Features of a negative ionization wave development preceding the full breakdown in a long capillary tube wrapped with a continuous or fine-sectioned grounded electrode

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Abstract. The experimental results on the study of negative ionization wave propagating along a long capillary tube are presented. The ionization wave was initiated by high-voltage pulse of negative polarity. The propagation of this surface ionization wave precedes and influences the establishment of complete electric breakdown within the tube. The spreading of this wave is accompanied by the surface charge deposition. The usage of the fine-sectioned outer electrode allows one to find out the general features of a negative ionization wave. The main of them is the tight correlation between local currents determining the formation of local surface charge and visual discharge images taken by the fast camera characterizing the pace of the ionization wave propagation.

1. Introduction

The development of an electric breakdown between the electrodes significantly depends not only on the gas sort and pressure \( P \) but also on the gas discharge system geometry. In the case of flat electrodes, the gap \( d \) between which is significantly smaller than their transverse dimensions, the breakdown mechanism is due to the development of Townsend avalanches from the cathode, if the \( Pd \) product is not too large [1]. In a situation with an inverse ratio of the longitudinal and transverse dimensions (a good example is a long capillary tube), the Townsend breakdown mechanism does not work due to the strong damping effect of the walls on the development of avalanches. In this case, the stage preceding the complete breakdown of the gap is the surface ionization wave propagation from a high-voltage electrode. In a certain sense, the surface ionization wave is an analog of Townsend avalanches, since in both cases the final breakdown stage, i.e. the reverse ionization wave propagation, begins after the arrival of the avalanche and the surface ionization wave to the opposite electrode.

However, there is an essential difference in the development of the surface ionization wave compared to Townsend avalanches. The ionization wave propagation in a dielectric tube filled with gas is accompanied by the deposition of a surface charge on the tube wall. In this case, the ionization wave velocity is largely determined by the charging rate of the dielectric tube wall at the wavefront. For this reason, the experimental determination of the charge deposition dynamics during the ionization wave movement is of great interest for gas-discharge physics.

This paper presents experimental data on the study of an ionization wave propagating in a long quartz capillary tube filled with helium at low pressure \( P = 10 \) Torr. The ionization wave initiation was done by the high-voltage pulse of negative polarity. To trace the dynamics of surface charge...
deposition on the tube wall, the external electrode wrapping the tube was fine-sectioned. The current of each small section was recorded by a multi-channel oscilloscope. Thus, the spatial distribution of the radial current along the tube was obtained. In addition, the wave motion was captured by a fast camera synchronized with the high-voltage pulse initiating the ionization wave. Comparison of the radial current spatial distribution with time-correlated discharge images allowed us to obtain new information about the dynamics of the ionization wave propagation.

2. Experimental setup
The sketch of the used experimental setup is presented in figure 1. The ionization wave in the tube was initiated by the high-voltage pulse of negative polarity transferred from the capacitor \( C = 50 \, \text{nF} \) to the high-voltage electrode through the ballast resistor \( R_b = 1.2 \, \text{kOhm} \). The tube is made of quartz, the length is 300 mm, the inner diameter is 2.5 mm, the outer diameter is 4 mm. Two inner electrodes are placed at the ends of the tube. Both of them are thin-wall copper cylinders each 25 mm in length and tightly pressed to the inner tube surface. The outer electrode was a thin copper film tightly covering the lateral tube surface. The outer electrode is either continuous one of 250 mm in length or fine-sectioned consisting of 16 sections 13 mm in length with 2 mm gaps between each pair of sections. Each isolated section was connected to the ground by an individual current shunt \( R = 50 \, \text{Ohm} \) to measure the radial electric current \( I_r \) which deposits the electric charge onto the tube surface during the ionization wave propagation. The outer electrodes both continuous and fine-sectioned have a narrow slit (2 mm) cut out along the whole length of the tube in order to observe what is happening inside the tube. The images of the discharge developing inside the tube were taken with a high-speed ICCD camera PCO. Dicam C4. Comparison of the spatial distribution dynamics of the radial current \( I_r(x, t) \) along the tube with time-correlated discharge images was done.

![Figure 1](image1.png)

Figure 1. Sketches of two experimental setups used: a) the outer electrode is continuous; b) the outer electrode is fine-sectioned.

Notations: \( C \) is the capacitor, \( T \) is the thyratron, \( R_b \) is the ballast resistor, \( R_{sh} \) is the current shunt.

3. Experimental results.

3.1. The outer electrode is continuous.
Figure 2 (a) presents the time behavior of the discharge current (blue curve) and the ionization wave velocity (red curve) after applying the high-voltage pulse \( U = -2 \, \text{kV} \). Recall that the discharge current is the radial current depositing the charge onto the tube wall and existing due to the ionization wave propagation. One can see, the discharge current appears not immediately after the voltage applying but with a delay of about 0.25 \( \mu \text{s} \). One can see also there is a good correlation between the discharge current and ionization wave velocity. After the ionization wave formation, both the current and velocity grow up sharply but further, they decrease linearly with time though the applied voltage \( U(t) \) is const.

Figures 2 (b) and 3 show that the glow emission intensity of the plasma formed by the ionization wave diminishes with the increase in the length of the area occupied by the ionization wave. Another interesting feature of the ionization wave driven by the negative high voltage is that there is no clearly distinguished thin and bright wavefront like that observed in the case of the ionization wave driven by
the pulse of positive polarity. There was observed also a great difference in the ionization wave velocities corresponding to the negative and positive driving pulses. Despite the smudgy outline of the negative wavefront, the velocity of the negative ionization wave exceeds approximately by factor 5 the velocity of the positive ionization wave at the same high-voltage pulse amplitude. One of the possible reasons for that is the absence of necessity in seed electrons for the propagation of the negative ionization wave - these electrons are provided by the plasma itself. In general, therefore, to reach the same amplitude of the discharge current it is necessary to apply a much higher amplitude of a positive pulse compared to that for negative polarity. This is why practically there was no delay in the appearance of the positive ionization wave after applying the positive high voltage.

**Figure 2.** a) The current and voltage oscillograms corresponding to the ionization wave propagation at the applied voltage pulse $U = -2$ kV. The red line is the ionization wavefront average velocity vs time. The labels' numbers correspond to the frames' numbers in the right figure. b) Six frames of the plasma glow intensity distribution along the tube. The frame numbers correspond to those near the photos presented in figure 3.

**Figure 3.** Six frames of the discharge images taken at different times in the course of the ionization wave movement along the tube. The IW propagation ends with a homogeneous plasma formation along the entire tube length. Exposure time is 60 ns for all six images. The applied voltage amplitude is $-2$ kV.
3.2. *The outer electrode is fine-sectioned.*

The existence of the fine-sectioned outer electrode allows one to trace the spatial-temporal dynamics of the electric charge deposition on the tube wall during the ionization wave spreading along the tube. Besides, it gives a possibility to find out the correlation between the surface charge dynamics and the discharge light emission distribution formed by moving negative ionization wave. The proper results are presented below in figures 4-7. Important to note that it turned out, the fine sectioning of the outer electrode does not change the general behavior of the discharge current and the ionization wave propagation.

The measurements of the individual currents collected by different sections have revealed many new features in the surface charge deposition by the ionization wave. First, the surface negative charge density formed by the ionization wave is not homogeneous along the tube but markedly decreases with a distance from the high-voltage electrode. Second, there is a large overlapping in time of the currents from many neighbor sections, that is, many neighbor sections collect the current simultaneously (figure 4). This fact is correlated with the markedly extended wavefront of the negative ionization wave shown in figure 5. In the case of positive ionization wave, the wavefront thickness is close to the width of an alone electrode section, and therefore there is no simultaneity in the current collection by neighboring sections.

The detailed time behavior of the individual currents of all 16 sections in the course of the ionization wave propagation from the HV cathode toward the opposite side of the capillary tube is presented in figure 6. One can see clearly the movement of the current wave along the tube. Also, one can see clearly that the current waveform increases its width with a distance and the overlapping in time of the currents from the neighbor section increases as well. A reason is that the thickness of the wavefront increases but the wave velocity monotonically diminishes with a distance from the cathode (see figure 7).

![Figure 4](image.png)

*Figure 4.* The applied voltage waveform and current oscillograms for the first six sections of the fine-sectioned outer electrode. Numbers 1-6 correspond to the sections’ numbers. The applied voltage pulse of negative polarity \( U = -3.2 \) kV. The red line is the average velocity of the negative ionization wave versus time. The roman numbers (I-VI) correspond to the frames’ numbers in figure 5.
Figure 5. The set of instant images I-VI of the moving negative ionization wave. The outer electrode is fine-sectioned. The arabic figures 1-16 enumerate the fine sections of the outer electrode. The roman figures I-VI correspond to those ones pointed in figure 4. The exposure time $\tau_{\text{exp}} = 60$ ns. The applied voltage $U = -3.2$ kV.

Figure 6. The current waveforms of all 16 sections of the outer fine-sectioned electrode. Numbers in boxes correlate with sections’ numbers in figure 5. The completed breakdown will happen approximately in 2 microseconds.
Figure 7. The spatial behavior of the negative ionization wave velocity along the tube. The applied voltage pulse $U = -3.2\, \text{kV}$. The vertical blue lines show the borders between sections of the fine-sectioned outer electrode.

4. Conclusions
The experimental results on the study of negative ionization wave propagating along a long quartz capillary tube showed that the ionization wave pace is determined predominantly by the rate of the charge deposition onto the dielectric wall surface. In contrast to the positive ionization wave, the velocity of the negative wave is higher by a factor of approximately 5 at the same experimental conditions. Another feature of the negative ionization wave is that the high-voltage pulse amplitude needed for initiation of the negative ionization wave is markedly lower compared to that for the positive ionization wave.

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References
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