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Nanosecond pulse discharge in helium

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Abstract. The investigation of breakdown characteristics of planar "open" discharge in helium by pulses excitation with nanosecond rise fronts are presented.
Keywords: "open" discharge, discharge development delay time, similarity criterion.

1. Introduction

Electrical breakdown in gases occurs when a potential difference to the gas gap is applied, above which a self-sustained discharge is ignited in the gas. This phenomenon is the basis for the creation of gas-discharge devices. In devices with a cold cathode, in most cases, the breakdown occurs according to the Townsend or streamer mechanisms, which are based on the development of electron avalanches from the initial electron concentration.

In stationary discharges, the breakdown voltage $U_{br} = f\,(p\times l)$, where p is the gas pressure, l is the length of the discharge gap (Paschen's similarity law). This means that the dependences $U_{br} = f\,(p\times l)$ for different l coincide with the corresponding change in p. If the l/r parameter (r is the discharge cell radius) is taken into account, the situation becomes more complicated. For the same values $(p\times l)$ the breakdown voltage in a longer discharge gap is greater than for a short gap [1]. The situation is even more complicated when the discharge is initiated by pulses excitation. With a decrease in the pulse duration, the breakdown voltages U_{br} increase significantly and correspond to large values $(p\times l)$ [1–6].

In this paper, the object of research is pulsed “open” discharge OD with mesh anode of high geometric transparency μ, which is realized in short discharge gap at a significant overvoltage of the electric field. Under these conditions, the electrons are emitted under the action of resonant photons with a Doppler shift generated by fast atoms, which arise in the process of recharging ions moving towards the cathode [4]. A feature of such discharge is the insignificant multiplication of electrons in the discharge gap [5]. Thus, the discharge current is determined mainly by the electron’s emission from cathode and the external electrical circuit. The discharges physics of this type attracts interest to the fact that electron beam *EB* keV energies with fast current development is generated in them with high efficiency. This makes it possible to create efficient frequency-operating plasma switching devices in the subnanosecond range based on OD. The current initiation and development mechanisms in "open" discharge and their application in switching devices raises questions about the features of breakdown (current development) in "open" discharge when excited by a pulsed discharge with nanosecond fronts. The aim of this research is to investigate the breakdown characteristics in nanosecond pulsed "open" discharges in helium under the predominance of the photoemission mechanism of electron generation.

2. Experimental Set Up

To investigate the breakdown characteristics a planar discharge device (kivotron), consisting of round silicon carbide cathodes with diameter of 4 cm and two anodes are molybdenum meshes with a geometric transparency of 0.92 was used. The length of the discharge gap was l = 7 mm. A drift space 11 mm long between the discharge gaps was located. Such kivotron design made it possible to investigate the discharge characteristics in two modes depending on the switching method: – “open” discharge OD; – “open” discharge with generation of counterpropagating electron beams ODCEB. In the first case, the grid and one of the cathodes of the discharge gap through current-measuring shunts were grounded and served as a collector. In the second case, the grids were grounded, and the same electric potential to the cathodes was applied. The design and switching circuits of the discharge cells are shown in Fig.1.

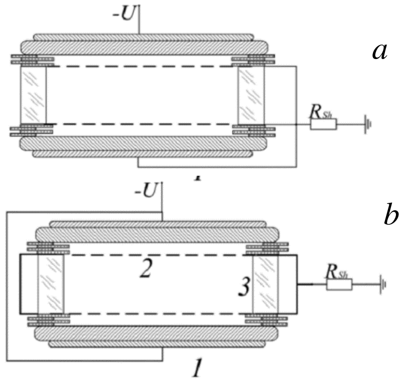

Fig.1. The design of the discharge cell and the circuit of switching the cell in OD (*a*) and ODCEB mode (*b*). 1 cathode; 2 anode; 3 insulator.

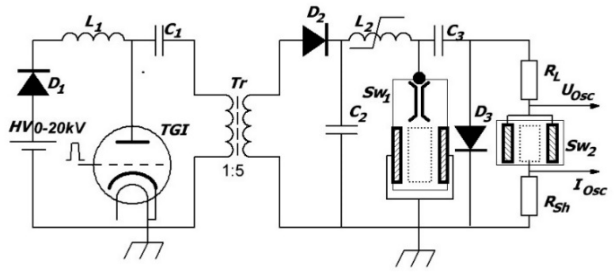

Fig.2. Power supply circuit.

A two-stage electrical circuit for power supply was used (Fig.2). The first stage is a device for the formation of a preliminary voltage pulse based on the TGI 1-1000/25 thyratron and a step-up pulse transformer. The second stage is a device for forming the main voltage pulse, in which a coaxial eptron was used as a fast switch, which made it possible to form voltage pulses with a leading-edge duration of ~5 ns at the load R = 33 Ω at the discharge working capacitance C_3 = 100 pF. The experiments in helium at a pressure p = 20–100 Torr в in the mode of regular excitation pulses with an amplitude U = 2–50 kV and a frequency of 100–200 Hz were carried out. Voltage pulses U, anode current I, pulse duration U, and current development time I were recorded. At the moment of switching, 2 current pulses were recorded: the discharge current of the cell's own capacitance and the discharge current of the working capacitance, which were superimposed on each other at high pressures. As a result, the registration of the current development time became uncertain. Therefore, the experiments the delay time for discharge development τ_d i.e., the moment of reaching 0.1 of the cell voltage amplitude before the start of the current growth, which corresponds to the voltage drop to a level of 0.9 of the amplitude

3. Experimental Result

Gas discharge occurs when the discharge cell with gas is filled and voltage applied to the cathode–anode gap. At a voltage above a certain value, an electron beam is formed, which, with a further increase in the voltage U penetrates behind the grid anode. In this case, a glow appears in the drift space. The length of the glow zone is determined by the path length of the formed electron beam in a gas with a certain pressure. In the *ODCEB* mode, the glow of the discharge is determined by the cumulative action, i.e., the excitation of the gas *EB*, which is simultaneously generated by both discharge structures. In this case, for a given geometry of the drift space, there are conditions for the voltage and pressure of the gas, when the glow zone fills the entire volume of space.

The character of electron beam propagation in the *OD* and *ODCEB* modes is different. In the first case, the small value of the cathodic potential drop provided a simple collision less acceleration of electrons emitted from the cathode and propagation of *EB* behind the anode in the drift space. In the second case, at high U, the range of electrons many times exceeds the linear dimensions of the cell; as a result, fast electrons, accelerating in the discharge gap, passing through the anode and the drift space, enter the discharge gap from the opposite side. There they slowdown in cathode fall to a complete stop. Then they accelerate again in the opposite direction, fly through the drift space and again slowdown in the discharge gap, thus performing oscillations.

From the oscillograms taken for different voltages and pressures of the working gases, the *I*(*U*) was plotted for the modes *OD* (Fig.3a) and *ODCEB* (Fig.3b). For all pressures in helium in both modes, the dependence *I*(*U*) is monotonically increasing; in general, it is approximated by a function of the type $I \sim U^x p^y$. The maximum voltages by the electrical strength of the discharge gap are limited.

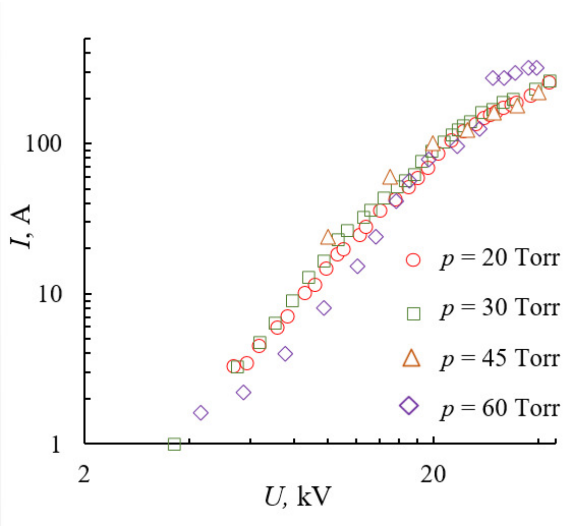

Fig.3a. Dependences of *I*(*U*) at different helium pressures. Mode of operation *OD*.

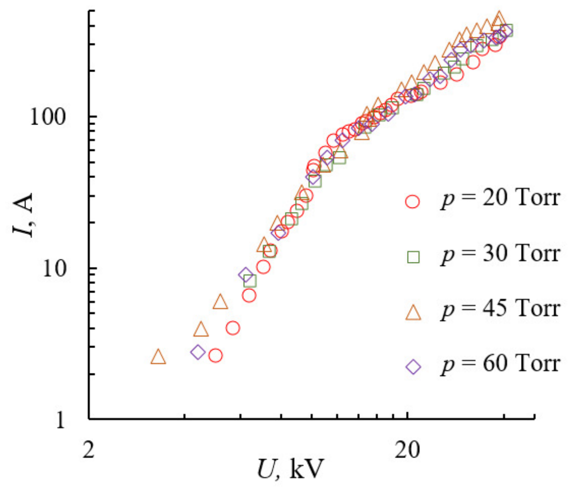

Fig.3b. Dependences of *I*(*U*) at different helium pressures. Mode of operation *ODCEB*.

A feature of any "open" discharge, as well as other forms of hindered gas discharge, is the presence of a delay between the application of voltage and the current development. In the present work, in the *OD* and *ODCEB* modes, the $\tau_d = f(U)$ is monotonically decreasing dependencies, with higher gas pressures corresponding to lower values of τ_d.

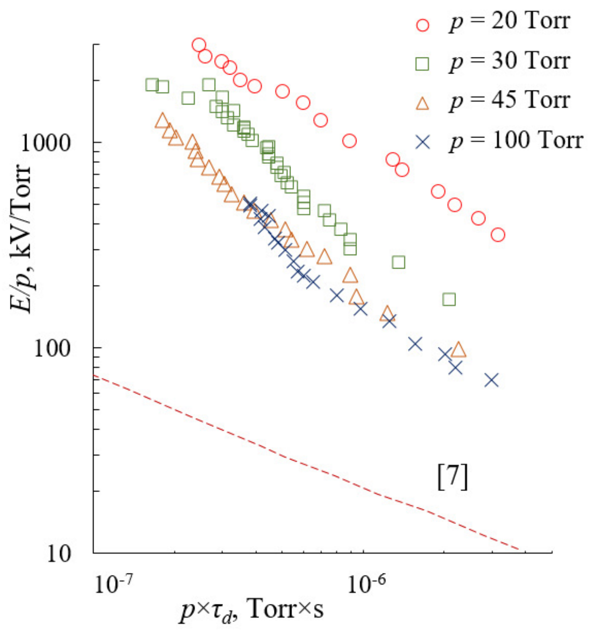

Fig.4a. Dependences $(E/p) = f(p \times \tau_d)$ at different helium pressures. Mode of operation *OD*.

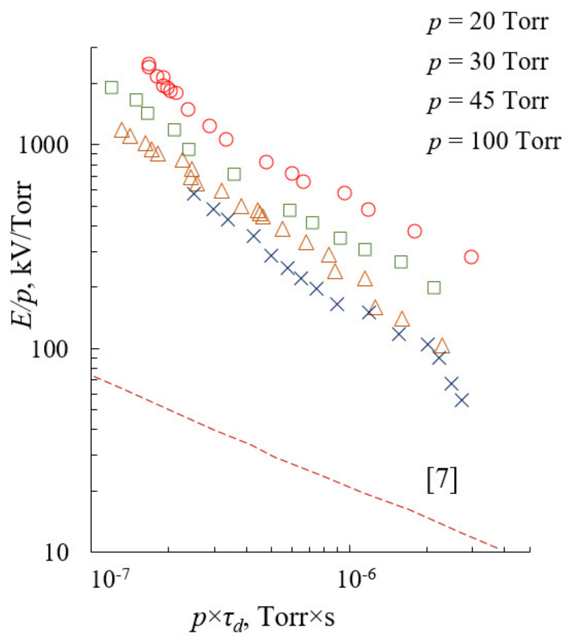

Fig.4b Dependences $(E/p) = f(p^2 \times \tau_d)$ at different helium pressures. Mode of operation *ODCEB*.

When studying the discharge development, the dependences $\tau_d = f(U)$ can be represented in a form consistent with the law of similarity of the dependence of the quantity $(p\times\tau_d) = f(E/p)$ [6]. In work [7] for different gases under pulsed excitation with U = 4–30 kV, pressure 1–760 Torr, gap length l = 0.1–6 cm, the validity of the expression $(p\times\tau_d) = f(E/p)$ is shown.

Fig.4a, 4b shows the dependences $(p\times\tau_d) = f(E/p)$ in the coordinates $(E/p) - (p\times\tau_d)$ for the *ODCEB* (Fig.4a) and *OD* (Fig.4b) modes and, for comparison, a similar dependence from [7]. In the coordinates $(E/p) - (p\times\tau_d)$ the dependencies are mismatched curves. Comparing the ODCEB and OD modes, it can be seen that ODCEB is characterized by significantly lower τ_d (for example, at p_{He} = 20 Torr and U = 40 kV, $\tau_d \approx 1$ ns) associated with more intense generation of VUV radiation during electron oscillations in the discharge gaps in the *ODCEB* mode and the absence of those in the OD mode. With an increase in the pressure of the working gas above $p \approx 60$ Torr, if the deceleration length of the beam electrons is less than the length of the drift space and, accordingly, there are no electron oscillations, then the rates of current development in the *ODCEB* and *OD* modes become equal and reach $\tau \approx 0.3$ ns in helium, at $p \approx 100$ Torr and U = 36 kV. The characteristic discharge development times in both types of “open” discharge correspond to significantly higher electric field strengths than for avalanche breakdown [7].

The behavior of the dependences presented $(E/p) - (p\times\tau_d)$ indicates that the similarity criteria $U_{br} = f(p\times l)$ in "open" discharges are not met.

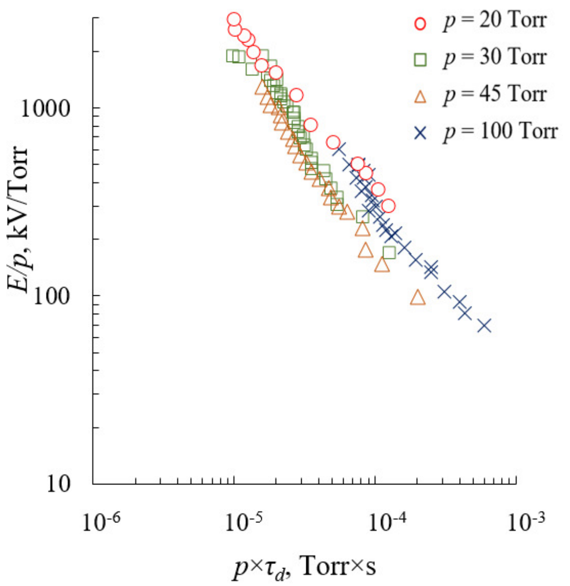

Fig.5a. Dependences $(E/p) = f(p^2\times\tau_d)$ at different helium pressures. Mode of operation *OD*.

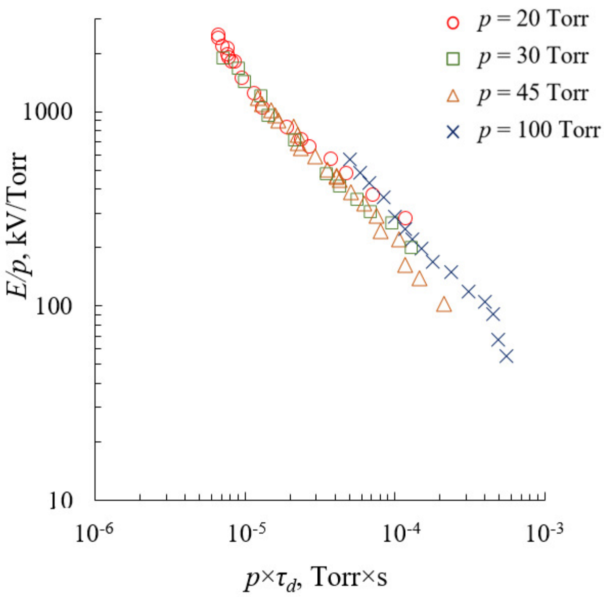

Fig.5b. Dependences $(E/p) = f(p^2\times\tau_d)$ at different helium pressures. Mode of operation *ODCEB*.

If it is assumed that when a certain voltage U is exceeded, the independent nature of *OD* and the rapid development of the current is ensured by resonant VUV photons generated in the discharge gap by fast excited atoms, which appear in reactions involving fast atoms and ions. In this case, similarly to [5], the number of emitted electrons n_e can be determined as $n_e \sim \gamma_{ph}\times R_s\times N^*$, where γ_{ph} is the photoemission coefficient; R_s is the radiation fraction intercepted by cathode; N^* the number of excited fast atoms is $N^* \sim \sigma_{RS}\sigma^+N^2l^2$, where σ_{RS}, σ^+ are the cross sections for excitation of the resonant state of an atom by a fast atom and the cross section of the resonant charge exchange of the ion on the atom of the working gas, respectively. The current rise constant is determined by $\tau \sim l/\sigma_{RS}NN_fR_sv_a\lambda$, where v_a, λ are the velocity and the path length of a fast atom. In this case, the similarity criterion is $(p^2\times\tau_d) = f(E/p)$. On Fig.5a, Fig.5b for the *ODCEB* and *OD* modes, the corresponding dependencies are shown. It can be seen that they coincide for different pressures with acceptable accuracy and, therefore, are due to the same processes associated with the photoemission of electrons under the action of VUV radiation generated with the participation of heavy particles.

4. Conclusion

The results of research of planar "open" discharge breakdown characteristics in helium when excited by pulses with nanosecond rise fronts in the mode of a classical "open" discharge and a discharge with the generation of colliding electron beams have shown that the development of the discharge is characterized by significantly higher values of the reduced electric field strength than in an avalanche discharge. A similarity criterion for such discharges is obtained, according to which the discharge development rate is proportional to the square of the pressure of the working gas.

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5. References

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