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Influence of current – conducting inserts in a drift tube on transportation of a pulsed electron beam at gigawatt power

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Abstract

This paper describes the results of experimental research on the influence of the current-conducting inserts in a drift tube on transportation of a pulsed electron beam at gigawatt power and nanosecond duration. The experimental investigation was conducted using a TEU–500 laboratory-pulsed electron accelerator (parameters of the accelerator: Up to 550 keV; output electron current: 11.5 kA; pulse duration (at half-height): 60 ns; pulse frequency: 5 pulses/s; pulse energy: Up to 280 J). Air was chosen as the propagation medium. The pressure in the drift tube is 50 Torr. It is revealed that the pulsed electron beam transport depends on the geometry of the current-conducting inserts in a drift tube. The direction of the pulsed electron beam propagation can be regulated by changing the geometry of the current-conducting insert. The experimental research was verified by theoretical calculations.

Keywords: Pulsed electron beam; Transport

1. INTRODUCTION

As an instrument in Engineering Science, pulsed electron beams of average power (10^6–10^8 W/cm^2) have a high potential for practical application in fields such as mechanical engineering, semiconductor electronics, chemical and biochemical manufacturing, synthesis of new compounds among others, nanosized (Sazonov *et al*., 2011; Ponomarev *et al*., 2013), medicine, and environmental protection. Development of the technologies in the above-mentioned areas is based on the results of experimental research, theoretical models of electrons, ions, atoms, and their clusters. Also development is based on the interaction of plasma, laser irradiation, and gamma rays with condensed matter and gases. The first investigations into electron beams were conducted by Bennet (1934) and Shipman (1971), who showed in 1939 that electron beams neutralized by ions could be focused by their magnetic field. In 1939, Alfven (1939), while analyzing the model of a symmetric beam with a homogeneous current density at total charge neutralization, obtained an upper limit for a propagating beam current. Then, Lawson obtained the limiting current for a similar model for unspecified charge neutralization. Studies of the dissipation process of the powerful electron beam energy, which were begun by Bennet, Alfven, and Lawson, determined the development and creation of powerful high-current electron accelerators that allowed the generation of electron beams with a high power of more than 10^{13} W in a pulse.

Nowadays, the obtained results of the experimental and theoretical investigations of the dissipation process of the electron beam energy into a neutral low-pressure gas (from 1 to 10 kP) have made it possible to determine the basic physical processes that influence the impact of beam energy on gases (Graybill & Nablo, 1966; Levine *et al.*, 1971; Benford & Ecker, 1972; Artamonov *et al.*, 1981; Erwin & Kunc, 1988; Yousfi *et al.*, 2006). These processes include current (magnetic) compensation, space charge neutralization, and instabilities of various types that change the conditions of electron beam propagation. Miller *et al.* (1972) studied the features of relativistic electron beam propagation in low-pressure argon experimentally and theoretically. The authors of the work focus mainly on the current (magnetic) compensation. Two accelerators with parameters of 1.5 MeV, 3 kA and 350 keV, 25 kA are used to conduct the experiment. The mathematical expressions that describe the operating range of the Alfven model are obtained, and these expressions are verified by the experimental research. Gladyshev and Nikulin (1997) present a theoretical model of relativistic electron beam propagation in rarefied gas. The authors show that when an electron beam is injected into gas, plasma with a heterogeneous linear density is generated, which leads to

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low energy losses including ionization losses and oscillation energy losses. On dissociative recombination of electrons and ions in plasma, the heat that heats up the propagation medium is released. Moreover, the authors indicate the development of a dissipative instability, which decreases effectively on plasma formation. As a result, electron beam propagation without significant energy losses along the drift tube is observed. Abrashitov *et al*. (1974) presents the results of an experimental investigation into the interaction of a relativistic electron beam (energy of electrons = 1 MeV, current = 5 kA, pulse duration = 70 ns) with plasma (density = 3×10^{14} cm^{-3}) in a magnetic field. The beam behavior is studied in both vacuum and plasma. When the beam passes through the plasma, the amplitude of the diamagnetic signals is 5–7 times higher in comparison with the measurements made in vacuum. Uhm *et al.* (1999) studied the effect of ion density on the efficiency of electron beam propagation in gas. A theoretical model is developed for the space charge of a relativistic electron beam propagating through the ion channel formed upon the injection of the electron beam into gas. The authors use simple analytical expressions for the space-charge-limited current that have been obtained for the case when the drift tube radius is much bigger than the beam radius. The analysis of the research findings reveals that the presence of the ion channel increases the Coulomb potential, which helps to effectively increase the kinetic energy of the electron beam. It is also shown that the space charge limited by an electron beam current is connected with the ion channel density by a non-linear increasing function.

Except for understanding the physical processes occurring at the interaction of the pulsed electron beams with condensed matters and gases, a crucial task is to consider the possibility of controlling the form of the electron beam and its direction during transport in a cross-section. For this purpose, various configurations of the drift tubes that enable us to change the form as well as the direction of the beam are used. Lee *et al.* (1988) used of an additional foil in the drift tube configuration (the foil is placed inside the drift tube). This foil acts as a current-conducting insert. A 9-MeV energy beam is extracted from a circular diode into the drift tube (length = 183 cm); at a particular distance from the outlet window the beam form is distorted due to the gradient of the external magnetic field. In this study, nitrogen at the pressure of 5 Torr is chosen as the propagation medium. Ozur *et al*. (2011) present theoretical and experimental research on the possibility of controlling the cross-section form of a non-relativistic high-current electron beam with the help of current-conducting inserts. The experiments are conducted using a "RHYTHM-M" setup. The typical parameters for this set-up are an accelerating voltage amplitude of 20–30 kV, beam current amplitude of 10–20 kV, and duration of 2.7–3.5 μs. The cross-section form of the beam is obtained by the authors with the help of the imprints on the stainless steel plates that have been left by the beam after the exposure. Beam imprints represent the areas of surface melting of the plates. The experimental and theoretical results obtained by the authors are in good agreement. The authors conclude that the transformation of the beam form occurs due to the formation of an axially non-heterogeneous magnetic field with the help of current-conducting inserts of various configurations.

The aim of the present paper is to experimentally and theoretically investigate the influence of the current-conducting insert on the transport of a pulsed electron beam of nanosecond duration with electron energy of up to 280 J in the air at low pressure (50 Torr).

2. EXPERIMENTAL SETUP

The experimental investigation was conducted using the laboratory setup including a TEU–500 pulsed electron accelerator and a dielectric drift tube. The TEU–500 pulsed electron accelerator consisted of the following basic units (Remnev *et al.*, 2004): A gas-filled generator of pulse voltages (an Arkadiev-Marx type), a double forming line, an autotransformer, and a diode assembly. The presence of the autotransformer is a peculiar feature of the given accelerator. The autotransformer was used for matching a low-resistance water double forming line to a high-resistance impedance of an explosive-emission planar diode in the operating pulse formation process. The operation stability of the pulsed electron accelerator was monitored by a Rogowski coil and a capacitive voltage divider (the range of current and voltage values recorded by sensors did not exceed 5%). The drift tube was a quartz tube (length = 35 cm; diameter = 13 cm; thickness = 3 mm) chucked between two metal flanges, which were braced with four metal rods.

To determine the influence of the current-conducting insert on the transport of a pulsed electron beam, several types of its configurations were made. These configurations could be conventionally divided into two groups: External and internal current-conducting inserts. The external current-conducting insert presented a single metal rod [Fig. 1(a)]. As the internal current-conducting insert, a copper bus (thickness = 1 mm; width = 70 mm) arranged inside the drift tube along its full length and four metal rods [Fig. 1(b)] were used. Part of the beam current was returned to the "ground" through the current-conducting inserts.

It is possible to present the general pattern of the experiments as the following scheme [Fig. 2(a)]: A diode chamber of the accelerator (1), where a planar graphite cathode (2), and an anode grid with a thickness of 3 mm (3) are installed. To generate an electron beam, a high vacuum is needed; in this work the beam was injected into the air (50 Torr); thus aluminum foil with a thickness of 140 μm (4) was used to provide a vacuum in the diode chamber as well as the possibility of letting any medium into the drift tube (5). To record a pulse electron beam profile, a dosimetry radiation-sensitive film (6) was used. Depending on the experiment, the test film was placed either along the full length of the drift tube (on the tube's wall, Fig. 2), or across the center of the pulsed electron beam propagation (Fig. 5).

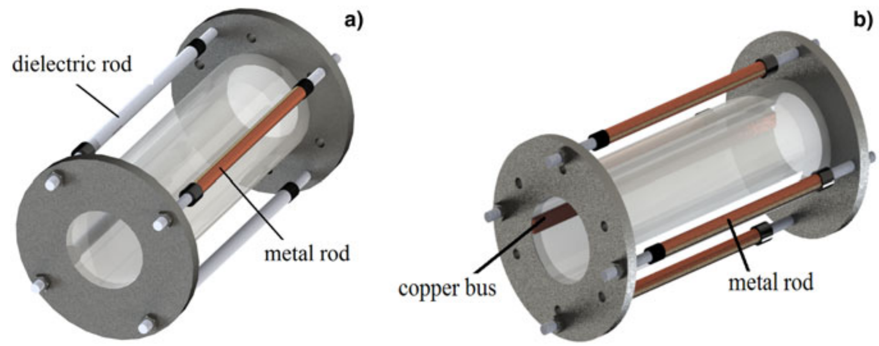

Fig. 1. Drift tubes with various configurations of the electron beam current-conducting inserts: (a) a single metal rod; (b) a copper bus and four metal rods.

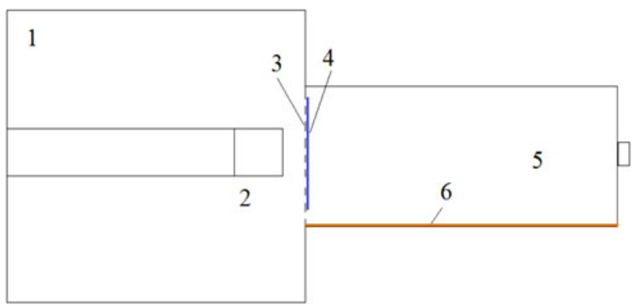

Fig. 2. Scheme of the experiment: Diode chamber of the accelerator (1); planar graphite cathode (2); anode grid with 3-mm thickness (3); aluminum foil with a thickness of 140 µm (4); drift tube (5); dosimetry radiation-sensitive film (6).

The dosimetry radiation-sensitive film was a polymeric film for single use designed for measuring an absorbed dose of photon and electron radiation in the range of 5–50 kGy. A radiation-sensitive polymeric layer with a thickness of 15–16 µm was deposited on a Lavsan substrate with a thickness of 100 µm. After the exposure of the dosimetry film to a pulsed electron beam the distribution of color strength (A, relative units) was obtained, which depended proportionally on the absorbed dose.

3. RESULTS AND DISCUSSION

The first series of experiments was aimed at studying the pulsed electron beam scattering on the walls of the drift tube while using various configurations of the current-conducting insert. The experimental scheme is given in Figure 3. Let us consider the situation [Fig. 3(a)] in which a single metal rod (2) was used as a current-conducting insert and the other rods were dielectric (3). The dosimetry films (4, 5) were arranged on the walls of the drift tube (1). One dosimetry film (4) was placed opposite the dielectric rod inside the drift tube, while another film (5) was placed opposite the metal rod inside the drift tube. The second experiment is presented schematically in Figure 3(b). Here, a copper bus (3) installed inside the drift tube (1) and four external metal rods (2) were used as a current-conducting insert. One dosimetry film (4) and the bus were arranged on the drift tube walls opposite to each other; another film (5) is positioned opposite the copper bus.

The dosimetry films were analyzed, and the following color strength distribution was obtained.

Figure 4 shows that the configuration of the current-conducting insert influences the pulsed electron beam distribution. Electron scattering on the walls of the drift

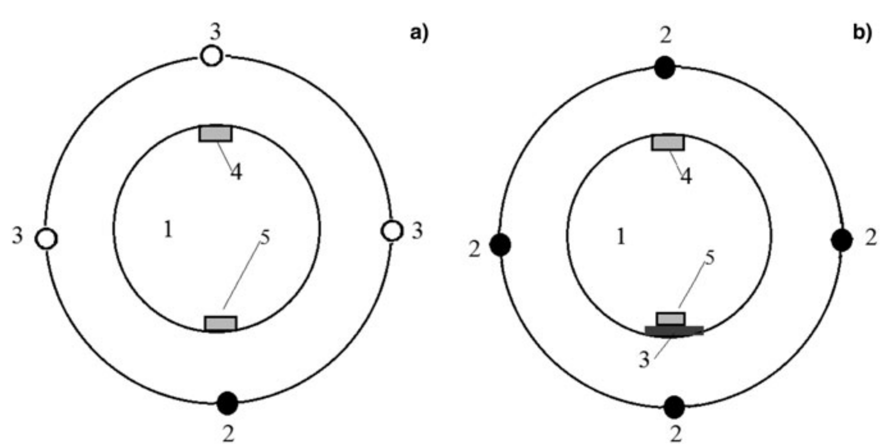

Fig. 3. Scheme of the experiment with a current-conducting inserts in the form of a rod. (a) A drift tube (1); metal rod (2); dielectric rods (3); dosimetry films (4, 5); copper bus. (b) Drift tube (1); metal rod (2); copper bus (3); dosimetry films (4, 5).

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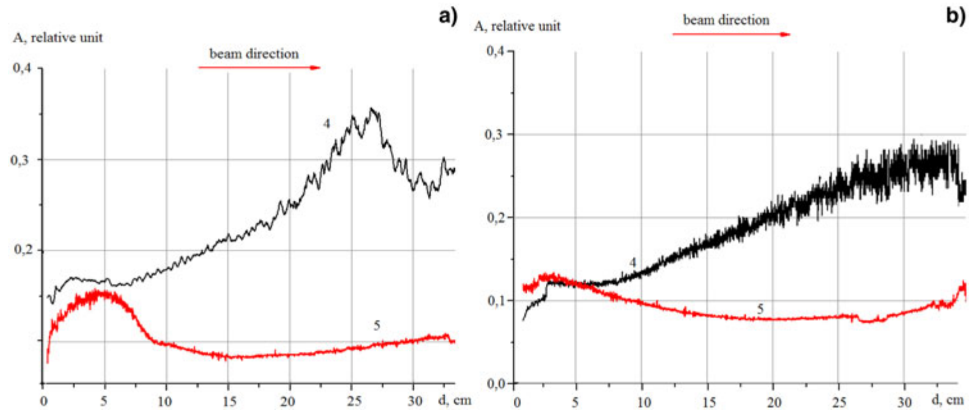

Fig. 4. Color strength distribution (A, relative units) of the dosimetry film (the numeric characters 4 and 5 correspond to the designations of the dosimetric films, whose arrangement is presented in Figure 3); (a) metal rod as a current-conducting insert; (b) copper bus and four external metal rods as a current-conducting insert.

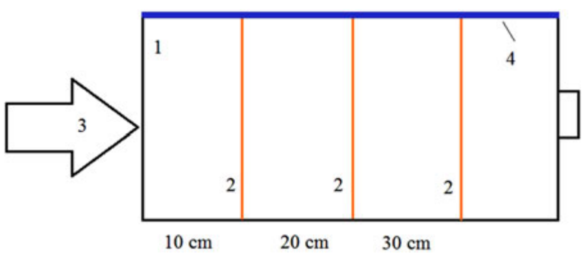

Fig. 5. Drift tube (1) for experiments with the cross-arrangement of dosimetry films (2) toward the pulsed electron beam (3) with a copper bus as a current-conducting insert (4).

This series of experiments can be described as follows: Initially, the dosimetry film is arranged at a distance of 10 cm from the accelerator's outlet window, and the beam transport medium is the air with a pressure of 50 Torr. A pulsed electron beam is injected into the drift tube, and its profile is recorded on the dosimetry film. Then, a new dosimetry film is placed at a distance of 20 cm from the outlet window and the whole experiment is repeated similarly to the first experimental series.

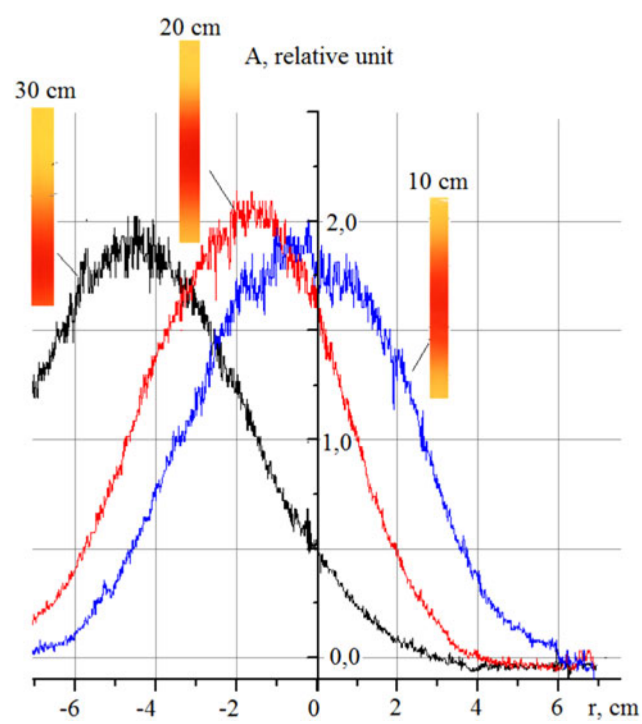

Fig. 6. Radial distribution of the dosimetry film color strength in the drift tube at various distances from the outlet window of the diode chamber and photographs of dosimetry films placed across the electron beam direction.

tube increases with the growth in the transport length. In the area of the magnetic field action produced by the current flowing through the current-conducting insert, the portion of the electrons falling on the drift tube walls is the lowest. The beam is repelled by the asymmetric current-conducting insert. An increase in the color strength of the dosimetry film [curve 5, Fig. 4(a)] at a distance of up to 7 cm is, hypothetically, connected with the Coulomb scattering of an electron beam. It is likely that the influence of the current-conducting insert field in this propagation area is low.

In the case when the current-conducting insert is a copper bus installed inside the drift tube [Fig. 4(b)] with four metal rods, the propagation of the pulsed electron beam does not differ from the case when the current-conducting insert is a metal rod except that the value of the dosimetry film color strength is lower. This is conceivably connected with the fact that four metal rods are placed symmetrically around the drift tube, which leads to the reduction of the influence of the magnetic field produced by the current flowing through the copper bus.

A series of experiments is presented below, in which the dosimetry film was placed across the center of the pulsed electron beam propagation. The film was arranged at various distances from the outlet window of the accelerator's diode chamber (Fig. 5).

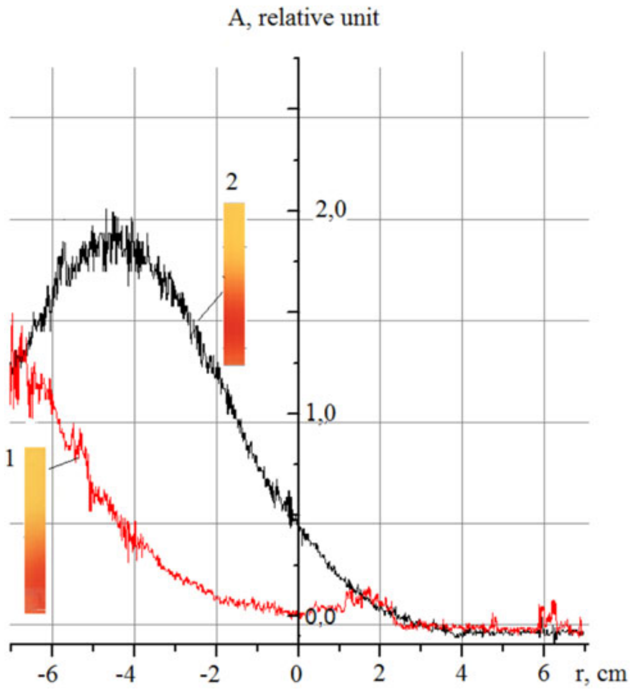

Fig. 7. Radial distribution of the dosimetry film color strength in the drift tube at a distance of 30 cm from the outlet window of the diode chamber: (1) a single metal rod; (2) a copper bus with four metal rods.

To verify the conclusion about the shifting action of a magnetic field of an axially asymmetric current-conducting insert, the experiments are conducted by measuring the cross-profile of an electron beam in the drift tube at various distances from the outlet window of the diode chamber (Fig. 6).

Figure 6 confirms the above obtained data (Fig. 4). Similar experiments have been conducted for the geometry of the current-conducting inserts as a single metal rod. In contrast, Figure 7 illustrates the radial distribution of the dosimetry film color strength in the drift tube at a distance of 30 cm from the outlet window for two cases: The current-conducting insert is represented by a single metal rod (curve 1, Fig. 7) and by a copper bus with four metal rods (curve 2, Fig. 7).

The presented data are in good agreement with the findings obtained for the electron beam scattering on the drift tube walls. When a single metal rod is used as a current-conducting insert, deviation of the pulsed electron beam profile from the center of the drift tube is greater and its scattering on the wall opposite to the rod is bigger compared with the situation when the current-conducting insert is represented by four metal rods and a copper bus arranged inside the drift tube.

To verify the obtained experimental data, the numerical calculations of the magnetic fields' configuration within the geometry of the experiments described above have been done using QuickField 5.10 software. QuickField 5.10 is a Finite Element Analysis Package for electromagnetic, thermal, and stress design simulation. When simulating the space charge ionization and neutralization, current losses are not taken into account (Fig. 8).

As Figure 8(a) shows, the magnetic field intensity inside the drift tube formed as a result of the beam current circuiting along the single metal rod may reach 0.03–0.05 tesla. In the model, the peak values for the reverse current (6 kA) are used, and are experimentally measured with the help of a reverse current resistor. It can be observed from Figure 8(b) that when a pulsed electron beam current is circuited in five parallel electric conductors (four rods and a copper bus with a thickness of 1 mm and a width of 70 mm), the magnetic field configuration is mainly dependent on the field produced by the current flow through the copper bus. However, the values of the magnetic induction inside the drift tube are close to the values obtained by the previous calculations. Moreover, in this geometry a pulsed electron beam can be “compressed” from above under the influence of the upper rod's magnetic field. This fact explains the difference in

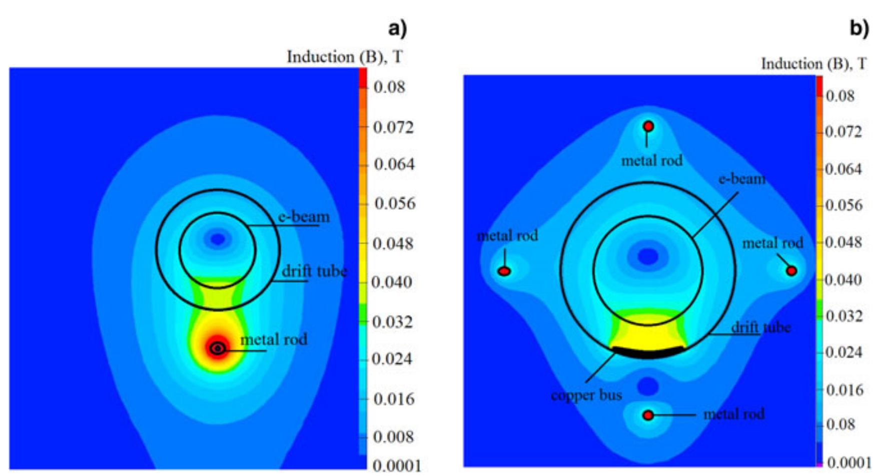

Fig. 8. Distribution of the magnetic fields in the drift tube at various configurations of the current-conducting insert: (a) a single metal rod; (b) a copper bus with four metal rods.

the curve's maxima at the radial distribution of the dosimetry films' color strength in the drift tube.

4. CONCLUSION

Pulse electron beams have wide application in various areas of science and technology. Among others, plasma-chemical technologies based on the initiation of the chemical processes by a pulsed electron beam are being intensively developed. In many cases, to achieve the maximum fineness of products and minimize the process of loss of active particles on the reactor walls, it is reasonable to withdraw from using metal reactors. In these situations, the frequently applicable reactors are in the form of quartz tubes with diameters that correlate to a beam diameter. Moreover, in plasma-chemistry, pressures of one to hundreds of Torr are often used. In these conditions, to ensure initiation of the optimal plasma-chemical process, it is necessary to provide uniform absorption of the electron beam energy by a gas phase. As experimental and theoretical investigations have shown, in the plasma-chemical processes initiated by a pulsed electron beam it is necessary to pay attention to the configuration of the current-conducting insert. Thus, for instance, the use of equidistant axially symmetric metal rods as a current-conducting insert may contribute to the effective propagation of a pulsed electron beam along the drift tube without changing its primary direction. However, in practice, we can deal with such tasks when it is more reasonable to inject the maximum energy of a pulsed electron beam into the particular sector of the plasma-chemical reactor. Varying the configuration of the current-conducting insert may also become expedient when shielding the structural elements of plasma-chemical reactors.

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