04.1;12.1;15.1

Dynamics of electron extraction from a grid plasma cathode based on a low-pressure arc discharge

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

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

Received March 16, 2023
Revised April 18, 2023
Accepted April 18, 2023

The paper proposes and experimentally demonstrates a method for estimating the coefficient of electron extraction from a plasma emitter based on a low-pressure arc discharge with layered/grid stabilization of the emission plasma boundary. The method is based on the exclusion of the emission current from the total current in the accelerating gap by „sharply" switching off the arc discharge current. The condition for the applicability of the method is an insignificant change in the concentration of the anode plasma during the cutoff of the discharge current pulse. The preliminary obtained data testify in favor of a change in the electron extraction coefficient by up to 20% during a discharge current pulse with duration of $150\,\mu$s.

Keywords: electron source, plasma cathode, arc discharge, layer stabilization of the plasma boundary, plasma anode with an open boundary, electron extraction coefficient.

DOI: 10.61011/TPL.2023.06.56376.19557

Electron sources with plasma cathodes are a promising tool for exposing materials to concentrated energy fluxes.

As a test facility, electron source „SOLO" with a grid plasma cathode based on a low-pressure arc discharge was selected in this work [1,2]. In this source, the arc discharge is created between the cathode *1* (Fig. 1) and anodes *2 3*, *4*, *6*. The boundary of the emission/cathode plasma was stabilized by a stainless-steel grid *4* 40 mm in diameter with the mesh of 0.1×0.1 to 0.3×0.3 mm. The anode plasma *7* is being created in the drift space by the beam itself, has an open boundary, and is confined by collector *10* and grid *4* separated from each other by the distance of 50 cm. The gap between the cathode and anode plasma, where the electron acceleration takes place, is being established self-consistently according to the Child–Langmuir law for a double layer [3]. The beam anode plasma is located inside the drift tube *9* 80 mm in diameter; its radial drift is hindered by the longitudinal magnetic field of 30–100 mT. Thus, during the beam generation, the emission grid and peripheral metallic part of the emission electrode *6* are exposed to a flux of accelerated ions emitted from the anode beam plasma boundary [4]; the ions significantly affect the plasma cathode operation [5] and give rise to secondary electrons whose share in the beam current can even exceed that of primary electrons extracted from the plasma cathode.

To describe the plasma cathode operation, the electron extraction coefficient is typically used, which is defined as a ratio between the emission and discharge currents: $\alpha = I_{em}/I_d$. Earlier, coefficient α was determined in the „SOLO" source for the lower limit of its operating pressure based on the reading of a calorimeter that averages the electron beam spatial and temporal dynamics; in the case of the emission grid mesh of 0.3×0.3 mm and argon pressure below 10 mPa, the coefficient was $\alpha \approx 0.55$. Assuming that the extraction coefficient is constant, the effective coefficient of secondary ion-electron emission from the surface of the stainless-steel emission electrode was determined and appeared to be $\gamma_{eff} \approx 1.6$ for 25–keV argon ions; this agrees well with the results published by other researchers [6]. The beam energy values calculated based on the coefficients obtained in a wide range of operating parameters at several experimental facilities correlate well with the calorimetric measurements.

Nevertheless, the secondary–emission coefficients determined either without preliminary thermal processing of the target or at facilities whose original destination was not the γ measurement are considerably higher [7,8]. In addition, measurements of the cathode plasma potential versus the ion current to the plasma cathode [5] may evidence that the electron extraction coefficient varies during the beam generation pulse. The presence of transient processes at the initial stage of the beam formation during the first $10-50\,\mu$s is also shown by the collector measurements of the dynamics of the radial current distribution in the cathode and by the analysis of oscillograms of the basic electrical circuits of the electron source [3]. During the subsequent time intervals, variations in the generation conditions are possible because of inertness of the processes of gas desorption from the electron source electrodes and target evaporation. Thus, variations in the electron extraction coefficient are to be expected during the entire submillisecond beam current pulse.

The fundamental condition for performing the experiments in question was using a plasma cathode power-supply

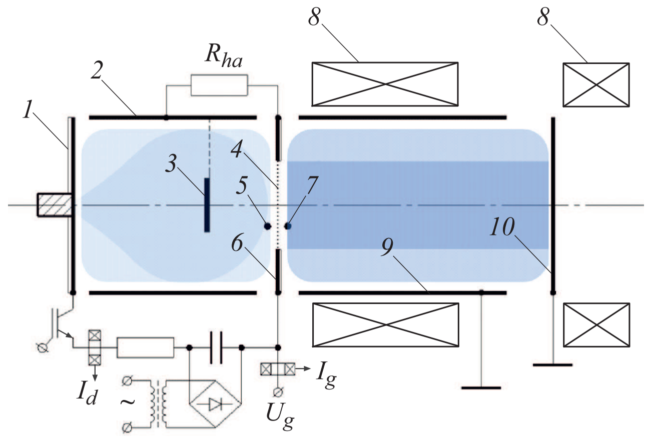

Figure 1. Electron source schematic diagram. *1* — cathode, *2* — anode insert, *3* — redistributing electrode, *4* — grid, *5* — cathode plasma boundary, *6* — emission electrode, *7* — anode plasma boundary, *8* — magnetic field coils, *9* — drift tube, *10* — collector.

circuit with a low output inductance, which ensured relatively sharp edges of the arc discharge current pulses ($\Delta t \approx 150\,\mathrm{A}/\mu\mathrm{s}$) [9]. The condition for the method applicability is slight variation in the anode plasma concentration during the discharge current pulse cutoff.

The accelerating-gap current I_g in the electron source with a grid plasma cathode and plasma anode with an open plasma boundary is determined by several components [9,10]:

$$I_g = \alpha I_d + I_i\big(1 + (1-\Gamma)\gamma_2 + \Gamma\gamma_1\big), \tag{1}$$

where I_i is the current of accelerated ions from the anode plasma, γ_2 is the coefficient of ion-electron emission from metal caused by bombarding the emission electrode with accelerated ions, γ_1 is the coefficient of ion-electron emission from emission plasma due to ion-electron processes in the plasma cathode (this coefficient was introduced in [10]), Γ is the effective geometric transparence of the emission electrode, which allows accounting for the ion flux having passed through the emission electrode grid to the plasma cathode.

The discharge current switch-off results in an increase in the cathode/emission plasma potential relative to the emission electrode *6* (Fig. 1) by a value ensuring the current continuity in the loop of its flowing from the collector to discharge cell electrodes. The reason for such a variation in the potential is, probably, an abrupt stepwise decrease in the number of negative charges in plasma due to shutoff of their main supply channel and fast exit of electrons through the open boundary into the accelerating gap and onto positively biased discharge-cell electrodes. The increased potential is to provide the same or somewhat lower (by a value of current of the possible secondary emission) total plasma-ion current to the negative electrodes. Once the discharge current is switched off, electrodes *1* and *3* which are still being irradiated with accelerated ions from the decaying anode plasma [9] obtain a potential positive with respect to the emission electrode. Therewith, cathode *1* gets isolated from other cell electrodes, and the supplied ion current has to be compensated by the plasma electron current of the same magnitude. Electrode *2* is connected to emission electrode *6* via resistor $R_{ha} = 5\,\Omega$ at which the auto-bias potential increases during the discharge current cutoff from negative 8 V–positive 9 V to 5–15 V; this hinders the secondary electron emission from electrodes *2* and *3* into the cathode plasma. Thus, there takes place termination of electron emission from the plasma emitter, including emission of electrons generated in the γ-processes, which means that $[I_{em} + I_i(1+\Gamma\gamma_1)] = 0$. The last component can hardly be separated from the share of current of the primary electrons generated in the cathode spot; however, this allows introducing the effective coefficient of electron extraction from the plasma emitter in the following form:

$$\alpha_{eff} = \big(I_{em} + I_i\Gamma\gamma_1\big)/I_d. \tag{2}$$

By ensuring a sharp edge of the discharge current pulse, we succeded in fixing two sections on the current I_g pulse, which differed in the current variation rate and pattern (Fig. 2, *a*). As per (1), the first section corresponds to the current extracted from the plasma cathode $\Delta I = [I_{em} + I_i(1+\Gamma\gamma_1)]$, the second one is associated with the exponential reduction in the ion current extracted from the decaying anode plasma in the absence of electron emission from the plasma cathode and also with relevant secondary electron current $I_{iee} = [I_i\big(1 + (1-\Gamma)\gamma_2\big)]$.

The region of the anode plasma relaxation is clearly seen in the oscillogram of the accelerating-gap current (Fig. 2, *b*). When the working gas (argon) pressure in the vacuum chamber is 65 mP, this region follows the region of a stepwise variation with the characteristic time of 0.25–0.4 μs and reduction rate of 100–120 A/μs. By approximating the oscillogram section 10 μs long, the plasma relaxation time was estimated and appeared to be 10–15 μs at the specified pressure. Such a significant time may be associated with the anode plasma production by secondary electrons generated as a result of ion-electron emission from the emission electrode surface and also with hindering of electrons removal to the drift tube walls across the guiding magnetic field lines.

Good reproducibility of the current pulse shape allows interpreting the measurements obtained for a series of different-duration pulses as a function of unit pulse duration. As a result, in certain modes of the beam generation, oscillograms of the accelerating-gap current for pulses 10–30 and 100–150 μs in duration could differ in amplitude by up to 15%. To exclude this effect and keep identical the mean impact power, the pulse repetition rate was varied from 0.3 to 1 Hz.

The analysis was carried out for characteristic oscillograms of the accelerating-gap current. The approximation was performed by the mean-square method with an exponential function, each oscillogram identically, free of any

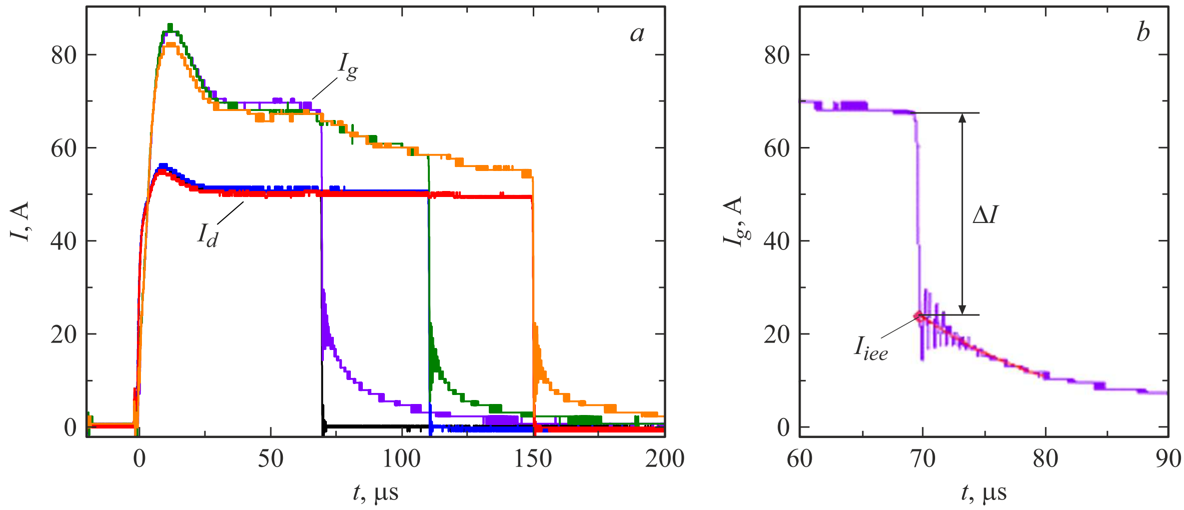

Figure 2. Typical oscillograms of discharge current I_d and current I_g in the accelerating gap of the electron source at the pressure of 65 mPa, accelerating voltage of 7 kV, and near-emitter magnetic field of 50 mT for three pulse durations (a), and the region of the accelerating-gap current cutoff for a pulse 70 μs in duration (b).

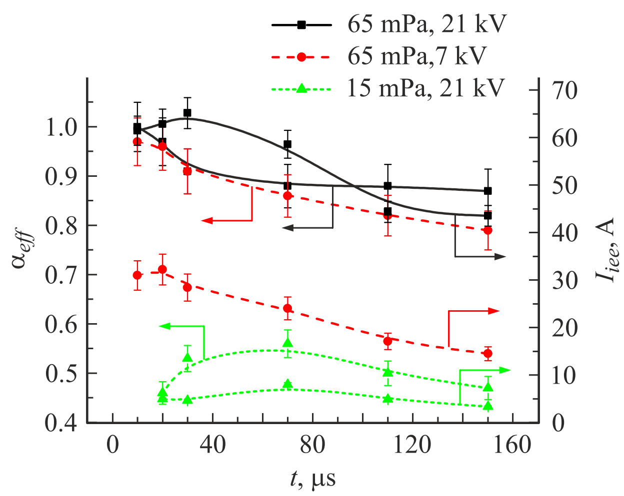

Figure 3. Dynamics of coefficient α_{eff} of electron extraction from the plasma emitter and of ion-electron emission current $I_{iee} = \left[I_i\left(1 + (1 - \Gamma)\gamma_2\right)\right]$ under different experimental conditions.

additional processing. The obtained data are presented in Fig. 3 and evidence for a decrease in the effective extraction coefficient α_{ff} by 35–50% with the operating pressure decrease from 65 to 15 mPa. In addition, in the given modes of electron beam generation at the working gas pressure of 65 mPa, coefficient α_{eff} decreases during the beam current pulse 150 μs long by 10–20%.

Variation in the I_{iee} value shown in Fig. 3 may be regarded as dynamics of ion current I_i. The source of varying during the first tens of microseconds may be an increase in the emission current due to Γ, γ_1, γ_2 or gas pressure.

Correct measurement of the dynamics of the decaying anode plasma concentration in the magnetic field under a flux of accelerated electrons seems to be a rather sophisticated problem. Nevertheless, the variation in concentration, or, more exactly, in ion current to the emission electrode during the discharge current cutoff, may be estimated by using calorimetric measurements of the beam energy and data on coefficients α_{eff} and γ_{eff}. However, it is necessary to be sure that at least one of these coefficients is measured reliably. The authors assume that, under the conditions used to demonstrate the given approach (at $p = 65$ mPa), the ion current might decrease by up to 10 A. In this case, the obtained coefficient α_{eff} would be overestimated.

Experimental separation of the electron emission governed by the α and γ_1 coefficients is rather difficult; therefore, this paper proposes a method for estimating the very effective coefficient of electron extraction from the plasma cathode based on a low-pressure arc discharge with a grid stabilization of the cathode/emission plasma boundary and open boundary of the anode/beam plasma; the method is applicable when there exists an ion flux to the emission electrode and to the discharge cell of the plasma cathode. The method is useful in studying the electron beam generation and transport in the systems where direct measurements of the extraction coefficiens are either hindered or impossible because of the design peculiarities of the system or impossibility of separating the emission current components.

Financial support

The study was supported by the Russian Science Foundation (project № 23-29-00939).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] 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

[2] 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.

[3] N.N. Koval, E.M. Oks, Yu.S. Protasov, N.N. Semashko, *Emissionnaya elektronika* (MGTU im. N.E. Baumana, M., 2009). (in Russian)

[4] N.N. Koval, S.V. Grigoryev, V.N. Devyatkov, A.D. Teresov, P.M. Schanin, IEEE Trans. Plasma Sci., **37** (10), 1890 (2009). DOI: 10.1109/TPS.2009.2023412

[5] P.V. Moskvin, S.S. Kovalsky, M.S. Vorobyov, J. Phys.: Conf. Ser., **1115** (2), 022004 (2018). DOI: 10.1088/1742-6596/1115/2/022004

[6] P. Cousinie, N. Colombie, C. Fert, R. Simon, Compt. Rend., **249**, 387 (1959).

[7] U.A. Arifov, *Vzaimodeystvie atomnykh chastits s poverkhnostyu tverdogo tela* (Nauka, M., 1968), s. 159–164. (in Russian)

[8] M.M. Shamim, J.T. Scheuer, R.P. Fetherston, J.R. Conrad, J. Appl. Phys., **70** (9), 4756 (1991). DOI: 10.1063/1.349067

[9] 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.

[10] V.A. Gruzdev, Yu.E. Kreyndel, Yu.M. Larin, TVT, **11** (3), 482 (1973). (in Russian)

Translated by Solonitsyna Anna