Radial current distribution along the ionization wave propagating in a long dielectric capillary tube filled with a low-pressure helium

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Abstract. The experimental results on the study of the ionization wave propagating along a long capillary tube are presented. The ionization wave was initiated by high-voltage pulse of positive or 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 the ionization waves.

1. Introduction
The development of an electric breakdown between the electrodes significantly depend 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.

To date, a large number of experimental and theoretical works were performed on the IWs study in bounded plasma under a wide variety of concrete conditions such as the tube and electrode geometry and their materials, the composition of the working mixture, gas pressure, and the amplitude, polarity, and rise-time of the applied voltage, etc [2-8]. However, there is a great physical interest in the deep insight of the breakdown dynamics at the ignition of low-current DC glow discharge in a capillary tube under the HV-pulses of positive and negative polarity. This issue has a close relation to the
dynamics of the IW propagation. A reason is that the surface charges affect the electrical potential distribution along the tube and therefore directly influence the velocity of slow IW. In turn, the surface charge dynamics has a tight link with the glow spatial-temporal distribution in the ionization waves. This link can be found by means of the time-spatial correlation between the electrical signals corresponding to the surface charge deposition and deletion and the visual images of the direct and backward waves taken at different moments of their propagation. To date, insufficient attention was paid to the mentioned issues in the literature. This is why the listed issues were the main subjects of our study.

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 positive and 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 positive or negative polarity transferred from the capacitor \( C = 50 \) nF to the high-voltage electrode through the ballast resistor \( R_b = 1.2 \) kOhm. The tube is made of quartz (\( \varepsilon = 4 \)), the length is 300 mm, the inner diameter is 2.4 mm, the outer diameter is 4.2 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 \( R_{sh} = 50 \) 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 processes 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](image.png)

**Figure 1.** Sketches of two experimental setups by the example of the positive polarity pulse 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. Continuous outer electrode

The outer electrode is continuous and the applied high voltage pulse $U$ is of positive polarity: in this case, the current directed to the tube wall $I_r(t)$ decreases linearly with time in the course of the IW propagation along the tube Figure 2(a) although $U(t)$ is const.

![Figure 2](image1.png)

**Figure 2.** The correlation in time of the IW velocity variation with that of the discharge current and voltage. (a) The initial voltage pulse amplitudes: $U^+ = +6.7$ kV; (b) $U^- = -2.0$ kV. The grey marks with numbers show the exposure and the position of frames with the same numbers in Figures 3 and 4.

![Figure 3](image2.png)

**Figure 3.** The plasma glow intensity distribution along the tube (a) and the images (b) of moving IW. The outer electrode is continuous. The numbers in (a) and (b) correspond to each other. The IW propagation ends with a homogeneous plasma formation along the entire tube length (images 1-6, $t_{exp} = 60$ ns). $U = +6.7$ kV.
Figure 4. The plasma glow intensity distribution along the tube (a) and the images (b) of moving IW. The outer electrode is continuous. The numbers in (a) and (b) correspond to each other.

The IW propagation ends with a homogeneous plasma formation along the entire tube length (images 1-4, $\tau_{\text{exp}} = 60$ ns, image 5, $\tau_{\text{exp}} = 100$ ns, image 6, $\tau_{\text{exp}} = 200$ ns). $U = -2$ kV.

The IW velocity was obtained from the processing of instantaneous discharge images set. Figures 2(a) and 2(b) show the information for $U^+$ and $U^-$ applied pulses respectively relating to the time interval during which the IW reaches the opposite end of the discharge tube. For pulses of both polarities, the changes in the direct IW velocity in time correlate with the similar changes in the discharge current. A reason is that the direct IW is similar to the plasma capacitor the capacity of which increases in time due to increasing the length of the plasma column formed by the IW. In this case, there is a direct relation $I \sim V$, where $I$ is the current, $V$ is the IW velocity. According to our assumption, the stepwise propagation is associated with periodical switching on the stepwise ionization or the ionization due to the collision of two metastables which accumulate in time.

However, the voltage polarity has a significant influence on the quantitative characteristics of the IW in a capillary tube. Indeed, the IW initiation with a positive polarity pulse $U^+$ requires several times more amplitude compared to that of a negative pulse $U^-$. Additionally, with a positive polarity pulse, the IW occurs almost immediately after the voltage applying. Contrarywise, with the $U^-$ pulse, there is a delay of about 300 ns, and after the IW start, the negative discharge current decreases faster than that with $U^+$. However, the initial IW velocity at the negative $U^-$ pulse is higher compared to that at the pulse of a positive polarity $U^+$.

4. Sectioned outer electrode
The sectioning impact on the current $I$, and IW behavior is shown in Figures 5 - 8.

In the case of the sectioned outer electrode, the positive IW moves not smoothly everywhere in the tube but with small leaps at the boundaries between sections. Before leaping to the next section, the IW stops for short time at the boundary of the previous section. During the IW jumping through the gap, the current of the previous section increases sharply for a short time. On average, the amplitude of the sharp spike decreases with the distance from the anode. Note this current splash contributes a bit in the total current of every section. The information shown in Figures 5 and 6 confirms what is said above.
Figure 5. (a) Oscillograms of the $U^+(t)$ and individual currents $I_r$ recorded from each section of the outer electrode, the grey marks with roman numbers shows the exposure and the position of frames with the same numbers in Figure 5(c); (b) Non-monotonic behavior of the positive IW velocity during the IW jumping through the gap between neighbor sections. The red vertical lines mark the boundaries between neighbor sections; (c) the high-speed imaging of the IW propagating along the tube. Voltage pulse amplitude $U^+ = +6.7$ kV.

Figure 6. (a) Photos 1-4 shows the stop of the IW before its abrupt transition from the previous section to the next. Letters c through f mark sections; frames 1-4 correspond to the time intervals marked with the same numbers in the adjacent figure. (b) Oscillograms of the currents in the neighbor sections at the moment of the IW transition from one section to another. (c) More detailed behavior of the IW velocity during IW transition from one section to another. $U^+ = +6.7$ kV.
In the case of a negative IW, there is a large overlapping in time of the currents from many sections simultaneously. This fact is explained by more extended negative IW front compared to that of a positive IW. Besides, the negative IW velocity is higher and changes monotonically when passing the gap between sections (Figures 7, 8), and the sections current amplitude decreases faster along the tube.

**Figure 7.** Oscillograms of the $U^-$ voltage and individual currents of sections 1 - 6; the red line is the average velocity of the negative IW propagating along the tube versus time. $U^-=3.2\text{kV}$.

**Figure 8.** The variation in the negative IW velocity along the tube. $U^-=3.2\text{kV}$. The vertical blue lines show the borders between sections of the fine-sectioned outer electrode.

### 5. Conclusion

The experimental results on the study of positive and negative ionization waves 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 significantly higher. 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. Note the sectioning does not change the basic properties of the IW. For instance, for continuous and sectioned outer electrodes, the velocity of the negative IW is the same for the same applied pulsed voltage amplitudes. However, the sectioned outer electrode allowed one to measure directly the distribution of the surface charge density deposited on the tube walls during the IW propagation.
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