Energy density distribution of a modulated electron beam in a source with a plasma cathode based on a low pressure arc

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Abstract. The article presents the results of studies devoted to the study of the energy density distribution in the amplitude-modulated regime of electron beam generation. It is shown that in the first \(\approx 50\) \(\mu\)s of the duration of the beam current pulse, its spatial rearrangement occurs, due to the development of the arc discharge current. Thus, the rearrangement of the arc current, which develops from the axis of the system, leads to an axial diving of the emission current density and the beam current density on the target. With the development of the arc current, the energy density on the target on the axis of the system decreases and after \(\approx 50\) \(\mu\)s takes on a steady-state value, which can change only as a result of a change in the conditions for generating an electron beam or the transition to a modulated regime of electron beam generation. It has been experimentally shown using calorimetric measurements that the shape of the electron beam current pulse with its amplitude modulation with a pulse duration of more than 100 \(\mu\)s has little effect on the distribution of the beam energy density in the target region.

1. Introduction

Currently, electron sources are used in various industries, such as metallurgy, medicine, and agriculture [1]. Due to their advantages, electron sources based on plasma emission with grid stabilization of the emission plasma boundary are widely used [2-5]. Such sources are used to generate both wide and focused electron beams with energies up to 300 keV with currents from fractions of amperes to several kiloamperes [6]. Plasma electron sources are used in scientific research (ionization of vapors and gases, generation of X-ray radiation, pumping of gas lasers, generation of microwave radiation), but to a greater extent their advantages are revealed in technological applications [7, 8]. Plasma sources of electrons successfully operate in collapsible vacuum installations, including under conditions of not very deep vacuum. The possibility of devacuuming the source of electrons allows periodic repair and maintenance of devices, replacement of worn-out parts. This is a very important advantage of plasma sources, since they are often operated in the presence of streams of harmful gases and vapors, dusty electrodes and insulators. One of the most important advantages of electron sources of this type is the ability to adjust the beam parameters with a weak dependence on each other, which significantly expands the scientific search for the most optimal beam generation mode for processing specimens [3, 5, 9].

Traditionally, for processing products and materials by the pulsed electron-beam method, a quasi-rectangular shape of the beam current pulse is used. However, this approach limits the potential of using such electron sources, since there are problems where it is necessary to change the power of the electron beam during a pulse (for example: maintaining the temperature of the specimen surface in the...
submillisecond range [10]). It is the weak dependence of the beam parameters on each other that made it possible to implement the amplitude, latitude and frequency modulation of the electron beam by changing the parameters of a low-pressure arc discharge during a pulse of submillisecond duration. A description of the implementation of amplitude modulation of an electron beam in an electron source with a plasma cathode with grid stabilization of the emission plasma boundary is described in [11]. The use of amplitude modulation of an electron beam opens up new applied possibilities of electron accelerators, and at the same time, questions arise about the effect of the shape of an electron beam current pulse upon modulation on such a parameter as the distribution of its energy density. It is these issues that the material of this article is devoted to.

2. Experimental setup
The work was carried out using an electron source "Solo" with a plasma cathode based on a low-pressure arc discharge with grid stabilization of the boundary of the emission plasma and a plasma anode (figure 1), the boundary of which is open and movable, which makes it possible to generate a wide (up to 40 mm in diameter) intense (current up to 200 A) submillisecond (up to 200 μs) electron beam [12].

![Figure 1. Scheme and appearance of the electronic source "Solo" with a grid plasma cathode and plasma anode.](image)

The “Solo” electron source with a plasma cathode is based on a 2-stage discharge ignition system. The ignition of the main arc discharge between the cathode 2 and the hollow anode 3 occurs by means of an auxiliary discharge, which is ignited between the hollow electrode 1 and the cathode 2 when a voltage pulse of 12-15 kV is applied. A hole 40 mm in diameter is made in the center of the emission electrode 5, which is a stainless steel plate. To ensure layer stabilization of the emission plasma boundary, the hole in the emission electrode is covered with a fine grid 4. A constant accelerating voltage is applied between the emission electrode 5 and the extraction electrode 6, made in the form of a diaphragm with a diameter of 82 mm. Extraction electrode 6, drift tube 7 and collector 8 are at ground potential. Initially, the selection of electrons from the emission plasma is carried out through the cells of the emission grid under the action of an electric field created by electrodes 6 and 7. After the formation of the anode plasma, the acceleration of electrons occurs in the double layer between the boundaries of the cathode and anode plasma.

Accelerated beam electrons are transported to the collector in the magnetic field of two coils 9, 10, the field strength in which can reach $B_1 = 1000$ G for the first (10) solenoid and $B_2 \approx 1000$ G for the second (9). The amplitude and duration of the beam current pulse are set by the amplitude and duration of the current pulse of the main arc discharge. Argon is used as a working gas. The gas pressure in the working chamber varies in the range $(0.6-6) \times 10^{-2}$ Pa.

To implement the amplitude modulation of the electron beam by changing the arc discharge current during a submillisecond pulse, an arc discharge power supply was developed, which was used in [11].
The following main values were used in experiments: discharge current – $I_d$, current in the accelerating gap – $I_g$, accelerating voltage – $U_{ac}$, magnetic field in the first coil (10) – $B_1$, magnetic field in the second coil (9) – $B_2$, gas pressure in the working chamber – $p$.

3. Results
Before proceeding to the study of the distribution of the energy density of the electron beam in the amplitude modulation mode, the authors estimated the spatial dynamics of the arc discharge current in the region of the emission grid using a probe measurement scheme. The measurements were carried out by three single tungsten probes with a diameter of 0.5 mm and a length of 5.5 mm, fixed on the emission electrode parallel to the axis of the system. The probes were at anode potential. One is on the axis, the second is at a distance of 15 mm, the third is at a distance of 30 mm (figure 2).

Using this probe measurement scheme, the distribution of the current from the emission plasma at different times was plotted at discharge current $I_d = 60$ A, pulse duration $t = 120$ μs, gas pressure $p = 25$ mPa, magnitude of the magnetic field of the solenoid (10) $B_1 = 20$ mT, magnitude of the magnetic field of the solenoid (9) $B_2 = 100$ mT. The distribution is shown in figure 3.

The discharge current, even at its constant amplitude, has a spatial rearrangement during the first tens of microseconds (depending on the conditions of its generation). As the steady-state regime is reached, the emission current in the central (axial) part of the emission electrode decreases and
increases in the peripheral part. This leads to some leveling of the emission current density. From this figure it follows that the time of spatial rebuilding is about 60 µs, then the current distribution over the area of the emission grid can be considered steady.

**Figure 4.** Oscillograms of the discharge current $I_d$, 25 A/cell (yellow), current in the accelerating gap $I_a$, 20 A/cell (turquoise), accelerating voltage $U_{ac}$, 5 kV/cell (magenta). Mode: $p = 20$ mPa, $B_1 = 30$ mT, $B_2 = 50$ mT.

**Figure 5.** Energy density distribution at $p = 20$ mPa, $B_1 = 30$ mT, $B_2 = 50$ mT, $U_{ac} = 20$ kV: a – $I_d = 100$ A (100 µs), $E = 160$ J; b – $I_d = 30$ A (300 µs), $E = 177$ J; c – $I_d = 100$ A (100 µs) + 30 A (300 µs), $E = 344$ J; d – $I_d = 30$ A (300 µs) + 100 A (100 µs), $E = 363$ J.
For calorimetric measurements, we used a sectioned calorimeter described in [13]. In the modulation mode, the arc discharge current had a stepped shape, consisting of 2 rectangles of different amplitudes and durations, so that the energy in the accelerating gap circuit passing through each step was the same. Also, from the conclusions made in the previous experiment, the minimum time for generating the arc discharge current, equal to 100 μs, was chosen. Calorimetric measurements were carried out separately for the first (figure 4 (a)) and second stage (figure 4 (b)) (taking into account the voltage drop across the capacitor bank), as well as for a pulse consisting of two steps (figure 4 (c), figure 4 (d)).

From figure 5 it can be seen that the SOLO electron source together with the developed and manufactured power supply system makes it possible to select modes in which the energy density of a pulse consisting of 2 steps is equal to the sum of the energy density of separate steps; the sequence does not affect the energy density distribution, which is due to the leveling of the processes associated with the development of the arc discharge current in the plasma cathode.

However, when carrying out calorimetric measurements with a shorter pulse duration \( t = 50-100 \mu s \), the amplitude modulation of the beam causes changes in the distribution of the energy density of the electron beam, which is associated with the spatial rearrangement of the arc current.

![Figure 6](image-url)

**Figure 6.** Electron beam energy density distribution: a – for the beam current on oscillogram 1; b – on oscillogram 2; c – on oscillogram 3.

As shown in figure 3, in the first 60 μs of the pulse, the main share of the current is in the center of the emission electrode. Thus, the higher the amplitude of the beam current in this time interval, the more so "sharp" is the distribution of the electron beam energy density. Figure 6 presents the results of calorimetric studies of the distribution of the electron beam energy density. From figure 6 it can be seen that the greatest energy density in the center of the beam \( j = 12 \) J/cm\(^2\) is reached at a current \( I_d = 200 \) A (50 μs). With an increase in the pulse duration of the beam current or a decrease in its initial amplitude, the absolute value of the energy density is reduced with the same amount of charge, reserved from the high-voltage capacitor battery. Thus, with a two-stage pulse of a beam current
\[ I_d = 150 \text{ A} \ (50 \mu\text{s}) + 50 \text{ A} \ (50 \mu\text{s}) \], the maximum energy density was \( E = 9 \text{ J/cm}^2 \). With a two-stage pulse \( I_d = 50 \text{ A} \ (50 \mu\text{s}) + 150 \text{ A} \ (50 \mu\text{s}) \), the energy density in the center of the beam was \( E = 7.5 \text{ J/cm}^2 \).

4. Conclusion
The method of amplitude modulation of an electron beam in a source with a plasma cathode with grid stabilization of the emission plasma boundary based on a low-pressure arc opens up new possibilities for using electron beams and expands the operating modes of the accelerator. With the help of probe measurements, it was shown that in the first 50 \( \mu\text{s} \) there is a spatial rearrangement of the arc discharge, which causes a change in the distribution of the emission current on the grid, but then this distribution can be considered steady. Using the diagnostics of the beam energy density distribution, it was shown that the distribution at a lasing time of 10 \( \mu\text{s} \) has a narrower shape than at 50 \( \mu\text{s} \). Using a sectioned calorimeter, it was shown that the shape of an electron beam current pulse with amplitude modulation with a duration of more than 100 \( \mu\text{s} \) does not affect the energy density distribution in the target area.

Acknowledgments
This work was supported by the Russian Science Foundation (project No. 20-79-10015).

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