Features of pulsed electron beam propagation with nanosecond duration in the air under the low (reduced) pressure

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Abstract. This paper presents the research of pulsed electron beam propagation with nanosecond duration in the air under the low pressure (3-8 Torr) with the help of a calorimeter with a vacuum cutoff and a Faraday cup. Investigations have been conducted with the laboratory setup, including the TEU-500 electron accelerator and a drift tube. The major parameters of the accelerator are as follows: 450-500 keV electron energy; 9-12 kA ejected electron current; 60 ns half-amplitude pulse duration; 5 pps pulse repetition rate; and 250 J pulse energy.

1. Introduction
At present, the majority of experimental results in electron beam propagation are obtained in axially symmetric drift spaces with the use of metal and dielectric drift tubes with a diameter comparable to the cross-sectional dimension of the electron beam [1-3]. Numerous experiments connected with electron beams transfer in various gases (in the mode of self-focusing at the distance L numbered of some betatron lengths) show that the most effective electron beam propagation occurs in the area of low pressures $p \sim 1$ Torr. If area’s pressure is lower than 1 Torr, effective pulsed electron beam propagation is hindered by the processes, connected with the specificity of current (magnetic) compensation, volume charge neutralization, and beam-plasma instabilities, changing the conditions of pulsed electron beam propagation (resistive firehose instability, lateral instability, etc.) [5-7].

Also, some theoretical investigations are devoted to the problem of electron beam propagation in gas environments (a computational study of low energy electron beam transfer along the drift tube, depending on the external magnetic field, experiment geometry, etc.) [9-11]. The authors of the paper [12] have obtained the results of the calculations of the magnetic field configuration and its size in the areas of forming, accelerating and transferring electrons in the electron-optical system of the electron plasma source. It is shown that the creation of a quasihomogeneous magnetic field in the electron-optical system of the electron plasma source allows improving beam focusing. In the given work the magnetic field source is a permanent magnet of a discharge chamber. This magnet is necessary for discharge initiation and combustion.

The paper [13] presents the results of a numerical simulation of non-steady processes in various schemes of charge neutralization for high-current electron beams (the calculations are obtained for hydrogen, nitrogen, and xenon plasma for various values of the external magnetic field and for its absence). The obtained results are in good agreement with the experimental data found for plasma-
filled diodes (current increase of transferred pulsed electron beams occurs at the partial neutralization of their volume charge).

In the work [14] the authors have conducted theoretical research connected with the influence of current neutralization and reverse current distributor geometry on the transformation of the low energy high-current beam in the plasma channel. Experimental conditions (the geometry and material of the reverse current distributor) are close to those that will be used in the given paper, therefore, it is necessary to note the results obtained by the authors, although the injection of the pulsed electron beam in the work [14] has been carried out in plasma. The parameters of the system and beam used by the authors in their calculations: the energy of electrons is 27 keV; a beam radius in the transfer channel entrance is \( r_b = 4.25 \) cm; beam current is \( I_b = 20 \) kA; a drift tube radius is \( R = 10.3 \) cm; a tube length from the cathode surface is 18.5 cm; the time of beam current front is 300 ns. In the calculations as a reverse current distributor was considered the following: 1) a symmetric current distributor (a drift tube); 2) two flat parallel bus-bars with the length \( L = 4 \) cm and the width \( h = 3.9 \) cm (current in each bus-bar \( I = 10 \) kA); 3) four parallel studs with the length \( L = 4 \) cm and the diameter \( d = 0.5 \) cm (current in each stud \( 5 \) kA). As a result, the authors have found that the maximum change in the form of the beam circular cross-section can be observed in the systems with the current distributors in the form of narrow plates or studs, and on the target the beam cross-section is close to rectangular or square, respectively. Moreover, the deformation of the beam cross-section during beam transfer to the target is accompanied by the change of electron density distribution. The beam, homogeneous in the drift tube entrance, at its cross-section transformation becomes heterogeneous in density with its maximum in the centre. At the same time, heterogeneous initial electron distribution becomes flatter on the target and even closer to homogeneous in the central part of the beam at high current neutralization because of the change in the cross-section configuration [11].

Despite the number of investigation results in the sphere of transferring and focusing of electron beams in various environments, which exist nowadays in Russia as well as abroad, the area of research connected with the physics of interaction of high power pulsed beams of charged particles with a gas environment and condensed matter is still open. Especially, it is applied to the gas environment of high pressure, what can be potentially used in such technologies as: refining of dump uranium hexafluoride, associated gas processing, catalyst and photocatalyst synthesis, oil cracking, functional and structural composite nanomaterials obtaining, radiation biology, etc.

The authors have earlier conducted the study of the pulsed electron beam energy dissipation at injecting into electronegative gases of high pressure. This part of work is devoted to the problems of pulsed electron beam energy injection into gases and gas compositions, consisting of argon, hydrogen, oxygen, silicon tetrachloride [8].

The aim of the present paper is to research the factors of pulsed electron beam propagation with nanosecond duration with varied energy density in the air under the low pressure with the help of a calorimeter with a vacuum cutoff and a Faraday cup.

2. Experimental

The investigation of pulsed electron beam propagation in the air under the low pressure is conducted with the help of the TEU-500 accelerator [15]. A characteristic feature of the given accelerator construction is a matching autotransformer that provides matching of a low-resistance water double forming line with a high-resistance impedance of an explosive emission planar diode.

An electron beam in the given accelerator is formed due to autoelectron emission from the surface of a graphite cathode with the diameter of 45 mm. Electron beam ejection is carried out through the anode area, presented by a support grid and aluminum foil with the thickness of 140 micrometers. In the present work the authors used 2 types of anode grids: the 1-st type – a riffled grid with optical transparency of 70 %; the 2-nd type – a honeycomb type of the anode grid with optical transparency of 95 %. The anode – cathode gap for all the experiments is 13 mm.

The operation stability of the accelerator was monitored with the help of a Rogowski coil and a capacitive potential divider (parameter spread of current and voltage, registered by the sensors, did not
exceed 5%). To register current pulses a Tektronix TDS 2022V oscillograph was used. The current carried to a diode assembly was ~10-12 kA, accelerating voltage of electrons – 450-500 kV (Figure 1. oscillograph records of current and voltage), pulse duration at a half-height – 60 ns.

Figure 1. Average values of voltage \((U_{\text{cap}})\) and beam current \((I_{\text{RC}})\) carried to a diode assembly.

The investigation of pulsed electron beam propagation in the air under the low pressure was conducted with the help of the Faraday cup and the calorimeter with a vacuum cutoff. This vacuum cutoff of measuring equipment included the following: the collector of the Faraday cup (or calorimeter) was closed by the support grid (optical transparency - 70 %) and the aluminum foil of 140 micrometers. The Faraday cup (or calorimeter) was installed in the drift tube at a varied distance from the outlet hole of the diode chamber of the pulsed electron accelerator. The drift tube looked like a quartz tube with the diameter of 14 cm, the length of 38 cm and the walls thickness of 4 mm, which was pinned between two metal flanges with the help of two metal studs. Metal studs in the given geometry of the experiment played the role of the reverse current distributor. The pressure in the reactor was of 3-8 Torr for all the experiments, presented in this paper. Figure 2 demonstrates the scheme of the experiment.
Figure 2. Scheme of the experiment: 1 - diode chamber of the TEU - 500 accelerator; 2 – cathode; 3 – anode grid (3 mm) and aluminum foil (140 µm); 5 – drift tube; 6 – collector of the Faraday cup.

The experiment was conducted in the following way: the Faraday cup was installed at a long distance from the diode outlet hole of the accelerator (d=35 cm, further the distance was shortened at a pitch of 5 cm), drift tube volume was pumped down by a roughing pump, the electron beam was injected and entered the drift tube, and then, it reached the collector of the Faraday cup. As far as the pulsed electron accelerator works invariably, 5 redoubling each other experiments were conducted at each distance for statistics. In the series of experiments, when the calorimeter was used as a measuring device and was installed like the Faraday cup at the distances of d= 35, 30, 25, 20, 15, 10, 4.5 cm the output energy of the electron beam was measured. According to two parameters of the beam (energy and charge) the conclusion was made about the behaviour of the pulsed electron beam with nanosecond duration in the air under the low pressure.

3. Results and discussions

In the course of conducting the research the following results are obtained and presented in the given part of the report. Figure 3 shows the experimental investigations of the dependence of a total beam charge, having reached the collector of the Faraday cup, on the distance in the air under the low pressure.

Figure 3 demonstrates that the dependence of the total beam charge, having reached the collector of the Faraday cup, on the distance in the air under the low pressure has a complicated character. When the collector of the Faraday cup is positioned at the distance from 5 to 20 cm from the outlet hole, the charge of the electron beam decreases. It should be noted that along the whole length of the reaction chamber the value of the beam charge, having reached the Faraday cup, in the case of using the anode grid with optical transparency of 95 % is higher than the similar value measured with the use of the
anode grid with optical transparency of 70%. This fact confirms bigger number of electrons injected in the drift tube. Having divided the charge value registered in the series of experiments with a honeycomb grid by the charge value registered in the second series of the experiments (a riffled grid) \(K=1.3895\). It is compatible with the ratio of transparencies of these grids: 95/70=1.357 with an accuracy of 2.4%. According to abovementioned and taking into the consideration the fact of a similar character between two beam charge dependencies, having reached the collector of the Faraday cup, on the distance further calorimetric measurements were conducted with the use of the anode grid with optical transparency of 95%. Experimental set up was similar to the scheme presented in Figure 2. The energy of the electron beam, having reached the calorimeter’s collector, was registered. In each series of experiments we calculated the value of the energy supplied to the diode from the data obtained with the help of the capacitive potential divider (accelerating voltage of electrons) and the Rogowski coil (I - accelerator total current). Data spread of energy delivered to the diode did not exceed 5%. The graph of beam energy dependence on the distance in the air under the low pressure is presented in Figure 4.

![Figure 4](image)

**Figure 4.** Dependence of ejected beam energy on the distance in the air under the low pressure (a 5 pulses averaged model).

Figure 4 shows that the dependence of ejected beam energy on the distance in the air under the low pressure is described by the dependence the character of which is similar to the dependence of the beam total charge, having reached Faraday cup’s collector, on the distance (Figure 4), but with a more significant minimum. It is possible to make an assumption that at the distance from 0 to 20 cm the process occurs where the transfer of the beam without charge neutralization can be observed, otherwise, the value of the ion background, appearing at electron beam injecting in gas, is small. At insufficient charge neutralization the electron beam is pushed apart under the influence of Coulomb force, and only a small part of electrons reaches the collector of the Faraday cup. When the collector is positioned at the distance from 20 to 35 cm from the outlet hole, the value of the electron beam charge exceeds the value recorded at the distance of 20 cm. It can be explained by the following fact: the value of the ion background integral increases due to the increase of the distance where the beam is transferred. As a consequence, charge neutralization of the beam increases, and its transferring characteristics are improved.
4. Conclusion
Thus, experimental investigations of the pulsed electron beam propagation with nanosecond duration in the air under the low pressure are given. It can be seen from the observed graphs that the dependence of the energy and total charge (having reached the collector of the Faraday cup) on the length of electron beam run in the air under the low pressure does not have an exponential form. There is a critical distance in the drift tube where maximum beam dissipation occurs. After crossing this dissipation the beam focuses, what is proved by the increased value of the beam energy in the end of the drift tube. This behaviour of the pulsed electron beam may be influenced by many factors. For example, this behaviour may be determined by the experiment geometry. Moreover, in the series of experiments the dielectric materials for the drift tube and metal studs, playing the role of the reverse current distributor, have been used. In this area of pressures the processes, connected with the specificity of the current (magnetic) compensation value, neutralization of beam volume charge as well as beam-plasma instabilities, also influence on the conditions of pulsed electron beam propagation. Further experimental research of the authors will be devoted to the exposure of all the main factors, preventing effective energy injection of the pulsed electron beam into the gases and gas compositions not only in the given area of pressures, but also under the high pressure.

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