Ionization wave propagation in a long capillary tube in the presence of a low-current glow discharge in low-pressure helium

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Abstract. The experimental results on the study of the positive ionization wave propagating along a long capillary tube are presented. The ionization wave was initiated by either high-voltage pulse of positive polarity applied over a long capillary tube with helium or high-voltage pulse applied over the same tube but in presence of low-current glow discharge. 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 features of the positive ionization wave in both cases (with or without low-current discharge).

1. Introduction
Strict requirements to breakdown are formulated, e.g., in laser gyroscopes used for navigation [1-8], as well as many other gas-discharge systems used in light engineering and radioelectronics. Development of breakdown in the situation in which the gap between the electrodes is much larger than the characteristic transverse dimension follows a complex scenario. The discharge ignition in such systems is preceded by propagation of one or several ionization waves (IW) appearing upon application of high voltage to the electrodes.

The Ionization Wave propagation in a dielectric tube filled with a gas is accompanied by the surface charge deposition on the tube wall. In this case, the IW velocity is determined by the rate of both processes: the ionization in front of the IW and the charging of the tube dielectric wall. At the same time, the rate of ionization processes depends on the number of seed electrons ahead of the IW front. In this work, the number of seed electrons was varied by changing the current amplitude of a low-current glow discharge.

2. Experimental setup
The IW was excited by a positive HV pulse of several kilovolts. The experiment setup is shown in Figure 1. The quartz tube had the length of 300 mm, the inner and outer diameters were 2.4 mm and 4.2 mm and the dielectric constant $\varepsilon=4$. The tube was provided with two inner electrodes that were placed at the tube ends. The inner electrodes had the form of thin-wall copper cylinders of 25 mm in length. These cylinders were tightly pressed to the inner tube wall. The grounded outer electrode of 250 mm in length was a thin copper film tightly wrapped around the lateral tube surface. The outer electrode consisted of 16 sections in a form of narrow strips of 13 mm in width with a 2 mm gap between sections. The outer electrode had a narrow slit (2 mm) cut out along the whole length of the tube in order to observe what
happens inside the tube in the course of the IW propagation. All experiments were performed with He at low pressure $P=10$ Torr. To remove the possible influence of long-lived by-products formed by plasma chemical reactions in the discharge, helium was constantly blown through the tube.

![Figure 1](image1.png)

**Figure 1.** The sketches of gas-discharge tubes and electrical schemes used for the initiation and studying the ionization waves in long capillary quartz tubes. The schemes for the IW initiation without (a) and with (b) the pre-existing plasma. In the tube, the pre-existing plasma was created by preliminary ignited low-current steady-state DC glow discharge. $C = 50$ nF; $R_b = 1.2$ kOhm; $R_{b1} = 100$ kOhm; $R_{b2} = 1.2$ kOhm; $R_{sh} = 50$ Ohm; $R_{sh1} = 1$ Ohm; $R_{sh2} = 1$ Ohm.

The electrical signals were recorded with the use of oscilloscopes: Tektronix MSO58 (2GHz, 8 channel) and GWInstek GDS-7204 (200 MHz, 4 channel). The high-voltage divider is AKTAKOM ACA-6039 (1000:1, 220 MHz, 900 MOhm). The instant images of the IW were taken with a high-speed ICCD 4-frame camera PCO.dicam C4. The exposure time of each frame is 60 ns.

### 3. Experimental results

The paper presents the experimental results on the influence of the glow discharge current on the IW velocity. In the experiments, fine-sectioned outer electrode allows one to measure the local surface charge on the tube wall deposited by the moving IW. This charge was measured by the integration of the local current recorded from each section. The distribution of both the local currents flowing to the wall and the deposited charges over the sections allows one to estimate the width of the IW front. Figure 2 shows the images of the IW propagating in the tube in the absence of low-current discharge plasma Figure 2(a) and in the presence of plasma Figure 2(b). As can be seen, in the latter case, the IW front is strongly blurred.

![Figure 2](image2.png)

(a)
Figure 2. The IW propagation along the tube without (a) and with (b) of a low-current discharge plasma with a current of 5 mA, (j ≈ 0.1 A/cm², ne ≈ 10¹¹ cm⁻³). The discharge current direction coincides with the IW direction. The voltage pulse amplitude of a positive polarity is 6.7 kV. Exposure time 60 ns; The moments corresponding to each image are indicated in the Figures 3(a) and 3(b) in roman numerals.

Figure 3 shows the current distribution over the outer electrode sections when the IW moves from the anode for two cases: 1) there is no preionization in the tube Figure 3(a), and 2) there is a plasma of the low-current glow discharge Figure 3(b). In the first case, one may see that the currents being collected by the adjacent sections do not intersect in time, i.e. the current to the next section starts only after the ending of the current to the previous section. In the second case, the current goes into several neighboring sections simultaneously (up to 5). The noted effect is consistent with Figure 2 (b), which shows a strong broadening of the IW front in the presence of pre-ionized plasma in the tube.

Figure 3. Oscillograms of the voltage U on the HV electrode and individual currents I being collected by the outer electrode sections. Roman numerals correspond to the images in the previous figure. He, 10 Torr, U = +6.7 kV. (a) no pre-ionization Only outer electrode is grounded; (b) the preionizing discharge current is 5 mA. Inner and outer electrodes are grounded.

As Figure 3(a) shows, the IW arrives at the opposite tube end in 1.8 μs. However, Figure 3(b) shows that the IW spends only 120 ns to pass the whole length of the tube. It means the IW increased its velocity by more than one order of magnitude in the presence of preionization in the tube. At the same time, the amount of local surface charge deposited by the IW remains at any point approximately the same for both cases. This effect can be explained if we suppose that the magnitude of the surface charge is
regulated predominantly by the applied voltage pulse amplitude, which was the same and equal to +6.7 kV in the case of Figures 3(a) and 3(b).

With the increase of the preionizing current $I$, the charging duration of the specific section also increases Figure 4. In this case, the time-averaged current for this section decreases with an increase in the $I$ amplitude. As for the IW velocity, it grows up with an increase of the preionizing glow discharge current $I$ (Figure 5, the outer electrode is the sectioned one).

![Figure 4](image1.png)

**Figure 4.** The time-behavior of the currents on some outer electrode sections vs the magnitude of the preionizing glow discharge current $I$. (a) $I = 20$ mA; ($n_e \approx 4 \cdot 10^{11}$ cm$^{-3}$) (b) $I = 40$ mA ($n_e \approx 8 \cdot 10^{11}$ cm$^{-3}$). The voltage pulse amplitude is +6.7 kV.

![Figure 5](image2.png)

**Figure 5.** (a) - (c) The IW velocity distribution along the tube in the presence of a preionizing glow discharge with different current amplitudes $I$. (a) $I = 5$ mA ($n_e \approx 10^{11}$ cm$^{-3}$); (b) $I = 20$ mA ($n_e \approx 4 \cdot 10^{11}$ cm$^{-3}$); (c) $I = 40$ mA ($n_e \approx 8 \cdot 10^{11}$ cm$^{-3}$). $U = +6.7$ kV.

(d) The surface charge deposited by the IW after a different currents of the preionizing discharges.
One can see in Figures 5(a), (b), (c) that there is a bit increase in the IW velocity when the concentration of the pre-existing plasma grows up. We suppose that a reason for this weak response of the IW velocity is a logarithmic dependence of this velocity on the background plasma density similar to that established by Loeb [9]:

$$v_s = \frac{v_{im} r_m}{\ln(n_{ch}/n_0)}$$

where $n_{ch}$ is the number density of electrons behind the streamer front, $n_0$ is the electron number density ahead of the front, $r_m$ is the radius of streamer head, $v_{im}$ is the frequency of direct ionization corresponding to the value of peak reduced field.

It is interesting to trace the behavior of the discharge after the arrival of the IW to the opposite inner electrode (cathode). The relevant information is presented in Figure 6 with numbering the sections, the currents of which are presented in the figure. The IW arrives at the cathode by the moment $t \approx 120$ ns. After that, the voltage across the discharge drops down, and the current between the anode and the cathode (blue curve) grows up. Simultaneously, the currents on all sections begin to flow in the opposite direction, i.e. the surface charge on the tube wall starts being neutralized by the current from the formed plasma column. After the surface charge neutralization, a high current discharge (5A and 1.5 kV) is established for short time.

Figure 6. Oscillograms of the voltage on the HV electrode, the currents of the numbered electrode sections, and the current between the anode and the cathode (blue curve). The figures show the section' numbers. The preionizing glow discharge current is 5 mA. The voltage pulse amplitude is $+6.7$ kV.

4. Conclusion

The performed experiments on the influence of the preliminarily formed plasma in the capillary tube on the IW behavior revealed two main effects:

1) The presence of the preionized plasma accelerates the IW propagation and noticeably extends the IW front, at that, the higher the preionized plasma volume density, the wider the IW front.

2) The usage of the sectioned outer electrode allowed one to reveal that the local density of the surface charge deposited by the IW on the tube wall practically does not depend on the IW velocity and the preionizing plasma density.

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