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Propagation of the pulsed electron beam of nanosecond duration in gas composition of high pressure

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Abstract. This paper presents the results of the investigation of the propagation of an electron beam in the high-pressure gas compositions (50, 300, and 760 Torr): sulfur hexafluoride and hydrogen, sulfur hexafluoride and nitrogen, sulfur hexafluoride and argon. The experiments have been performed using the TEA-500 laboratory accelerator. The main parameters of the accelerator are as follows: an accelerating voltage of 500 kV; an electron beam current of 10 kA; a pulse width at half maximum of 60 ns; a pulse energy of 200 J; a pulse repetition rate of up to 5 pulses per second, a beam diameter of 5 cm. The pulsed electron beam was injected into a 55 cm metal drift tube. The drift tube is equipped with three reverse-current shunts with simultaneous detecting of signals. The obtained results of the investigation make it possible to conclude that the picture of the processes occurring in the interaction of an electron beam in the high-pressure gas compositions is different from that observed in the propagation of the electron beam in the low-pressure gas compositions (1 Torr).

1. Introduction

For years, in Russia, especially in Tomsk, the particle accelerators of different types have been developed and implemented in technological processes [1-4]. Among a great variety of the accelerators, the DC accelerators and the linear accelerators are widely applied for commercial purposes (through a high efficiency of electrical energy conversion to beam energy, stability of beam parameters, etc.). However, having many advantages the DC accelerators and the linear accelerators have a huge disadvantage, namely, a high cost, which is the result of dc high voltage application, as well as high vacuum diodes (10^{-7} Torr). Using the pulsed accelerators, especially nanosecond ones, enables to sharply decrease the dimensions of high voltage formation schemes through the increase in insulating strength under pulse action. Besides, the nanosecond vacuum diodes are significantly simpler in construction and are capable to operate at relatively low vacuum up to forevacuum ~10^{-2} Torr.

The sources of pulsed energy flows of average power (10^6-10^8W/cm^2) as an instrument in engineering sciences have a high potential of practical application in many fields of economy: mechanical engineering, semiconductor electronics, chemical and biochemical industry, agriculture, medicine, etc. [5-8]. The important factor which constrains the development of particular technological processes in these fields is the necessity to modify the physical model of the interaction of the pulsed electron beams with the matter in a gas phase, the model being supported by the experimental data of the processes which occur in the interaction of such beams not only with model objects in a gas phase, but also with the objects with the complex chemical compound, which are the basic objects in the technological processes.

The physical model complexity is determined by the nonlinear nature of the energy absorption transferred by the beams, by the formation of the charged and excited particles, by the chemical reactions in the interaction zone, by the secondary radiation, and by a set of the phenomena which accompany the interaction of the pulsed electron beams with the matter in a gas phase. A significant part in solving this problem is assigned to the experimental data both regarding the results for forming the model and the model testing and regarding the quantitative description of the processes following the development of the particular technological processes [9-12]. In [13], the investigation results are

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presented for the electron beam propagation in vacuum and gases (nitrogen, helium, and carbon dioxide). The experiments are performed using the accelerator with the following parameters: an electron energy of 430 keV, a beam current of 10 kA, and a current pulse duration of 15 ns. The beam current was detected using the Faraday cup, when an electron beam was propagated to the drift tube. The authors noted that in the case of the electron beam propagation in nitrogen under a pressure of 50 mTorr, the gas underionization occurs and therefore a partial current neutralization of the beam. The electron beam is dissipated under the action of the electrical repulsion forces. Nevertheless, for nitrogen the current recorded using the Faraday cup is much higher than for the same distances in vacuum. When the pressure in the drift tube reaches 100 mTorr, the effective ionization occurs and the bulk charge neutralization is realized. With increasing the pressure in the drift tube, the determining role in the electron beam propagation is played by the current neutralization for all the types of gases used in this work. In [14], the authors present the results of the experimental and theoretical investigations of the pulsed electron beam in the drift tube filled with the N_2 gas. The pressure range is from 10^{-3} to ~ 10^{3} Topp. The experiments were performed using the Hermes-III accelerator (an electron energy of 19 MeV, a beam current of 700 kA, a duration of 25 ns). The authors demonstrate the results, which indicate that for the given type of the electron beam there are two modes of the effective propagation, which are in their turn related to the nitrogen pressure in the drift tube. The first mode is described with the pressure range from 1 to 100 mTorr (low-pressure region), the second mode is from 1 to 100 Torr (high-pressure region). Beyond the given types of the pressure, the fast-developing instability was observed, which results in the total decomposition of an electron beam. In the first mode of propagation, the beam is significantly ionized, and after the plasma ion generation the bulk ion charge is formed, which will restrict the electron beam. The authors of paper [15] studied the behavior of the intensive relativistic electron beam in its propagation in a high-voltage gas media. The resistive firehose instability occurs under such conditions. The gas media was a mixture of argon with air. The authors showed the possibility to decrease the impact of instability during propagation of the electron beam varying the parameters of the beam (including a beam current, a beam radius, a pulse duration reduction).

Nowadays, there is a lack of experimental results of the electron beam propagation in different gas compositions. The data mainly concern the single-component gas media. The purpose of the current work was to study the efficiency of the pulsed electron beam propagation in the high-pressure gas compositions (50, 300, and 760 Torr): sulfur hexafluoride and hydrogen, sulfur hexafluoride and nitrogen, sulfur hexafluoride and argon. The choice of the specified gas compositions is determined by the wide application of the given gases in the technological processes of many industrial technologies as a work media.

2. Experimental setup

The pulsed electron beam propagation in this work has been studied using the TEA-500 pulsed electron accelerator [16-17]. The electron beam in the TEA-500 accelerator is formed caused by the explosive emission from a surface of the graphite cathode with a diameter of 45 mm. The beam was ejected through an anode window, which was a support grid (with an optical transparency of 95%), and through an aluminum foil of 140 μm thickness. The anode-cathode gap for all the experiments was 13 mm. The stability of the accelerator operation was controlled using a Rogowski coil and a capacitor voltage divider. The dispersion of the values of current and voltage recorded by sensors did not exceed 5 %.

The electron charge ejected behind the anode foil is 390-430 μC. A drift tube equipped with reverse current shunts was designed for performing experimental investigations of the pulsed electron beam propagation in the high-pressure gas compositions (Fig. 1). The drift tube was a metal pipe of 15.1 cm in diameter and 55 cm long.

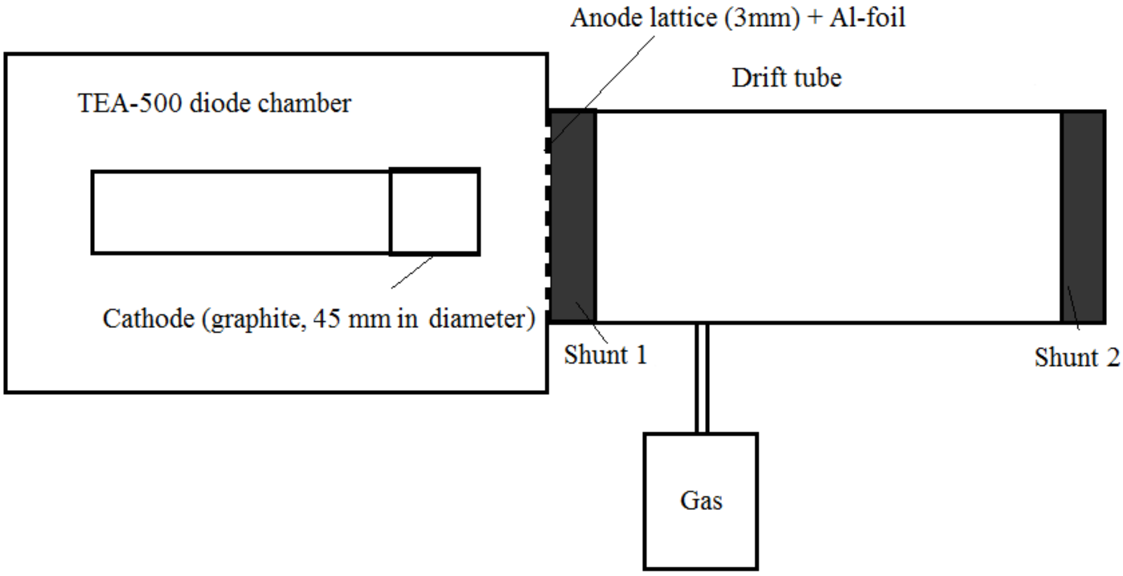

Figure 1. Scheme of the experimental stand to study the pulsed electron beam propagation in gases using reverse current shunts

The experiments were carried out as follows: the drift tube was filled with the gas under study, the electron beam was injected, and the reverse current shunts detected oscillograms of currents at the same time. Using Shunt 1, we registered the total reverse current closed on the walls of the drift tube; Shunt 2 was used to register the electron current reached the back flange of the drift tube. The value for the charge of the electrons fallen on the walls of the drift tube as a quantitative assessment of the efficiency of the pulsed electron beam propagation in high-pressure gas compositions: sulfur hexafluoride and hydrogen, sulfur hexafluoride and nitrogen, sulfur hexafluoride and argon. The experiments were performed with the transportation both in pure argon, nitrogen, hydrogen, and sulfur hexafluoride and in the mixtures of the specified gases with sulfur hexafluoride. The total pressure in the drift tube was fixed as 760 or 300 or 50 Torr, and the relations Ar: SF_6= 1:1, Ar : SF_6= 2:1, and Ar : SF_6= 1:2. The analogical relations are also for the other gas compositions.

In our work, we also used a calorimeter, which was located in the drift tube at the varied distance from the output window of the electron accelerator. The calorimetric investigations are performed for the gas compositions Ar:SF_6=1:1, Ar:SF_6=2:1, Ar:SF_6=1:2 under a pressure of 300 Torr.

3. Results and discussions

Figure 2 presents the oscillograms obtained for the gas compositions under a pressure of 50 Torr. I_1 is the total reverse current closed on the walls of the drift tube, I_2 is the electron current reached the back flange of the drift tube.

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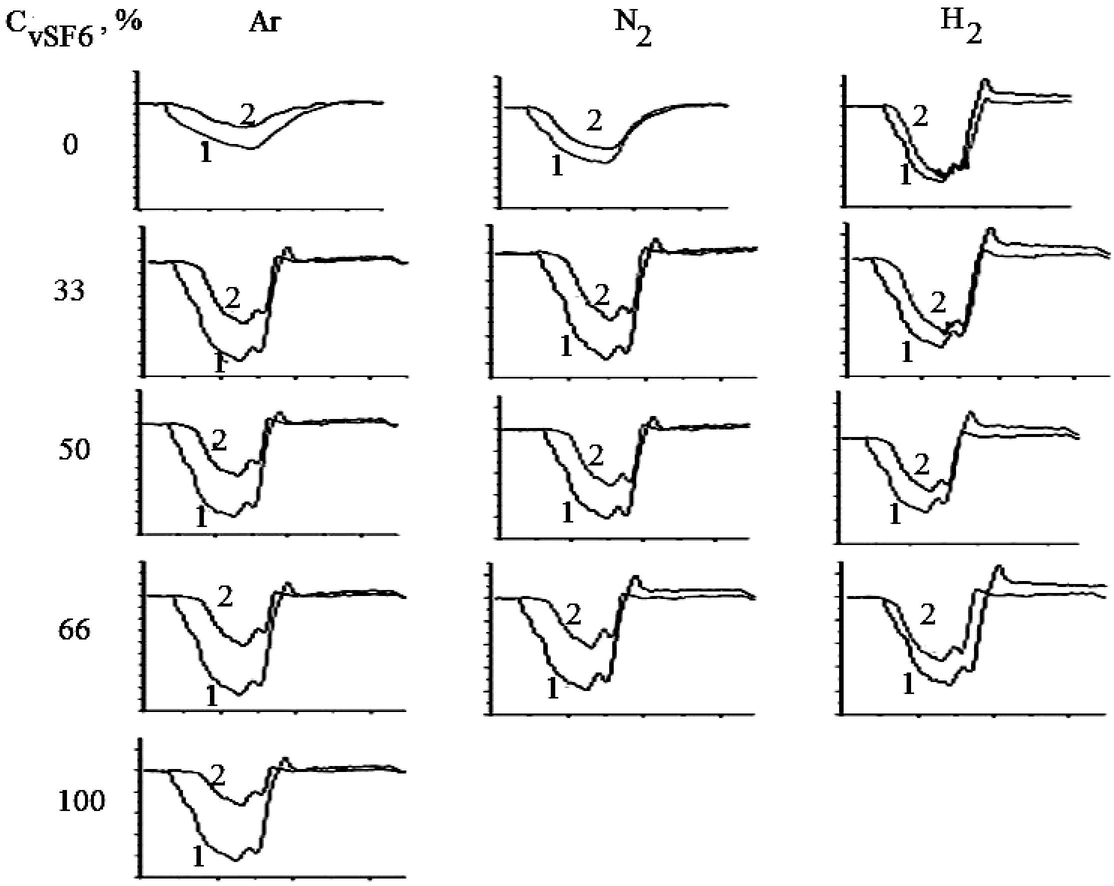

Figure 2. The oscillograms of the total reverse current closed on the walls of the drift tube (1) and the electron current reached the back flange of the drift tube (2).

Figure 2 shows that during the propagation of the electron beam in argon and nitrogen with the total pressure in the drift tube of 50 Torr the amplitudes of the total reverse current closed on the walls of the drift tube are almost similar, but the shapes differ. In nitrogen and argon under a pressure in the drift tube of 50 Torr, the handover of the falling edge of the signal is observed, which is more pronounced for argon. However, such a characteristic of the falling edge is not typical to hydrogen. In hydrogen, the amplitude of the total reverse current closed on the walls of the drift tube and the current of electrons reached the back flange of the drift tube correlate, the minimum scattering of the beam electrons onto the walls of the drift tube occurs. During the propagation of the electron beam in sulfur hexafluoride, the charge of the electrons reached the back flange of the drift tube is 98 μC, and the charge of the electrons fallen on the walls of the drift tube is 293 μC, respectively. For argon, nitrogen, and hydrogen, the charge of the electrons fallen onto the walls of the drift tube is 175 μC, 98 μC, and 43 μC, respectively. When in the drift tube a gas composition $Ar:SF_6$ = 2:1 or $N_2:SF_6$ = 2:1, the value of the charge of electrons reached the back flange of the drift tube and the charge of the electrons fallen on the walls of the drift tube correlate within the limits of experimental error ($Ar:SF_6$: 195 μC and 212 μC, $N_2:SF_6$: 171 μC and 185 μC). In the case when in the drift tube the amount of sulfur hexafluoride is higher, then a large dissipation of an electron beam occurs ($Ar:SF_6$: q=255 μC, $N_2:SF_6$: q=226 μC). In the gas composition when $H_2:SF_6$=1:1, 2:1, 1:2 the values of the charge of electrons reached the back flange of the drift tube q_1 and the charge of the electrons fallen on the walls of the drift tube q_2 are 183 μC /250 μC, 243 μC /98 μC, 203 μC /141 μC, respectively. The main feature typical to the specified pressure and all the ratios of the gas compositions is that the value of the total charge of the beam closed on the walls of the drift tube is always less than the charge of the electrons ejected behind the anode foil. It can be caused by the beam reverse current shorting on the skin-layer of plasma.

For the experiments with a higher pressure of 300, 760 Torr, the results of the experiments are presented in Table 1.

Table 1. The value of the electron charge reached the back flange of the drift tube q_1 and q_2 fallen onto the walls of the drift tube under the total pressure of 300 and 760 Torr (q_1/q_2, μC).

	300 Torr			760 Torr		
C_{vSF6}, %	Ar	N_2	H_2	Ar	N_2	H_2
0	0/163	77/244	55/272	0/163	42/273	76/267
33	0/356	0/329	24/297	0/289	0/313	0/275
50	0/357	0/336	0/322	0/256	0/262	0/257
66	0/350	0/282	0/310	0/246	0/232	0/253
100	0/337	-	-	0/145	-	-

Analyzing the data presented in the table, we can make the following conclusions: despite the increase in the total pressure in the drift tube, the most effective transportation of the electron beam is observed in nitrogen, hydrogen, and gas composition H_2:SF_6=2:1 (judging from the value of the charge of electrons reached the back flange of the drift tube). With increase in the pressure in the drift tube for all the gas compositions, the maximum dissipation of the electron beam on the walls of the drift tube is typical. Adding sulfur hexafluoride to argon, nitrogen, and hydrogen causes more qualitative energy absorption of the electron beam. The value of the charge of the electrons fallen on the walls of the drift tube in argon under the considered pressures within the given work is similar within the limits of experimental error and is 170 μC. Under the pressures of 300 and 760 Torr for argon and all the gas compositions with it, the charge of electrons reached the back flange of the drift tube is 0. Here when there is pure argon in the drift tube (300 and 760 Torr), the value of the charge of the electrons fallen on the walls of the drift tube is minimum compared to all other gases and gas compositions presented in the given work. It can be related to the fact that the electron beam is turned off as a result of the formation of the virtual cathode or the beam reverse current is closed on the skin-layer of plasma. To realize if the virtual cathode is formed, we performed the calorimetric study for argon, gas compositions Ar:SF_6 for three pressures 50, 300, and 760 Torr. The typical dependence of the ejected beam energy on the distance in the gas mixture of argon and sulfur hexafluoride, 300 Torr, is represented in Figure 3.

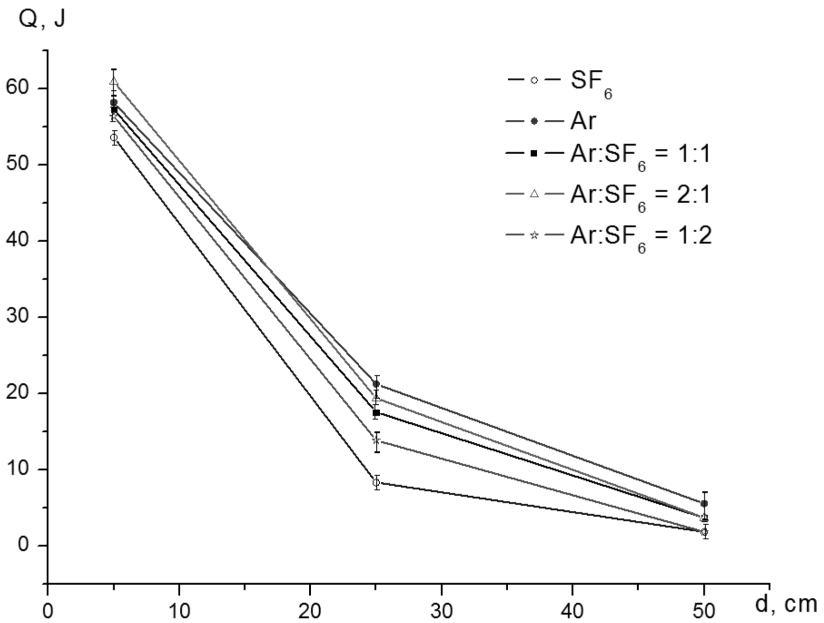

Figure 3. The ejected beam energy vs. the distance in the gas mixture of argon and sulfur hexafluoride, 300 Torr.

Figure 3 shows that the electron beam is propagated throughout the length of the drift tube. The virtual cathode is not formed.

4. Conclusion

Thus, the obtained results of investigations make it possible to conclude that during the propagation of the pulsed electron beam in argon, nitrogen, hydrogen, sulfur hexafluoride, and gas compositions on their basis under the total pressure in the drift tube of 50, 300 or 760 Torr the virtual cathode is not formed. The specific feature of the pulsed electron beam transportation in argon is plasma formation, because the conductivity of plasma is enough for the beam current to close over it. Consequently, argon is more effective as a plasma-forming gas in technological processes regarding the optimization of energy pumping into the gas media.

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