Plasma source for auxiliary anode plasma generation in the electron source with grid plasma cathode

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Abstract. This paper presents an auxiliary source of anode plasma developed for the electron source with a plasma cathode based on a low-pressure arc discharge. The plasma source consists of three cells: the main ion-plasma system with closed electron drift and two auxiliary ones. The latter include a hollow cathode and a reflective discharge cell. The construction allows to generate and transport a submillisecond low-energy beam up to 25 keV with a diameter of 40 mm in axial magnetic field up to 80 mT. In the main mode of the auxiliary discharge, the anode plasma is created at a current of up to 15 A and with discharge voltage about 300 V. Using the source of auxiliary anode plasma allows you to expand the range of operating pressures of the electron source down to 3.6×10⁻³ Pa of argon and get rid of high-frequency beam current oscillations when operating at low pressure (up to 1.2×10⁻² Pa).

1. Introduction
Sources of intense electron beams are used in technologies for treating the surface of materials, using electron beams to simulate the effects of intense energy flux on heat-resistant materials, the sources of electrons are used as elements of experimental facilities as gas ionizers [1–3].

Among other equipment, it is possible to separately distinguish electron sources with plasma emitters with a grid (layer) stabilization of the plasma emission boundary. Such emitters are able to generate beams with independently and in a wide range of variable basic parameters such as electron energy, duration and beam current, that is especially useful in research work when scientific experiment is carry out. The generated beam is transported to the region of its interaction with the target under conditions of neutralization of the spatial charge of the beam, that makes it possible to avoid current limiting caused by the formation of a virtual cathode. Usually, the plasma in the transport channel is created by the beam itself, which greatly simplifies the construction of the electron source. However, with this approach it is possible that a virtual cathode appears at the initial stage of electron beam formation due to an insufficient charge neutralization. This, in turn, may lead to losses of the beam current to the extraction electrode or the beam drift tube, that may even stimulate an electrical breakdown of the accelerating gap, for example, as a result of intense gas evolution from these electrodes. Thus, [4] shows that the electrical strength of the accelerating gap increases significantly when a preliminary ionization of the working gas in the acceleration and beam transport region creates by auxiliary crossed-field discharge.
This paper presents a multi-stage discharge cell developed by authors to create an auxiliary anode plasma in the emission, acceleration and transport areas of the electron beam, which is necessary to improve the operating of the electron source in low pressure range (up to $1.2 \times 10^{-2}$ Pa).

2. The experimental installation
The work was done by using a modified electron source "SOLO" with a grid plasma cathode [5].

![Figure 1](image1.png)

Figure 1. Electron source circuit with a discharge cell of the auxiliary plasma anode. 1 – cathode of main arc discharge, 2 – main discharge cell anodes, 3 – emission grid, 4 – collector, 5 – magnetic coils, 6 – magnetic conductors, 7 – magnets, 8 – annular anode, 9 – hollow cathode, 10 – reflective cathode.

Electrons are extracted from a low-pressure (~ $10^{-2}$ Pa) arc discharge plasma through an aperture 40 mm in diameter covered by grid 3, and accelerated in the gap between the cathode (arc) plasma and anode plasma. The border of the cathode plasma is stabilized by the grid, the border of the anode plasma is open. If there is no plasma in the drift space at the initial stage of beam formation, then acceleration occurs between electrodes 1 and 2. The current and duration of the arc discharge determine the operating parameters of the electron beam, which varied from 50 to 200 A, 50 to 200 us in the present work. Accelerated electrons are transported to the high-melting collector 4 in the magnetic field of the solenoids 5.

The distinctive feature of the experimental electron source was the possibility to create an auxiliary anode plasma in the drift space before the passage of the electron beam. Created discharge cell, which formed by cathodes 6, 9, 10 and anodes 8, 4, is located behind the emission grid for this. The main element of the anode discharge cell is the ion-plasma system based on a discharge with closed electron drift. It consists of an annular anode 8 and magnetic conductors 6, which concentrate the field of magnets 7 in a gap of 10 mm. The field of permanent magnets 7 is directed oppositely to the field of magnetic coils 5. The hollow cathode 9 with diameter of 64 mm and length of 92 mm is fixed at the magnetic field conductor, which situated far from the emission grid, and a reflective cathode 10 is fixed at the near field conductor.

The equivalent of a plasma anode power supply is a 200 μF capacitor which is charged up to 0.5–6 kV and connected to the discharge gap through a ballast of 150 Ω.

3. Results and discussion

3.1. Low current anode discharge
The regular (standby) mode of operation of the plasma anode and electron source as a whole implies the presence of a high (up to ~ 25 kV) accelerating potential on the emission electrode and grid 3 (figure 1) relative to the collector 4, which is grounded. Then the negative relative to the ground potential is supplied to the electrodes 6, 9 and 10 of the anode cell. And glow anode discharge is ignited with a current of up to 15 mA. Due to the fact that the annular anode 8 and the collector 4 are
grounded, the anode discharge current can be closed through both these electrodes. This separation allows you to reduce the release of anode discharge power on the annular anode. At the same time, the part of current closing through the collector circuit increases with increasing supply voltage. In the range of 2–5 kV the discharge has a linearly growing IV characteristic, which figure 2a shows.

![Figure 2a](image-url)

**Figure 2a.** The IV characteristic of the discharge in the low-current mode at $p = 1.3 \times 10^{-2} \text{ Pa}$ (a) and the transition voltage to the main mode (b).

It is determined that the anode discharge with a current of only 7–8 mA affects the initiation of the main arc discharge of plasma cathode. Thus, in the absence of an anode discharge, the minimum pressure was $4.8 \times 10^{-3} \text{ Pa}$ at which the main discharge of plasma cathode was reliably initiated. The presence of the anode discharge has expanded the working gas pressure to $3.6 \times 10^{-3} \text{ Pa}$.

### 3.2. The main mode of the anode discharge

A further increase in the supply voltage of the anode discharge leads to an intermittent growth in its current. The voltage of the transition depends on working gas pressure; in addition, it is lower in the presence of the magnetic field of solenoids 5 (see figure 2b). Thus, there are operating modes in which the low-current mode of the anode discharge (standby discharge) operates with a current of up to 15 mA, and it switches to the main mode with a current of up to 15 A when the magnetic field is turned on (figure 3a).

Transition of the discharge to the main mode under the action of a magnetic field occurs due to the presence of a hollow cathode 9 (see figure 1) and the opposite direction of the magnetic field in the gap of the ion-plasma system of the auxiliary plasma anode relative to the field of solenoids 5. On increase the field of solenoids weakens the field in the gap, making it difficult for the discharge operation in it; at the same time conditions are made for the discharge with a hollow cathode.

The discharge voltage in the basic mode for the electrode configuration shown in figure 1 weakly depends on the discharge current and in the range of 0.5–15 A at argon pressure of $6.6 \times 10^{-2} \text{ Pa}$ is 300 V. Decreasing pressure to $1.2 \times 10^{-2} \text{ Pa}$ leads to an insignificant increase in voltage to 320 V. The current of the annular anode in this case does not exceed 2.5 % of the whole current of plasma anode discharge. With an auxiliary discharge current of 15 A, a current of about 0.5 A was detected in a high-voltage acceleration electrode circuit at a potential of 10 kV.

The magnetic field up to 80 mT does not substantially change the current-voltage characteristic of this discharge. This result was obtained due to introduction of cathode 10 (see figure 1) into the electrode system of the plasma anode. If the cathode-reflector 10 is replaced by 80 mm diameter drift tube with the same length (figure 4a), the magnetic field will magnetise the electrons and make it difficult to drift to the hollow cathode 9. As a result, at a certain magnetic field, the less the lower the pressure of the working gas, the discharge from the main mode will revert to the duty (figure 3b). As a result, the discharge from the main mode will revert to the standby mode at a certain magnetic field. This threshold magnetic field is smaller the lower gas pressure.
Figure 3. Typical waveforms of main circuits of the auxiliary anode plasma source: (a) in a typical configuration, as in figure 1 at a pressure of $1.1 \times 10^{-3}$ Pa with magnetic field up to 75 mT; (b) with a drift tube with a diameter of 80 mm instead of the reflective electrode (10) with a pressure of $1.6 \times 10^{-3}$ Pa and a magnetic field up to 56 mT. Accelerating voltage is 10 kV. CH1 is the current in two coils near the emitter $I_B$, 0.5 A/div, CH2 is the total current of the plasma anode $I_p$, 2.5 A/div, CH3 is the discharge voltage of the plasma anode $U_p$, 500 V/div, CH4 is the ring anode current $I_a$, 50 mA/div.

Figure 4. Configuration of auxiliary plasma anode cell (a) with a drift tube instead of a reflective cell, (b) without a drift tube and without a reflective cell. 1 – emission grid, 2 – magnetic conductors, 3 – hollow cathode, 4 – annular anode, 5 – magnets, 6 – magnetic coils, 7 – drift tube, 8 – extraction electrode, 9 – insulator between cathode cell and grounded coil flange.

The different geometry of the discharge cell, in which there was no reflective electrode 10 had an ion-plasma system located directly behind the emission electrode (figure 4b). It was found that in this configuration of electrodes at a pressure higher than $1.5 \times 10^{-2}$ Pa the transition of the discharge from low-current mode to main one is observed at a lower voltage than in the configuration with emission electrode remote to about 70 mm. However, at lower pressures the transition to the basic mode stopped even when an external magnetic field was applied and at comparable cathode-anode voltage. Although this mode was operational for the initial configuration of the anode cell. For example, the anode discharge goes into the basic mode later than the moment of electron beam generation at a pressure of $5.6 \times 10^{-3}$ Pa and supply voltage of 3 kV (figure 5). The latter fact also argues in favor of using a reflective cell or drift tube.
Figure 5. Typical waveforms of main circuits of auxiliary anode plasma source as in figure 4b with a pressure of $5.6 \times 10^{-3}$ Pa and magnetic field up to 32 mT. Accelerating voltage is 3 kV. CH1 is the current in two coils near the emitter $I_B$, 0.5 A/div, CH2 is the plasma anode discharge voltage $U_p$, 500 V/div, CH3 is the total current of the plasma anode $I_p$, 2.5 A/div, CH4 is the ring anode current $I_a$, 50 mA/div.

Thus, the developed electrode system of auxiliary plasma anode consists of three cells. The main one is formed by cathodes 6 (figure 1) together with anode 8 and it is the ion-plasma system with closed electron drift. This cell creates a preliminary plasma due to discharge with current up to 15 mA. The hollow cathode 9 and the anode-collector 4 form a discharge cell with a hollow cathode, which contributes to the ignition of main discharge with a current up to 15 A when external magnetic field is applied. In this case, the current mainly closes through the collector 4. The cathode 10 together with the adjacent cathode 6 create a discharge like reflective between these cathodes and anodes 8 and 4, increase the plasma concentration in the area of emission grid 3 and support the discharge of the plasma anode in electron magnetization conditions.

Figure 6. Typical waveforms of the main circuits of the electron source: (a) without auxiliary anode plasma; (b) with auxiliary discharge current of 7 A. Accelerating voltage is 10 kV, pressure $1.2 \times 10^{-3}$ Pa. CH1 is the main arc discharge current of the plasma cathode $I_d$, 20 A/div, CH2 is the current in the accelerating gap $I_g$, 20 A/div, CH3 is the discharge voltage of the plasma cathode $U_d$, 40 V/div.

The SOLO electron source is capable to operate in a wide range of pressure. A decrease in pressure below $4.8 \times 10^{-3}$ Pa led to the fact that the main discharge of the plasma cathode could be initiated with
a delay of microseconds tens, or not initiated at all when the electron source operated at a frequency of one pulse per second or more. However, even with a reliable initiation of discharge, the lower limit of the working pressure can be limited by the occurrence of high-frequency current oscillations in the accelerating gap and the discharge current (see figure 6a). Such oscillations are especially undesirable when using an electron source in studies associated with measurements of electrophysical parameters, for example, the parameters of the generated plasma. The appearing electromagnetic interference can affect not only the precise measuring equipment, but also the elements of the automation system of the electron-beam unit. The using of an auxiliary plasma anode allows to get rid of high-frequency noise (see figure 6b). The mechanism of suppressing high-frequency oscillations on pulse durations of tens microseconds is hardly associated with an increase in the degree of neutralization of space charge of the auxiliary anode plasma, because of the discharge current of plasma anode in the provided research did not exceed 10 % of the electron beam current. It is possible that the operation of the discharge causes a local dynamic increase in pressure in the region of the beam transportation.

Now pay attention to the initial stage of the current of the electron beam. The noise observed at the current front in the accelerating gap, most noticeable when the discharge current of the plasma cathode is less than 20 \( \mu \text{s} \) (figure 7a). Experiments have shown that the use of an auxiliary plasma anode allows to get rid of oscillations at the beam current front and to reduce the training time of the accelerating gap due to ionic cleaning of the emission grid.

It should be noted also that in the absence of an auxiliary discharge, an increase in the pressure of the working gas, at which the current amplitude in the accelerating gap does not noticeably increase, does not lead to the disappearance of high-frequency oscillations at the beam current front.

![Figure 7](image_url)

**Figure 7.** Typical waveforms of the main circuits of the electron source: (a) without auxiliary anode plasma; (b) with auxiliary discharge current of 7 A. Accelerating voltage is 10 kV, pressure is \( 1.2 \times 10^{-3} \) Pa. CH1 is the main arc discharge current of the plasma cathode \( I_d \), 20 A/div, CH2 is the current in the accelerating gap \( I_g \), 20 A/div.

4. Conclusion
It was found that even a small, of the order of ten milliamps, auxiliary discharge current makes it possible to reliably initiate the arc discharge of the plasma cathode of the electron source at a lower working pressure of \( 3.6 \times 10^{-3} \) Pa than in the absence of an auxiliary discharge.

It was also found that the presence of an auxiliary discharge with a current of several amperes makes it possible to improve the conditions for generating an electron beam at a low (less than \( 1.2 \times 10^{-2} \) Pa) pressure in the first 15 \( \mu \text{s} \) of the source operation. High-frequency oscillations of the beam current disappear.

In addition, the use of an auxiliary plasma anode reduces the training time of the accelerating gap, which opens up new technological possibilities for sources of electrons of this type.
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