The deflection of a wide electron beam from the longitudinal axis of the source with a plasma cathode and plasma anode

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Abstract. An electron source with a plasma cathode based on a low-pressure arc discharge having a grid (layer) stabilization of the emission (cathode) plasma boundary and the open edge of the anode plasma has been used to study the deflection of a broad intense submillisecond electron beam from the electron source axis by a leading magnetic field. Measurements of the energy density distribution of the generated electron beam were made both under conditions of its deflection and in the mode of “direct” transport, when the collector target is in direct line of sight from the emission electrode. It was experimentally shown that the stability of the electron source operation with a beam deflection significantly increases. It allows to expand the range of beam parameters, which opens up new possibilities for use the electron source for both scientific and technological purposes.

1. Introduction
Sources of pulsed high-current electron beams are of considerable interest, primarily due to the promise of their use for processing the surface of materials, improving the wear resistance of the cutting tool, increasing the fatigue strength of turbine blades and compressors, increasing the corrosion resistance of metallic materials, increasing the electrical strength of vacuum insulation, etc. [1–3], and need further study and technological improvement. The main advantages of pulsed electron beam irradiation, compared with the traditional form of exposure to a concentrated energy flow to the surface – laser, can be attributed to a higher efficiency (up to 90%) of electron sources, high efficiency of energy input to the surface volume of the material (low electron reflection coefficient), the possibility of complete control and management of all irradiation parameters with a high degree of localization of energy in the surface layer is much greater (up to 10 cm²) surface area treated per pulse [4–6], as well as relatively low (± 10%) inhomogeneity of the current density distribution over the beam cross section. High energy efficiency, higher uniformity of the energy density over the beam cross section, good reproducibility of pulses and high frequency of their following favorably distinguish pulsed electron beams also from pulsed flows of low-temperature plasma with the potential use of both for technological purposes [7].

Thus, at present, it is possible to make an unequivocal conclusion about the prospects for using an electron beam in various technological processes and scientific purposes, allowing to achieve effects on the surface of materials that cannot be implemented using alternative methods. Sources in which the emission of charged particles comes from the plasma of a vacuum or gas discharge have several advantages compared to sources with explosive emission cathodes, and in some cases, for example, for the generation of ions, are the only acceptable ones. In addition, more rational than sources with
explosive cathodes, sources with plasma cathodes solve the problem of obtaining micro- and millisecond electron beams. Since systems of the discharge power supply and electron acceleration in such sources are separated, the beam parameters can be controlled within wide limits [8–14]. The prospects of such sources have been repeatedly demonstrated, for example, for surface modification of various inorganic materials, the functional properties of which in some cases are improved by an order of magnitude and higher [15].

However, regardless of the type of cathode used, the interaction of the beam with the target leads to intense gas desorption, evaporation of various contaminants from the target surface, as well as melting of the target itself. These vapors, expanding at a speed of \( \sim 10^4 \text{ cm}\cdot\text{s}^{-1} \) in the transport channel, can reach the emission electrode, contaminating and poisoning its surface, therefore, reducing the electric strength of the high-voltage accelerating gap. Also, as a result of ionization by the electron beam of pollution vapors, a collector plasma is formed, whose expansion rate is \( \sim 10^6 \text{ cm}\cdot\text{s}^{-1} \). The ions of the collector plasma are not magnetized by the leading magnetic field, and are capable of an expanding flow to reach the surface of all the source electrodes, including the emission electrode. A part of collector plasma ions whose velocity vector is directed towards the plasma cathode, summing up with the flow of anode plasma ions, will inevitably affect the generation and transportation of the electron beam, as well as reduce the electric strength of the high-voltage accelerating gap [8, 9]. That is why this work is devoted to solving the problem of increasing the stability of the electron source with a grid plasma cathode by reducing the reverse gas and ion fluxes in order to further expand the operating parameters of the generated electron beam.

2. Experimental setup

The work was performed with the use of the electron source "SOLO" (included in the list of unique installations of Russia "UNICUUM") with a plasma cathode based on a low-pressure arc discharge with grid stabilization of the emission plasma boundary and a plasma anode, the boundary of which is open and mobile (figure 1), which allows generating a broad (with a diameter of up to 40 mm) intense current (up to 200 A) submillisecond (up to 200 \( \mu \text{s} \)) electron beam [5, 16–18].

![Figure 1. Scheme and appearance of the pulsed-beam installation with a plasma cathode, allowing](image-url)
to deflect the electron beam.

The initiating (igniting) discharge lights up between the hollow electrode 1 placed in the field of permanent magnets and the cathode 2 when a voltage pulse \( U_{\text{trig}} = (12–15) \text{ kV} \) is applied. The main arc discharge burns between the cathode 2 and the hollow anode 3. A constant accelerating voltage (up to 25 kV) is applied between the flat emission electrode 5 and the extracting electrode 6, made in the form of a diaphragm with a diameter of 82 mm. The emission electrode is a flat plate of stainless steel, in the center of which there is an emission hole 40 mm in diameter, covered with a fine-meshed stainless steel grid 4. The extracting electrode 6, the drift tube 7, and the collector 8 are under the potential of the "earth". Initially, electrons are taken from the emission plasma through the cells of the emission grid under the action of the electric field created by electrodes 6 and 7. After the formation of the anode plasma, the electrons are accelerated in a double layer between the cathode and anode plasma boundaries. The influence of the reverse gas and ion flux on the electron beam generation was reduced by introducing a magnetic system of electron beam deflection (circled by a dotted line) consisting of solenoids 11–15 and a sector tap 16 of length \( \approx 630 \text{ mm} \) and radius of curvature \( \approx 400 \text{ mm} \). There are solenoids 9, 10 used both with and without deflection system.

The distribution of the beam energy density was recorded by a calorimeter with 9 sensors, the distance between the axes of the neighboring 7 mm located on the diameter line of the autograph of the electron beam. The parameters at which the distribution of energy density and beam profile were recorded: accelerating voltage \( U = 14 \text{ kV} \), chamber pressure \( p = 45 \text{ mPa} \), pulse duration \( t = 50 \mu\text{s} \), beam current \( I = 170 \text{ A} \), magnetic field in solenoids 11–15 is equal to \( B_1 \approx 30 \text{ mT} \), in solenoids 9, 10 the magnetic field is \( B_2 \approx 50 \text{ mT} \).

3. Results

As can be seen from figures 2 and 3, the radial distribution of the beam energy density during its transportation in the deflecting system does not noticeably change, the beam autograph after deflection has a round shape. The beam diameter is \( \approx 23 \text{ mm} \).

![Figure 2. The distribution of the beam energy density over its cross section.](image)

For a conditioned (trained) high-voltage accelerating gap of the electron source, an experimental comparison of the stability of the source operation with and without a deflection system was made. Stability \( S \) was determined as the percentage of pulses that passed without initiating electrical breakdown of the high-voltage accelerating gap (out of 20 beam current pulses) that could occur both during the beam current pulse and after its passage. The current magnitude in the experiments is the limit for modes without deflection. A sample of aluminum was chosen as a collector target, differing
as a material with a low melting point and intense gas evolution when it is heated. The target was made in the form of a disk with a diameter of 120 mm, a thickness of 7 mm. First experiments were carried out without using the electron beam deflecting system, when limiting modes of its generation were obtained. Limit regimes of beam generation are called, the source's stability $S$ at which it is below 80%, which prevents their use in any technological processes. The results of the experiments are shown in table 1. It is seen that when the electron beam deflects from the axis of the electron source, its stability $S$ of operation increases. As a result, the use of the electron beam-deflection system made it possible to increase the limiting modes of its generation, which are summarized in table 2.

![Beam autograph on titanium plate.](image)

**Table 1.** Stability $S$ of the electron source operation in the regimes limiting for a configuration without a beam deflection system.

| $p$ (mPa) | $U_{ac}$ (kV) | $t$ (µ) | $I$ (A) | $S$ (without beam deflection system) (%) | $S$ (with a beam deflection system) (%) |
|----------|---------------|--------|--------|----------------------------------------|----------------------------------------|
| 25       | 14            | 50     | 230    | 54                                     | 90                                     |
| 25       | 14            | 150    | 110    | 26                                     | 100                                    |
| 25       | 20            | 50     | 160    | 42                                     | 100                                    |
| 25       | 20            | 150    | 55     | 80                                     | 100                                    |
| 45       | 14            | 50     | 170    | 44                                     | 90                                     |
| 45       | 14            | 150    | 85     | 52                                     | 100                                    |
| 45       | 20            | 50     | 105    | 66                                     | 80                                     |
| 45       | 20            | 150    | 35     | 80                                     | 100                                    |

**Table 2.** Limiting modes for source with beam deflection system.

| $p$ (mPa) | $U_{ac}$ (kV) | $t$ (µ) | $I$ (A) | $S$ (in %) |
|----------|---------------|--------|--------|------------|
| 25       | 14            | 50     | 380    | 48         |
| 25       | 14            | 150    | 330    | 20         |
| 25       | 20            | 50     | 370    | 74         |
| 25       | 20            | 150    | 330    | 80         |
| 45       | 14            | 50     | 200    | 28         |
| 45       | 14            | 150    | 190    | 68         |
| 45       | 20            | 50     | 190    | 48         |
| 45       | 20            | 150    | 180    | 80         |
4. Conclusion
It has been shown experimentally that the use of a magnetic system to deviate an electron beam from the longitudinal axis in the electron source with a grid plasma cathode allows increase many times the stability of the source operation, which consists in reducing the number of electrical breakdowns of the accelerating gap, and thereby expanding the limiting parameters of the electron beam. It is necessary to separately note the high content of the sputtered target material at the sector outlet in the region of the interaction of the beam with the target, which is observed visually. At the same time, the opposite side of the outlet remained clean, which also confirms the authors' assumption about an increase in the electric strength as a result of achieving a higher purity of the emission electrode surface.

Also from tables 1 and 2 it can be seen that there are different mechanisms of electrical breakdown of the accelerating gap: the first is associated with the total energy content of the beam, which is gained by increasing the pulse duration of the beam, and the other with impaired stabilization of the emission plasma boundary, which is most clearly observed with increasing current amplitude of the electron beam.

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References
[1] Proskurovsky D I, Rotstein V P and Ozur G E 1996 Proc. of 11th Int. Conf. on High Power Particle Beams (BEAMS-96) 259
[2] Proskurovsky D I, Ivanov Yu F, Rotstein V P et al 1998 Journal of Vac. Sci. & Tech. A16 2480
[3] Engelko V, Mueller G and Bluhm H 2001 Vacuum 62 97
[4] Rotstein V, Ivanov Yu and Markov A 2006 “Materials surface processing by directed energy techniques” ed. Y Pauleau (Oxford: Elsevier) chapter 6 205
[5] Devyatkov V N, Koval N N, Schanin P M, Grigoryev V P and Koval T V 2003 Laser and Particle Beams 21 243
[6] Ozur G E, Proskurovsky D I and Karlik K V 2004 Proc. 7th Intern. Conf. on Modification of Materials with Particle Beams and Plasma Flows (Tomsk, Russia) 20
[7] Uglov V V, Cherenda N N, Anishchik V M et al 2007 J. High Temp. Mater. Proces 11 383
[8] Schanin P M, Koval N N, Tolkachev V S and Gushenets V I 2000 Russian Physics Journal 43 427
[9] Oks E M 2006 Plasma Cathode Electron Sources: Physics, Technology, Applications (Weinheim: WILEY-VCH)
[10] Belyuk S I, Gruzdev V A and Zherdev Yu I 1975 PTE 3 30 [in Russian]
[11] Gavrilov N V, Kovalchuk B M, Kreindel Yu E, Tolkachev V S and Shchanin P M 1981 PTE 3 152 [in Russian]
[12] Gushenets V I, Koval N N, Kuznetsov D L, Mesyats G A, Novoselov Yu N, Uvarin V V and Shchanin P M 1991 PZhTF 17 26 [in Russian]
[13] Burdovitsin V A, Kuzemchenko M N and Oks E M 2002 Tech. Phys. 47 926
[14] Vorobyov M S, Koval N N and Sulakshin S A 2015 Instrum. Exp. Tech. 58 687
[15] Gromov V E, Yurev A B, Morozov K V and Ivanov Yu F 2016 The microstructure of quenched rails (Cambridge: Cambridge Int. Sci.)
[16] Grigoriev S V, Koval N N, Devyatkov V N and Teresov A D 2008 Proc. 9th Intern. Conf. on Modification of Materials with Particle Beams and Plasma Flows (Tomsk, Russia) 19
[17] Devyatkov V N and Koval N N 2014 Journal of Physics: Conference Series 552 012014
[18] Koval T V, Devyatkov V N, Nguyen B H and Uglov V V 2015 High Temperature Material Processes 19 19