Investigation of a plasma potential in the plasma emitter of electrons under the influence of an ion flow

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Abstract. The work is devoted to the pulse electron emitter based on an arc discharge of low pressure (about $5 \times 10^{-2}$ Pa) with stabilization of the emission plasma boundary by a metal grid. It is created for the purpose of surface treatment of metal and metal-ceramic materials. It generates an electron beam of a few centimetres diameter with a current up to 500 A, with an energy up to 25 keV and a pulse duration up to 250 $\mu$s. This paper studies the I-V characteristic of the discharge and the plasma potential depending on the parameters of the electron beam. It is established and showed experimentally that the greatest influence on the operation of this electron emitter is exerted by the pressure of the working gas in the discharge cell and accelerating space. When the gas pressure is increased and the electron beam is generated, the discharge cell voltage can change the polarity, an important role in this process is played by the ion flux to the discharge cell, which flows through the stabilizing grid from the boundary of the anode (beam) plasma.

1. Introduction
Intense electron beams are used to solve a wide range of experimental and applied problems. For example, they are used to modify a surface of materials [1], to simulate extreme thermal effects, for plasma heating in magnetic traps, for evaporation of target material in EB-PVD processes, for ionization of gas flows, etc. A distinctive feature of the plasma electron sources is stable operation in a wide range of parameters, functioning in a pulsed mode, significant resource, noncriticality to a residual atmosphere. Sources with grid stabilization of the emission (cathode) plasma boundary also allow to vary the current, the beam duration and the electron energy independently from each other.

But the effective emission of electrons from the plasma leads to change of its parameters [2]. In an electron source with open boundary of the anode plasma [3] a perceptible ion flux from the anode region can influence significantly on the parameters of the emission plasma [4].

The present work is devoted to the study of changes of plasma parameters during the effective electron extraction from emission plasma in the electron source based on low-pressure arc discharge in an axial magnetic field.

2. Technique of the experiment
The investigations were performed in the electron source, the scheme of which is shown in a figure1.
Figure 1. The scheme of the electron source with a plasma emitter. 1 – cathode-reflector of the ignition discharge, 2 – diaphragm, 3 – anode of the ignition discharge, 4 – cathode insert (AlSi), 5 – hollow cathode of the main discharge, 6 – emission electrode with the outlet overlapped by the grid (anode of the main discharge), 7 – drift tube, 8 – collector.

The electrons are extracted from the arc discharge plasma through a 40 mm diameter hole in the emission electrode 6, which is the anode of the arc discharge. The emission electrode with a diameter of 150 mm and a length of 170 mm is covered by a metal grid with a cell of 0.18×0.18 mm$^2$. The cathode 4 of the main discharge is made of an alloy of aluminum and silicon in the form of a ring with a diameter of 76 mm, and width of 10 mm. The cylindrical hollow cathode 5 with a diameter of 60 mm and a length of about 100 mm is installed coaxially with the main cathode at a distance of 80 mm to the emission grid. It is connected to the main cathode through a resistor $R=5 \Omega$. The discharge cell is placed in a converging magnetic field.

To measure the potential of the cathode plasma a floating emission probe [5] was placed in the discharge cell at a distance of (10-15) mm from the end and (5-10) mm from the edge of the emission aperture.

The probe is made in the form of a loop with a diameter of 4 mm made of tungsten wire with a diameter of 100 μm. The ends of the loop were placed inside a two-channel corundum tube, where they were connected with copper current leads. The ceramics were covered with a foil shield. The power supply of the probe is assembled according to the scheme of a forward-path converter. The control of the key element (IGBT module) was carried out by optical PWM signal generated by the controller, which automatically increased the glow current of the probe to a predetermined value and switched off its power for the measurement time.

The discharge of the plasma cathode has a typical of a low-pressure arc discharge I-V characteristic. At a pressure of $9\times10^{-2}$ Pa a change of the discharge current in the range from 100 to 425 A leads to an insignificant increase in the discharge voltage, from 50 to about 60 V. Reducing the operating pressure to $4\times10^{-2}$ Pa does not lead to a significant change in the I-V characteristic. The discharge voltage in this case varies from 55 to 75 volts with the same current change.

It should be noted that due to the specificity of the discharge with a cathode spot and some features of the design of the plasma cathode electrode, the discharge voltage can vary by 5 or even by 10 V from pulse to pulse. Sometimes changes can be observed during the discharge current pulse, but on average the I-V characteristic like above.

In plasma electron sources based on a glow or arc discharge the current of a plasma cathode determines the emission current. In this case the emission current is less than or equal to the discharge current and depends little on the accelerating voltage. In our case, at a pressure of $4\times10^{-2}$ Pa, the behavior of the current in the accelerating gap is similar, but at increased pressure of $8\times10^{-2}$ Pa with increasing acceleration voltage from 4 to 20 kV, the current of the accelerating gap increases from 120
to 150 A at a constant discharge current of 100 A. It is associated with the influence of secondary processes from the emission electrode [3].

A change of the working pressure in the range from $4\times10^{-2}$ to $9\times10^{-2}$ Pa at a discharge current of 100 A does not cause a noticeable change of the voltage $U_d$ of interelectrode discharge gap, if electrons are not extracted from discharge. However, when the accelerating voltage is applied to the emission electrode the voltage between the cathode 4 and the anode 6 of the discharge cell decreases [6], which is especially noticeable at increased pressure. For example, at the accelerating voltage of 14 kV the voltage $U_d$ of interelectrode discharge gap decreases nonmonotonically from 45 to 5 V when pressure is increased, and the potential of the cathode plasma relative to the anode increases from 5 to 45 V respectively (figure 2). Reducing the accelerating voltage to 8 kV did not lead to noticeable changes in the graphs.

![Figure 2](image.png)

**Figure 2.** Dependence of the interelectrode discharge gap voltage $U_d$ and the plasma potential $\phi$ on the argon pressure $p$.

When electrons extract from the discharge the increase of the plasma potential $\phi$ relative to the anode may indicate an increase in $\alpha$ coefficient, equal to the ratio of the current flowing through the gap $I_0$ to the discharge current $I_d$ ($\alpha=I_0/I_d$). The discharge current begins to flow to the collector 8 through the accelerating gap, and to a lesser extent to the anode 6 of the discharge cell.

It is also established that an increase in the discharge current from 100 to 200 A at a pressure of $9\times10^{-2}$ Pa leads to an increase in the plasma potential by 17%, and the voltage of interelectrode discharge gap decreases during the cathode potential drop is almost unchanged.

### 3. Results and discussions

As noted earlier, the feature of the work of the electron source under investigation is the acceleration of electrons occurs in the gap between the cathode (arc) plasma and the anode plasma which is created by the electron beam during its transportation in the working gas. The position of the boundary of the cathode plasma is stabilized by a fine-mesh metal grid, and the boundary of the anode plasma is open. The presence of the anode plasma leads to the fact that the emission electrode is bombarded by an intense ion flow during the beam current pulse. In addition, ions emitted from the anode plasma can penetrate into the discharge gap through grid cells and affect of the plasma cathode operation.

It can be seen that during beam generation the most significant changes in the plasma potential and the voltage $U_d$ of interelectrode discharge gap occur when the working gas pressure changes. The increase in the grid cell size to $0.3\times0.3$ mm$^2$ and the diameter of the emission area to 80 mm leads to greater decrease in the voltage $U_d$, up to a change in its polarity. Figure 3 shows the variation of the ion current from the anode plasma boundary depends on the working gas pressure and the corresponding voltage $U_d$ of interelectrode discharge gap when the large ($0.3\times0.3$ mm$^2$) grid is installed and the discharge current is 100 A and the accelerating voltage is 10 kV.
Figure 3. Dependence of the voltage of interelectrode $U_d$ discharge gap and the ion current $I_i$ from the anode plasma boundary on the argon pressure $p$.

The magnitude of the ion current $I_i$ was calculated by measurements of a beam energy:

$$I_i = \frac{E_g - E_b}{U \tau},$$

where $E_g$ is the integral of the product of current and voltage in the accelerating gap, $E_b$ is the energy measured on the collector, $U$ is the middle voltage in accelerating gap, and $\tau$ is the pulse width.

Under these conditions (figure 3) the voltage $U_d$ without electron emission varies within 54 up to 50 V from the minimum to the maximum of pressure.

In the case of increased pressure, the concentration of the anode plasma increases, which leads to the increase in the ion current density emitted from the anode plasma boundary. This factor plays an important role in the formation of the distribution of electrical potentials on the electrodes of the discharge system, which can be demonstrated also in the following experiment.

We created additional ionization of the working gas in the electron beam transport space by introducing an asymmetric reflective discharge. For this purpose, a 0.2 $\Omega$ wire resistor was placed in the collector circuit. Thus an auto-bias potential on the collector of the electron source occurs during the beam current pulse. The reflected electrons oscillate in the drift space and additionally ionize the working gas if they have sufficient energy. It can occur because the drift of electrons to the walls of the vacuum chamber and the drift tube is hampered by the magnetic field, and the electrons do not reach the emission electrode because it has a high negative potential. Such approach makes it possible to increase the concentration of the anode plasma at a constant gas pressure.

The typical waveforms of the voltage $U_d$ of interelectrode discharge gap and potential of the heated probe $U_{pr}$ are shown in figure 4.

Figure 4. Typical waveforms of emission probe (1) and discharge gap voltage (2) in ordinary condition (left) and with additional ionization (right). The scale is 1:1.
These waveforms were obtained at a discharge current of 100 A, at gas pressure of $6.7 \times 10^{-2}$ Pa, and at accelerating voltage of 6 kV. An increase in concentration of the anode plasma by asymmetric reflective discharge in the electron beam transport space led to an increase in the plasma potential relative to the anode from 30 to 60 V. This fact indicates a significant effect of anode plasma on the plasma electron emitter operation.

4. Conclusion
It is shown that in the plasma emitter based on a low-pressure arc discharge the plasma potential relative to the anode and the decrease in the anode-cathode voltage of the discharge cell significantly depend on a magnitude of the ion current in the emitter region when electrons are extracted.

For a better understanding of the operation conditions of the plasma electron source in the presence of such an ion current to the emitter, further investigations are needed, including measurements of other parameters in plasma cathode.

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