12

Method of estimation of electron extraction coefficient and ion-electron emission coefficient from the grid plasma cathode

© R.A. Kartavtsov, M.A. Mokeev, M.S. Vorobyov, P.V. Moskvin, S.Yu. Doroshkevich, N.N. Koval, A.A. Grishkov, V.N. Devyatkov, M.S. Torba

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia
E-mail: maks_mok@mail.ru

Received September 3, 2024
Revised October 14, 2024
Accepted October 16, 2024

The method for estimating the electron extraction coefficient and the ion-electron emission coefficient from the arc discharge plasma in an electron source with a grid plasma cathode is presented. The method is based on the separation of two different scenarios of electron emission development in the case when the arc discharge current generation stops, but under the conditions of continuous flow of ions from the accelerating gap: 1) emission from the plasma cathode is absent; 2) electron emission from the plasma continues when an equipotential space is created in the region of the plasma cathode. This method allows to estimate the contribution of each summand in the total current in the accelerating gap.

Keywords: arc discharge, plasma cathode, electron source, open plasma boundary, electron extraction coefficient, ion-electron emission.

DOI: 10.61011/TPL.2025.02.60636.20104

When it comes to choosing a tool for modifying the surface of metal products, arc discharge-based sources of electrons with a grid plasma emitter (GPE) seem to be the most promising due to their ability to achieve large amplitudes of beam currents at the level of hundreds of amperes at micro- and submillisecond pulse durations, as well as the possibility of mutually independent variation of the electron beam current and the energy of the accelerated electrons, which makes it possible to achieve high (tens to hundreds of J/cm^2) electron beam energy density sufficient to modify the surface of metal products [1–3].

The current in the accelerating gap circuit in such sources is expressed as

$$I_0 = \alpha I_d + I_i + I_i(1-\Gamma)\gamma_c + I_i\Gamma\gamma_{pl}, \tag{1}$$

where I_d — discharge current; α — coefficient of electron extraction from the cathode plasma of arc discharge; I_i — current of accelerated ions from the anode plasma; γ_c — coefficient of ion-electron emission from the emission grid and the emission electrode; γ_{pl} — the ion-electron emission coefficient from the plasma, introduced in [4], equal to the number of electrons appearing in the accelerating gap when one ion enters the GPE from the anode plasma; Γ — the effective geometric transparency of the emission electrode.

Each summand in expression (1) describes a separate group of charged particles born as a result of different processes and passing the accelerating gap: αI_d — the current of electrons born in the cathode spot; I_i — the current of accelerated ions from the anode plasma; $I_i(1-\Gamma)\gamma_c$ — the current of secondary electrons born due to ion-electron emission when accelerated ions bombard the surface of the emission grid and the emission electrode with accelerated ions; $I_i\Gamma\gamma_{pl}$ — the current of electrons from the cathode plasma born as a result of accelerated ions entering the GPE region.

In [5,6], the effective extraction coefficient α_{eff} was used to describe the GPE emissivity

$$\alpha_{eff} = (\alpha I_d + I_i\Gamma\gamma_{pl})/I_d, \tag{2}$$

which combines both the emission of electrons born in the cathode spot of an arc discharge and ion-electron emission from the plasma. The purpose of this paper is to propose a method for separating these two types of emission and its implementation in the experiment.

In the paper, an electron source „SOLO“ with a grid plasma cathode based on a low-pressure arc discharge [5–8], the schematic of which is shown in Fig. 1, was chosen as a research bench. A cathode plasma *5* with controlled concentration, whose emission boundary is stabilized by a fine-structured grid *7*, is created by a two-stage discharge cell. An auxiliary discharge is ignited between the electrodes *1* and 20 μs before the main discharge. The cathode common to the main and auxiliary discharges *3* is in the form of a magnesium tube placed in the field of a permanent magnet *2*. The hollow anode of the main discharge cell *4* contains a redistributing electrode *6*, electrically connected to it short-circuited, and to the grid *7*, to which the positive terminal of the power supply is connected, — through a resistor R_{ha}. An anode plasma with an open and moving boundary is generated by the electron beam as it is transported in a working gas (argon) environment at a pressure of 10−50 mPa. The electrons are extracted through stainless steel grid *7* cells overlapping the 40 mm diameter emission hole in the anode of the discharge cell

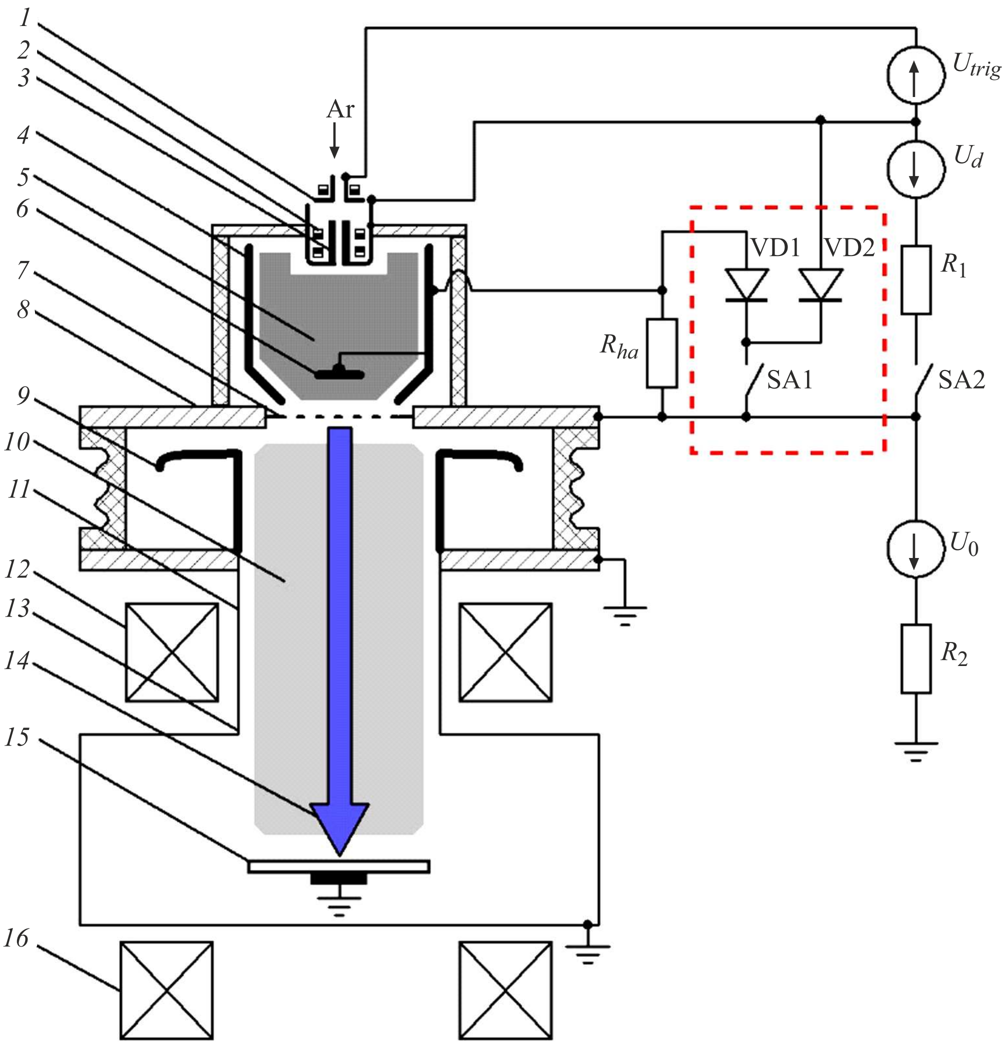

Figure 1. Diagram of the electron source „SOLO". *1* — ignition electrode, *2* — permanent magnets, *3* — plasma cathode arc discharge cathode, *4* — hollow arc discharge anode, *5* — cathode/emission plasma, *6* — redistributing electrode, *7* — plasma cathode emission grid, *8* — emission electrode, *9* — extraction (accelerating) electrode, *10* — anode/beam plasma, *11* — drift tube, *12, 16* — magnetic field coils, *13* — vacuum chamber, *14* — electron beam, *15* — target/collector.

and accelerated in the double layer between the cathode and anode plasma boundaries. The grid *7* is under a constant accelerating potential up to -25 kV, which determines the energy of the beam electrons. The beam current density distribution can be described by a Gaussian function, and its diameter within 10–40 mm can be varied by changing the configuration of the leading magnetic field given by solenoids *12* and *16*. As a result, the electron beam *14* is transported in the leading magnetic field to the collector or sample *15* over a distance of 45 cm without significant losses.

The use of the effective extraction factor α_{eff} is justified by the difficulty of separating the current components in the accelerating gap from each other, which consists in the following: after the discharge current ceases, the electrodes *3* and *6*, still subject to bombardment by accelerated ions from the decaying anode plasma, acquire a positive potential relative to the emission electrode. In this case, the cathode *3* is isolated from the other electrodes of the cell, and the incoming ion current must be compensated by an equally large current of plasma electrons. The electrode *6* is connected to the emission electrode *8* through a resistor R_{ha} where during the discharge current cutoff time the potential autoshift relative to the emission electrode and grid changes from negative to positive, which makes it difficult for secondary electrons to escape from the electrode *6* into the cathode plasma, the potential of which becomes negative relative to the electrode *6* [5]. Thus, the emission of electrons from the plasma emitter, including those generated during γ-processes, is stopped:

$$(\alpha I_d + I_i \Gamma \gamma_{pl}) = 0. \quad (3)$$

A method is proposed as part of this study to evaluate both of these summands. The method is based on a change

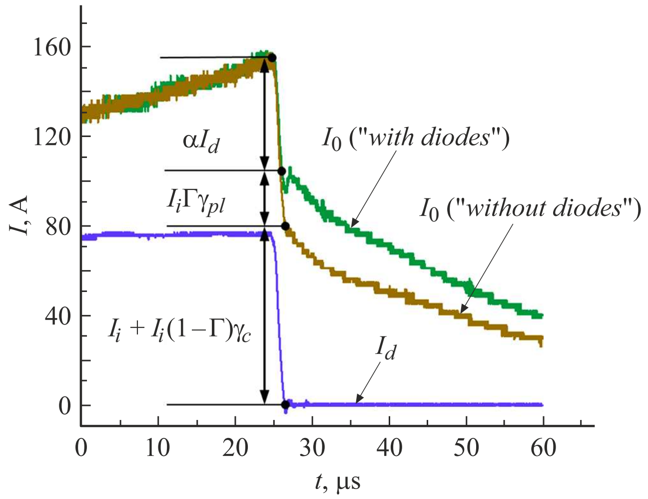

Figure 2. Typical oscillograms obtained during the experiment at $p = 20\,\mathrm{mPa}$, $I_d = 75\,\mathrm{A}$ and $U_0 = 10\,\mathrm{kV}$.

in the arc discharge power supply scheme by including diodes (the section highlighted by a dashed line in Fig. 1), which allow to provide equipotential space in the plasma emitter after the arc discharge current ceases under the conditions of the ion flux coming from the accelerating gap. This ensures that γ-electrons leave the GPE at the moment of discharge current termination I_d. This method allows evaluating the contribution of each component to the current in the accelerating gap, as well as estimating the values of the coefficients α and γ_{pl} depending on the conditions of electron beam generation, which in turn allows describing the operation of the plasma electron source in more detail. The fundamental condition for our experiments was the use of a plasma cathode power supply scheme with a low output inductance, providing a relatively short slice of the arc discharge current pulse ($\Delta t \approx 150\,\mathrm{A}/\mu\mathrm{s}$) [5,6], from which the contribution of each individual current component in the accelerating gap was estimated.

Fig. 2 shows experimentally obtained oscillograms of the arc discharge current I_d, as well as oscillograms of the currents in the accelerating gap I_0superimposed on each other under different beam generation conditions: obtained with the standard discharge power supply and the upgraded one, i.e., in the discharge power supply scheme „without diodes" and „with diodes". The shape of the I_d pulses and currents in the accelerating gap before the discharge current pulse cutoff were identical, which indicates the same energy contribution of the beam to the irradiated collector surface. Providing a steep cutoff of the discharge current pulse and comparing the oscillograms of the currents I_0 with each other allowed fixing three sections characterizing all summands in (1). The magnetic field produced by the upper solenoid, — 50 mT, in the lower solenoid — 60 mT.

Consider the oscillogram of the current in the accelerating gap I_0 „without diodes". It is easy to see that after the arc discharge source ($I_d = 0$) is turned off, the current in the accelerating gap I_0 has decreased its value by a value equal to the sum of the currents due to the coefficients α and γ_{pl}, i.e. $(\alpha I_d + I_i\Gamma\gamma_{pl}) = 0$. According to the formula (1), the current in the accelerating gap in this case will be due to only one component:

$$I_0 = I_i + I_i(1 - \Gamma)\gamma_c. \tag{4}$$

Thus, using the discharge power supply scheme„without diodes" and knowing the ion-electron emission coefficient $\gamma_c$one can estimate the current of accelerated ions from the anode plasma. The values of the coefficient γ_c were obtained from the work [9] for the case of argon ion bombardment of the stainless steel surface with energies in the range of 5−13 keV.

Next, we consider the oscillogram of the current in the accelerating gap I_0 „with diodes". In this case, the current drop in the acceleration gap I_0 at the moment when the discharge current I_d stops is only due to the value of αI_d. Further decline is due to the decay of the anode plasma under the conditions of both ion-electron emission from the surface of the emission grid and electron emission from the GPE due to γ-processes, i.e., in this case we can write down

$$I_0 = I_i + I_i(1 - \Gamma)\gamma_c + I_i\Gamma\gamma_{pl}. \tag{5}$$

Thus, by comparing the oscillograms of the currents in the accelerating gap I_0 of „with diodes" and „without diodes" one can estimate the contribution of each summand from formula (1) to the current in the accelerating gap I_0.

For the estimation, it was assumed that the effective geometric transparency of the emission electrode is about $\Gamma = 0.4$. Thus, under the experimental conditions indicated in Fig. 2, the electron extraction coefficient is $\alpha = 0.63$, and $\gamma_{pl} = 1.25$. Estimates show that the fraction of the current in the accelerating gap due to ion-electron emission from the plasma can be tens of percent of the arc discharge current and make an appreciable contribution to the electron emission from the GPE. The measurement error of ion-electron emission from the plasma is $\pm 10\%$.

As a result, a method for estimating the electron extraction coefficient from the plasma of a low-pressure arc discharge, as well as for estimating the ion-electron emission coefficient from the same plasma due to the accelerated ion flux from the anode plasma entering the GPE space, is proposed and described in this study. The proposed method makes it possible to estimate the contribution of each component to the current in the accelerating gap, as well as to estimate the values of the coefficients α and γ_{pl} depending on different conditions of electron beam generation, which in turn makes it possible to describe in more detail the operation of the plasma electron source.

Funding

The study was supported by a grant from the Russian Science Foundation (project № 23-29-00998).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.E. Gromov, Yu.F. Ivanov, S.V. Vorobiev, S.V. Konovalov, *Fatigue of steels modified by high intensity electron beams* (Cambridge International Science Publ., 2015).

[2] M.S. Vorob'ev, S.A. Gamermaister, V.N. Devyatkov, N.N. Koval', S.A. Sulakshin, P.M. Shchanin, Tech. Phys. Lett., **40** (6), 506 (2014). DOI: 10.1134/S1063785014060261.

[3] *Silnotochnye impulsnye electronnye pychki dlya aviatsionnogo dvigatelestroeniya*, edited by A.S. Novikov, V.A. Shulov, and V.I. Engelko (Dipak, M., 2012). (in Russian)

[4] V.A. Gruzdev, Y.E. Kreindel, and Y.M. Larin, TVT, **11** (3), 482 (1973). (in Russian)

[5] M.S. Vorobyov, P.V. Moskvin, V.I. Shin, T.V. Koval, V.N. Devyatkov, N.N. Koval, K.T. Ashurova, S.Yu. Doroshkevich, M.S. Torba, V.A. Levanisov, High. Temp., **60** (4), 438 (2022). DOI: 10.1134/S0018151X22040162.

[6] P.V. Moskvin, M.S. Vorobyov, A.A. Grishkov, M.S. Torba, V.I. Shin, N.N. Koval, S.Yu. Doroshkevich, R.A. Kartavtsov, Tech. Phys. Lett., **49** (6), 38 (2023). DOI: 10.61011/TPL.2023.06.56376.19557.

[7] V.N. Devyatkov, N.N. Koval, P.M. Schanin, V.P. Grigoryev, T.V. Koval, Laser Particle Beams, **21** (2), 243 (2003). DOI: 10.1017/S026303460321212X

[8] M.S. Vorobyov, P.V. Moskvin, V.I. Shin, N.N. Koval, K.T. Ashurova, S.Yu. Doroshkevich, V.N. Devyatkov, M.S. Torba, V.A. Levanisov, Tech. Phys. Lett., **47**, 528 (2021). DOI: 10.1134/S1063785021050291.

[9] B. Szapiro, J.J. Rocca, J. Appl. Phys., **65** (9), 3713 (1989). DOI: 10.1063/1.342600

Translated by J.Savelyeva