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Competing types of electron emission in a grid plasma emitter based on a low-pressure arc

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In this work, we have studied electron emission in an electron source with a grid plasma emitter and plasma anode with an open plasma boundary over a wide range of parameter variations. The competition between two types of electron emission from the surface of cathode electrodes of grid plasma emitters under the impact of accelerated ions coming from the accelerating gap has been experimentally demonstrated. The paper shows that the increase in the accelerating-gap current leads to current redistribution in the grid plasma emitters and is accompanied by an increase in the ion-electron emission current and proportional decrease in the cathode-spot electron emission current down to zero.

Keywords: plasma electron source, low-pressure arc, ion-electron emission, cathode spot, anode plasma.

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Electron sources with a grid plasma emitter (GPE) are widely used in the fields of science and technology [1,2]. Such sources are capable of generating a broad electron beam of submillisecond duration having at the same time a wide range of energy density (up to 100 J/cm^2). These characteristics make GPEs of great importance and demand in materials science research [3–6].

One of the representatives of this-type electron sources is source „SOLO" with GPE based on a low-pressure arc discharge. The electron beam generated by this source has the following limiting parameters: beam diameter of up to 50 mm, pulse duration of up to 1 ms, current in the accelerating gap of up to 300 A and accelerating voltage of up to 25 kV. The source's operating principle is described in [7–9].

A distinctive feature of the „SOLO" sources with GPE is the presence of anode plasma which emerge while the electron beam is transported to the collector and has a significant impact on the operation of the source as a whole. On the one hand, the anode plasma promotes improvement of the beam transport conditions, that is, increasing the accelerating gap perveance and allowing creation of an electron beam with the current exceeding the Child-Langmuir value due to ionic compensation of the electron-beam space charge. On the other hand, accelerated ions extracted by the accelerating field from the anode plasma boundary and moving towards the electron beam may cause an uncontrolled growth of the accelerating-gap current.

In [10], the effect of emission enhancement under ion bombardment of the emission electrode was investigated. The authors showed that the increase in current in the accelerating gap directly depends on the type of working gas and ion energy, and also is governed by the emission electrode material. Experimental data obtained in [10] demonstrate a significant contribution to the generated electron beam energy from secondary ion-electron processes. Thereat, a portion of accelerated ions penetrates into the plasma emitter region through the emission grid openings [11–14]. However, at present there are no quantitative estimates aimed at studying the mechanism of current redistribution in the plasma emitter concerning emission processes on the discharge-system cathode surface.

Current flowing in the accelerating gap of the electron source with GPE satisfies the following relation [9,11]:

$$I_0 = \alpha I_d + I_i + I_i(1 - \Gamma)\gamma_2 + I_i \Gamma \gamma_p, \tag{1}$$

where I_0 is the accelerating-gap current, α is the coefficient of electron extraction from the plasma emitter, I_d is the current measured in the GPE power-supply circuit, I_i is the current of accelerated ions extracted from the anode plasma, Γ is the effective geometric transparency of the emission electrode, γ_2 is the coefficient of ion-electron emission from the emission electrode surface, γ_p is the coefficient of ion-electron emission from the emission plasma. Current I_d is determined by the power-supply U_d and remains quasi-constant throughout the entire pulse duration. In the absence of the accelerated ion flow (i. e., when accelerating voltage is $U_0 = 0$), current I_d is the cathode-spot current I_{cs} with a fraction of low-energy plasma ions I_{i1e} also closed in the cathode circuit:

$$I_d(U_0 = 0) = I_{cs} + I_{i1e}. \tag{2}$$

When accelerating voltage is applied ($U_0 \neq 0$), the flow of accelerated ions penetrating into the GPE space through the emission grid openings and bombarding the arc-discharge cathode electrodes initiates ion-electron emission, which leads to redistribution of GPE currents and is accompanied by a reduction of the cathode-spot emission current

$$I_d(U_0 \neq 0) = I_{cs} + I_{i1e} + I_{iee}, \quad (3)$$

where I_{iee} is the ion-electron emission current from the arc-discharge cathode surface equal to

$$I_{iee} = I_i \Gamma(1 + \gamma_1), \quad (4)$$

where γ_1 is the ion-electron emission coefficient.

The goal of this study was to conduct experiments on subdividing current I_d into components caused by the cathode spot functioning (I_{cs}) and by bombardment of the arc discharge cathode surface by accelerated ions (I_{iee}).

Schematic diagram of the experimental setup is shown in Fig. 1. To separate the electron emission current from the arc-discharge cathode surface, additional cathode *4* was introduced into the GPE design, which was made from aluminum and served as a collector for accelerated ions. Aluminum possesses a relatively high ion-electron emission coefficient, which allows explicit demonstration of the influence of accelerated ions on the GPE operation. In the center of cathode *4* there is a hole 12 mm in diameter through which the discharge arc exits into the GPE region. To intercept accelerated ions entering the GPE space along the system's symmetry axis, aluminum electrode *5* 26 mm in diameter is installed at the distance of 40 mm from electrode *4* to which it is short-connected. Thus, it is possible to separate from each other the GPE emission regions: the cathode spot acts on the electrode *3* magnesium insert, while ion-electron processes associated with the impact from accelerated ions proceed on electrodes *4* and *5*.

Typical current oscillograms are presented in Fig. 2. At the initial time moment, a high-voltage pulse is applied between ignition electrode *2* and cathode *3*, which initiates the cathode spot formation and excitation of the arc discharge between cathode *3* and emission electrode *10* equipped with emission grid *8*. In the oscillogram, this process manifests itself as a sharp increase in current I_{cs}.

The emitter space is filled with emission plasma *6* from which electrons are extracted under the action of high voltage through the holes of emission grid *8*, accelerated, and transported to the collector in the magnetic field of coils *12* and *17*. While being transported, electrons ionize working gas in the drift space, which leads to the formation of anode plasma *14*. The anode plasma ions are extracted and accelerated towards GPE thus bombarding the emission grid *8* surface or penetrating into the GPE space. The oscillogram exhibits this process as an increase in current I_0; when product αI_d is constant [9], the process stems from enhancement of the role of terms $[I_i + I_i(1-\Gamma)\gamma_2 + I_i\Gamma\gamma_p]$ in (1).

Accelerated ions passing through the emission grid *8* openings bombard the surfaces of cathode electrode *4* and redistribution electrode *5* and knock out secondary

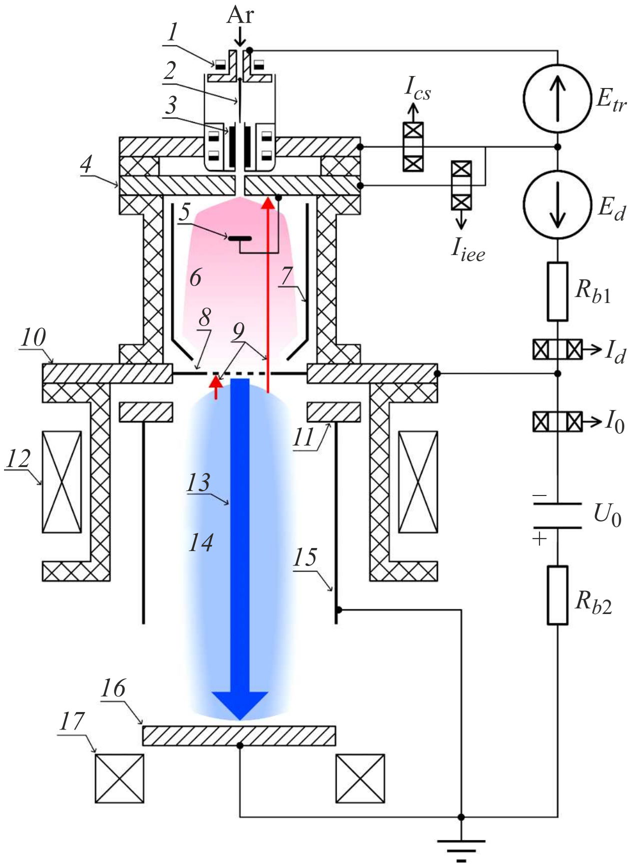

Figure 1. Schematic diagram of modernized electron source „SOLO“. *1* — permanent magnets, *2* — ignition electrode, *3* — magnesium arc-discharge cathode, *4* — electrode for detecting the ion-electron emission current, *5* — redistribution electrode, *6* — cathode/emission plasma, *7* — anode insert, *8* — emission grid, *9* — accelerated ion flow, *10* — emission electrode, *11* — extraction electrode, *12*, *17* — solenoids, *13* — electron beam, *14* — anode/beam plasma, *15* — drift tube, *16* — collector.

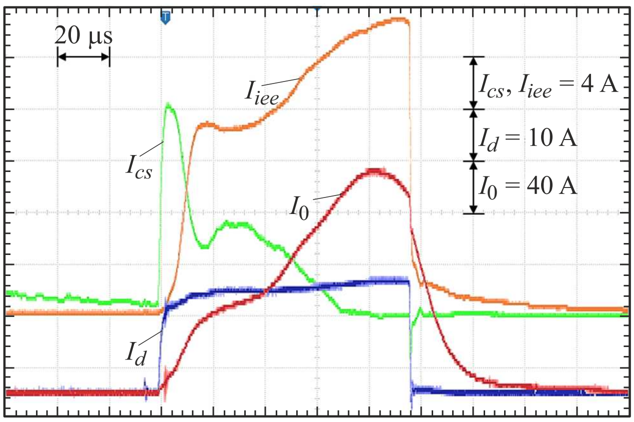

Figure 2. Typical current oscillograms at $p = 60$ mPa, $U_0 = 17$ kV, $I_d = 20$ A.

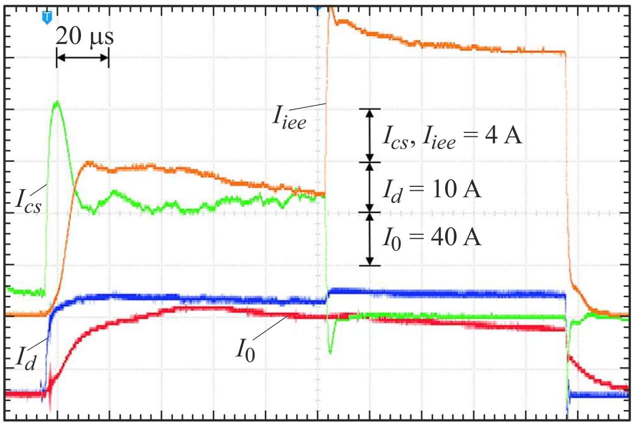

Figure 3. An oscillogram characteristic of the cathode spot initiation on electrode *4* or *5*, $p = 60$ mPa, $U_0 = 12$ kV, $I_d = 20$ A.

γ-electrons which contribute to current I_{iee}. As the accelerating-gap current I_0 increases, a relevant increase in current I_{iee} is observed, while current I_{cs} decreases.

In the main gap, the ion and electron currents are mutually consistent and interrelated. As for the nature of the beam current growth, its primary source at the beginning of the pulse is the electrons extracted from GPE. It is they that generate plasma in the drift space and produce the current of secondary electrons, which in turn makes this process self-sustaining provided the current amplitude reaches a certain value. Electrons extracted from the cathode spot and secondary electrons produced by the secondary ion-electron emission may differ only in the initial energy with which they enter the accelerating gap; however, no appropriate energy measurements were performed in this study. The experiments have shown that, while the processes of the cathode-spot emission dominate (as shown in the current I_{cs} oscillogram), the source of the current I_0 increase may be assumed to be electrons from the cathode spot; however, when the dominating factor is ion-electron emission, the source of the current I_0 increase is the increase in current I_i.

In the process of the beam generation, gas is intensely desorbed from the electrode surfaces, and the collector gets partially molten and evaporated, which results in an increase in gas pressure and variation in its composition. This prevents instantaneous measurement of the pressure in the system; therefore, in analyzing the experimental results, the pressure measured prior to the beginning of the electron beam generation (initial pressure) is used. When the pressure is relatively high (($p \geqslant 60$ mPa), conditions are possible under which the energy and concentration of ions entering the GPE region are sufficient to completely suppress the cathode-spot emission by ion-electron emission from these electrodes (marked in the setup scheme as *4* and *5*). In this case, current I_{cs} terminates, and current transport in the plasma emitter proceeds exclusively due to ion-electron processes.

To prove that in this case no cathode spot initiation took place on the electrodes subjected to ion bombardment, let us consider the cathode spot initiation on electrodes *4* and *5* (Fig. 3). At the discharge pulse length of 100 μs, the process of the cathode spot initiation on electrode *4* or *5* is observed, which is accompanied by a sharp increase in current I_{iee} with simultaneous decrease to zero in current I_{cs}. At the same time, no stepwise changes are observed in the current I_0 oscillogram. This fact evidences that the currents' redistribution on electrodes *3*, *4* and *5* is associated not with variations in the accelerated ion flow but with the cathode spot formation on electrodes *4* and *5*.

Based on experimental data, current ratio I_{iee}/I_d versus working pressure p was plotted (Fig. 4). All the dependences were measured at the moment when the accelerating-gap current was maximal. In the absence of accelerating voltage, low-energy plasma ions I_{i1e} get closed to electrodes *4* and *5*; the fraction of those ions does not exceed 15 % of the total arc discharge current I_d.

When the accelerating voltage is applied, anode plasma begins to form; with an increase in both the ion energy (due to an increase in U_0) and anode plasma concentration (due to an increase in gas pressure), the role of ion-electron processes becomes increasingly significant, which may ultimately lead to complete cessation of current I_{cs}. In this case, it may be assumed that the discharge type changes from the self-sustaining arc discharge to non-self-sustaining glow discharge. This is confirmed by a decrease in the arc-discharge cathode-anode voltage [15–17], since the current as a whole is caused only by the ion-electron emission from cathode electrodes *4* and *5*.

Note that, since the radial distribution of the current density of accelerated ions from the anode plasma is Gaussian, the maximum ion current density corresponds to redistribution electrode *5* [7–11,18]. Thereat, electrode *5* in the standard-configuration source „SOLO" is connected via a resistor to emission electrode *10*. In this configuration, the current of ions arriving at electrode *5* and that of electrons

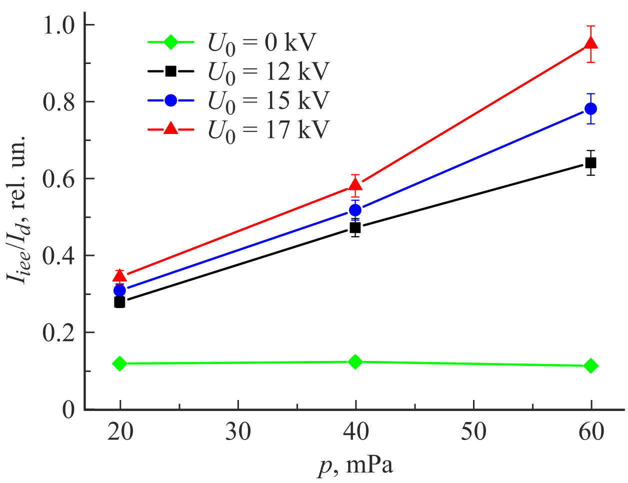

Figure 4. Current ratio I_{iee}/I_d versus gas pressure p at different values of accelerating voltage U_0.

emitted from its surface are compensated by the cathode-spot current. In this case, no decrease in current I_{cs} is observed. Nevertheless, in the standard-configuration GPE a small portion of ions still reaches cathode *3*, which makes the cathode-spot emission current decreasing, though not so significantly.

The obtained results demonstrate a considerable effect of the accelerated ion flow on the GPE operation and promotes advanced understanding of the operating principles of plasma electron sources with GPE. The obtained results may be useful in developing and designing electron sources with GPE in view of expanding the range of its parameters and stabilizing the generated electron beam current, which is extremely important for practical applications of sources of this type.

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Conflict of interests

The authors declare that they have no conflict of interests.

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