Maximal current of a pulsed constricted arc discharge operating in the forevacuum plasma electron source

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Abstract. The paper presents results of investigation of maximal current of the pulsed constricted arc discharge generating emission plasma in the forevacuum plasma electron source. Distinctive feature of the forevacuum plasma electron source is the absence of pressure differential between region of formation of emission plasma and the region of acceleration and propagation of electron beam. Therefore, the operating conditions of the constricted arc in the forevacuum plasma source are significantly different from the conditions in the plasma electron sources generating electron beams at pressure 10⁻³–10⁻¹ Pa. The constriction of the positive column of the arc discharge provides, as it known, to reduce influence of instability and chaotic behavior of the cathode spot of the arc on the formation of emission plasma. In the investigated pressure range 3–20.5 Pa, the maximal current of the constricted arc discharge has been limited either by extinction of the arc or by initiation of the cathode spots on the constricting electrode and transition of the arc operation to the cascade mode. Increase of gas pressure and the use of working gas with large ionization cross section (e.g. argon) have provided increase of the maximal arc current. The increase in the constricting channel diameter has provided the increase of maximal current and provided lower minimal gas pressure, at which stable operation of the constricted arc ensured. The decrease of length of the constricting channel has provided noticeable increase in the maximal arc current only at gas pressure more than 12 Pa.

1. Introduction

Plasma electron sources provide generation of pulsed and continuous electron beams in a wide range of gas pressure and in the presence of active gases (nitrogen, oxygen, etc.) [1–5]. The ability to operate in these gas conditions is one of the advantages of the plasma electron sources compared to thermionic (hot cathode) electron guns. In particular, forevacuum plasma electron sources provide generation of the low-energy (up to 25 keV) electron beams in the previously inaccessible pressure range from 1 to 100 Pa [4, 5]. Generation of the electron beams in the forevacuum pressure range has provide to treat electrically non-conductive materials (ceramics, polymers and glasses) directly by the electron beam [6, 7], and also provided generation of rather dense beam-produced plasma in various gases [8–10]. This beam-produced plasma can be used to treat materials [10] and as a source of gas ions with low energy [9].

The parameters of the plasma electron sources are greatly determined by the features of the emission plasma from which the electrons, forming the electron beam, are extracted. Usually different
types of self-sustained and non-self-sustained gas discharges are used to generate emission plasma [1–3]. In particular, an arc discharge with a cathode spot (cathodic arc) is used often enough to generate emission plasma in pulsed plasma electron sources [1, 3]. Despite useful advantages (high discharge current, long pulse duration, etc.), the cathodic arc has drawbacks caused by the operation features of the cathode spot [11]. For example, the chaotic movement of the cathode spot can significantly disturb the uniformity of the density distribution of the emission plasma, and the flow of macro-particulates (small droplets) and vapor of the cathode material, which are formed during the cathode spot operation, can penetrate into accelerating gap. The last reduces the electric strength of the accelerating gap of plasma electron source. A constricted arc discharge is used to reduce these negative influence of the cathode spot operation [3, 12–14]. Usually an auxiliary metal electrode, which has constricting channel, is used to constrict positive column of arc discharge between a cathode and an anode in the plasma electron sources. The diameter of 1.5–6 mm and length of 2–6 mm are common sizes for the constricting channel. The features and operation parameters of the constricted arc discharge have been studied in the plasma electron sources generating electron beams in the standard gas pressure range of $10^{1–10^{2}}$ Pa [3, 12–14].

Introduction of the constricted arc discharge to generate emission plasma in the forevacuum plasma electron source, generating pulsed large-radius electron beam, is attractive task, and the features of the constricted arc for this case have not been previously studied. The aim of this work has been to investigate the stable maximal current of the constricted arc discharge operating in the forevacuum plasma electron source of pulsed large-radius electron beam.

2. Experimental setup and techniques

A scheme of electrodes of the forevacuum plasma electron source for the investigation of the constricted arc discharge is shown in figure 1. The cathode assembly consists of a cylindrical copper cathode 1 with a diameter of 6 mm, a ceramic insulator 2, an igniter electrode 3 and a current lead 4. The current lead and the igniter electrode are made of stainless steel. The cathode assembly is mounted on an insulator 5 made of polyamide. The constriction of the positive column of the arc discharge has been provided by two planar electrodes (constricting electrodes) 6 and 7 with coaxial holes. The constricting electrodes are made of stainless steel and are 1 mm thick each. Both constricting holes are aligned with the cathode symmetry axis. The diameters of the constricting holes $d$ have been varied from 2 mm to 4 mm (the diameters of the constricting holes in the electrodes 6 and 7 have been identical). The electrical separation of the constricting electrodes has been provided by an insulator 8. The constricted electrodes have been interconnected by a conductor. The distance between the constricting electrodes has been varied from 0.5 mm to 2.5 mm, which ensured the length of the constricting channel $h$ from 2.5 mm to 4.5 mm, respectively. The hollow cylindrical anode 9 with inner diameter of 114 mm and a height of 150 mm is made of stainless steel. The anode has a hole with a diameter of 40 mm on the side facing to the constricting electrode 7. An insulator 10 provides isolation of the constricting electrodes from the anode. Both constricting electrodes have been under the floating potential. On the opposite side to the cathode assembly, the anode bottom end has been covered by stainless steel mesh 11.

The plasma electron source has been placed on a flange 12 of a vacuum chamber, which has been pumped out by a roughing pump. The pump has provided minimal gas pressure 2.5 Pa. Operating pressure $p$ in the range of 3–20.5 Pa has been regulated by the gas flow rate into the vacuum chamber at constant pumping rate. Argon (Ar), nitrogen (N$_2$) and helium (He) have been used as working gases. In the plasma electron sources generating electron beams at pressure $10^{-3–10^{2}}$ Pa, working gas was injected into the cathode region of the constricted arc, therefore, the pressure in the cathode region could reach 10 Pa, but the gas came into the hollow anode (or expander) through the constricting channel, and the pressure in the hollow anode did not exceed 0.1 Pa [3, 12–14]. The forevacuum plasma electron sources usually operate in isobaric mode, i.e. the pressure in the vacuum chamber and in the source are the same. Therefore, in the present work, the gas pressure in vacuum chamber and pressure in the hollow anode have been equal, i.e. pressure in the anode has been 2–3 orders of
magnitude higher as compared to [3, 12–14]. Moreover, gases have penetrated into the cathode region through the constricting channel from the hollow anode.

The constricted arc discharge has been powered using a pulsed power supply unit, which provides discharge current $I_d$ of up to 150 A. In the experiments, the pulse duration has been 110 μs, and the pulse repetition rate has been 1 Hz. The discharge current $I_d$ has been measured by current transformer “Pearson”, and the arc voltage $U_d$ has been measured by the oscilloscope voltage prob “Testec”. The maximal current $I_{d,max}$ of the constricted arc discharge is limited on the one hand by arc current break (current fall to 0 A, and discharge extinction), and on the other hand, by a transition of arc operation to the cascade mode [3, 12–14]. In the cascade mode, cathode spots appear on the constricting electrode, and main part of discharge current passes though these cathode spots operating on the constricting electrode. To register the transition of the arc operation from the constricted mode to the cascade mode, the current $I_c$ between the constricting electrodes 6 and 7 has been measure by a current transformer. The transition of the arc to the cascade mode leads to the current $I_c$ arises between the electrodes 6 and 7. The value of current $I_c$ can reach value close or equal to the discharge current $I_d$ in the cascade mode. The maximal current $I_{d,max}$ of the constricted arc discharge has been determined as the discharge current at which the probability of extinction of the arc discharge or transition of the arc operation to the cascade mode has not exceed 3%. This probability has been estimated as the ratio of the quantity of pulses in which the arc discharge has went out or has transited to cascade mode to the total quantity of pulses.

![Scheme of the experimental setup](image1)

**Figure 1.** Scheme of the experimental setup: 1 – cathode; 2 – ceramic insulator; 3 – igniter electrode; 4 – current lead; 5 – insulator; 6 and 7 – constricting electrodes; 8 – insulator; 9 – hollow anode; 10 – insulator; 11 – stainless steel mesh; 12 – flange of the vacuum chamber; 13 – pulsed power supply unit; 14 – isolator; 15 – arc plasma.

### 3. Experimental results and discussion

For our experimental conditions, the use of helium as working gas has not provided the stable operating of the constricted arc discharge. In case of using helium, at discharge current $I_d$ up to 15 A, current falls (down to 0 A) and arc extinctions have been observed; at discharge current $I_d > 15$ A, the probability of the transition of the arc discharge to the cascade mode has been high. The use of nitrogen and argon has provided stable operation of the constricted arc.

Figure 2 shows typical pulse shapes of arc discharge current $I_d$ and arc voltage $U_d$. The investigation of the pulse shapes of current and voltage has showed that the arc voltage $U_d$ increases during the pulse, and the discharge current decreases. At constant gas pressure $p$, the voltage $U_d$ growth rate increases with increasing the discharge current $I_d$ on the other hand, current decrease rate increases with increasing the initial discharge current $I_d$. An increase in gas pressure $p$ has led to the
decrease of the voltage growth rate and has provided lower decrease in discharge current \( I_d \) during the pulse at the same initial arc current \( I_d \) (we have compared the pulse shapes with the same current \( I_d \) during 25 \( \mu \)s in the beginning of the pulse) (figure 2, b). In addition, the use of argon at the same pressure has provided smaller growth rate of voltage and smaller decrease of arc current during the pulse.

Figure 3 shows the dependence of the maximal current \( I_{d,\text{max}} \) of the constricted arc discharge on the gas pressure \( p \) at different diameters of the constricting canal \( d_c \) (hereinafter, values of \( I_{d,\text{max}} \) are averaged per pulse). An increase in pressure \( p \) has led to an increase in the maximal arc current \( I_{d,\text{max}} \).

For each value of diameter \( d_c \), there is minimal gas pressure \( p_{\text{min}} \) at which the constricted arc discharge still operates stably. At a gas pressure \( p \) less than \( p_{\text{min}} \), the arc discharge either has went out or has transitioned to the cascade mode. An increase in the diameter \( d_c \) has led to the increase in the maximal current \( I_{d,\text{max}} \) at the same gas pressure \( p \), and also has provided lower minimal pressure \( p_{\text{min}} \), i.e. has provided to extend the pressure range which provided stable operation of the constricted arc. For example, in case of using nitrogen and \( h_c = 4.5 \) mm, at diameter \( d_c = 2 \) mm the minimal gas pressure \( p_{\text{min}} \) has been 14 Pa, and at diameter \( d_c = 4 \) mm the pressure \( p_{\text{min}} \) has been 4.5 Pa (figure 3). Compared to nitrogen, the use of argon has provided higher maximal current \( I_{d,\text{max}} \) of the constricted arc at the same gas pressure \( p \) (figure 4). In addition, the use of argon has provided the stable operation of the constricted arc discharge at lower pressure \( p_{\text{min}} \). Decrease of the constricting channel length \( h_c \) has provided noticeable increase of the maximal current \( I_{d,\text{max}} \) only at gas pressure \( p > 12 \) Pa (figure 5).

![Figure 2. Pulse shapes of discharge current \( I_d \) and arc voltage \( U_d \) \((d_c = 3.0 \text{ mm}, h_c = 4.5 \text{ mm})\): \(a) - p = 8 \text{ Pa}; b) p = 15 \text{ Pa}\).](image1)

![Figure 3. Dependence of the maximal current \( I_{d,\text{max}} \) of the constricted arc discharge on the gas pressure \( p \) for nitrogen and \( h_c = 4.5 \text{ mm} \): \(1 - d_c = 2.0 \text{ mm}; 2 - d_c = 2.5 \text{ mm}; 3 - d_c = 3.0 \text{ mm}; 4 - d_c = 3.5 \text{ mm}; 5 - d_c = 4.0 \text{ mm}\).](image2)
The observed dependences can be explained by the change in gas conditions in the constricting channel during the arc current “passes” through it. As in works [3, 12, 13], this change in gas conditions is caused by the “electron pump-down” of gas from the constricting channel. In case of “electron pump-down” of gas, a decrease in gas density is caused by the removal of neutrals from the constricting channel due to elastic collisions of gas atoms and molecules with electrons accelerated in double electrostatic layer (this electrostatic layer appears near the constricting electrode on side facing to the cathode assembly), as well as due to escape of gas ions to the cathode region of the discharge. The increase in arc voltage $U_d$ is caused by the increase of voltage drop on the double electrostatic layer due to the decrease in the density of gas neutrals in the constricting channel during the pulse. The voltage drop on the double electrostatic layer increases to maintain ionization rate, and consequently to maintain arc current through the constricting channel. However, the arc current $I_d$ decreases if the density of gas neutrals falls rather fast during pulse. The maximal arc current $I_{d,max}$ is limited by the minimal density of gas neutrals in the constricting channel. When the minimal density is reached, the balance between the ion generation rate and the ion loss rate in the arc discharge is broken, and the arc current rapidly falls (down to 0). After this current fall, the constricted arc either goes off or transit to the cascade mode. Both these cases are considered inoperative for the generation of emission plasma.

The use of argon has provided higher $I_{d,max}$ and lower pressure $p_{min}$ due to Ar has the large ionization cross section as compared to N$_2$.

![Figure 4](image1.png)

**Figure 4.** Dependence of the maximal current $I_{d,max}$ of the constricted arc discharge on the gas pressure $p$ for $d_c = 2.5$ mm and $h_c = 4.5$ mm.

![Figure 5](image2.png)

**Figure 5.** Dependence of the maximal current $I_{d,max}$ of the constricted arc discharge on the gas pressure $p$ for nitrogen and $d_c = 3.0$ mm: 1 – $h_c = 2.5$ mm; 2 – $h_c = 3.5$ mm; 3 – $h_c = 4.5$ mm.
4. Conclusion
We have investigated the stable maximal current of the constricted arc discharge operating in the forevacuum plasma electron source of pulsed large-radius electron beam. The maximal current of the constricted arc discharge is limited either by extinction of the arc or by transition to the cascade mode. Increase of gas pressure and the use of gas with large ionization cross section have provided increase of the maximal arc current. The increase of the constricting channel diameter has provided the increase in maximal current and provided lower minimal gas pressure, at which stable operation of the constricted arc still ensured. The length of the constricting channel has had little effect on maximal current. Only at gas pressure more than 12 Pa, the decrease in the constricting channel length has provided noticeable increase of the maximal arc current.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (RFBR) under Grant No. 20-08-00123.

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