Methods of increasing the dielectric strength of the accelerating gap in an electron source with a plasma cathode

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Abstract. This work represents the investigations for decreasing acceleration gap breakdown probability of plasma source of electrons SOLO, with grid stabilization of the boundaries of the arc cathode plasma. We increased the distance to the treated target, bent the transportation channel of the electron beam, created additional plasma in the anode space, and increased the beam front. The effect of the above measures on the breakdown probability when the target is exposed of a low-energy electron beam with a power density of up to 0.5 MW/cm² with a diameter of 2.5 cm was investigated separately. Beam deflection is most effective at relatively long pulse durations of 150 μs and accelerating voltage of 20 kV, rather than a lower one. It was possible to double the maximum power for the same beam transport length applied to a low-melting target. Preionization in the anode proved to be effective for relatively short beams of 15 μs duration.

1. Introduction
Plasma electron sources are used in small-scale production equipment for surface modification of metallic materials [1], but they are more often found in electrophysical research facilities. Sources are used as a tool for studying the effect of energy flows on materials, for ionizing a working medium or heating a plasma [2]. To expand the applicability of electron-beam equipment, a minimum probability of breakdown of the high-voltage accelerating gap is required. For example, it is noted in [3] that the creation of an anode plasma before the generation of an electron beam makes possible to reduce the number of breakdowns. This paper also presents methods for increasing the dielectric strength in an electron source with a grid plasma cathode based on a low pressure arc discharge.

2. The experimental technique
The studies were carried out using a pulsed plasma electron source SOLO [4]. A low-pressure arc discharge creates an emission cathode plasma. Plasma also serves as an anode, it is created by the beam itself. And in this work, an additional anode plasma was also created with a special device. The border of the cathode plasma is stabilized by a grid, and the border of the anode plasma is open. The pulse duration and beam current are controlled independently by the cathode discharge current. The electron energy is independently controlled by the accelerating voltage. Electrons are extracted through the cells of the emission grid 4 (figure 1) with a diameter of 40 mm. The electron beam is transported to the target in a longitudinal magnetic field.
2.1. Increasing the length of the transport channel

The length of the transportation path was previously determined by the design features of the electron source and the vacuum chamber. In the electron source, it was the height of the high-voltage insulator and the path through the magnetic field coil, that is conveniently located near the grounded electrodes. The minimum applied distance from the emission grid to the target was 30 cm. In this work we increased the transport channel to 80 cm. To do this, instead of a drift tube with a diameter of 80 mm, a tube with an inner diameter of 125 mm was installed, on which additional magnetic field coils were installed. At the next stage, the elongated transport channel was bent at an angle of 90 degrees (figure 1) to exclude the direct visibility of the emission grid from the collector [5].

Figure 1. Scheme of the electron source with a bent transport system [5]. 1 – ignition cell anode, 2 – cathode, 3 – main discharge anode, 4 – emission grid, 5 – emission high-voltage electrode, 6 – extracting electrode, 7 – vacuum chamber, 8 – collector, 9-15 – magnetic field coils, 16 – drift tube.

In this case, aluminum was chosen as the collector material due to increased interest in the modification of aluminum and silicon alloys, therefore, these data will be especially useful. The effect of using different transportation systems was characterized by the limiting regime. The limiting regime here is a regime in which the probability of breakdown of the high-voltage accelerating gap is about 50%. In the studies, we set the working gas pressure, the duration of the current pulse, the accelerating voltage, and the discharge current was a variable parameter. Of course, we tried to achieve that the width of the profile of the beam energy density distribution on the target was similar in experiments.

2.2. Creation of additional anode plasma

To find out how the preionization of the gas affects the probability of electric breakdown, a auxiliary plasma generator was placed in the region of electron beam transport after the emission electrode. It is based on a closed electron drift discharge. The field of magnets 7 is concentrated in the annular gap of cathodes 6 (figure 2). Initially, the discharge is concentrated in this area, then an external magnetic field is turned on, that is opposite to the field in the gap, and most of the current is closed through collector 4, which is also an anode, like the annular electrode 8. Additional cathodes 9 and 10 serve to facilitate the transition of the discharge from the localized to the volumetric stage and to match the range of operation in the magnetic field with the electron source [6]. The plasma source was worked in the pulse-periodic mode. It was turned on 1 ms before the electron beam current and turned off after the beam passage. If the plasma source was not used, all of its electrodes were connected to ground. A massive niobium target was used in these experiments. During our studies, we registered the probability of breakdown of the accelerating gap in several modes with and without additional plasma.
2.3. Changing of current increase rate in the accelerating gap

The last experiment dealt with the source of electrons without any changes. We have added a region of slow (9 A/μs) discharge current increase before the usual square wave. The target in this case was made of stainless steel, the area of influence was moved after a series of impulses. The modes of exposure were alternated.

3. Results and discussion

One of the reasons for the breakdown of the accelerating gap of the electron source is the evaporation of the target material, its ionization, and contamination by vapors of high-voltage electrodes. This is especially true for low-melting materials. In this case, a logical way out would be to increase the distance from the target to the accelerating gap, as is done in ion implanters, or even to exclude the line of sight of the cathode and the target. This has been accomplished.

We investigated the behavior of the main currents of the electron source for different modes when exposed to an aluminum target in the limiting modes with a beam width of 2.5 cm. With a pulse duration of 150 μs under the indicated conditions, a gradual increase in the current in the accelerating gap $I_g$ can be observed at constant discharge current $I_d$ (figure 3a). It is associated with an increase in the part of the ionic component due to an increase in the concentration of the anode plasma. An increase in the transport channel from 30 to 80 centimeters allows not only to increase the current, but also to reduce its change per pulse (figure 3b). If the elongated channel is bent, the excess of the current $I_g$ over the current $I_d$ will be observed only for the first 100 μs and at the maximum will be no more than 30% (figure 3c). More details about the excess mechanism can be found in [7, 8].

Due to the fact that after the end of the current pulse $I_d$, the accelerating voltage $U_g$ is still supplied, in the limit mode, a side current pulse may develop in the accelerating gap $I_g$ after the end of the discharge current $I_d$. This is due to residual ionization, increased pressure and particle flow from the collector. With a decrease in the working pressure or with a decrease in the pulse duration, it is possible to achieve a certain reduction in the side impulse or its elimination with an elongated
transportation system. But most importantly, even in these difficult conditions in the limiting mode for an aluminum target with a bent transport system, this negative effect is almost absent (figure 3c).

![Typical oscillograms of the main circuits of an electron source in the limiting mode for the initial geometry (a), for an elongated transport channel (b) and for a bent system (c). τ = 150 μs, Ug = 20 kV, p = 45 mPa.]

The dependence of the maximum current in the accelerating gap for the limiting modes is shown in table 1 and table 2 below. For the 45 mPa, 14 kV, 50 μs mode with a transport channel length of 30 cm, the integral energy in the accelerating gap was 220 J, and the energy density at the target was at a maximum of about 15 J/cm². With a duration of 150 μs, it was possible to reach 300 J of the integral energy and about 20 J/cm², respectively. It is shown that by increasing the transportation distance from 30 to 80 cm, it is possible to increase the maximum current in the accelerating gap by 1.5 – 2.7 times. The integral energy in the accelerating gap can be increased by a factor of 1.1 – 2. Bend of the elongated transport channel additionally allows to increase the maximum current 1.4 and 2.3 times in the modes 45 and 25 mPa, respectively, at 150 μs and 20 kV. The integral energy in the accelerating gap circuit in the 45 mPa mode remained the same, and in the 25 mPa mode it increased 1.2 times according to the measurement results. The data in favor of reducing the maximum current and integral energy may be associated with an insufficient degree of reproduction of the experimental conditions, namely, the state of the target, the degree of training of the emission electrode, and insufficient statistics.

### Table 1. Maximum current \( I_{gm} \) in the accelerating gap for limiting modes.

| \( p \) (mPa) | \( U_g \) (kV) | \( \tau \) (μs) | Orig. \( I_{gm} \) (A) | Elong. \( I_{gm} \) (A) | Curved \( I_{gm} \) (A) | Elong./Orig. | Curved/elong. | Curved/Orig. |
|---|---|---|---|---|---|---|---|---|
| 25 | 14 | 50 | 195 | 360 | 365 | 1.8 | 1.0 | 1.9 |
| 25 | 14 | 150 | 130 | 330 | 290 | 2.5 | 0.9 | 2.2 |
| 25 | 20 | 50 | 150 | 400 | 340 | 2.7 | 0.9 | 2.3 |
| 25 | 20 | 150 | 90 | 140 | 315 | 1.6 | 2.3 | 3.5 |
| 45 | 14 | 50 | 210 | 320 | 315 | 1.5 | 1.0 | 1.5 |
| 45 | 14 | 150 | 130 | 255 | 230 | 2.0 | 0.9 | 1.8 |
| 45 | 20 | 50 | 170 | 290 | 240 | 1.7 | 0.8 | 1.4 |
| 45 | 20 | 150 | 105 | 155 | 220 | 1.5 | 1.4 | 2.1 |

The best result was obtained in the 25 mPa, 20 kV, 150 μs mode, when the maximum current was increased first from 90 to 140 A with increasing distance, and then up to 315 A when the beam was rotated. The integral energy was increased from 300 to 600 J and from 600 to 740 J, respectively.
A significant effect of the use of a bent transport system is a controlled repeated current pulse in the acceleration gap even in the limiting mode when aluminum is irradiated.

Contamination of the accelerating electrode in the form of adsorbed gas and oxide films also causes breakdowns. We applied additional anode plasma to clean the emission electrode. A discharge with a current of 12.5 A created a plasma with a concentration of $10^{11}$ cm$^{-3}$ and acted on the high-voltage electrode for 1 ms before the beam. We used a preliminary training of a molybdenum target with 5000 beam current pulses at 65 mPa, and less than 1000 pulses at 20 mPa (table 3). The result of use of anode plasma is in a decrease in the probability of accelerating gap breakdown in the first 15 μs from about 20% to 13% and to 3% at a working gas pressure of 20 mPa and 65 mPa, respectively (table 3). The results are valid for a pulse repetition rate of (0.3 – 1) Hz.

### Table 2. Integral energy in the accelerating gap $E_g$ for limiting modes.

| $p$ (mPa) | $U_p$ (kV) | $\tau$ (μs) | Orig. $E_g$ (J) | Elong. $E_g$ (J) | Curved $E_g$ (J) | Elong./Elong. | Curved/Elong. | Curved/Orig. |
|-----------|------------|-------------|----------------|-----------------|-----------------|--------------|--------------|--------------|
| 25        | 14         | 50          | 170            | 235             | 245             | 1.4          | 1.0          | 1.4          |
| 25        | 14         | 150         | 280            | 490             | 420             | 1.8          | 0.9          | 1.5          |
| 25        | 20         | 50          | 215            | 400             | 350             | 1.9          | 0.9          | 1.6          |
| 25        | 20         | 150         | 300            | 605             | 740             | 2.0          | 1.2          | 2.5          |
| 45        | 14         | 50          | 220            | 250             | 230             | 1.1          | 0.9          | 1.0          |
| 45        | 14         | 150         | 300            | 440             | 365             | 1.5          | 0.8          | 1.2          |
| 45        | 20         | 50          | 285            | 380             | 285             | 1.3          | 0.8          | 1.0          |
| 45        | 20         | 150         | 330            | 565             | 565             | 1.7          | 1.0          | 1.7          |

With an increase in the pulse duration to 50 μs, the breakdown probability increases from 34% and 28% to about 40%. It is associated with the fact that a potential is applied to the electrodes of the plasma generator during the beam current pulse. The current that flows in the cathode circuit exceeds the current of the cathode spot formation. The cathode spot near the emission electrode provokes the accelerating gap breakdown. Thus, it is worthwhile to ground the electrode system of the additional anode plasma generator during the passage of the beam current pulse. The system is effective for short pulses with a duration of about 15 μs.

### Table 3. Percentage probability of accelerating gap breakdown.

| Anode discharge current $I_p$ (A) | Working gas pressure and pulse duration under investigation |
|----------------------------------|----------------------------------------------------------|
|                                  | 20 (mPa), 15 (μs) | 20 (mPa), 50 (μs) | 65 (mPa), 15 (μs) | 65 (mPa), 50 (μs) |
| 0                                | 20             | 34             | 19             | 28             |
| 1.25                             | –              | –              | 22             | 43             |
| 12.5                             | 13             | 40             | 3              | 44             |

Intense desorption of gas from the surface of the electron source electrodes and from the target causes a dynamic increase in the working pressure and, as a consequence, causes an increase in the concentration of anode plasma and accelerating gap current. An increase in the current in this case can be observed at the front of the pulse (figure 4a), it provokes a breakdown. For millisecond beam current pulses, it is possible to decrease the desorption intensity by increasing the time of this process, when the gas will have time to be carried away from the region of the emission electrode.

In the present work we added a region of slow growth of the current of 30 μs in front of the discharge current pulse of 100 μs, 250 A, 20 kV. So, the current in the accelerating gap began to
increase by 9 A/μs instead of the usual 65 A/μs at an operating pressure of 37 mPa and with power supply in use [9]. The peak current at the front has disappeared (figure 4b).

![Figure 4](image)

**Figure 4.** Typical oscillograms of the main circuits of an electron source in the usual case (a) and with a section of slow current rise (b). \( \tau = 100 \mu \text{s}, U_g = 20 \text{kV}, p = 37 \text{ mPa}. \)

We treat the SUS316 steel target in packs of 100 pulses at a frequency of 0.3 Hz, alternating a train with a slow and fast current rise. After each pack, we moved the beam to another place. A total of 1200 impulses were performed, after 600 impulses we open the vacuum chamber. In total, 147 breakdowns were recorded in 600 pulses with a current growth rate in the accelerating range of 65 A/μs and 50 breakdowns in 600 pulses with an average growth rate of 9 A/μs. Thus, the probability of a breakdown has decreased threefold from 24.5% to 8%.

4. Conclusion

It was found that an increase of the transport channel length from 30 to 80 cm allows to increase the limiting mode for longer beam pulses formed at a higher accelerating voltage. For example, for an aluminum target at an argon pressure of 25 mPa, an accelerating voltage of 20 kV, and a pulse duration of 150 μs, the maximum integral energy in the accelerating gap doubled from 300 to 600 J. Bend of the transport channel with a channel length of 80 cm in the same mode allows to increase the energy by another 20% to 740 J. With increased pressure up to 45 mPa and for shorter durations, the difference between the limiting mode of the deflection and direct transport system may not be in favor of the last one. However, the shape of the current pulse in the limiting mode becomes more controllable and repeatable.

It is shown that a plasma with a concentration of $10^{11}$ cm$^{-3}$ created in the drift space by a special discharge cell 1 ms before the arc pulse reduces the probability of breakdown of the accelerating gap for pulses with a duration of 15 μs. So, at a pressure of 65 mPa for a current of 400 A, when exposed to molybdenum, the probability of breakdown decreases from 19% to about 3%. At a pressure of 20 mPa, the probability of breakdown decreased from 20% to 13%.

It was found that a decreasing the rising-edge of the current in the accelerating gap from 65 to 9 A/μs due to a change in the rising-edge of the discharge current in plasma emitter when exposed to pulses with a current in the accelerating gap of 200 A, duration 100 μs, an initial accelerating voltage of 17 kV and the argon pressure 37 mPa on the surface of steel SUS316, leads to a decrease in the breakdown probability from 25 to 8%.

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