Efficiency of electron beam extraction to the atmosphere in an accelerator based on ion-electron emission

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Abstract. The use of a modern element base makes it possible to create power supplies with a transition from a direct mode of generation of an auxiliary discharge to a pulse-periodic mode with a pulse repetition rate at the level of several tens of kHz. This allows for a more flexible adjustment of the discharge parameters, keeping the average value of its current, but changing its amplitude with a corresponding change in the pulse duty cycle. In this work, using an electron accelerator based on ion-electron emission, generating a wide-aperture electron beam, we research the effect of auxiliary discharge generation mode (direct and pulse-periodic) on the efficiency of electron beam extraction into the ambient atmosphere. It is shown that, in a direct mode of electron beam generation at an accelerating voltage of 150 kV, the beam extraction coefficient does not exceed 0.25. The possibility of increasing the extraction coefficient to \( K = 0.55 \) at the same accelerating voltage of 150 kV was demonstrated without making changes to the design of the accelerator, but switching to a pulsed-periodic mode of emission plasma generation.

1. Introduction

One of the important characteristics of all accelerators generating electron beams with a large cross section (~ 1000 cm²) is the efficiency of beam extraction from the vacuum gap into the atmosphere [1]. The coefficient describing the efficiency of beam extraction is defined as the ratio of the beam current in the atmosphere to the current in the accelerating gap [2]. To increase the extraction coefficient, electrodes geometry is calculated and selected so as to provide the optimal ion-electron optical system (IEOS) of the accelerator. However, it is known that in electron accelerators based on ion-electron emission with a non-self-sustaining high-voltage glow discharge, the beam extraction coefficient can strongly depend on its generation parameters [3]. A change in the IEOS in such systems leads to a change in the efficiency of electron beam extraction into the atmosphere [4]. In this case, the efficiency can both increase and decrease, which, first of all, is determined by the position of emission plasma boundary [5].

The use of modern element base makes it possible to create discharge power supplies with a transition from a direct mode of generation of an auxiliary discharge to a pulse-periodic mode with a frequency at the level of several tens of kHz [6]. This allows for a more flexible adjustment of the
discharge parameters, keeping the average value of its current, but changing its amplitude with a corresponding change in the pulse duty factor.

In this paper, using an electron accelerator based on ion-electron emission [7], generating a wide-aperture (450 × 650 mm) electron beam, we study the effect of the auxiliary discharge generation mode (direct and pulse-periodic) on the efficiency of electron beam extraction into the atmosphere.

2. Experimental procedure and results discussion

The structural diagram of the wide-aperture electron accelerator [7], on which the experiments were carried out, is shown in figure 1. Operation principle of the accelerator is based on the phenomenon of secondary ion-electron emission. From the region of anode plasma generated by the auxiliary discharge, ions are emitted into the region of the accelerating gap, in which the main non-self-sustained high-voltage glow discharge is ignited. Region of anode plasma generation and the accelerating gap are separated by a slit-type anode grid. Accelerated ions and neutrals formed as a result of recombination bombard the surface of high-voltage cathode, from which secondary electrons are emitted. The resulting accelerated flux of electrons passes through the anode grid, drifts through the anode plasma and, passing through the foil output window, is outputted into the atmosphere. Role of the auxiliary discharge is played by a self-sustaining glow discharge with a hollow cathode and two anode wires. An auxiliary discharge is generated using an average-stabilized current source capable of operating in direct and pulse-periodic modes with a frequency of 1 – 100 kHz.

![Figure 1. The structural diagram of an accelerator with an electron beam collector.](image)

For registration the current of electron beam outputted into the atmosphere, a collector was used, which was a stainless steel plate covering the entire output window of the accelerator. The voltage drop created by the beam current relative to the grounded accelerator body was measured on a resistor \( R_m = 100 \text{ Ohm} \) (common point in figure 1). The electron beam extraction coefficient was determined through the ratio of the current of beam extracted into the atmosphere to the current in the accelerating gap \( K = I_b/I_0 \). In the direct mode of operation, the extraction coefficient weakly depended on the value of the auxiliary discharge current in the studied range (figures 2 and 3) and was less than 0.25 at an accelerating voltage of 140 kV.
The weak dependence of $K$ on the auxiliary discharge current is probably associated with a weak change in the position of the anode plasma boundary in the current range of 30 – 80 mA, and a value less than $K = 0.25$ indicates significant losses of the beam current inside the electrode system of the accelerator and non-optimal IEOS. The losses of the electron beam current are summed up from the losses on the anode and support grids, as well as losses inside the aluminum-magnesium output foil 30 μm thick.

The applied pulse-periodic mode of generation of the auxiliary discharge allows for a more flexible adjustment of the discharge parameters. So, when fixing the average value of the discharge current, it is possible to control its amplitude by changing the pulse dirty factor, in addition, it is possible to adjust the pulse repetition rate, which allows you to control the minimum pause between the discharge current pulses in the range of $\approx (10 \div 1000)$ μs.

**Figure 2.** Dependence of the beam current extraction coefficient on the accelerating voltage in a direct mode ($p_{\text{He}} = 0.9$ Pa).

**Figure 3.** Oscillograms of currents: CH1 – current in the accelerating gap $I_0$ (10 mA/div), CH3 – auxiliary discharge current $I_d$ (20 mA/div), CH4 – beam current $I_b$ (5 mA/div) at the direct mode (50, 70, 80, 100, 120, 140, 150 kV).

**Figure 4.** Dependence of the discharge voltage on the generation frequency of the auxiliary discharge ($I_d = 50$ mA, $D = 40\%$, $p = 0.6$ Pa).

**Figure 5.** Dependence of the beam current extraction coefficient on the accelerating voltage in the pulsed-periodic mode ($I_d = 50$ mA, $D = 30\%$, $p = 0.9$ Pa).
With an increase in the generation frequency, a sharp drop in the discharge voltage is observed in the range of 10–30 kHz (figure 4), apparently associated with the appearance of a constant component at the moment of the pause of the discharge generation. Since the power supply stabilizes the average value of the current, the appearance of a constant component leads to a corresponding decrease in the amplitude value of the current, as a result of which, with an increasing I–V characteristic, the discharge voltage decreases. A change in the discharge voltage affects the value of the near-cathode potential drop, and thus on the IEOS. Figure 5 shows that with a decrease in the frequency to 20 kHz, the beam extraction coefficient, estimated at the moment of the maximum of the auxiliary discharge current, increased to $K \approx 0.35$.

**Figure 6.** Dependence of the beam current extraction coefficient on the accelerating voltage in a pulsed-periodic mode with different $D$ ($p = 0.75$ Pa, $I_0 = 30$ mA, $f = 10$ kHz).

**Figure 7.** Oscillograms of currents ($I_0 = 30$ mA, $f = 10$ kHz, $D = 20\%$ $p = 0.75$ Pa): CH1 – current in the accelerating gap $I_0$ (10 mA/div); CH3 – auxiliary discharge current $I_d$ (50 mA/div); CH4 – beam current $I_b$ (5 mA/div).

Taking into account the dependencies in figure 4 and 5, the frequency was reduced to 10 kHz (at a frequency of 5 kHz or less with an average current of 30 mA, the discharge is unstable and may be extinguished). Adjustment by the duty factor $D$ of the pulses allows both the pulse duration and the amplitude value to be changed when the average discharge current is stabilized. Figure 6 shows the extraction coefficient for different $D$, so at $D = 20\%$ the extraction coefficient exceeded the value $K = 0.5$ at an accelerating voltage of 150 kV. Figure 7 shows typical oscillograms of currents for pulse-periodic mode at a frequency of 10 kHz and a duty factor of $D = 20\%$.

3. Conclusion

The coefficients of the electron beam current extraction from the vacuum into the atmosphere are determined for different modes of anode plasma generation. It is shown that, in a direct mode of electron beam generation at an accelerating voltage of 150 kV, the beam extraction coefficient does not exceed 0.25. The possibility of increasing the extraction coefficient to $K = 0.55$ at the same accelerating voltage of 150 kV was demonstrated without making changes to the design of the accelerator, but switching to a pulsed-periodic mode of emission plasma generation. Apparently, an increase in the discharge current and voltage caused by a decrease in the dirty factor $D$, and, consequently, an increase in the concentration of the emission plasma and a decrease in the width of the near-cathode layer, leads to a decrease in losses at the electrodes of the anode and support grids and the formation of a more optimal IEOS. This makes it possible to obtain a higher pulsed beam power at a lower power in the accelerating gap, which not only increases its energy efficiency, but also
opens up new possibilities for the further use of such accelerators for scientific and technological purposes.

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