Nanosecond breakdown in a pulsed open discharge

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Abstract. The paper presents the results of studies of open discharge breakdown characteristics at nanosecond supply pulse in helium, neon, argon in a wide pressure range. It is shown that the open discharge exists in the range of $p_{He} = 20$–100 Torr, $p_{Ne} = 1.5$–25 Torr, $p_{Ar} = 0.5$–3.7 Torr with used experimental conditions. With increasing pressure, the role of separate elementary processes increases which can lead to a change of the discharge form to a presumably avalanche or streamer discharge. However, in this case, due to the photoemissive nature of the open discharge initiation, the similarity law $E_p = f(p\tau)$ does not coincide with that for a nanosecond avalanche discharge.

1. Introduction

In [1, 2] convenient tools for investigation of the breakdown development in pulsed gas discharge - similarity laws were determined and criteria of their applicability were formulated. Among them there are two main ones: a great number of initiating electrons and sufficient intensity of processes. The authors of these works considered avalanche and streamer pulse discharges in nanosecond range. However, there are other types of pulsed discharges that are based on other processes. In particular, in open discharge [3] at nanosecond excitation the avalanche electron multiplication is suppressed by operating conditions and the main mechanism of the discharge development is photoemission from the cathode under the influence of VUV radiation of fast excited atoms, shifted in frequency due to Doppler effect. In other words, new electrons do not appear mainly due to direct ionization of the working gas atoms, but due to combination of processes and interactions [4]. However, all these processes belong to resolved ones [5], that is occurring in the discharge and under the action of discharge. This leads us to suppose that similarity law formulated in [2] may have another form in case of open discharge and, probably, there may be a characteristic combination of parameters uniquely defining this type of discharge. This will be useful in investigation of properties of open discharge at nanosecond excitation and high reduced electric field strength which is especially actual at transition to pressures of the order of atmospheric pressure, using gases of different atomic weight, and also molecular gases. For example, in some cases in works on open discharge with generation of counter propagating electron beams there was observed a competition of elementary processes at discharge formation [6], which can be caused by transition of the discharge from one type to another. Similarity laws unique to each type of discharge could clearly demonstrate this. This paper presents a study of the existence of similarity laws for open discharge and open discharge with counter-propagating electron beams in helium, neon and argon medium in a wide range of conditions at nanosecond excitation.
2. Experimental setup

As a generator of high-voltage nanosecond pulses the apparatus from work [7] was used. In this setup the pulse shaper with nanosecond front is eptron [8] - switch based on combination of open and capillary discharges. Its main feature is a degree of compression of initial pulse, which reaches in conditions of given work up to $S = 300$ at active load. The maximum amplitude of the pulse formed by the eptron reached 100 kV with an edge of 1 ns. In order to increase the efficiency of the eptron with a capacitive load in the nanosecond mode, an open discharge preignition generator in the cathode cavity was additionally installed. As a result, the efficiency was raised at least by a factor of 2.

The research was carried out with an open discharge device based with a planar geometry (figure 1 (a)) consisting of two parallel silicon carbide cathodes with an active area of 12 cm$^2$ and two molybdenum grids with a geometrical transparency of 92%. The length of the accelerator gaps was 7 mm. A drift space of 7 mm length was located between the grids. The total natural capacitance of the cell was 10 pF. The device was placed relative to the eptron, so the inductance of its charging circuit determined the duration of charging the self-capacitance 7 ns. The voltage range was determined by the open-discharge ignition threshold from the bottom, which was 3 to 5 kV under the conditions of the present work, and from the top by the electric strength of the accelerating gap of 40 to 45 kV.

![Figure 1](image)

**Figure 1.** a) The open discharge based device design: 1 – cathode, 2 – grid-anode, 3 – insulator; b) connection for open discharge with counter propagating electron beams; c) connection for open discharge.

The gas-vacuum system allowed fixing the working gas pressure independently in the eptron and in the investigated cell, but it did not allow filling them with different gases, so the eptron worked with the same gas, which at the moment was filled in the investigated cell. In general, this did not affect the charging pulse characteristics of the investigated cell. In addition, there was an opportunity to organize slow flowing of the working gas through the cell in order to keep the experimental conditions clean. The flowing speed was chosen so that the working gas in the cell volume was renewed for about 10 minutes. We used high purity grade A gases, which, apart from argon, were additionally passed through a nitrogen trap with activated carbon.

3. Experimental results

The process of open discharge development with and without generation of counter propagating electron beams in various noble gases in a wide range of pressures and voltages was investigated in this work. The emission in these discharges takes place under the action of VUV radiation of fast heavy particles, so the rate of current development is determined by the type and concentration of working gas. In normal conditions of open discharge ($E/p \sim 10^4$ V/cm$\cdot$Torr) the Townsend electron multiplication factor decreases dramatically and becomes insufficient to sustain the discharge, and the
electrons pass into runaway mode and through the anode grid fall either into the drift space or in case of open discharge mode with counter propagating electron beams oscillate between accelerating gaps.

Experiments were carried out with working gases He, Ne, Ar in modes with one and two acceleration gaps. In the first variant the second cathode was connected to the grids and grounded through a common current shunt (figure 1 (c)). In the case of two accelerator gaps an open discharge with counter propagating electron beams was realized (figure 1 (b)). This led to a faster development of the discharge. At the same time the pressures for gases were the following: $p_{\text{He}} = 20–100$ Torr, $p_{\text{Ne}} = 1.5–25$ Torr, $p_{\text{Ar}} = 0.5–3.7$ Torr. The level of 0.1 of the power pulse amplitude was defined as the beginning of the discharge development delay. The end of the delay was conveniently assumed to be the beginning of the commutation. The duration of commutation was determined by the level of 0.1 to 0.9 of the voltage drop at the cell cathode. Experimental dependences for both these times were obtained in coordinates $E_p = f(p t)$.

The researches were carried out in the regime of regular pulses $f = 100–200$ Hz. In experiments with helium the breakdown in the regime with one acceleration gap and two was observed at $U \approx 2$ kV. A glow was observed inside the cell after the breakdown. At rise of voltage $U > 6$ kV the glow filled the whole volume. In neon and argon, the similar pattern was observed. At the same time with pressure decrease the discharge ignition voltage increased. Thus, in argon at pressure 0.5 Torr even at 20 kV we could not steadily ignite the open discharge. On the other hand, when pressure and voltage were increased, the breakdown characteristic changed sharply which can be seen in the figure 2. Curve 1 shows a typical open discharge switching pattern [4] with a relatively long breakdown delay and rapid switching. Curve 2 has the same delay, but the breakdown development continues much longer. It is supposed that in this situation the type of discharge has been changed due to the competition of elementary processes. At the same time with increasing pressure, especially in argon, this process took place at lower and lower voltages. This was the upper limit of the range of pressures investigated.

![Figure 2. Changing of the discharge behaviour with voltage increasing at the same pressure: 1 – typical oscillogram of the open discharge switching, 2 – other discharge type (see explanation in text).](image)

It can be seen from the figure 3, that the curves for both types of open discharge both for time of its formation and for time of commutation differ from those presented in [1, 2]. The main difference of the dependences obtained in the course of the experiments is that the curves are not completely overlapped but are nearly parallel at some small distance. A similar picture was observed for all gases, and the distance between the curves increases with the mass of the atom. It is also seen that the graphs...
in our case lie higher and to the left of the curve for the avalanche discharge taken from [1]. This shows that the formation of the open discharge is due to different mechanisms.

Figure 3. Breakdown characteristics for open discharge with counter propagating electron beams a) – c) and open discharge d) – f) at different pressure of working gas He, Ne, Ar.
It is interesting that with increasing pressure in neon and argon starting from $p_{Ne} = 19$ Torr and $p_{Ar} = 2.5$ Torr the curves begin to overlap each other, i.e. the law of similarity $E/p = f(pt)$ begins to be observed, though this curve still lies higher than the curve from [1]. This correlates with the change in commutation character described above. On the other hand, the distance between the curves increases as the pressure decreases. This is most pronounced in argon. Another section of your paper

4. The discussion on the results
It is evident from the obtained data that for the open discharge it is necessary to choose another combination of parameters which will be the law of similarity for it. Open discharge development is determined by ionization potential at the initial stage of formation, and then by photoemission coefficient from cathode under the action of resonant VUV radiation $\gamma_{ph}$ and dynamics of Townsend coefficient. In [9] data about $\xi(E/p) = \alpha(E, p)/p$ for helium, neon and argon are presented. All gases are characterized by a sharp decrease in $\alpha/p$ with increasing reduced electric field strength, but while for helium the curve maximum falls at ~ 500 V/cm×Torr, for argon it almost reaches 2000 V/cm×Torr. At the same time, the $\gamma_{ph}$ for argon is about 3 times smaller than for helium [10]. The process of open discharge development is shown in more detail in [11]. Although it refers to a continuous open discharge, similar processes take place in a pulsed discharge. As the voltage rises on the accelerator gap, first the Townsend electron multiplication occurs, after which the transition to the photoemission mechanism begins, determining the delay of the breakdown. And $\alpha/p$ decreases by more than an order of magnitude in the characteristic operating conditions of the open discharge. These characteristics are most successfully combined in helium. At the same time in argon for the same process the reduced electric field strength is more than 10 times higher while the resonant quantum energy is two times less ($\lambda = 58.4$ nm for helium [12] and $\lambda = 104.8$ nm and $\lambda = 106.7$ nm for argon [12]). This well explains the transition of the open discharge in heavier gases into presumably some form of a Townsend discharge as the pressure increases, as can be seen in the given characteristics.

For the existence of an open discharge an effective generation of runaway electrons which weakly interact with the working gas inside the accelerator gap and a high photo-emission coefficient from the cathode under the action of radiation of fast excited gas atoms are necessary. Obviously, both of these conditions are fulfilled at lower pressures within the framework of this work. However, for unambiguous description of open discharge development it is not sufficient to use parameters $E/p = f(pt)$ since apart from direct ionization at the initial stage of discharge development, a number of reactions with momentum and excitation transfer between heavy gas particles, as well as photoemission under the action of radiation of these gases participate in this process, and therefore in the similarity law there should be parameters describing these processes. Besides, in the switching power mode in open discharge with counter electron beams under some conditions the electrons of the beam can reach the counter cathode with energy sufficient for occurrence of secondary electron-electron emission from them. In this case the similarity law will also be different.

5. Conclusion
The paper has shown the possibility of existence of similarity laws for open discharge. It is seen from the results that these laws should differ significantly from analogues for avalanche and streamer discharges. However, the analysis of the curves $E/p = f(pt)$ allows to see the transition of the open discharge into another form. A set of parameters for the open discharge similarity law will be determined later on.

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