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Negative current feedback in the accelerating gap in electron sources with a plasma cathode

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Using the example of an electron source with a plasma cathode based on a low-pressure arc discharge with grid stabilization of the cathode/emission plasma boundary and an open anode/beam plasma boundary, a mechanism is described for increasing the electrical strength of a high-voltage accelerating gap by introducing a series negative current feedback (NCF) in the accelerating interval, which makes it possible to level out uncontrolled bursts of the beam current during its pulse. The introduction of NCF is achieved by using a special electrode in the space of the plasma emitter connected through a resistance to the anode of the arc discharge, and the main task of which is to intercept accelerated ions penetrating into the emitter from the high-voltage accelerating gap, due to which the current of electron emission from the arc discharge plasma decreases by a value proportional to the ion current in the accelerating gap. Since most sources and accelerators of electrons with plasma cathodes based on discharges of various types have a similar principle of operation, the use of this method will not only expand the limiting parameters of the generated electron beams, but also increase the stability of the operation of such electron sources, and, accordingly, beam irradiation of various materials and products.

Keywords: arc discharge, plasma cathode, electron source, electron beam, ion beam, negative feedback.
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The electron sources with grid plasma cathodes are ones of the most promising electron sources when potentially considering them for technological purposes [1–4]. In scientifically searching optimum irradiation modes, these sources have a unique property of generating an electron beam, which is correlated to weak interrelation of its main parameters [5–8]. This property is achieved by using operating modes of the plasma cathode in the modes of so-called grid/layer stabilization of a boundary of the emission plasma [5,9,10]. For example, using this property of the plasma cathodes allowed demonstrating a unique possibility of dynamically controlling the power of the electron beam for the pulse duration of a millisecond [11,12]. It allowed controlling an energy input rate of a surface of metallic materials and even maintaining the surface temperature of irradiated sample at thousands of degrees within the same time range [13].

Like in the electron sources with the cathodes of another type, in the electron sources with the plasma cathodes researchers pay special attention to dielectric strength of a high-voltage accelerating gap, which most often allows extending the other parameters of the generated beam (an amplitude, duration or pulse repetition rate) [5]. The dielectric strength of the accelerating gap can be decreased due to charging dielectric inclusions on the emission electrode surface, malfunction of the plasma generators, disruption of the layer stabilization of the boundary of the emission plasma, triggering cathode spots on the plasma emitter electrodes due to an increased potential of the emission plasma, etc. As decrease in the dielectric strength of the accelerating gap is always accompanied by preliminary increase in the current thereof, then one of the ways of increasing the dielectric strength can be introduction of negative current feedback (NCF) within the accelerating gap. It allows reducing this current in case of any destabilizing factor. These factors may include increase in gas pressure, target melting, dynamics of the electron beam (spatial changes in the beam current density for the duration of its pulse), etc. [5].

One of the ways of NCF introduction was demonstrated in the study [14], whose authors get decrease in the emission current by proportionally reducing the arc discharge current and, consequently, concentration of the emission plasma for the duration of the pulse of its generation. However, this method is hard to implement in stochastic conditions of emerging factors, which destabilize operation of the electron sources and electron accelerators with the plasma cathode. Because it requires introduction of high-speed NCF of hundreds of kHz and even several MHz, which substantially increases requirements to a circuitry used in the systems of power supply and control of the plasma cathode and, consequently, results in its complication and rise in the price thereof.

The studies [15,16] have experimentally demonstrated a mechanism of beam current control by changing a potential of the emission plasma. These plasma sources were different in their design, but the idea was to input a special control electrode separated from the emission plasma by a fine-structured grid used to forcefully switch the discharge current. In case of the study [15] it allowed implementing the mode with high efficiency (up to 100%) of extracting the electrons out of a hollow anode, when the emission current is equal to the discharge current and the current of the control electron circuit is almost zero. This mechanism of control of generation of the electron beam is based on reduction of the electron emission current by increasing the potential of the emission plasma when switching to the special control electrode of fast emission plasma electrons, which accounted for transfer of the discharge current [17]. The present paper studies this mechanism of control of the electron beam current as a method of self-consistent NCF introduction within the accelerating gap by bombarding the special electrode within the space of the plasma emitter with accelerated ions, which penetrate the emitter through cells of an emission grid. Thus, as the dielectric strength of the accelerating gap and the stability of operation of the electron source generally depend on parameters of the generated beam, in particular, on its amplitude, then the aim of the present study is to demonstrate and explain the accelerating gap's NCF mechanism, which allows stabilizing its amplitude for the duration of the pulse of a sub-millisecond duration.

As in [11], the present study also uses the „SOLO" electron source with the grid plasma cathode and the plasma anode with the open plasma boundary (Fig. 1). This source is in a list of unique Russian plants included in the „UNIQUUM"system, whose principle of operation is described in the paper [8]. This source is designed to generate the electron beam of the following parameters: the electron energy of 25 keV, the beam current of 10–300 A, the duration of the beam current pulses $50-300\,\mu$s at the pulse repetition rate of $0.1-5\,s^{-1}$ and the beam diameter up to 40 mm.

An triggering (ignition) discharge of the duration of several microseconds and the current of several amperes lights up between the ignition electrode *1* and the cylindrical magnesium cathode *2* of the internal diameter of 8 mm and the length of 50 mm when applying the voltage pulse U_{trig} of 12–15 kV. The main arc discharge is burning between the cathode *2* and the anode electrodes *5, 6* of the discharge system. The anode insert *3* electrically connected to the arc discharge anodes *5, 6* via the current-limiting resistance R_{HA} is required for facilitating light-up conditions for the arc discharge and fixing an additional redistribution electrode *4* in electrical contact therewith. Usually, the electrode *4* is used to equalize the distribution of the emission current density [5,18–20]. The present study deals with a niobium electrode *4*, which is made as a disc of the diameter of 35 mm, the thickness of 0.2 mm and placed at the distance of about 20 mm to the emission grid *5*. The direct accelerating voltage is applied between the flat emission electrode *6* with the fine-structured (0.5×0.5 mm) emission grid *5* (they are the anode electrodes of the discharge system) of diameter of 40 mm and the extracting electrode *7* made as a diaphragm of the diameter of 80 mm. The extracting electrode *7*, the drift tube *8* and the collector *10* are at the „ground"potential. The drift tube has an internal diameter of 82 mm, while the length of a transport channel is 0.5 m. Initially, the electrons are extracted out of the emission plasma through the emission grid cells under an electric field created by the electrodes *7* and *8*, while after the anode (beam) plasma is formed, the electrons are accelerated in a double layer between the boundaries of the two plasmas: the cathode (emission) one and the anode (beam) one.

It is important to note that for this operating mode (which is a standard one for this electron source) the boundary of the emission plasma is stabilized by the grid, while the anode plasma created by the electron beam itself within the space of its drift has a movable (open) boundary. The beam electrons accelerated within the gap between the cathode and anode plasma are transported to the collector in the magnetic field of the coils *9*, and the field therein can reach 0.1 T for the first solenoid (in reference to the emission grid) and 0.05 T for the second one (the said fields are given for a center of each solenoid). The amplitude and the duration of the beam current pulse are set by the amplitude and the duration of the current pulse of the main arc discharge. Argon is used as an operating gas. The experimental pressure was adjusted by puffing of the gas into the source discharge system. The gas pressure within the operating chamber varies within the range (50–100) mPa, while the pressure in the main discharge cell of the plasma cathode was several times higher. Rogowski coils were used as sensors to measure the pulse currents.

In the electron source with the grid plasma cathode and the plasma anode, the current within the accelerating gap I_g is determined by several components [5,8,21,22] and can be written as

$$I_g = \alpha I_d + I_{i2}\left[1 + (1-\Gamma)\gamma_2 + \Gamma\gamma_1\right], \qquad (1)$$

where $\alpha = I_{em}/I_d$ — the coefficient of extraction of the electrons out of the plasma emitter, which is equal to a ratio of the emission current I_{em} to the discharge current I_d; I_{i2} — the current of the accelerated ions out of the anode plasma; γ_2 — the coefficient of ion-electron emission from the metal when bombarding the grid *5* and the emission electrode *6* with the accelerated ions; γ_1 — the coefficient of ion-electron emission out of the emission plasma due to ion-electron processes inside the plasma emitter [21,22]; Γ — effective geometric transparency of the emission electrode, which allows taking into account a flux of ions passed through the emission grid into the plasma emitter. At the same time, contribution of each summand can be different depending on a specific type of the electron source with the plasma cathode, parameters of the generated electron beam, the geometry of the electrodes and a material thereof, the working pressure, etc.

It is clear from the formula (1) that for the pulse duration the current I_g can change as a result of several mechanisms, i.e.: a) as a result of changing a portion of the electrons extracted out of the plasma emitter (a change of the coefficient α); b) as a result of changing the current of the accelerated ions generated by ionization of residual, working, desorbed gases, as well as vapors of a target material, which also determines the current of gamma electrons generated as a result bombarding the emission electrode with these accelerated ions. Besides, it is clear from the formula (1) that a part of the current of the accelerated ions equal to $(I_{i2}\Gamma)$ does not contribute to production of the gamma electrons from the emission electrode surface, as it penetrates the space of the plasma emitter through the cells of the emission grid. These ions result in changing the conditions of generation of the emission plasma, having a contradictory nature in terms of the operation stability of the electron source. Since, on the one hand, they increase the potential of the emission plasma and result in uncontrolled increase in its concentration [5] (most often, locally), but, on the other hand, they can provide for more stable burning of the discharge in the space of the plasma emitter (they reduce its impedance) and facilitate discharge triggering, including in the modulated mode, providing for, if required, a bigger pause between the discharge current pulses when generating a bundle of the discharge current pulses of the sub-millisecond duration [13].

Finally, we can conclude that the occurrence of the accelerated ions within the high-voltage gap results in the current destabilization I_g, resulting, most often, to increase in its amplitude, both by increase in the extraction coefficient α, and by the portion of the gamma electrons (both from the surface of the emission electrode γ_2, and out of the emission plasma γ_1).

Taking into account the formula (1), we can say that the current?I_{HA} recorded in a resistor circuit R_{HA} is a sum of the currents out of the emission plasma (electron?I_e and ion I_{i1} components), the current of accelerated ions passed through the grid cells into the space of the plasma emitter and bombarding the electrode *4* only on the one side facing to the accelerating gap, as well as the electron current resulting from bombarding the electrode *4* with the accelerated ions and depending on the coefficient of the ion-electron emission γ_3 of the material, from which the electrode is made *4*:

$$I_{\text{HA}} = I_e - I_{i1} - I_{i2}(S_4\Gamma/S_5)(1+\gamma_3), \qquad (2)$$

where S_4 — the area of projection of the redistribution electrode onto a plane of the emission electrode, which is limited by an emission hole overlapped by the grid *5* (Fig. 1) and S_5 — the area of the emission window.

The portion of the discharge current (the components I_e and I_{i1}), which is closed within the circuit of the hollow anode and the redistribution electrode, decreases with increase in the resistance R_{HA}. The influence of the value of R_{HA} on switching the discharge current to the

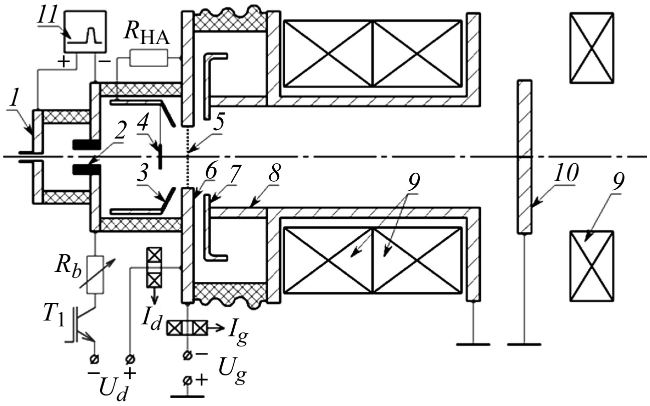

Figure 1. Diagram of the „SOLO“electron source: *1* — the ignition electrode, *2* — the cathode, *3* — the hollow anode (anode insert), *4* — the additional electrode (the redistribution electrode or the feedback electrode), *5* — the emission grid, *6* — the emission electrode, *7* — the extracting (accelerating) electrode, *8* — the drift tube, *9* — the magnetic coil, *10* — the collector, *11* — the ignition power supply.

emission grid and, as it is generally accepted in [2,5], the increase in the extraction coefficient α are determined by the dynamics of a wall ion layer of the spatial charge within the cells of the emission grid.

It is clear from the dependences of Fig. 2, which are recorded for steady-state modes of the arc discharge current without the accelerating voltage, that the increase in the resistance R_{HA} results in exponential reduction of the current in the circuit of the hollow anode?I_{HA}. First of all, it is correlated to the reduction of that discharge current portion, which closes to the electrode *4*. However, we should also note an important feature consisting in that decrease in the current I_{HA} with increase in the resistance R_{HA} is accompanied by increase in the auto-bias voltage U_{HA} (which is negative relative to the arc discharge anode), which tends to saturation at the level of $-(10-25)$ V and also depends on the amplitude of the arc discharge current I_d. It is this available potential bias U_{HA} that results in predominantly switching the discharge current to the emission electrode area, improving the efficiency of extracting the electrons out of the plasma emitter to the accelerating gap.

Besides, it is clear from the formula (2) that the current I_{HA} also depends on the current of the ions out of the accelerating gap I_{i2}. It is clear from the oscillograms of Fig. 3 that at $R_{\text{HA}} = 0$, when the potential of the electrode *4*, the anode insert *3* and the arc discharge anode *5, 6* is the same, the current amplitude I_{HA} is comparable with the discharge current amplitude I_d (Fig. 3, *?a*). At this moment, the discharge current predominantly closes along the system axis via the electrode *4*, which has been confirmed by separate probe measurements. In case of occurrence of the accelerating voltage, it is clear that during the first twenty microseconds the discharge is switched to the emission grid

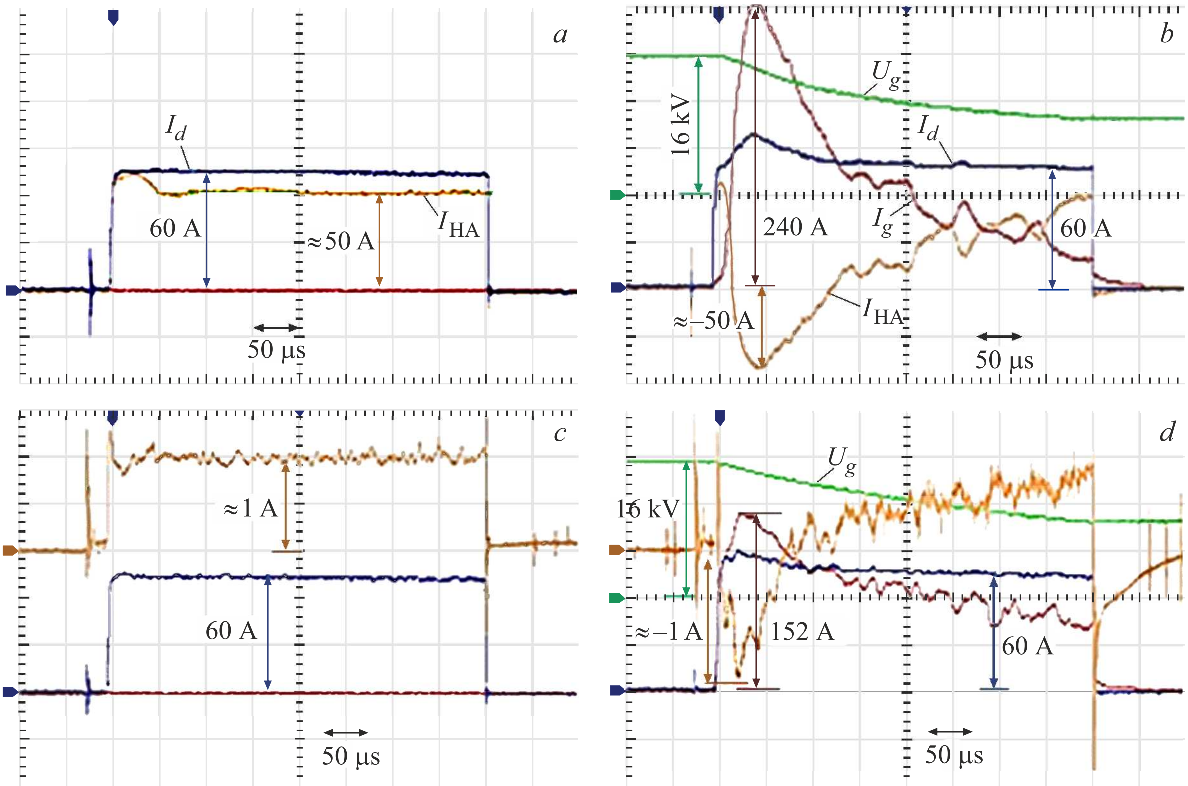

Figure 3. Typical oscillograms of the discharge current I_d (blue (in the online version)), the anode insert current I_{HA} (brown (in the online version)), the current in the accelerating gap I_g (dark-red (in the online version)), the accelerating voltage U_g (green (in the online version)) at $R_{HA} = 0$ (a, b) and 51 Ω (c, d) without (a, c) and with (b, d) the accelerating voltage $U_g = 16$ kV.

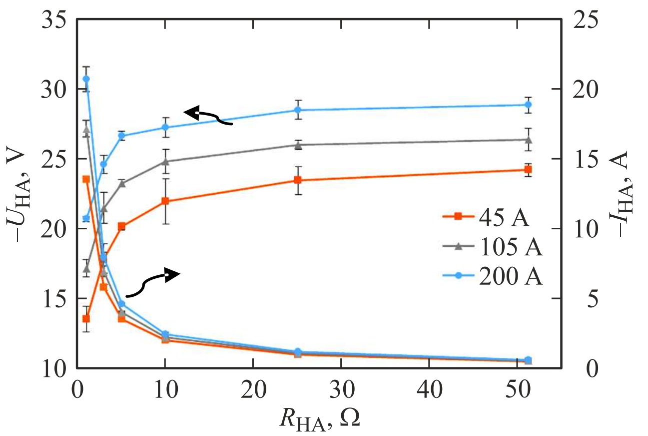

Figure 2. Dependence of the current I_{HA} and the voltage drop U_{HA} on the resistance R_{HA} at the various discharge currents I_d.

area, thereby resulting in the occurrence of the current I_g, whereas the current?I_{HA} is changing the polarity (Fig. 3, ?*b*). It can be explained by intense ion bombardment of the electrode *4* from the accelerating gap. At the same time, the amplitude of the reverse polarity current I_{HA} is also measured to be dozens of amperes.

The resistance R_{HA} was input into the emitter's electrode system to result in reduction of the current I_{HA} (Figs. 2 and 3, ?*c*), but in occurrence of auto-bias U_{HA}. The similar reduced current I_{HA} can be observed when the pressure of the working gas is increasing without the accelerating voltage, which is due to increase in the concentration of the emission plasma and the growing current of the ions I_{i1} out of this plasma to the insert *3* and the electrode *4*. It is clear from Fig. 3 that without the accelerating voltage inputting the resistance $R_{HA} = 51\,\Omega$ results in occurrence of high-frequency modulation of the current I_{HA} with the typical frequency at ≈ 50 kHz (the modulation frequency increases with increase in R_{HA}). At the same time, the discharge current I_d has an almost constant amplitude and there is no HF-modulation on it, which indicates its dynamic restructuring within an interelectrode space of the plasma cathode. With the accelerating voltage U_g and turning on the arc discharge, the accelerating gap exhibits the current I_g (Fig. 3, *d*), whose amplitude has a pronounced maximum within the first dozens of microseconds in the same manner as at $R_{HA} = 0$. However, the amplitude of this surge is less by ≈ 30%, and there is almost no current delay I_g relative to I_d. The available current I_g again results in intense ion bombardment of the electrode *4* up to changing the polarity of the current I_{HA}, which is also due to predominant influence of the ion component of the current of the accelerated ions over the electron component of the current of the discharge gap. In the conditions of the intense ion

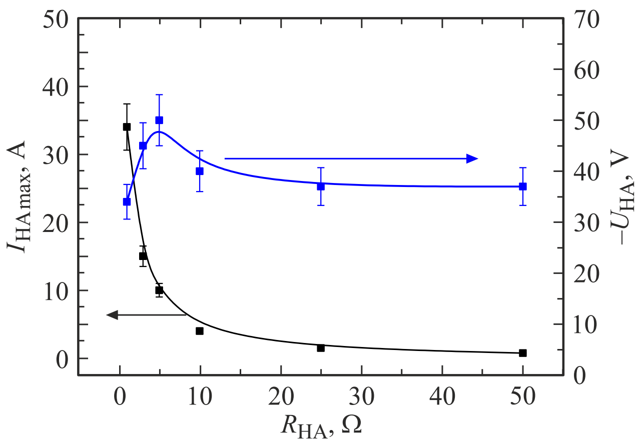

Figure 4. The dependence of the current maximum $I_{\text{HA max}}$ (the point of the maximum current $I_{\text{HA max}}$ coincides with the maximum current within the accelerating gap I_g) and the voltage drop $U_{\text{HA max}}$ on the value of the resistance R_{HA}.

bombardment of the electrode *4*, with changing the polarity of the current I_{HA}, the polarity U_{HA} is also changing and the space of the plasma emitter exhibits positively biased electrodes relative to the discharge anode, thereby resulting in switching the portion of the discharge current to these electrodes *3* and *4*, and, consequently, in the reduction of the extraction coefficient α. And, therefore, it exhibits the mechanism of the subsequent NCF within the accelerating gap, resulting in stabilization of its amplitude. Thus, when inputting the resistance R_{HA}, it is the NCF mechanism within the accelerating gap that results in corresponding reduction of the amplitude of the current I_g by fixing the portion of its ion component on the electrode within the space of the plasma emitter.

It is important to note that increase in the resistance R_{HA} within the range $(0-51)\,\Omega$ and above results in reduction of the amplitude of the current surge $I_{\text{HA max}}$ (the reverse polarity of the current I_{HA} of Fig. 3, *?d*) in such a way that the voltage $U_{\text{HA max}}$ has a non-monotonic function and its maximum value varies within the range $+(25-35)$ V (Fig. 4).

The interrelation of the main parameters of the plasma cathode can be determined from the balance equations [21,23,24]. Based on the equation of current continuity, provided that the electrons are extracted from the open plasma surface and there is a current of the fast ions from the accelerating gap the relationship for efficiency of extraction of the electrons from the plasma cathode can be written as follows:

$$\alpha = \left[1 + \frac{S_{5f}}{S_e}\exp\left(-\frac{\phi_a}{kT_e}\right) + \frac{S_3}{S_e}\exp\left(-\frac{\phi_{\text{HA}}}{kT_e}\right) + \frac{S_4}{S_e}\exp\left(-\frac{\phi_{\text{HA}} - \phi_I}{kT_e}\right)\right]^{-1}. \quad (3)$$

Here S_e — the area of the plasma emission surface, S_4 — the area of the redistribution electrode, S_{5f} and S_3 — the areas of the metal surface of the grid electrode and the anode insert, φ_a and φ_{HA} — the plasma potentials relative to the anode and relative to the hollow anode, φ_i — the potential due to the current of the fast ions to the electrode *4*, T_e — the temperature of the electrons, k — the Boltzmann's constant. The summands in the relationship (3) are relative currents of the electrons to the emission electrode, the anode insert and the redistribution electrode; the current of the plasma ions is not considered here. It is clear from the formula (3) that increase in the resistance R_{HA} inside the hollow anode circuit and, consequently, in the potential φ_{HA} results in increase in the extraction coefficient α. However, with increase in the ion component of the current of the accelerated ions to the redistribution electrode *4*, the potential difference $(\varphi_{\text{HA}} - \varphi_i)$ decreases, thereby resulting in reduction of α.

Finally, we presently know a large number of the electron sources and electron accelerators with the plasma cathode, which are designed to generate the beams of a different configuration, whose emitter is designed with the redistribution electrode. Most often, this electrode is input to equalize the beam current density across its section, to switch the discharge current to the emission grid area in order to increase the energy efficiency of the plasma emitter and to reduce the beam generation delay relative to a front of the discharge current generation. In contrast to all these studies, the present study has experimentally demonstrated that in the conditions of closing the accelerated ions to the special electrode within the interelectrode space of the plasma emitter (which is connected to the discharge anode via the resistance — the emission electrode), the accelerating gap exhibits the subsequent NCF based on reduction of the emission current due to switching the portion of the discharge current to this electrode. It is important to stabilize the discharge current not only from the point of parameter controllability of the generated electron beam (which is extremely important for any technological process), but it also allows increasing the dielectric strength of the high-voltage accelerating gap in the electron sources of this type so as to multiply reduce its electric breakdowns. It has also been recorded during experiments described in the present study. In order to demonstrate the subsequent NCF, the pressure of the working gas was specially selected to be an increased one (about 100 mPa), and with increase in the resistance R_{HA} within the range $R_{\text{HA}} = (0-5)\,\text{k}\Omega$, at the constant setting of the discharge current $I_d = 20$ A (the current setting was realized without the accelerating voltage), the uncontrollable current surge within the accelerating gap has decrease from $I_g = 240?$ to 140 A, which is indicative of the NCF efficiency. The proposed and proven method allows extending the range of the stable operation of the electron source with the plasma cathode and, consequently, a range of its applications.

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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, 2015).
[2] V.A. Burdovitsin, A.S. Klimov, A.V. Medovnik, E.M. Oks, Yu.G. Yushkov. *Forvacuumnye plazmennye istochniki electronov* (Izd-vo Tomskogo un-ta, Tomsk, 2014). (in Russian).
[3] N.N. Koval, V.N. Devyatkov & M.S. Vorobyev. Russ. Phys. J., **63** 1651, (2021). DOI: 10.1007/s11182-021-02219-3
[4] A.B. Belov [et al]. *Silnotochnye impulsnye electronnye puchki dlya aviatsionnogo dvigatelestroeniya*, ed. by A.S. Novikov, V.A. Shulov, V.I. Engelko (Dipak, M., 2012). (in Russian).
[5] E. Oks. *Plasma Cathode Electron Sources: Physics, Technology, Applications* (Weinheim : Wiley - VCH, 2006).
[6] N.V. Gavrilov, V.V. Osipov, O.A. Bureev [et al.]. Tech. Phys. Lett., **31** (2), 122 (2005). DOI: 10.1134/1.1877622
[7] M.S. Vorobyov, S.A. Gamermaister, V.N. Devyatkov, N.N. Koval, S.A. Sulakshin, P.M. Shchanin. Tech. Phis. Lett., **40** (12), 506 (2014). DOI:10.1134/S1063785014060261
[8] 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
[9] A.V. Zharinov, Yu.A. Kovalenko, I.S. Roganov, P.M. Teryukanov. ZhTF, **56** (1), 66 (1986) (in Russian).
[10] A.V. Zharinov, Yu.A. Kovalenko, I.S. Roganov, P.M. Teryukanov. ZhTF, **56** (4), 687 (1986) (in Russian).
[11] 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** (7), 528 (2021). DOI: 10.1134/S1063785021050291
[12] M.S. Vorobyov, N.N. Koval, P.V. Moskvin, A.D. Teresov, S.Yu. Doroshkevich, V.V. Yakovlev, V.I. Shin, J. Phys.: Conf. Ser., **1393**, 012064 (2019). DOI: 10.1088/1742-6596/1393/1/012064
[13] M.S. Vorobyov, T.V. Koval, V.I. Shin, P.V. Moskvin, My Kim An Tran, N.N. Koval, K. Ashurova, S.Yu. Doroshkevich, M.S. Torba. IEEE Trans. Plasma Sci., **49** (9), 2550 (2021). DOI: 10.1109/TPS.2021.3089001
[14] S.Yu. Doroshkevich, M.S. Vorobyov, V.V. Yakovlev. IOP Conf. Series, **1115**, 022017 (2018). DOI: 10.1088/1742-6596/1115/2/022017
[15] V.I. Gushenets, P.M. Schanin. Russ. Phys. J., **44** (9), 962 (2001). DOI: 10.1023/A:1014362023321
[16] R. Gunzel. Vac. Sci. Technol., **17** (2), 895 (1999).
[17] V.L. Galanskii, Y.E. Kreindel', E.M. Oks [et al.]. High Temperature, **25** (5), 632 (1988).
[18] L.G. Vintizenko, N.V. Gavrilov, N.N. Koval, Yu.E. Kreindel, V.S. Tolkachev, P.M. Shchanin.*Impulsnye vysokovoltnye istochniki elektronov s plasmennym emitterom dlya formirovaniya puchkov bolshogo secheniya, v knige Istochniki elektronov s plazmennym emitterom*, ed. by Yu.E. Kreindel (Nauka, Novosibirsk, 1983). (in Russian).
[19] S.P. Bugaev, Yu.E. Kreindel, P.M. Shchanin. *Elektronnye puchki bolshogo secheniya* (Energoatomizdat, M., 1984). (in Russian).
[20] I.Yu. Bakeev, A.V. Kazakov, A.V. Medovnik, E.M. Oks. J. Phys.: Conf. Ser., **1488**, 012001 (2020). DOI: 10.1088/1742-6596/1488/1/012001
[21] V.A. Gruzdev, Yu.E. Kreindel, Yu.M. Larin. TVT, **11** (3), 482 (1973). (in Russian).
[22] V.A. Gruzdev, Yu.E. Kreindel, Yu.M. Larin. ZhTF, **43** (11), 2318 (1973). (in Russian).
[23] N.V. Gavrilov, D.R. Emlin, A.S. Kamenetskikh. Tech. Phys., **53** (10), 1308 (2008). DOI: 10.1134/S1063784208100083
[24] T.V. Koval, Le Hu Zung. Izv. vuzov. Fizika. **57** (3–2), 118 (2014). (in Russian).