Measurement of the electron beam energy in a source with a plasma anode and the beam extraction into the atmosphere through a foil window

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Abstract. Measurements of the energy of an electron beam in an electron beam source with an explosive-emission cathode, a plasma anode and a foil window, providing the extraction of an electron beam with a cross-section of (100–200) cm² into the atmosphere, have been performed. The high voltage source was a Marx generator based long lines with matched loads. The energy values were calculated from the results of measurements of the temperature of a beam collector placed in vacuum using thermistors and an infrared imager. At an accelerating voltage of ~200 kV, a current of (1–2) kA, and an electron beam duration of 5 µs, the maximum values of the energy released in the collector with a cross section of 74 cm² were (650–850) J/pulse. A decrease in the current and energy of the beam was recorded approximately by a factor of two after passing through an AMG-2n aluminum-magnesium foil with a thickness of 30 µm. The use of infrared imager for recording the beam structure in the plane of the output window in air has been tested.

1. Introduction
Electron beam sources and accelerators with an explosive-emission cathode and the output of a large cross-section beam into a gas or atmosphere are characterized by a wide range of accelerating voltages and currents, but have a limited duration of the electron beam. The restriction is resulted from the increase in the conductivity of the accelerating interelectrode gap due to filling with cathode plasma, as well as with the anode one. This anode plasma is formed due to gas emission from the surface of the foil and the support grid of the output window under the action of the beam.

A common way to increase the current and duration of the electron beam in sources with an explosive-emission cathode is the use of a plasma anode. In a source with a plasma anode, the current value is determined by the concentration of artificially created anode plasma. The influence of the expansion of the cathode plasma, as well as the plasma formed due to ionization of the gas released from the anode, on the beam current value decreases. Pre-injection of plasma provides compensation of the spatial charge of the beam by ions, which allows increasing the length of the interelectrode gap and, thus, complicating the breakdown formation.

The possibility to use a plasma anode in an electron beam source with a beam output through a foil was demonstrated earlier [1]. To date, a variant of an electron beam source with a plasma anode and a foil window has been developed and manufactured [2, 3]. Experiments have been started on generating electron beams and releasing them into the atmosphere. The high voltage source was a
previously developed Marx generator with stages in the form of artificial long lines with matched loads [4, 5]. At a quasi-constant accelerating voltage of up to (200–220) kV, electron beams with an adjustable current of up to (1.5–2) kA, and duration of 5 µs of a circular or rectangular cross-section with an area of up to (100–200) cm² were obtained. The values of the beam energy in the electron beam source, calculated as the integral over the time of the product of the accelerating voltage by the beam current entering the collector with a diameter of 97 mm (an area of 74 cm²), placed in a vacuum chamber, reached 1 kJ. The maximum energy values obtained from the results of measurements of collector temperature using thermistors were ~ (600–700) J or (0.6–0.7) of the values calculated from the waveforms. The maximum values of the energy of the beam extracted through a window closed with an aluminum-magnesium foil AMG-2n with a thickness of 30 µm into the atmosphere, recorded using calorimeters, were up to (250–270) J/pulse [3].

Due to the differences in the values of the beam energy released on the collector, calculated from waveforms and measured using thermistors, and the relatively low efficiency of energy output through the foil window into the atmosphere, experiments were performed. They were intended to refine the values of the beam energy entering the collector of the electron beam source in the absence and in the installation of the AMG-2n aluminum-magnesium foil in front of the collector, which was previously used as an output. Additional data on the beam energy were obtained using thermistors and an infrared imager. The use of the imager for recording the beam structure in the plane of the output window in the open air has been tested.

2. Experimental technique and results
A detailed description of the electron source is given in [2, 3]. A simplified circuit of the power supply is shown in figure 1.

The electron beam source was located in a cylindrical vacuum chamber consisting of the pipes with diameters of 350 and 200 mm. To carry out the experiments, the source design was partially changed. In contrast to the original version, in the electron beam source used in the work, a funnel-shaped pipe with a flange containing a rectangular output window was replaced by a flange with collectors installed on it for measuring the electron beam currents, or by an additional 200 mm diameter pipe with optical windows for obtaining thermal images of the collector. The position of the collectors is marked in the figure.

In the experiments, we used multi-pointed cathodes of round and rectangular cross-sections. The tops of the points were deepened into the cavity of the shielded electrodes up to (10–20) mm, which, in the presence of a plasma anode and a guiding magnetic field, provided the formation of weakly convergent electron beams.

![Figure 1](image-url) 

Figure 1. The scheme of the electron beam source.

A stainless steel cylinder with a diameter of (100–120) mm or a piece of rectangular tube with a cross-section of 90×180 mm², filled with plasma using 4–8 coaxial plasma guns with a discharge
along the dielectric surface and axes oriented perpendicular to the axis of the vacuum chamber served as the plasma anode. The capacitance of the capacitors in the discharge circuit of the guns is (0.1–0.5) μF, the charging voltage is up to 20 kV. Limiting resistances in the chains of guns are (54–112) Ω.

The beam was formed by applying a longitudinal weakly increasing and weakly decaying magnetic field behind the anode with an induction in the anode region of (300–600) G.

The Marx generator used in the work consists of 6 stages based on artificial long lines with a wave impedance of 4.2 Ω and an electrical length of 5 μs and equipped with matched loads switched to the stages [4, 5]. The charging voltage of the generator \( U_{ch} \) is (30–50) kV. Due to the use of matched loads, the generator provides rectangular voltage pulses without reflections on an arbitrary constant resistive load. In the case of a changing resistive load, the pulse waveform differs from rectangular, but the pulse duration is preserved and reflected pulses are absent. In a number of experiments, to limit the current, a 7 Ω protective resistance was included in the generator discharge circuit in series.

In the course of the experiments, the measurements of the accelerating voltage \( U \), the guns current \( I_g \), the current \( I_c \) of the electron beam supplied to the collector, and the total generator current \( I_t \) were carried out. Voltage measurements were performed using a resistive voltage divider. To measure the generator current, a resistive shunt was used, connected between the case of the source and "ground" terminal of the generator. Measurements of the guns current and the beam current supplied to the collector were performed using a Rogowski coils. The obtained waveforms were used to calculate the values of the electron beam energy \( E_c \) supplied to the collector, as well as the total energy \( E_t \) supplied to the electron beam source from the Marx generator.

Collectors with diameters of 180, 150 and 97 mm, connected to the ground, were used. Collectors of 150 and 97 mm diameter with a thickness of 0.38 mm and 10 mm, respectively, are made of copper, each equipped with thermistor, what allowed them to be used as calorimeters. Collectors were placed on the axis of the electron beam source behind the plasma anode. The readings from the thermistors were registered in an interval of time necessary for realization of quasi-uniform distribution of temperature on the collector surface.

To obtain additional data on the heating process of the collector and to clarify the values of the beam energy supplied to the collector, obtained earlier, the Testo-868 infrared imager was used. The spectral range of the imager is (7.5–14) μm. The output of radiation from the electron beam source was carried out through the output windows of zinc selenide ZnSe and calcium fluoride CaF₂. The transmission region of the windows is ~ (0.4–20) μm and ~ (0.15–9) μm, respectively, the transmittance is ~ 0.7 and 0.9. The infrared imager, an optical channel with windows, and thermistors were calibrated using a mercury thermometer.

In the experiments to measure the energy released in the collector using an infrared imager and thermistors, the values of the temperature of the collector reached after exposure to the beam were registered, the establishment of nearly uniform temperature distribution over the collector surface using infra-red imager was recorded, and its value was recorded with help of thermistor. From the measurement data, the values of the thermal (measured) energy \( E_{th} \) released in the collector were calculated. The measured values of \( E_{th} \) were compared with the calculated \( E_c \) values obtained by integrating the dependences of the beam power on time, plotted using the waveforms of voltage \( U \) and current \( I_c \).

To record the energy of the beam, after passing through an aluminum-magnesium foil, a sheet of foil with a diameter of 200 mm was installed between the anode and the collector, while providing electrical contact of the sheet around the circumference with the chamber wall. The values of the beam energy released in the collector were determined using a thermistor. When using a foil, the calculated values of \( E_c \) are overestimated by the amount of energy loss of electrons in the foil.

In experiments on recording the structure of the electron beam, an infrared photograph of the output window in the air in the initial configuration of the electron beam source was performed, while the additional pipe with optical windows was not used. To obtain the thermal "autograph" of the beam, a model of a rectangular grid of the output window with dimensions of (115×225) mm made of stainless steel was used. The output window was closed with a sheet of stainless steel foil with a
thickness of 0.26 mm, opaque to the beam electrons. The use of stainless steel having a relatively low thermal conductivity as structural material ensured the preservation of the registered image for \(\sim (5–10)\) s, which is sufficient for registration.

The waveforms of the accelerating voltage \(U\), the current of the plasma guns \(I_g\), the current of the 97 mm diameter collector \(I_c\), the total current of the Marx generator \(I_t\) as well as the dependences \(E_c(t)\) and \(E_t(t)\) constructed from them illustrating the operation of the electron beam source are shown in figure 2.

![Waveforms of accelerating voltage, currents, and dependences](image)

**Figure 2.** Waveforms of accelerating voltage \(U\), currents \(I_g, I_c, I_t\) and dependences \(E_c(t)\) and \(E_t(t)\) constructed from waveforms in the absence (a) and in the presence of an aluminum-magnesium foil in front of the collector (b). Vertical scale 50 kV/div, 0.5 kA/div, 0.2 kJ/div, sweep 2 μs/div. For convenience, the graphs of the dependences \(E_c(t)\) and \(E_t(t)\) in the figures are shifted downward from the zero line. The charging voltage of the Marx generator is 45 kV.

To eliminate the possible influence of the injected plasma and gun power supply circuits on the current value of the collector, the operating modes with a short time of gun current flowing (4–6) μs were mainly used before the moment when the Marx generator was turned on and the beam generation started. Moreover, most of the experiments related to the measurement of the beam collector current in vacuum were carried out in the absence of direct electrical contact of the outer and inner electrodes of the guns with the "ground" of the electron source. It was assumed that with such a connection of the guns, the injected plasma is under the floating potential relative to the grounded collector, and therefore there is practically no current flow from the plasma to the collector.

In other variant, external electrodes of the guns were connected directly to the case of the source. As a result, a possibility was provided to apply negative bias to the collector for cutting-off the low energy electrons in case they are present in the beam.

From the given waveforms in figure 2a it can be seen that the beam collector current \(I_c\) and the generator current \(I_g\) are close to each other. The differences in the value of the beam energy \(E_c\), calculated from the waveforms, and the total energy \(E_t\) transmitted from the generator reflect the difference in currents and can be related to the losses of the beam current at the anode and the walls of the vacuum chamber. The attachment of the guns bodies to the ground and the inclusion of \(\sim (0.1–0.2)\) Ω resistances in the collector circuit are accompanied, as a rule, by a decrease in the collector current, which may indicate the presence of slow electrons in the beam.

Experiments have shown that the passage of the beam through the aluminum-magnesium foil is accompanied by significant losses of current \(I_c\) and energy \(E_{th}\) of the electron beam. The obtained values of \(I_c\) and \(E_{th}\) are \(\sim 0.5\) of the values recorded in the absence of the foil in front of the collector under comparable conditions.

It can be seen from the waveforms that the collector current \(I_c\) is (1.2–1.3) kA at accelerating voltages of (190–200) kV in the absence of the foil in front of collector (figure 2a) and decreases to 600 A in its presence (figure 2b). The beam energy released at the collector and recorded by the
thermistor $E_{\text{th}}$ is in these cases, respectively, 735 and 336 J, and thus, in the presence of foil, it is approximately halved.

The obtained values of the fraction of the current $I_c$ and beam energy $E_{\text{th}}$ in the presence of the foil $\sim 0.5$ of the values of $I_c$ and $E_{\text{th}}$ in its absence are less than the transparency values of the output windows of high-power lasers with a supporting structure and an external magnetic field, which are (0.6–0.7) [6]. They are also less than the values of the transmission coefficients of electrons with energies of 200 keV with an aluminum foil 30 μm-thick in terms of the number of particles and energy, which are 0.92 and 0.84, respectively, in the absence of magnetic field [7]. The probable reasons for the observed decrease in the current and energy of the electron beam can be a change in the configuration of the drift region when placing the foil, the presence of the slow electrons in the electron beam.

A condition for increasing the accuracy of measurements of the beam energy released in the collector using a limited number of thermistors is probably a decrease in energy losses as a result of cooling until a close to uniform temperature distribution required for measurements is achieved. Cooling down can be decreased by reducing the efficiency of heat transfer. It is also possible to reduce the time before measurements are made by increasing the uniformity of the distribution of the beam current density over the collector surface.

Experiments on measuring the energy of an electron beam, performed in this work, with the registration in one pulse of the accelerating voltage and current of the beam, the collector temperature using a thermistor and a infrared imager, showed that the time to establish a close to uniform temperature distribution over the surface of a collector with a diameter of 97 mm can be $\sim (15–30)$ s or more. As a result of the modernization of the heat sink of the collector, the maximum measured values of the energy $E_{\text{th}}$ released in the collector, recorded with a thermistor, amounted to $\sim (650–850)$ J/pulse at an energy value of $E_c \sim (750–950)$ J/pulse, calculated from the waveforms. Thus, in comparison with [3], the discrepancies between the measured and calculated energy values are reduced, the maximum values of the $E_{\text{th}}/E_c$ ratio were $\sim (0.8–0.9)$.

The recorded thermal images of the collectors are shown in figure 3. It can be seen that the temperature distributions over the collector surface is close to uniform under conditions of both sufficiently high and low temperatures, which indicates the relative uniformity of the distribution of energy input over the collector surface.

Figure 3. Thermal images of collectors with a diameter of 150 (a) and 97 mm (b).

Examples of the structure of an electron beam on a stainless steel foil opaque to electrons using the infrared imager are shown in figure 4.

The convenience of diagnostics is the possibility to obtain "autographs" of the beam with an arbitrary number of pulses in the absence of the need to open the vacuum chamber (for example, to extract prints on viniproz sheets).
3. Conclusion
In the electron beam source with an explosive-emission cathode, a plasma anode, and a foil window for extracting the electron beam into the atmosphere, measurements were made of the energy of the electron beam entering the collector in vacuum, as well as the energy of the beam after passing through a 30–μm–thick aluminum magnesium foil. Energy values were calculated from waveforms of voltage and current, and were also measured using thermistors and the infrared imager. The possibility of increasing the accuracy of temperature measurements using a thermistor by reducing losses for cooling the collector as a result of heat removal has been demonstrated. The maximum values of the beam energy scattered in a copper collector with a diameter of 97 mm were up to (650–850) J/pulse, or ~ (0.8–0.9) of the energy values calculated from the waveforms of the accelerating voltage and collector current. At accelerating voltages up to ~ 200 kV using a thermistor, a decrease in the current and energy of the electron beam after passing through an AMG-2n aluminum-magnesium foil 30–μm–thick to 0.5 from the initial values in its absence was recorded. The use of the infrared imager for registration of the beam structure in the plane of the output window of the electron beam source in air has been tested.

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