Measurement of plasma parameters in an electron source with a plasma cathode based on a low-pressure arc discharge

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Abstract. In the electron source with a grid plasma cathode based on a low-pressure arc discharge, the parameters of the emission plasma were investigated depending on the different conditions of its generation (type of gas, operating pressure, discharge current amplitude, resistance in the hollow anode circuit of a plasma emitter). For this purpose, a single cylindrical Langmuir probe was used. To measure the current-voltage characteristics of the probe, taking into account the features of the functioning of the electron source (galvanic isolation from high accelerating voltage, the use of high-voltage cables with high parasitic parameters, etc.), an automated measurement circuit was used, allowing for a relatively short time to collect high statistics of experimental data (depending on the frequency the impulses of the discharge current and their total number). To eliminate the influence of the parasitic parameters of the circuit, the measurement circuit was located in the maximum proximity to the generation space of the emission plasma (in a vacuum chamber), which significantly increased the accuracy of the experimental data obtained.

1. Introduction

Electron sources that allow the generation of electron beams of large cross-section with their output into the ambient atmosphere, are increasingly used in industry, medicine, agriculture and other areas of human activity [1–3]. That is why such electron accelerators are constantly being improved, and their development and modernization are primarily aimed at expanding the limit parameters of the generated beam and the stability of such electron sources as a whole.

According to the principle of operation, three basic types of electron accelerators can be distinguished: on the basis of thermal emission, explosive emission and emission of electrons from a gas-discharge plasma. Each of them has its own niche in the field of application. Thus, sources with thermal cathodes make it possible to obtain electron beams in a continuous mode or long pulses (about 1 s and more) with a heterogeneity over the beam section less than 10% [4]. Electron sources with explosive cathodes generate beams with the highest current density values for a nanosecond duration [5]. However, unlike electron sources based on thermal and explosive cathodes, plasma cathode sources are distinguished by relatively high emissivity, low inertia, good repeatability of current beam pulses during frequency operation of the source, high efficiency, etc. In addition, the emission of electrons from a gas-discharge plasma allows to generate electron beams with parameters that are independent of each other, which makes it possible to use such electron sources in a wider range of applications, and especially for experimental (search) purposes. One of the sources of this...
type is the object of study of this work – the electron source "Duet" with a grid plasma cathode based on a low-pressure arc discharge and a beam output to the ambient atmosphere. One of the key parts determining the stability of the whole source is the plasma cathode, and the gas-metal plasma generated inside the plasma cathode determines the parameters of the electron beam. In this regard, the purpose of this work was to determine the mechanisms of generation of emission plasma in an electron source with a grid plasma cathode under different gas and parametric conditions. In the near future, these studies will allow the modernization of the electron source to further expand its limiting parameters and increase the stability of its work.

2. Experimental procedure and results discussion

The research was conducted on a modernized pulsed wide-aperture electron source "Duet" with a grid plasma cathode [6]. The schematic diagram of the source is shown in figure 1. In a vacuum chamber with dimensions of 130×80 cm², a grid plasma emitter is fixed on the bushing insulator, at the ends of which there are two cathode assemblies based on a low pressure arc initiating a cathode spot by a discharge on the dielectric surface. The boundary of emission plasma is stabilized by an emission grid made of stainless steel with a cell size 0.4×0.4 mm². The extraction of electrons from the plasma and their acceleration occurs under the action of a constant high voltage up to 200 kV. Passing aluminum magnesium foil with a thickness of 30 μm, electrons form a 15×75 cm² beam in the atmosphere.

![Figure 1. Scheme of electron accelerator with grid plasma emitter.](image)

A characteristic oscillograms of currents and voltage during operation of the plasma generator are shown in figure 2, which shows a linear decrease in discharge current \( I_d \) (CH1) and also a decrease in current to the hollow anode \( I_{ha} \) (CH3) associated with switching the arc discharge to the emission grid.

The plasma parameters were determined using a cylindrical Langmuir probe with a diameter of 0.3 mm and a length of 5 mm. To measure the probe current-voltage characteristics (CVC), taking into account the features of the functioning of the electron source (galvanic isolation from high accelerating voltage, the use of high-voltage cables with high parasitic parameters, etc.), the scheme shown in figure 3 was used. To eliminate the influence of parasitic parameters, the measurement circuit was located in the maximum proximity to the beam generation space in the vacuum chamber (with the ability to be under the potential of a plasma cathode when an accelerating voltage is applied – however, in these experiments there was no accelerating voltage). Measurement of the probe CVC
was carried out using a microcontroller (MC) (voltage and current of the probe on the resistances $R_2$ and $R_{sh}$, respectively). Data transmission from the vacuum side was carried out in the pause between the generation of discharge current pulses in a digital code through the conductors of a high-voltage cable that supplies power to a 3.5 V microcontroller. The receiving MC, the 3.5 V supply circuit and the source of the pulse potential displacement of the probe were located in the high-voltage electrostatic screen from the atmospheric side along with the plasma cathode power supply circuit. Further, the data were transferred to a computer using fiber-optic communication channels.

To research the parameters of the emission plasma, a single plasma generator was used with the initiation of a cathode spot by an electrical breakdown over the dielectric surface. The mask on the top of the emission grid was absent (figure 1). The probe was installed on the side of the hollow anode of the plasma emitter to a depth of 60 mm at various distances from the plasma generator. To get each probe CVC 2000 points recorded. During one pulse of the discharge current, a single point was measured. So, at a pulse repetition rate of discharge current of 3 s$^{-1}$, it took about 10 minutes to obtain one probe CVC. After getting the set number of points, the arithmetic average of the probe current was performed for the same voltage values, and then the final probe CVC was obtained (figure 4).

The plasma parameters were calculated using the electron branch of the probe CVC. To obtain the electron temperature, the dependence of the natural logarithm of the electron current on the potential...
of probe was plotted. When calculating the obtained dependences, the typical plasma concentration was \( n \approx 5 \times 10^{10} \text{ cm}^{-3} \), while the temperature of the electrons reached \( T_e \approx 80 \text{ eV} \). Such high temperatures can be explained by the presence of high-energy electrons in the discharge [7]. Also from the CVC it can be seen that the plasma potential relative to the discharge anode is positive, and its typical value is \( \varphi \approx 150 \text{ V} \). The high positive potential of the plasma can be associated with its high temperature, as well as with a high ratio of anode area to cathode area \((S_a/S_c) \geq 3000\) [8].

![Figure 4. Probe CVC low-pressure arc discharge: discharge current \( I_d = 40A \), working gas pressure (Ar) \( p = 40 \text{ mPa} \).](image)

In work [7], devoted to the study of the operation of electron accelerators with an emitter based on a low-pressure arc discharge, using shielding a probe and measuring the energy spectrum, a high-energy electron produced in an emission plasma, most likely, in the cathode region of the discharge. The presence of a stream of fast electrons makes it difficult to determine the parameters of the plasma, as a result of which it was proposed to shield the probe from the electron flow from the cathode side of this discharge system.

The screen was made of stainless steel foil, 50 \( \mu \text{m} \) thick (figure 5). The screen, which is under floating potential, was removed from the collector part of the probe by 30 mm in order to cut off the flow of high-energy electrons without disturbing the plasma near the probe.

![Figure 5. Appearance (a) and construction (b) of a cylindrical probe with a screen: 1 – stainless steel foil tube; 2 – ceramics; 3 – stainless steel tube; 4 – probe; 5 – stainless steel foil screen.](image)

Depending on the mode of plasma generation as a result of the screening probe concentration was obtained \((1 \pm 5) \times 10^{10} \text{ cm}^{-3}\), the electron temperature is decreased to the range 20–45 eV, the plasma potential was 90–100 V (figure 6). Due to decrease as the electron temperature and the plasma potential it can be also confirmed a conclusion about the presence in the plasma arc of a high electron
flux with energy exceeding the discharge voltage, which is likely due to the hump of a potential in the cathode region that are described in [9, 10].

An increase in the amplitude of the discharge current leads to an increase in the plasma concentration, which is confirmed by an increase in the saturation current of the probe (figure 7). Owing to an increase in plasma concentration, a decrease in the electron temperature occurs, which is confirmed by an increase in the inclination angle of the probe CVC (figure 7), which is associated with an increase in the number of interactions between particles. A change in the gas pressure at a constant amplitude of the discharge current leads to a weak increase in the plasma concentration. The electrons temperature in this pressure range also varies slightly (figure 8).

A spatial research of the parameters of the emission plasma was carried out by moving the probe at different distances from the cathode of the discharge system (10, 20 and 30 cm). As can be seen from figure 9a, and when moving away from the cathode, the plasma concentration decreases, most likely due to a decrease in the number of ionization interactions. However, in this case the electron temperature at the far point is higher than at the near one. It can be assumed that the increase in the electron temperature with distance from the cathode may be associated with a decrease in the fraction of slow thermalized electrons and, as a consequence, a decrease in their contribution to the slope of the probe CVC after averaging. With an increase in the discharge current, the electron temperature variation decreases (figure 9b), which indicates a more uniform distribution of the plasma deep into the emitter.
Probe characteristics using nitrogen as a working gas showed the same character of changes in plasma concentration and temperature as in the case of argon when the probe is removed from the cathode.

![Figure 9. Probe CVC at different distances from the cathode to the probe at $p = 40$ mPa (Ar): (a) $I_d = 20$ A; (b) $I_d = 40$ A.](image)

When comparing probe CVCs with different working gases (Ar and N$_2$), it was shown that at a distance of 10 cm from the cathode (figure 10a) the plasma parameters slightly differ from each other. Probably, the similarity of the parameters is associated with the determining effect of ionized metal vapor (Mg) near the cathode of discharge. However, when the probe is removed at a distance of 30 cm (figure 10b), there is a difference in both plasma concentration and electron temperature. This behavior of the parameters can be explained by the greater contribution of the gas component of the plasma and is due to the difference in the ionization cross section of nitrogen and argon at close values of the ionization potentials $U_i$ (Ar) = 15.8 eV; $U_i$ (N$_2$) = 15.6 eV [11].

Inclusion of resistance in the hollow anode circuit, which is usually equal to $R = 10$ Ohm, increases the potential barrier for electrons on the hollow anode, which leads to an increase in the number of oscillations in the plasma emitter space and, as a result, to an increase in plasma concentration inside the emitter (figure 11).

![Figure 10. Probe CVC with working gas Ar and N$_2$, $p = 40$ mPa, $I_d = 40$ A at different distances from the cathode to the probe: (a) 10 cm; (b) 30 cm.](image)
3. Conclusion

Probe measurements of the plasma parameters of a low-pressure arc discharge in an electron accelerator with a grid plasma cathode and beam output to the atmosphere were carried out using an automated measurement system that allows to record the bias voltage and probe current inside the vacuum chamber, thus reducing electrical pickups during measurements. The shielding of the probe made it possible to reduce the distortions of the probe CVC by fencing the collector part of the probe from a stream of high-energy electrons propagating from the cathode of the discharge. Depending on the plasma generation mode, as a result of shielding the probe, a concentration \((1-5) \times 10^{10} \text{ cm}^{-3}\) was obtained, the electron temperature was in the range of 20–45 eV, the plasma potential was (90–100) V. With an increase in the amplitude of the discharge current, an increase in the plasma concentration and a decrease in the electron temperature were observed, associated with an increase in the ionization interactions. An increase in pressure in the studied range of 20–70 mPa leads to a weak increase in plasma concentration, the electron temperature does not change significantly, which is probably due to an insignificant change in gas conditions for numerous electrons with a free path exceeding a meter. When moving the probe along the emitter, a decrease in plasma concentration was observed, as well as an increase in the electron temperature. Probably, this effect is associated with a smaller contribution of thermalized electrons at the far point of the emitter when the probe characteristic is removed. A change in the working gas (nitrogen instead of argon) leads to both a change in concentration and temperature of plasma, which is appropriately associated with similar potentials, but with different ionization cross-sections of the gases studied. The inclusion of resistance in the hollow anode circuit, leading to the appearance of negative auto-bias, leads to an increase in plasma concentration due to an increase in electron oscillations inside the emitter. The work carried out is the beginning of studies of plasma generation processes in an electron accelerator with a plasma cathode and is necessary for further study and understanding of processes in an emission plasma when electrons are selected from it and a beam is formed.

Acknowledgments
The work was supported by the grant of Russian Science Foundation (project No 18-79-00011).

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