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Modernization of cathode assemblies of electron sources based on low pressure arc discharge

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Abstract. The paper presents modified cathode assemblies, including their main characteristics, for plasma electron sources based on a constricted low-pressure arc initiated by a discharge in crossed electric and magnetic fields. One of the modified cathode assemblies allows the electrode system of the auxiliary discharge to operate at a pressure of ≈ 0.3 Pa, as against ≈ 10 Pa before the modification, provides a larger diameter constriction of the pulsed (up to τ = 250 μs) arc, and thus extends the range of operating currents for the plasma-cathode discharge system up to I_d = 300 A. The other modified assembly operates at widely varying discharge currents I_d = 5–100 A, provides lesser amounts of cathode microdroplets at the discharge electrodes, and allows the arc to operate at comparatively low voltages. The use of cathode assemblies adapted for specific discharge systems extends the capabilities of plasma-emitter electron sources as well as the range of their applications in scientific and technological fields.

1. Introduction

Low-pressure arc discharges are widely used in plasma-cathode electron sources [1,2]. This type of discharge allows generation of emission plasma in a wide pressure range and provides discharge currents of hundred amperes with a single cathode and of several kiloamperes with multicathode discharge systems. Due to the low arc operating voltage (tens of volts), the discharge system requires low power to operate. In a discharge system of this type, depending on the method of cathode spot initiation, an open arc can be used or the discharge current can take the path through a constriction channel. This channel provides a pressure difference between the cathode and anode regions of the discharge system and hence assists the initiation of an arc. It is known that during the operation of a cathode spot at the cathode surface, the cathode is severely sputtered [3]. Separation of the cathode and anode regions of an arc discharge impedes the penetration of the sputtered cathode material into the anode region. Also, the positioning of cathode assemblies crosswise the electron extraction axis in a plasma emitter allows an increase in the dielectric strength of the high-voltage acceleration gap [4]. Likely, the increase is also due to lesser amounts of cathode microdroplets formed at the emission grid and in the region of the high-voltage acceleration gap during the cathode spot operation.

The paper presents modified cathode assemblies for two types of plasma-cathode electron sources with a grid-stabilized plasma emission boundary. The characteristics of the discharge systems before and after modification of its cathode assemblies are compared.

2. Cathode assembly for a wide-aperture pulsed electron source

The cathode assembly was developed for a modified DUET wide-aperture (≥ 10^3 cm^2) pulsed electron source with a grid plasma cathode [5]. The proposed cathode assembly (figure 1), which replaces the unit of cathode spot initiation by a dielectric flashover [6,7], is such that the hollow anode and the emission grid are screened from the cathode spot (from its line of sight) and the penetration of the cathode material into the anode region of the discharge is thus decreased. The cathode spot in the hollow cathode is initiated by a low-pressure gas breakdown at a point on the left branch of the Paschen curve close to its minimum. The use of hollow electrodes (cathode and trigger electrode) at fixed gas flow rates makes it possible to decrease the voltage for a discharge to arise and transform into an arc. At an applied voltage of amplitude ≈ 10 kV, a glow gas discharge is ignited between hollow cathode 4 and trigger electrode 1 with subsequent initiation of a cathode spot and glow-to-arc discharge transition. The gas breakdown obviates the necessity of using a dielectric which, being contaminated by the cathode material, decreases the lifetime of the cathode assembly [6,7].

For easier ignition of the discharge and its stabilization at low gas pressures, when the discharge operates mostly in vapors of cathode material 4 (figure 1), the cathode is made of magnesium whose ionization potential and melting temperature are rather low [8].

The use of permanent ring magnet 3 (figure 1) provides a magnetic field distribution with a maximum field strength in the expanded region of trigger electrode 1, and this lengthens the paths of electrons and increases their interactions with the gas supplied to the discharge system. At the same time, due to the ability of a cathode spot to shift toward the acute angle the magnetic field lines make with the cathode, the spot is confined at the cathode surface by the magnetic field [9]. Therefore, in this magnetic field geometry, the cathode spot is held at the inner face of hollow cathode 4 facing trigger electrode 1 and provides stable operation of the discharge with decreasing minimum arc current. If the cathode spot leaves the working face of the cathode for its lateral surface, the discharge continues to operate because the magnetic field returns the cathode spot back to the cathode face.

It should be noted that in cathode assemblies based on a Penning cell [10], the arc discharge is constricted in the hole of one of the electrodes which, as a rule, is placed at floating potential, and this increases the discharge operating voltage. A plasma bunch surrounded by the electric double layer of the space charge, which provides electron acceleration and focusing, is normally formed from the cathode side of the constriction channel [11]. The typical voltage across the layer is 50–80 V and this provides a high ionizing capacity of electrons accelerated in the layer. The constriction channel produces an additional pressure difference between the plasma generation region and the high-voltage acceleration gap, thus allowing an increase in the dielectric strength of the latter. However, a decrease in gas flow rate or an increase in discharge current results in arc current cutoffs in the constriction channel, making possible the initiation and stable operation of a cascade arc at a comparatively high voltage but widely varying discharge current amplitudes and durations [10].

The constriction hole in the new cathode assembly is 4 mm in diameter which provides comparatively high discharge current densities at fixed durations with no arc current cutoffs, as opposed to cathode assemblies based on a Penning cell [10,12]. If we compare the current-voltage characteristics (figure 2) for low-pressure arc discharges with cathode assemblies based on a Penning cell [13] (curve 1), open arc [16] (curves 3,4), and arc produced in the proposed design (curves 2,5), it can be seen that the discharge operating voltage in the latter case is lower. The lower discharge operating voltage is due to the absence of external magnetic field effects on the main discharge, which actually decrease the anode area for the discharge current to take path through (compared to curve 1), and to the processes occurring in the cathode region of the discharge (compared to curves 3,4). In the new cathode assembly, the effect of the external magnetic field on the current of the main discharge is eliminated by using ferromagnetic insert 6 (figure 1) which precludes the magnetic flux from the permanent magnet in the hollow anode region of the main discharge.

With an external magnetic field, the ionization processes occurring in the cathode assembly, namely the enhanced interaction of primary magnetized electrons with atoms of the working and residual gas at a constant electron free path, lead to a decrease in the voltage across the near-cathode layer compared to the cathode assembly based on an open arc [6,7]. With no external magnetic field in the new cathode assembly, the discharge operating voltage increases (figure 2, curve 2) because the number of interaction events between the primary electrons and the working gas at the same electron free path length decreases. The chosen hole diameter (4 mm) in the proposed cathode assembly allows a decrease in the amount of microdroplets from the cathode to the plasma emitter and acceleration gap with no constriction-induced cutoffs of the discharge current at a low discharge operating voltage.

Life tests of the new cathode assembly show that compared to the cathode assembly with cathode spot initiation by a dielectric flashover, the increased mass of the cathode with its re-sputtering due to the hollow design and the absence of a dielectric insert on which the cathode material is deposited have made it possible to decrease the wear of the cathode and lengthen the time of stable operation of the cathode assembly to $\approx 10^7$ pulses.

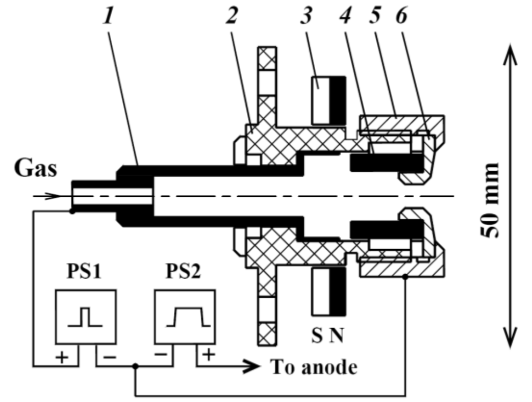

Figure 1. Cathode assembly: 1 – trigger electrode with gas supply, 2 – insulator, 3 – ring magnet, 4 – hollow magnesium cathode, 5 – stainless steel nut, 6 – ferromagnetic insert; PS1 – auxiliary discharge power supply, PS2 – arc discharge power supply.

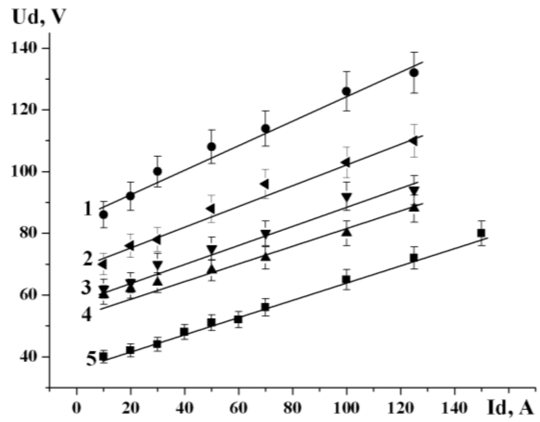

Figure 2. Current-voltage characteristics of arc discharges at p = 50 mPa (Ar) for different cathode assemblies: 1 – cathode assembly based on a Penning cell [13]; 3,4 – cathode assembly based on an open arc with a tungsten and magnesium cathode, respectively [7]; 2,5 – new cathode assembly with no and with a ring magnet, respectively.

3. Cathode assembly for an intense pulsed electron source

The cathode assembly was developed for a SOLO electron source [14–16]. The source is based on an arc discharge with a grid plasma cathode; the discharge current is I_d=20–300 A, the pulse duration is up to τ = 200 μs, the initial beam diameter is 40–60 mm. The cathode assembly is similar in its basic design and principle of operation to that shown in figure 1. Its modification brings the auxiliary discharge system closer to a reflex discharge (figure 3). Ring electrode 2 serves as the anode of the reflex discharge. Resistor Rc provides the formation of a cathode spot at main magnesium cathode 1 without its formation at auxiliary cathode 5. After the initiation of the cathode spot, the main arc discharge takes the path from cathode 1 through constriction channel 4 to an emission grid anode (not shown in the figure).

The change in the electrode configuration allowed us to decrease the pressure required for auxiliary discharge initiation from 5–10 to 0.2–0.3 Pa. The decreased requirements on the pressure difference in the discharge system made it possible to increase the diameter of 12-mm constriction channel 4 from 6 to 10–11 mm with a simultaneous decrease in the auxiliary discharge initiating voltage (figure 4). Till the instant at which the auxiliary discharge was ignited, the rate of voltage rise was 0.8 kV/μs. The discharge initiating voltage was fixed at the point of a steep voltage drop. Noteworthy is the effect of the anode geometry in the reflex discharge on its initiating voltage. In experiments, the anode width was 6 and 23 mm. The anode of larger size made it possible to decrease the auxiliary discharge initiating voltage at low gas (Ar) pressures but somewhat impaired the conditions for discharge ignition in the operating pressure range of the electron source (p = 25–100 mPa).

The increase in the diameter of channel 4 allowed us to stabilize the arc discharge at low pressures and to increase its maximum current, which was limited before the modification (in part of the pulses) by cutoffs of the discharge current at low gas flow rates and pressures in the discharge system (figure 5). On cutoffs of the discharge current, the rate of current rise is defined by the inductance of the isolation transformer in the discharge power supply; the transformer is also responsible for the voltage polarity reversal in the discharge gas on completion of the discharge current pulse. The amplitude of the discharge current with no cutoffs for the channel of diameter 11 mm is no less than I_d = 300 A (figure 6). Figure 7 presents current-voltage characteristics of the main arc discharge for the cathode assembly before and after the modification. The increase in the discharge operating voltage U_d with decreasing discharge current can be due to a decrease in the no-load voltage of the arc power supply and associated impairment of the discharge operating conditions. The arc discharge operating voltage U_d depending on the pressure p is shown in figure 8. It is seen that the pressure dependence of the voltage is strong.

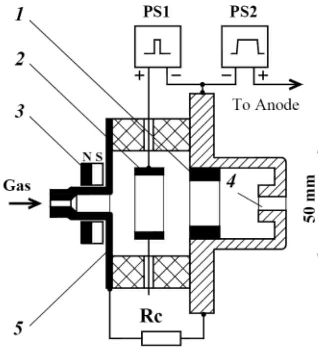

Figure 3. Cathode assembly with arc initiation by a reflex discharge. 1 – Mg cathode, 2 – anode, 3 – permanent magnet, 4 – constriction channel, 5 – auxiliary cathode. PS1 – auxiliary discharge power supply, PS2 – arc discharge power supply.

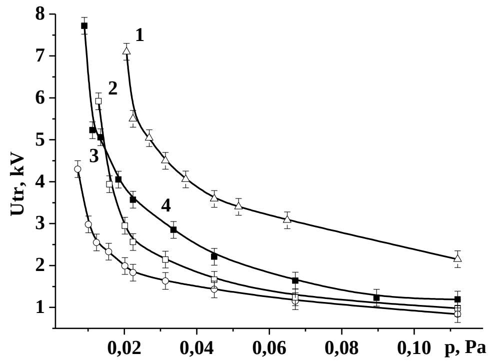

Figure 4. Auxiliary discharge initiating voltage Utr vs the pressure p at a constriction channel diameter of 6 (1), 11 (2), 10 (3), and 11 mm (4); the width of the reflex discharge ring anode is increased from 6 to 23 mm.

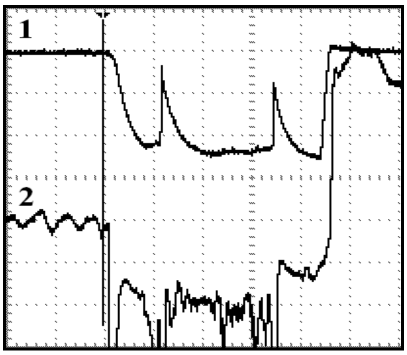

Figure 5. Typical waveforms of the discharge current I_d (1) and voltage U_d (2) for the non-modifed cathode assembly at p = 45 mPa. Scale: 100 A/div, 50 μs/div, 40 V/div.

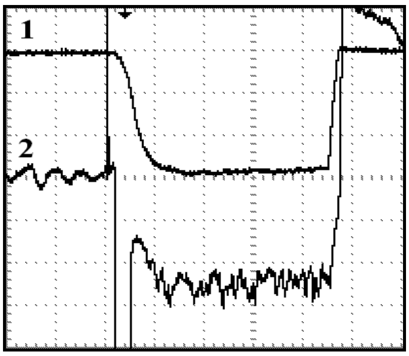

Figure 6. Typical waveforms of the discharge current I_d (1) and voltage U_d (2) for the modified cathode assembly at p = 45 mPa. Scale: 100 A/div, 50 μs/div, 40 V/div.

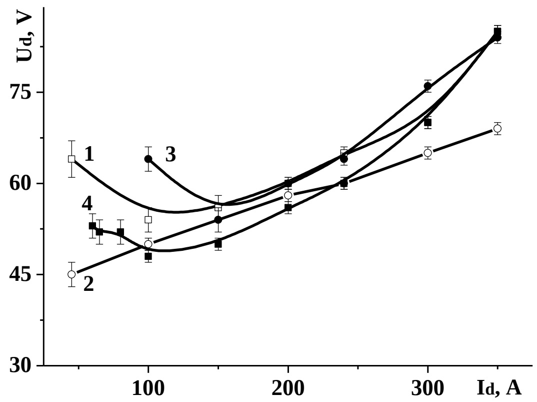

Figure 7. Current-voltage characteristics of the arc discharge for the cathode assemblies with a constriction channel diameter of 6 (1,2) and 11 mm (3,4) at p=0.067 Pa (1,3) and p=0.11 Pa (2,4).

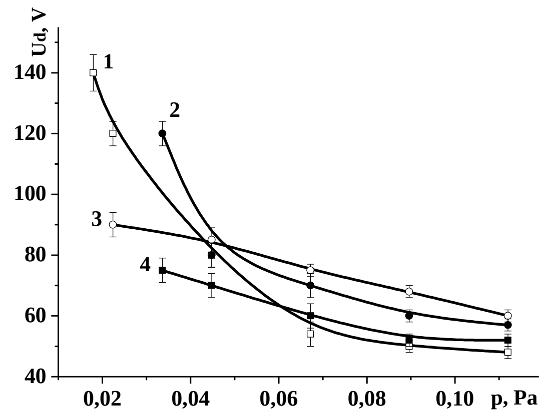

Figure 8. Arc discharge operating voltage Ud vs the pressure p at a discharge current of 150 (1,4) and 250 A (2,3) for the cathode assemblies with a constriction channel diameter of 6 (2,4) and 11 mm (1,3).

4. Conclusion

Thus, the modification of the cathode assemblies of electron sources through changing the mechanism of cathode spot initiation (the use of a gas discharge and a reflex discharge, instead of a dielectric flashover) and through optimizing the constriction channel for a specific operating range of the plasma cathode discharge systems made it possible to greatly improve the operation of the devices. The operating current range of the discharge systems was extended and the time of stable operation of the electron sources in the mode of electron beam generation was increased.

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References

[1] Kreindel Yu E 1977 Plasma Electron Sources (Moscow, Atomizdat) (in Russian)
[2] Koval N N, Oks E M, Protasov Yu S, Semashko N N 2009 *Emission electronics* (Moscow, MGTU) (in Russian)
[3] Mesyats G A 2011 *Explosive Electron Emission* (Moscow: Izd. Fiz. Mat. Lit.) (in Russian) 280 pp.
[4] Gavrilov N V, Kovalchuk B M, Kreindel Yu E, Tolkachev V S, Schanin P M 1981 Plasma-emitter high-voltage electron source for generation of large-cross-section beams *J Prib. Tekh. Eksp* **24** Issue **3(2)** 727
[5] Vorob'ev M S, Denisov V V, Koval' N N, Shugurov V V, Yakovlev V V, Uemura K and Raharjo P 2015 Radiation Processing of Natural Latex Using a Wide Aperture Electron Accelerator with a Plasma Emitter *J High Energy Chemistry* **49**, Issue 3 143
[6] Koval N N, Kreindel Yu E, Месяц G A, Tolkachev V S, Schanin P M 1983 Efficient use of a low-pressure arc in a grid plasma electron emitter *J Pis'ma Zh. Tekh. Fiz.* **9** Issue 9 568
[7] Koval N N, Kreindel Yu E, Tolkachev V S, Schanin P M 1985 The effect of gas on the development of a vacuum arc with a hollow anode. *IEEE Transactions on electrical insulation V.EI-20* **4** 735
[8] Gulyaev A P. 1986 *Metal Science. Textbook for higher educational institutions, 6rd ed., rev. ad.* (Moscow, Metallurgia) (in Russian) 544 p.
[9] Andreev A A, Sablev L P, Grigoryev S N 2010 *Vacuum arc coatings* (Kharkov, NSC KIPT) (in Russian) 318 p.
[10] Kreindel Yu E, Oks E M, Schanin P M 1984 Plasma-emitter pulsed electron source based on a cascade arc. *J Prib. Tekh. Eksp.* **4** 127

Journal of Physics: Conference Series **652** (2015) 012066 doi:10.1088/1742-6596/652/1/012066

[11] Zlobina A F, Kazmin G S, Koval N N, Kreindel Yu E 1980 Plasma parameters in the expander of an electron emitter with a constricted arc discharge *J Zh. Tekh. Fiz.* **50** Issue 6 1203
[12] Gavrilov N V, Kreindel Yu E, Oks E M, Schanin P M 1983 Transition of a low-pressure arc discharge from constricted to cascade mode *J Zh. Tekh. Fiz.* **53** Issue 10 1947
[13] Gavrilov N V, Kreindel Yu E, Schanin P M 1984 Pulsed electron source based on a non-self-sustained high-voltage glow discharge *J Prib. Tekh. Eksp.* **2** 143
[14] Koval' N N, Shchanin P M, Devyatkov V N, Tolkachev V S, and Vintizenko L G 2005 A Facility for Metal Surface Treatment with an Electron Beam *J Instruments and Experimental Techniques*, **48** Issue **1** 117
[15] Koval N N, Devyatkov V N, Grigoryev S V, Sochugov N S 2006 'SOLO' Plasma electron source *Proc.II Intern. Kreindel Workshop «Plasma emission electronics»* (Ulan-Ude: Russia) 79
[16] Grigoriev S V, Devjatkov V N, Koval N N and Teresov A D. 2008 The automated installation for surface modification of metal and ceramic-metal materials and products by intensive pulse submillisecond electron beam *Proc. 9th Intern. Conf. on Modification of Materials with Particle Beams and Plasma Flows* (Tomsk: Russia) 19