FREQUENCY MODE OF OPERATION OF THE SOURCE OF LOW-ENERGY HIGH-CURRENT ELECTRON BEAM

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Abstract. The frequency mode of operation (1 pulse/s) of a source of low-energy high-current electron beams based on an explosive emission cathode was investigatedwith built-in plasma arc sources initiated by breakdown on the dielectric surface. It was found that the source stably (without gaps) generates a beam under vacuum and gas-filled diode conditions at a given pulse repetition rate and charging voltages of the generator feeding the electron gun, equal to 5–20 kV.

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1. INTRODUCTION

Sources of low-energy (up to 30 keV) high-current (tens of kA) electron beams (LHEB) of microsecond duration (2–4 μs) are widely used for modification of surface layers of metals and alloys by the method of pulsed melting [1–5]. As a result of such modification, the surface layers acquire improved physicochemical properties, which ultimately affects the quality of the product itself. For example, corrosion resistance, wear resistance, fatigue strength, etc. are increased. Typically, several dozen pulses per sample (product) are required to achieve a positive effect from irradiation. If the system implements the supply of a large number of samples to the beam irradiation site, the number of pulses in one vacuum cycle can reach several thousand. Under such conditions, the productivity of the LHEB source can be significantly increased by raising the pulse repetition rate (f).

Previously, the value of f did not exceed 0.2 pulses/s, as it was limited by the power of the power supply units available to us. This mode of operation of LHEB sources with a plasma anode and multi-wire copper explosive emission cathode [6] was quite stable. When attempting to increase f from 0.2 to 1 pulse/s (when it became technically possible), a large number of beam generation misses was recorded (up to 30%, while the plasma anode formed stably) [7]. In our view, this is due to partial degassing of the cathode surface, which results in instabilities in the excitation of explosive emission.

In 2020, we created a new cathode assembly with arc plasma sources built into the cathode, initiated by surface breakdown of the dielectric [8, 9]. In the single-pulse mode ($f \leq 0.2$ pulses/s), this cathode assembly provides high stability of operation of all arc sources in the cathode, including at reduced voltages (from 5 kV). Additionally, the possibility of operating this assembly in vacuum or gas-filled diode mode, i.e., without preliminary creation of a plasma anode, was demonstrated. This gave us reason to believe that using a cathode with arc plasma sources in frequency (pulse-periodic, burst) mode ($f = 1$ pulse/s) of the LHEB source would solve the problem of beam generation misses. The present work is devoted to the study of the frequency mode of operation of an explosive emission cathode with built-in arc plasma sources.

2. EXPERIMENTAL METHODOLOGY

Figure 1 shows the experimental setup. The cathode assembly of the gun includes an explosive emission cathode *1* in the form of a perforated copper disk with a diameter of 30 mm, with ceramic tubes *2* and copper electrodes *3* inserted flush into the holes, forming arc plasma sources together with the cathode; 10 arc sources are arranged in a circle with a diameter of 15 mm and 15 arc sources - in a circle with a diameter of 24 mm. Each of the 25 electrodes is grounded through resistors *5* (three resistors connected in series, each with a nominal value of 750 Ohm). To increase the number of explosive emission centers in the cathode (across the entire surface), bundles of thin (80 μm) copper wires *4* were also pressed into the cathode, totaling 25 pieces (6 pieces are conditionally shown on the right in Fig. 1). Thus, the emitting part of the cathode is effectively a ring with an external diameter of approximately 24 mm and a width of 4.5 mm. A bowl-shaped metal screen *11* was also located on the cathode. It covered the resistors from the plasma formed during the pulse and thereby reduced the probability of breakdown along their surface.

The amplitude of the accelerating voltage supplied from the high-voltage pulse generator (HPG) *7*, determined by the charging voltage of the HPG (U_{char}), varied in the range of 5-20 kV. The pulse repetition frequency *f* could vary from 0.2 to 1 pulse/s. The number of pulses in a series varied from 10 to 50, followed by a pause of 1 - 2 min. The beam collector was a plate *12* made of stainless steel with a thickness of 1 mm. The pulsed guiding magnetic field, ensuring beam transport, was created by a sectioned solenoid *14*.

The registration of accelerating voltage pulses was carried out using an active divider, the total diode current and the beam current to the collector - by Rogowski coils. Signals from the sensors were fed to the inputs of a 4-channel broadband (200 MHz) digital oscilloscope Tektronix TDS 2024. The oscilloscope operated both in single pulse mode and in accumulation mode (to obtain oscillograms averaged over a series of pulses).

The experiments were conducted both in a vacuum diode environment (residual gas pressure p = 0.01 Pa) and with the injection of working gas (argon) up to a pressure of 0.027–0.054 Pa.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show voltage and current oscillograms averaged over a series of 20 pulses, made in accumulation mode at various values of charging/accelerating voltage and working/residual gas pressure. The pulse repetition rate in all cases was 1 pulse/s.

In general, the obtained oscillograms are similar to those we observed when generating single pulses [9, 10]. With an increase in the charging voltage of the high-voltage pulse generator, the amplitude of the total diode current grows almost proportionally. The growth in the amplitude of the beam current to the collector is observed only at charging voltages up to 10–12 kV, after which it practically does not change and amounts to 16–18 kA. This corresponds to the known concepts of the cathode plasma transition to saturation mode, characteristic for centimeter accelerating gaps [11]. The amplitude of the total current in the diode continues to grow with increasing charging voltage due to the development of breakdown in the cathode assembly, as well as breakdown to the gun housing wall, which has not yet been suppressed.

The cathode showed the most stable operation in a gas-filled diode environment. Figure 4 shows the oscillograms of several pulses from the series. It can be seen that the beam current oscillograms practically repeat each other, the scatter of the beam current amplitude does not exceed ±10%. In the case of a vacuum diode, this scatter could reach ±25%.

4. CONCLUSION

A stable frequency mode of operation (f = 1 pulse/s) has been demonstrated for a source of low-energy high-current electron beams based on an explosive emission cathode with arc plasma sources embedded in it. During the source operation, not a single beam generation miss was recorded across the entire range of accelerating voltage amplitudes (5–20 kV). Estimates of the thermal resistance of resistors in the circuits of arc plasma sources indicate the possibility of further increasing the pulse repetition rate to 2–3 pulses/s, however, the risk of failure of the storage capacitor (IK-50/3) of the high-voltage pulse generator has forced us to refrain from this for now.

The most stable oscillograms from pulse to pulse (beam current amplitude scatter not more than ±10%) were observed in the modes with working gas (argon) injection up to pressures of 0.027–0.054 Pa. In the case of a vacuum diode (residual gas pressure 0.01 Pa), the scatter of the beam current amplitude to the collector could reach up to ±25%. At the same time, the average full current amplitude over a series of pulses in the vacuum diode was approximately equal to the similar value for the case of a gas-filled diode.

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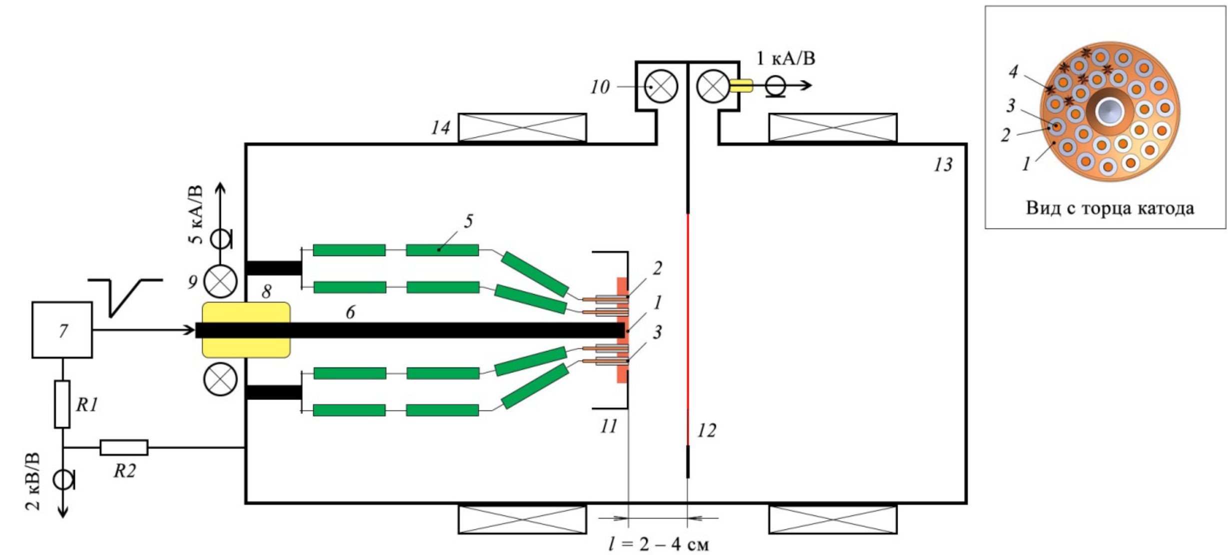
FIGURE CAPTIONS

Рис. 1. Experimental setup: *1* – cathode, *2* – ceramic tubes, *3* – copper electrodes, *4* – bundle of copper wires, *5* – resistor TVO-2 (750 Ohm), *6* – cathode holder, *7* – high-voltage pulse generator, *8* – accelerating voltage input insulator; *9* and *10* – Rogowski coils, *11* – screen, *12* – collector (anode), *13* – vacuum chamber, *14* – solenoid; *R1* , *R2* – active voltage divider.

Рис. 2. Average oscillograms over a series of pulses of accelerating voltage (Ch1), total diode current (Ch2), and beam current to the collector (Ch3): **a** – $U_{charging}$ = 5 kV, **b** – $U_{charging}$ = 10 kV, **c** – $U_{charging}$ = 15 kV, **d** – $U_{charging}$ = 20 kV. Residual gas pressure (air) – 0.01 Pa. Cathode-anode gap width – 3 cm. Guiding magnetic field induction 0.15 T. Vertical scales: **a** – Ch1 – 4 kV/div, Ch2 – 5 kA/div, Ch3 – 5 kA/div; **b** , **c, d** – Ch1 – 10 kV/div, Ch2 – 10 kA/div, Ch3 – 10 kA/div. Horizontal scale 1 μs/div.

Рис. 3. Oscillograms averaged over a series of pulses of the accelerating voltage (Ch1), total diode current (Ch2), and beam current to the collector (Ch3): **a** – U_{charge} = 5 kV, **b** – U_{charge} = 10 kV, **c** – U_{charge} = 15 kV, **d** – U_{charge} = 20 kV. Argon pressure 0.04 Pa. Cathode-anode gap width 3 cm. Guiding magnetic field induction 0.15 T. Vertical scales: **a** – Ch1 – 4 kV/div, Ch2 – 5 kA/div, Ch3 – 5 kA/div; **b, c, d** – Ch1 – 10 kV/div, Ch2 – 10 kA/div, Ch3 – 10 kA/div. Horizontal scale 1 μs/div.

Рис. 4. Oscillograms of accelerating voltage (Ch1, 10 kV/div), total diode current (Ch2, 10 kA/div) and beam current to the collector (Ch3, 10 kA/div): **a** – 1st pulse in the series, **b** – 10th pulse in the series, **c** – 20th pulse in the series, **d** – 30th pulse in the series. Charging voltage 20 kV. Argon pressure 0.04 Pa. Horizontal scale 1 μs/div.



1 кА/В
10
14
13
5 кА/В
5
9
8
6
2
1
3
7
R1
R2
2 кВ/В
11
12
l = 2 – 4 см
4
3
2
1
Вид с торца катода

Fig. 1

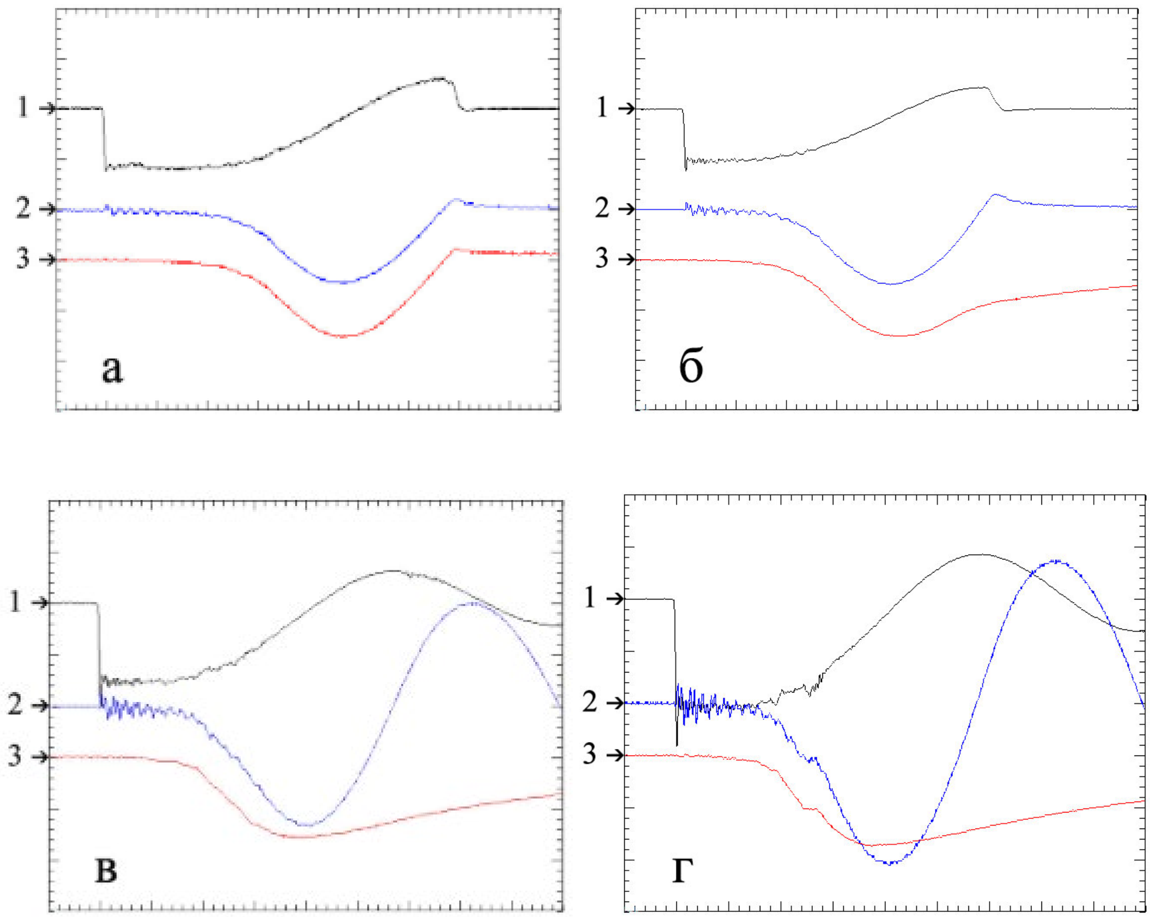


Fig. 2

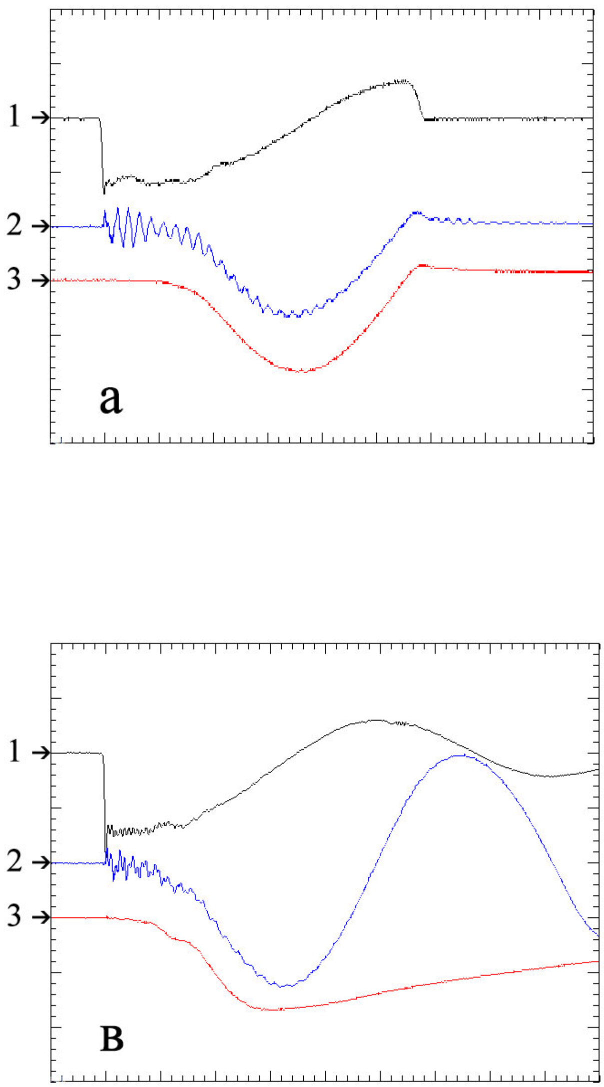


Fig. 3

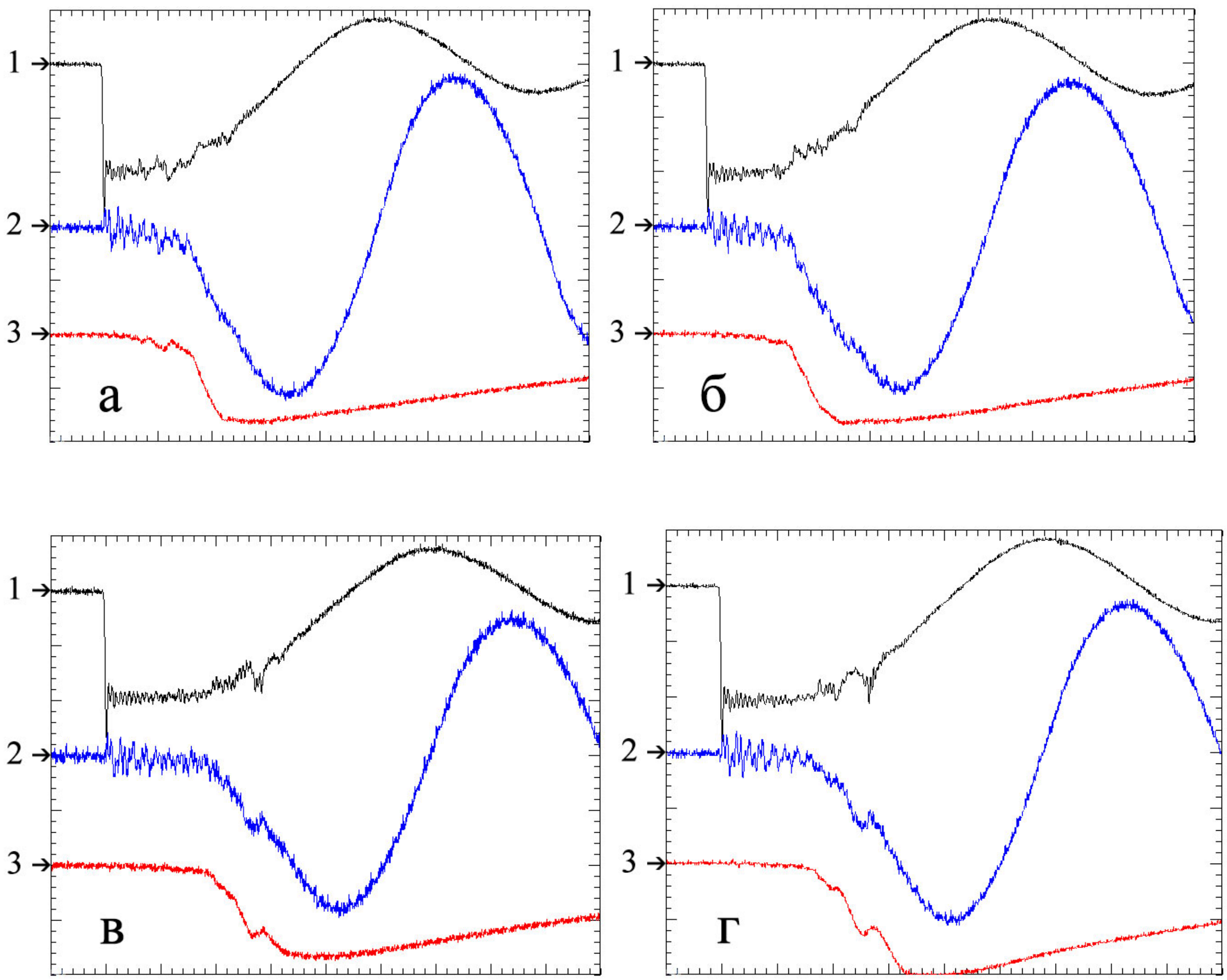


Fig. 4