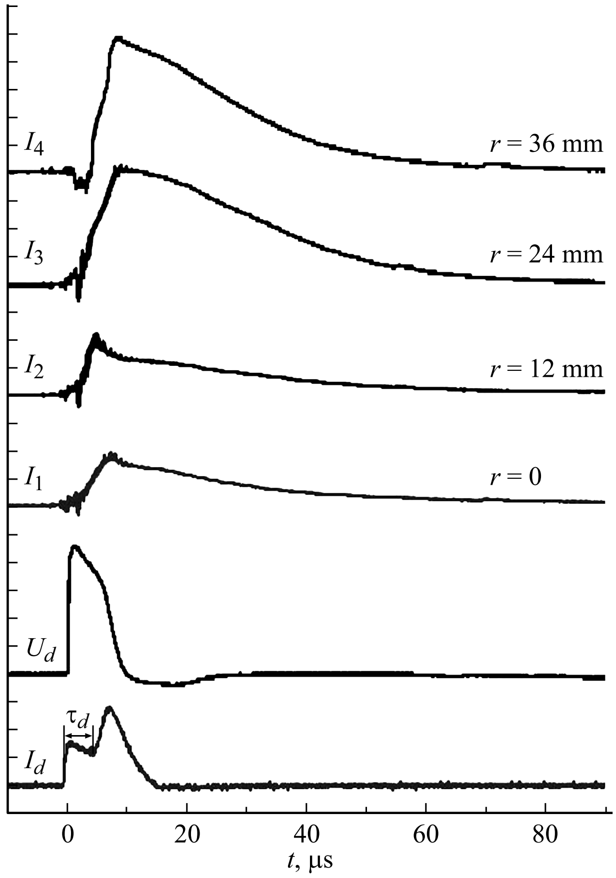

Figure 5. Waveforms of voltage pulses at the discharge anode (U_d , 1 kV/div), discharge current (I_d , 400 A/div) and probe currents (I_1–I_4, 0.025 A/div). Hybrid anode [16].

times (see table). The table shows the values of the cathode current and the beam current to the collector by the time the guide edge of the pulse ends, i.e. $0.3-0.5\,\mu$s after the pulse starts. These values most adequately characterize the emission capacity of the cathode and the flow capacity of the layer. The second maximum on the cathode current waveform is a short-circuit current, i.e. when the accelerated electron beam has actually ceased to exist; this stage is not of interest. The observed increase in the average current density for the case of a cathode assembly with integrated arc plasma sources is due, in our opinion, not only to an increased number of simultaneously functioning explosive emission centers, but also to an increased rate of expansion of the cathode plasma, at least in the first half of the pulse. Since the arc plasma sources embedded in the cathode are both plasma guns, the rate of expansion of this plasma along the magnetic field lines is several times higher than the rate of expansion of the plasma of the explosive emission center [4,21]. An increase in the velocity of the emission boundary of the cathode plasma should lead, according to [4], to increase the flow capacity of the double layer, and hence the beam current to the collector.

Relative spread (standard deviation) both amplitude and pulse average values of the beam current in optimal generation modes (delay times $\tau_d = 15-25\,\mu$s after the start of the discharge current pulse) was $4.3-7.6$%, which is in $2-3$ times less than similar values for the multi-wire copper cathode case.

Conclusion

1. The high emission capacity of the cathode assembly with resistively decoupled arc plasma sources built into it has been confirmed, which is 1.4–2.4 times higher than the corresponding value characteristic of the traditional gun circuit with a plasma anode and a multi-wire copper explosive-emission cathode.

2. In optimal operating modes, this cathode assembly provides a relative spread of the beam current to the collector $2-3$ times less than in the case of the most commonly used multi-wire copper cathode (also in optimal modes).

3. The addition of a third resistor to the circuit of each arc plasma source increased the electrical strength of the cathode assembly, which made it possible to use accelerating voltage pulses with an amplitude of up to 30 kV and thereby proportionally increase the energy density of the beam.

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Conflict of interest

The authors declare that they have no conflict of interest.

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