The ionization waves propagation in a long capillary dielectric tube in the absence of surface charge

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Abstract. The initiation of the electrical breakdown in a narrow tube filled with a gas under reduced pressure requires the voltage higher compared to that for a much broader tube. Besides, at the fixed applied voltage formally sufficient for breakdown, the probability for the breakdown happening in a narrow tube is far from 100%. This probability can be increased appreciably if to organize the surface ionization waves preceding the volume breakdown in a narrow tube. The breakdown development in a long capillary dielectric tube induced by the surface ionization waves was investigated in this work. The experiments were carried out with the use of a quartz capillary tube with a high aspect ratio of length to diameter. The tube was filled with helium at pressures of 1 - 30 Torr. The pre-posted surface charge on the tube wall was absent. It has been found the completed high-current breakdown between two electrodes located at the ends of the long capillary tube develops with a high probability with the presence of surface ionization waves within the tube.

1. Introduction

Steady-state low-pressure DC discharge between two electrodes in the sealed tubes of different configurations is a well-known phenomenon widely used in a variety of fields of science and practice. From a gas discharge physics point of view, DC discharge in a long capillary tube takes a special place among other glow discharges. The distinguish feature of this discharge is the inception voltage providing the electrical breakdown (or ignition of discharge) exceeds appreciably the voltage needed for supporting steady DC discharge. Besides, at the fixed applied voltage formally sufficient for breakdown, the probability for the breakdown happening in a narrow tube is far from 100%. The mentioned leads to many serious problems at the practical usage of DC discharge in a long capillary tube. Thus, the diminishing of the breakdown voltage accompanied simultaneously by essential increasing the breakdown probability is a real challenge for plasma science in relation to the capillary discharges.

This task may be solved by using the surface ionization waves formed in the capillary tube by the auxiliary surface barrier discharge. These waves will generate the plasma sheet covering the walls inside the capillary tube which can promote the breakdown at the lower voltage and 100% probability. This is a reason why the main topic of this paper is the surface ionization wave propagation in a long
capillary dielectric tube. The propagation of this wave is supported by a low amplitude displacement current through the tube and accompanied by the electric charge deposition on its internal walls. Charge deposition takes the time, so the velocity of the surface ionization wave is substantially lower than that of the volume ionization wave of streamer type propagating in open space [1-8]. In principle, the auxiliary surface barrier discharge can be initiated by the pulsed voltage at lower amplitude compared to the breakdown voltage of the capillary discharge. However, the length of the plasma sheet formed by surface discharge will depend on the amplitude U of applied voltage and its rise-time \( \frac{dU}{dt} \). In its turn, the formed plasma sheet length will determine the breakdown voltage of the capillary discharge - the longer length, the lower voltage of the completed breakdown forming the plasma in tube between electrodes. So, the detail information on the surface ionization wave influence on the capillary discharge breakdown and plasma formation in the long tube has a great importance, for example, to develop methods for increasing the reliability of fast switching-on the lasers and other devices using gas discharges in dielectric tubes with a high aspect ratio of length to diameter. This work experimentally investigated the propagation of surface ionization waves in the capillary tube and their effect on the breakdown formation by the example of low-pressure DC discharge in He.

2. Experiment and results
The generalized scheme of the used experimental setup is shown in Figure 1a. Helium was used as plasma-forming gas at pressures \( P = 1 - 30 \) Torr. The 300 mm long quartz capillary tube had inner and outer diameters of 2.5 and 4 mm, respectively. Two configurations of electrode systems were used in the experiments - two-electrode and three-electrode ones. The two-electrode system consisted of two internal electrodes that were located on opposite edges of the quartz tube. These electrodes were hollow and thin-walled copper cylinders with an inner diameter of 2 mm, an outer diameter of 2.5 mm, and a length of 25 mm, which fitted tightly to the inner surface of the quartz tube. The distance between the edges of the inner electrodes facing each other was 250 mm. The three-electrode system consisted of two internal electrodes and one external electrode. The outer electrode was copper foil, which was tightly glued to the quartz tube from the outside along its entire length. The outer electrode could be at a floating potential or connected to the ground via a current shunt. The applied pulsed voltage serves two goals: to generate the surface ionization wave and to form the breakdown between the inner electrodes.

A narrow slit was cut in the foil along the entire length of the tube to observe visually the development of the breakdown in the tube. The width of the slit was 3 mm. Three light guides with inlet holes of 100 \( \mu \)m were located along with the slot. The light guides are rigidly fixed at a distance of 1 cm from each other and can be simultaneously moved on the optical rail along the tube. Each light guide is connected to a separate PMT. In addition, another PMT was permanently near the edge of the inner high voltage electrode. The signal of this PMT was a reference and determined the moment of the breakdown development beginning in the tube. The discharge voltage was measured by the
PINTEK HVP-39 high voltage divider (1000:1, 40 kV, 200 MHz). The rise-time of the applied voltage \( \frac{dU}{dt} \) was kept approximately the same in all experiments and equal \( 6 \times 10^{10} \) V/s. The current, voltage and PMTs electrical signals were simultaneously recorded by two multi-channel INSTEK GDS-72204E oscilloscopes (200 MHz, 1GS/s). Experiments were carried out with weak and continuous gas pumping through the capillary tube, ensuring the preservation of certificate purity of helium, as well as the removal of possible products of plasma chemical reactions taking place in the discharge. Gas pressure and gas flow rate were measured by PIZA 111 pressure transducer and Tiny Leak-2 leak valve. The tube was pumped out by NVR-5D vacuum pump. The discharge image from the tube face was taken by the Canon EOS 550 camera (Figure 1b).

The uniqueness of the used discharge setup is the possibility to realize in the capillary tube the different breakdown scenarios when its development will be determined mainly either by volume or surface ionization waves. In the latter case, it is possible to observe the simultaneous propagation of counter waves from opposite inner electrodes. The sketches of different electrode configurations used under experimental investigation are shown in Figure 2.

![Three-electrode configuration](image)

**Figure 2.** The sketches of different electrode configurations used under experimental investigation. a) - d) Three-electrode configuration: a) The external and internal electrodes are grounded; b) The external electrode is grounded, the internal electrode is not; c) (+HV) The external electrode is disconnected from the ground; d) (-HV) The external electrode is disconnected from the ground; e) Two-electrode configuration. The external electrode is absent. Brown arrows show the ionization waves direction.

For the sake of clarity, each electrode configuration in Figure 2 is provided with an illustration constructed on the base of the close examination of experimental data corresponding to a helium pressure of \( P = 10 \) Torr and \( U = +6.7 \) kV and \( U = -6.7 \) kV. The illustration qualitatively explains the main features of the development of the breakdown in the long capillary tube with a given electrode configuration. Let us give more detail comments to each configuration:

a) After applying the high voltage of any polarity, the surface ionization wave arises in some delay near the HV electrode and always moves towards the grounded electrode. A completed breakdown (establishing in the tube an electric current between the internal electrodes) occurs when the surface ionization wave arrives at the grounded electrode, i.e., after the barrier discharge phase is fully being completed.

b) At any polarity of the applied voltage, volume breakdown as such does not occur - only the propagation from the HV electrode of the surface ionization wave associated with the development of the surface barrier discharge inside the tube is observed.
At any polarity of the applied voltage, the volume breakdown completion happens due to the meeting of two counter surface ionization waves originating from the inner electrodes. The direct surface ionization wave always arises near the HV electrode in some delay after applying the high voltage and moves towards the grounded electrode. The counter surface ionization wave originates from the grounded electrode when the direct ionization wave passes approximately 3 cm. The counter wave velocity exceeds appreciably the direct wave velocity.

e) At any polarity of the high voltage, the breakdown in the two-electrode capillary tube happens due to the propagation of the volume ionization wave from the HV electrode. The breakdown itself occurs much faster compared to the three-electrode tube, but its start has a long lag relative to the beginning of the applied voltage that leads even to the absence of the breakdown at all.

![Figure 3](image1.png)

**Figure 3.** Typical waveforms of the electrical signals in three-electrode configuration. The outer and inner electrodes are grounded; there is only the direct wave. a) $U(t)$, $U_{\text{PMT}}(t)$ at different locations; b) $I_{\text{out}}(t)$, $I_{\text{in}}(t)$ are the current collected by the outer and inner electrodes. $U_0=+6,7 \text{ kV}$; He, $P=10 \text{ Torr}$.

![Figure 4](image2.png)

**Figure 4.** Typical $X(t)$ dependences for direct (from the anode) and counter (from the cathode) ionization waves correlated with the discharge voltage $U(t)$ and discharge current $I(t)$ oscillograms. He, $U_0 = +6,7 \text{ kV}$. The $X=0$ coordinate corresponds to the anode, i.e. the high voltage electrode coordinate. a) $P = 1 \text{ Torr}$, the outer electrode is disconnected with ground; b) $P = 10 \text{ Torr}$, the outer electrode is absent.

Close examination of the results similar to those presented in Figs. 3-4 revealed the following. The magnitudes of the discharge current and voltage being established after the breakdown in tube fall slightly with pressure increase and are about $I \approx 5 \text{ A}$, $U \approx 2 \text{ kV}$ ($P=1 \text{ Torr}$) and $I \approx 4 \text{ A}$, $U \approx 1 \text{ kV}$ ($P=10 \text{ Torr}$). In general, the velocities of the direct and counter ionization waves decrease as they get further away from the proper electrodes. At a fixed voltage, the average velocity of direct ionization
wave increases almost quadratically with gas pressure from $2 \cdot 10^6$ cm/s ($P = 1$ Torr) to $1.2 \cdot 10^8$ cm/s ($P = 10$ Torr). The average velocity of the counter surface wave (in case it occurs) is about an order of magnitude higher than the velocity of the direct wave. At a fixed pressure ($P = 10$ Torr), the average direct wave velocity increases with the increase in the applied voltage. The average velocity of the counter surface wave (in case it occurs) is about an order of magnitude higher than the velocity of the direct wave. At a fixed pressure ($P = 10$ Torr), the average direct wave velocity increases with the increase in the applied voltage.

The results of the numerical calculations (Figure 5) are qualitatively consistent with the experiment.

![Figure 5](image)

**Figure 5.** The calculated axially-symmetric distribution of the static electric fields in the tube at different shapes of the internal electrodes. The applied voltage amplitude is 6.7 kV. a) and b): the internal electrodes are hollow cylinders, the outer electrode is disconnected from the ground; a) the E-field distribution before the ionization wave start; b) the E-field distribution after the wave has passed 3 cm away from the HV electrode. c) the internal electrodes are thin wires of 0.5 mm diameter located on the tube axis; the external electrode is grounded; the E-field distribution before the ionization wave starts.

Indeed, two-dimensional calculations of electrostatic fields formed in the capillary tube when a voltage pulse is applied to the electrodes of different shapes have shown that:

1) in a three-electrode configuration with internal electrodes in the form of hollow cylinders and when the external and internal electrodes are grounded, the maximum electric field is formed not on the axis but on the tube surface near the HV electrode, while the axial and surface electric fields near the grounded electrode are close to zero; such field structure should cause the breakdown to begin with the propagation of an ionization wave along the tube surface.

2) in a three-electrode configuration with internal electrodes in the form of hollow cylinders and when one internal electrode is grounded, the maximum electric field being formed is also not on the axis. However, in this case, the same high fields are formed on the tube surface as near the HV electrode, and near a grounded electrode as well. While the direct surface ionization wave propagates, the electric field at the front of this wave falls but the surface field near the grounded electrode
increases. In such a case, the propagation of the direct ionization wave from the HV electrode may trigger the appearance of the counter surface wave propagating from the grounded electrode.

3) in a three-electrode configuration with inner electrodes in the form of fine wires of 0.5 mm diameter and when both the outer and one inner electrode are grounded, the maximum electric field is formed on the axis near the top of the HV electrode rather than on the tube surface near that electrode, while the axial and surface electric fields at the grounded inner electrode are close to zero. Such field structure should cause the breakdown to begin with the propagation of a volume ionization wave (like streamers) along the tube from the HV electrode.

3. Conclusion

Thus, the studies carried out revealed the main features of breakdown development in a long capillary tube in the absence of a pre-posed charge inside the tube. They consist in the fact that in the presence of an external electrode a fast volume breakdown is preceded by a slow stage of development of surface barrier discharge inside the tube due to propagation of direct (from the HV electrode) and opposite (from the grounded electrode) surface ionization waves. In the absence of an external electrode, a volume breakdown (i.e., establishing an electric current between the internal electrodes - the cathode and the anode) occurs much faster than that in a three-electrode system, but with a very large scatter of the breakdown lag (up to no breakdown) relative to the voltage pulse application. One may note, in many applications, the instability of switching-on of the gas discharge apparatus presents a much greater problem than the slow but more stable its activation. Therefore, the results of the studies carried out are not only scientific but also practical value.

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