Effect of electron extraction from a grid plasma cathode on the generation of emission plasma

V N Devyatkov\textsuperscript{1,*} and N N Koval\textsuperscript{1,2}

\textsuperscript{1} Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russian Federation
\textsuperscript{2} National Research Tomsk State University, 36 Lenin Ave., Tomsk, 634050, Russian Federation

E-mail: vlad@opee.hcei.tsc.ru

Abstract. The paper describes the operating mode of a plasma electron source based on a low-pressure arc discharge with grid stabilization of the plasma emission boundary which provides a considerable (up to twofold) increase in discharge and beam currents at an Ar pressure in the vacuum chamber $p = 0.02$–0.05 Pa, accelerating voltages of up to $U = 10$ kV, and longitudinal magnetic field of up to $B_z = 0.1$ T. The discharge and beam currents are increased on electron extraction from the emission plasma through meshes of a fine metal grid due to the energy of a high-voltage power supply which ensures electron emission and acceleration. The electron emission from the plasma cathode and arrival of ions from the acceleration gap in the discharge changes the discharge plasma parameters near the emission grid, thus changing the potential of the emission grid electrode with respect to the discharge cathode. The load is not typical and changes the voltage polarity of the electrode gap connected to the discharge power supply, which is to be taken into account in its calculation and design. The effect of electron emission from the plasma cathode on the discharge system can not only change the discharge and beam current pulse shapes but can also lead to a breakdown of the acceleration gap and failure of semiconductor elements in the discharge power supply unit.

1. Introduction

Grid stabilization of the plasma emission boundary has rather long been used in plasma-cathode electron sources. The authors of [1] considered the generation of pulsed electron beams with high current density ($j = 1$–10 A/cm$^2$). The basic processes involved in electron emission from plasma were considered elsewhere [2–4]. The grid stabilization method, which is applied to provide stable electron emission from a plasma cathode, assumes the use of a grid with a mesh size comparable to the extent of the space charge layer separating the plasma from anode and emission grid electrode. Electrons, in this case, are emitted from a partially open plasma surface in the center of grid meshes and through a potential barrier at their edges. The operating mode of the cathode is stabilized because the Langmuir layer thickness separating the plasma from the grid increases with an arbitrary increase in electron emission current and the emitting plasma surface area decreases with an increase in plasma potential. The electron emission from the plasma can change not only the plasma potential but also other plasma parameters, resulting in unstable operation of the discharge (which generates the emission plasma), high-frequency oscillations [5, 6], change in the plasma concentration, and attendant change in the discharge current. Besides, the maximum parameters of plasma-cathode electron sources are much...
affected by the ion current from the anode (beam) plasma surface formed through ionization of working gas and gas desorbed from the electrodes (anode, collector, drift tubes) to which the beam current takes its path [7, 8]. This plasma serves as a plasma anode and defines in many respects the main characteristics of an electron source.

The paper considers the mode of electron extraction from a plasma cathode based on a low-pressure arc discharge with grid stabilization of the plasma emission boundary which, in the presence of a longitudinal magnetic field in the emission grid electrode region, provides a considerable increase in discharge current amplitude compared to the mode with no electron extraction from the plasma cathode. The experimentally observed increase in discharge current, which is due to the energy brought into the discharge power supply circuit by an accelerating voltage source, provides an increase in emission current from the plasma cathode. The arising positive feedback induces a simultaneous increase in discharge and emission currents, and this can result in failure of the plasma cathode operation due to uncontrollable changes of the electron beam parameters and in a breakdown of the acceleration gap. This mode of plasma cathode operation, associated with discharge power supply parameters and electron emission from the plasma through emission grid meshes, can be considered as one of the factors that limit the maximum characteristics of energy complexes comprising a plasma cathode, power supply units, and accelerating voltage source. The processes occurring in the emission grid electrode region should be taken into account in designing both plasma emitters and their power supplies. Understanding these processes will allow one to more accurately define the requirements on power supply parameters, disclose the causes for emergency operation of semiconductor elements which leads to their failure, and determine the ways of increasing the operation stability of grid-stabilized plasma cathodes and their maximum parameters.

2. Experimental setup
In the experiments, an electron source with a grid plasma cathode was used [9, 10]. Schematic of the electrode and discharge power supply circuits is shown in figure 1. In this system, an arc discharge cathode spot is initiated on magnesium cathode \( I \) by a pulse from the secondary winding of transformer \( TR1 \) having a voltage amplitude of up to 10 kV and current amplitude \( I_d = 10 \) A at a pulse duration \( \tau = 30 \) \( \mu \)s. The main arc discharge (current \( I_0 \)) is powered through isolating transformer \( TR2 \). A partial discharge of storage capacitor \( C_2 \) is used. The discharge current pulse is formed when switch \( S_1 \) is closed. The discharge current amplitude is determined by the voltage across capacitor \( C_2 \) and is limited by ballast resistor \( R_b \). Also shown in the figure are elements \( D_1, C_1 \) and \( D_2, R_i \) (protection elements of switch \( S_1 \)) which, along with \( TR2 \), can influence the arc discharge current pulse shape. The pulse voltage \( U_d \) across the gap between the cathode and grid electrode \( 3 \) is controlled with a Rogowski coil from the current in resistor circuit \( R_i \). The plasma cathode discharge system is partially placed in a divergent magnetic field of solenoid 7 which provides \( B_z = 0.1 \) T in the coil centre (in the emission grid region, \( B_z = 35 \) mT). Solenoid 6 creates a field of \( B = 25 \) mT in the region of collector 5. The electron beam is extracted through an emission window of diameter 60 mm covered with a stainless steel grid with a mesh of 0.3 x 0.3 mm and is transported in drift tube 4 of diameter 80 mm to collector 5 located 250 mm away from grid electrode 3.

---

**Figure 1.** Electrode and power supply circuits of the plasma-cathode electron source: 1 – cathode; 2 – anode insert of diameter 80 mm; 3 – emission grid electrode; 4 – drift tube; 5 – collector; 6, 7 – solenoids. \( R_1 = 100 \) \( \Omega \), \( R_2 = 20 \) \( \Omega \), \( R_3 = 2.3 \) \( \Omega \), \( R_i = 4.9 \) \( \Omega \), \( R_b = 1.25 \) \( \Omega \), \( C_1 = 1 \) \( \mu \)F, \( C_2 = 570 \) \( \mu \)F, \( C_b = 6 \) \( \mu \)F.
The electron source has two important peculiarities: operation with a plasma anode [11] and considerable ion current from the acceleration gap to emission electrode $J$. The ion flow governs the secondary ion-electron emission from the grid electrode surface with attendant increase in total current in the acceleration gap [8] and the ion injection from the acceleration gap into the plasma cathode discharge system.

3. Results and discussion

Figure 2 shows typical waveforms of the discharge current $I_d$ and voltage $U_d$ (between electrodes $I$ and $J$) at an initial voltage $U_{c2} = 400$ V across capacitor $C_2$ and accelerating voltage $U_{cb} = 0$. In this mode, almost the whole discharge current takes the path to emission electrode $J$. At $p = 0.07$ Pa, the discharge gap voltage $U_d$ increased from 20 to 70 V as the discharge current $I_d$ increased from 80 to 280 A. Figure 3 (a) shows a simplified discharge circuit. In this case, the load for the power supply is nonlinear load $RD$ (discharge resistance) on which the voltage $U_{rd}$ varies in the range 20–70 V. The current in the $D_2R_d$ circuit starts flowing only at the instant the discharge current pulse ends. The dependence of $U_d$ on the operating pressure for the mode with no electron extraction from the plasma cathode is shown in figure 4 (curves 3, 4).

As an accelerating voltage $U_{cb} = 10$ kV is applied and electrons are extracted from the plasma through the fine grid meshes, which stabilize the plasma emission boundary, the discharge current switches from the emission electrode to the acceleration gap and the voltage $U_d$ changes its polarity (figure 4, curves 1, 2). In this case, the discharge circuit (figure 3 (b)) has, along with load $RD$, an additional voltage source $E > U_{rd}$ which increases the current $I_d$ (from 152 to 218 A). Waveforms of the currents $I_d, I_b$ and voltage $U_d = U_{rd} + E$ for this mode are presented in figure 5. The voltage source $E$ is the potential difference between the anode discharge plasma and the emission grid electrode. The maximum voltage $E$ in the experiments was $E \geq 1$ kV. This voltage was obtained with the discharge circuit shown in figure 6. Oscillogram 1 (figure 6) reveals an instant (no longer than $\sim 2 \mu$s) sharp increase in the current $I_d$ due to a jump of the voltage $E$ immediately before breakdown of the acceleration gap.

Despite the positive feedback, which simultaneously increases the discharge and emission currents due to the energy of the acceleration gap power supply, rather good pulse shape reproducibility of the discharge and emission currents is observed in the examined operating parameter range of the electron source. It is seen from the oscillograms that the voltage $U_d$ (of positive polarity) increases with increasing the discharge current, magnetic field, and gas pressure. The discharge and emission currents cease to increase once the increase in $U_d$ ceases. Besides, on cutoffs of the discharge current (with subsequent repeated discharge ignition and current recovery), a steep increase in $U_d$ by 20–40 V is observed. A characteristic peculiarity is that $U_d$ decreases by the end of the pulses and oscillations of $U_d$ arise on the oscillogram (figure 5, curve 3).

The operation of the electron source in the plasma anode mode defines a rather weak dependence of the discharge current on accelerating voltage. As the voltage $U_b$ is decreased from 10 to 4 kV, the beam current and the voltage $U_d$ decrease by no more than 5 %. A rather strong pressure dependence of $U_d$ (figure 4) allows the assumption that the effect of emission from the plasma cathode on the discharge circuit is defined mainly by the accelerated ion flow arriving through the grid meshes from the acceleration gap in the plasma cathode.

The voltage $U_d$ of reversed polarity (figure 4) is, in fact, equivalent to cutoff voltage applied to the emission grid of the plasma cathode. However, this cannot decrease the emission current under our conditions, because $U_d$ changes precisely due to electron emission processes, but can probably be a factor that somewhat limits the increase in currents. On the other hand, the position of the plasma emission boundary in the grid meshes provides efficient electron emission from the plasma and most of the electron current not to the emission grid but to the acceleration gap through its meshes. The accelerating voltage source and the discharge power supply, in this case, are connected in series.
A change in the grid electrode potential with respect to the discharge plasma can cause not only an increase in discharge current. An increase in plasma potential can lead to a breakdown of the plasma-anode (grid electrode) gap, resulting in cathode spots at the emission electrode surface or directly at the emission grid. This is confirmed by cathode spot erosion traces on the emission electrode surface and by occasional substantial short-time growth of \( I_d \) on the oscillograms of the currents \( I_d, I_b \) (figure 7) which does not, however, lead to a breakdown of the acceleration gap. It is seen that at the instant the beam current \( I_b \) increases, the discharge current \( I_d \) remains almost unchanged. It should be noted that if a cathode spot arises at the emission grid, the attendant steep rise of \( I_b \) is more likely to result in a breakdown of the acceleration gap, making this mode difficult to record. With the discharge circuit shown in figure 1 and \( R_2 = 0 \), we managed to obtain a stably reproducible mode in which it was possible to detect the incipience of a cathode spot at electrode 2, being, in this case, part of the emission electrode. Figure 8 shows a fragment of oscillograms (early in the pulse) for the currents \( I_d, I_b, (2) \) and anode insert current (3). Analysis of these oscillograms allows the conclusion that at the instant the emission current reaches \( I_b \approx 200 \) A, a cathode spot arises at electrode 2 and an additional arc discharge (in addition to the main discharge) is ignited between electrode 2 and anode discharge plasma such that the arising additional electron current takes the path through the acceleration gap: the total emission current \( I_b \) increases along with the current of electrode 2. The instant at which the emission current becomes higher than \( I_b = 400 \) A can probably be considered as the onset of breakdown of the acceleration gap.

The influence of electron emission on the generation of emission plasma can not only show up during the formation of the main beam current pulse but can also lead to another undesirable effect. With xenon (instead of argon) at high operating pressures, spurious repeated pulses of the discharge and electron beam currents are observed at times. Such pulses, having parameters different from the operating ones, are inadmissible for some applications of the electron source (e.g., for pulsed electron beam surface modification). The repeated pulses arose within ~ 100 \( \mu \)s after the end of the main discharge pulse at the instant storage capacitor \( C_2 \) in the discharge power supply started to be charged. When capacitor \( C_2 \) was charged, voltage of opposite polarity was applied to the electrodes of the plasma cathode discharge system which provoked the ignition of a discharge. Due to the effect of electron emission from the plasma cathode on the discharge circuit, repeated discharge current pulses and corresponding beam current pulses were formed. The parameters of the pulses unambiguously suggested that they were formed mainly due to the energy of the accelerating voltage source (the rise and fall times of the discharge current pulses were extended; their duration and amplitude differed from the parameters provided by the discharge power supply).
Figure 4. Voltage $U_d$ vs pressure $p$ in the emission grid region: $U_{cb} = 10$ kV (1,2); $U_{cb} = 0$ (3,4); $I_d = 250$ A (1,4); $I_d = 150$ A (2,3); $B_g = 25$ mT.

Figure 5. Typical waveforms of the currents $I_d$ (1), $I_b$ (2) and voltage $U_d$ (3). $B_g = 25$ mT, $p = 0.1$ Pa, $U_{cb} = 10$ kV.
Scale: 100 A/div, 50 μs/div, 40 V/div.

Figure 6. Waveforms of the currents $I_d$ (1) and $I_b$ (2) and discharge circuit in which $E \geq 1$ kV; $L = 20$ μH, $R = 0.7$ Ω, $C = 50$ μF ($U_c = 200$V). Scale: 100 A/div, 25 μs/div.

Figure 7. Waveforms of $I_d$ (1) and $I_b$ (2) for the discharge circuit in figure 6. Scale 100 A/div, 25 μs/div.

Figure 8. Fragment of waveforms of $I_d$ (1), $I_b$ (2), and current of electrode 2 (3) for the circuit in figure 1 at $R_2 = 0$. Scale: 100A/div, 10 μs/div.

4. Conclusion
The considered effects of electron emission from the plasma cathode on the generation of emission plasma often lead to uncontrollable changes in the electron beam parameters (pulse shape and current amplitude) and can be the factors that limit the maximum parameters of the electron source. At the same time, they can probably be used for increasing the efficiency of emission plasma generation due to the energy redistribution between the power supplies of the acceleration and discharge gaps.

The observed amplification of the discharge current depends on the voltage of the discharge power supply, its output resistance, and also on the grid geometry (mesh size), acceleration gap width, and high voltage applied to the gap. Low voltage and output resistance of the discharge power supply causes a substantial increase in discharge current. So, with seven concurrently operating arc discharge
power supplies based on storage capacitors and ballast LR circuits at a charge voltage of 80 V (figure 6), the total discharge current increased from 120 to 300 A on applying the accelerating voltage. The current amplitude, in this case, failed to reach its maximum value due to breakdown of the acceleration gap. Stabilizing the discharge current requires a power supply with parameters approximating as close as possible those of a perfect current source. If it is required to have power supplies with high efficiency, they can probably be based on circuits with inductive energy stores, which efficiently stabilize load currents.

The described effect of electron emission on the generation of emission plasma results in two types of additional voltage present in the discharge power supply circuit: relatively low voltage in normal pulse formation mode and short high-amplitude voltage pulses arising with a steep increase in emission current before breakdown of the acceleration gap (figure 6). The generation of such pulses defines the necessity to use additional protective circuits in discharge power supplies. At the same time, the presence of protective elements in discharge power supplies can add to the increase in discharge current because these circuits decrease the output resistance of the power supplies.

This work was partially supported by program of the Presidium of RAS No. 12 and RFBR project No.13-08-98108.

References
[1] Koval N N, Kreindel Yu E, Schanin P M 1983 Generation of pulsed electron beams with uniform high current density distribution in systems with a grid plasma emitter J Zh. Tekh. Fiz. 53 Issue 9 1846
[2] Zharinov A V, Kovalenko Yu A, Roganov I S, Tyuryukanov P M 1986 Plasma electron emitter with grid stabilization I J Zh. Tekh. Fiz. 56 Issue 1 66
[3] Zharinov A V, Kovalenko Yu A, Roganov I S, Tyuryukanov P M 1986 Plasma electron emitter with grid stabilization II J Zh. Tekh. Fiz. 56 Issue 4 687
[4] Koval N N, Oks E M, Protasov Yu S, Semashko N N 2009 Emission electronics (Moscow, MGTU)
[5] Gavrilov N V, Emlin D R, Kamenetskikh A S 2008 High - efficiency emission from a grid-stabilized plasma cathode J Zh. Tekh. Fiz. 78, Issue 10 59
[6] Gavrilov N V, Kamenetskikh A S 2013 Self-oscillating mode of electron beam generation in a source with a grid plasma emitter J Zh. Tekh. Fiz. 83 Issue 10 32.
[7] Astrelin V T, Kandaurov I V, Trunev Yu A 2014 Generation of a submillisecond beam of high current density in a plasma-cathode diode with emission from an open plasma boundary J Zh. Tekh. Fiz. 84 Issue 2 106
[8] Koval N N, Grigoryev S V, Devyatkov V N, Teresov A D, Schanin P M 2009 Effect of Intensified Emission During the Generation of a Submillisecond Low-Energy Electron Beam in a Plasma-Cathode Diode IEEE Transactions on Plasma Science 37 1890
[9] Koval N N, Devyatkov V N, Grigoryev S V, Sochugov N S 2006 Plasma electron source «SOLO» Proc.II Intern. Kreindel Workshop «Plasma emission electronics» (Ulan-Ude: Russia) 79
[10] Grigoriev S V, Devyatkov 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
[11] Devyatkov V N, Koval N N and Schanin P M 2001 Generation of high-current low-energy electron beams in systems with plasma emitters J Russian Physics Journal 44 No.9 937