Positive streamers in a point-to-plane gap filled with air and nitrogen at low and high voltages

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Abstract. The formation of positive streamers in a point-to-plane gap filled with atmospheric pressure air and nitrogen under threshold and overvoltage conditions was experimentally investigated using a HSFC PRO 12-bit four-channel ICCD camera. Waveforms of the voltage and current pulses were simultaneously recorded with shooting. Nanosecond voltage pulses with a positive polarity, an amplitude of 8 and 24 kV were applied to the pointed electrode. Under threshold conditions, branching of the streamer in nitrogen was observed. Under the same conditions, a single streamer was formed in air. At a high voltage, only one large streamer was observed in nitrogen and air. The characteristic X-ray radiation produced by runaway electrons likely pre-ionizes the gas ahead of a streamer at a high overvoltage.

1. Introduction
The formation of streamers in different gases has been actively studied [1–4]. There are different factors that determine the parameters of the streamers. The main factors include the electric field strength and the overvoltage level. At a high (100–1000%) overvoltage, large streamers (inception clouds [3]) form. The transverse dimensions of these streamers are comparable with the interelectrode distance. A thin streamer with low conductivity forms in the case of a low (1–10%) overvoltage. For both cases, the mechanism of preliminary ionization of the gas ahead of the streamer is debatable. The photoionization mechanism is well known for air [2, 3]. However, there are difficulties in describing the formation of streamers in pure atomic or molecular gases. Many experimental studies show that with a high overvoltage in atomic and molecular gases at different pressures, including above atmospheric pressure, a diffuse discharge forms [4, 5]. It is considered that under these conditions, runaway electrons play a fundamental role in streamer formation. The aim of the present work is to compare the streamer formation dynamics in air and nitrogen at low and high voltages.

2. Experimental setup
Figure 1 shows a schematic of the experimental setup. The setup allowed the simultaneous recording of the voltage and current pulses and the plasma glow with a HSFC-Pro four-channel ICCD camera. The gas discharge chamber was equipped with a capacitive voltage divider (CVD) and a current viewing resistor (CVR). The CVR was composed of chip resistors. Signals from the CVD, CVR, and the first channel of ICCD camera were recorded with a Tektronix TDS3054B digital oscilloscope (500 MHz, 5 GSa/s). It allowed to synchronize the ICCD images and waveforms of the voltage and current pulses. The potential electrode was made of a stainless steel needle with a curvature radius of
its tip of 75 µm. The grounded electrode was flat. The interelectrode distance was 8.5 mm. The discharge chamber was pumped out with a forevacuum pump and filled with atmospheric pressure air or nitrogen. The minimum exposure time of the ICCD camera is 3 ns. The first channel of the ICCD camera was switched-on at 2–3 ns prior to the start of a streamer. Switching-on of the second and third channels was shifted relative to the first one by 3 and 6 ns at the lowest voltage amplitude or by 1 and 2 ns at the highest voltage. The fourth channel registered 10-ns time integrated images.

Figure 1. Schematic of the experimental setup.

3. Results
Figure 2 shows the waveforms of the voltage and current pulses as well as ICCD images of a plasma glow in air at the lowest (8 kV) amplitude of voltage pulse at which a streamer appears. Under these conditions, streamers sometimes appeared. The amplitude of the voltage pulse doubled due to its reflection by the discharge gap. The CVR registered a displacement current of $I_{\text{displ}} = C_{\text{gap}} \frac{dU(t)}{dt}$ ($C_{\text{gap}}$ – capacitance of the gap without a plasma) during a voltage rise. When the streamer appeared, the CVR registered a rapid increase in current with a rise time of 0.7 ns that corresponds to the duration of the oscilloscope transient response. This spike in current (a dynamic displacement current) is the result of a rapid redistribution of the electric field strength in the gap during the plasma formation. High rates of the ionization processes are due to the high (1 MV/cm) electric field strength near the pointed electrode. Redistribution of the electric field strength means a change in the capacitance of the gap. The dynamic displacement current in this case can be estimated as the product of the voltage by the time derivative of the gap capacitance ($I_{\text{displ}} = U \cdot \frac{dC(t)}{dt}$). Calculations show that $C_{\text{gap}} = 0.50$ pF for the gap without a plasma. When a plasma ball with a diameter of ~1 mm covers the pointed electrode, $C_{\text{gap}} = 0.55$ pF. Assuming that the 1-mm plasma ball is formed over ~100 ps, the dynamic displacement current is $I_{\text{displ}} = 7$ A. This value correlates with the measurement results (Figure 2a).

Images taken for the first and second channels of the ICCD camera (Figure 2b) show that the streamer had a ball shape during the initial stage. An increase in the streamer size leads to a decrease in the electric field strength on its front. As a result, the streamer velocity decrease, that leads to a decrease in the values for $\frac{dC(t)}{dt}$ and $I_{\text{displ}}$ (Figure 2a). However, $I_{\text{displ}}$ increased again at the final stage. Images taken for the third and fourth channels (Figures 2b) show that a streamer with a small diameter crossed the gap during the final stage. The small sizes of the streamer were due to the low electric field strength in this region. Nevertheless, as the distance between the streamer front and the flat electrode decreased, the electric field strength increased, and the streamer velocity increased. The average streamer velocity was $\approx 0.1$ cm/ns. After crossing the gap, the sum of the conduction current and the displacement current ($C_{\text{gap}} \frac{dU(t)}{dt}$) was recorded with the CVR (Figure 2a).
Figure 2. (a) Waveforms of the voltage and current pulses for the discharge in air. The amplitude of the incident voltage wave is 8 kV. (b) Images of a plasma glow taken with the HSFC-Pro four-channel ICCD camera during the formation of the streamer in air. Ch1, Ch2, Ch3, and Ch4 are the ICCD camera channels. Lengths of the rectangles correspond to the exposure times of the channels.

The streamer always branched in nitrogen under the same conditions (Figure 3b). The ball streamer formed only at the initial stage near the pointed electrode (Figure 3b, channel 1). The current spike was registered with the CVR during this time (Figure 3a). Formation of separated streamers with a small diameter was observed during the next 3 ns (Figure 3b, channel 2). The side streamers were shorter than streamers near the axial zone. Their velocities were different and depended on the electric field strength. The electric field strength in the axial zone was the highest. The CVR recorded the increase in the dynamic displacement current during the formation of the separated streamers (Figure 3a) until the axial streamers crossed the gap. The average streamer velocity was ≈0.12 cm/ns.

Figure 3. (a) Waveforms of the voltage and current pulses for a discharge in nitrogen. The amplitude of the incident wave is 8 kV. (b) Images of a plasma glow taken with the HSFC-Pro four-channel ICCD camera during the formation of streamers in nitrogen. Ch1, Ch2, Ch3, and Ch4 are the ICCD camera channels. Lengths of the rectangles correspond to the exposure times of the channels.

A single streamer was still formed in air upon application of voltage pulses with an amplitude of 24 kV (Figure 4b, channel 1); however, the streamer dimensions were larger than that at a voltage pulse amplitude of 8 kV. The streamer velocity increased approximately tenfold. The glow in the entire gap was observed in the images taken on channel 2 (Figure 4b). Furthermore, cathode spots
were observed on the flat electrode in images taken on channels 2, 3, and 4. An anode spot was observed in the image taken on channel 4.

A voltage drop was observed after crossing the gap by a streamer. However, the voltage drop could start even at the stage of streamer propagation. A high streamer velocity provides high dynamic displacement currents. We consider that the current rise (Figure 4a) corresponds a stage when a dynamic displacement current flows. At that time, the conduction current flows in the plasma behind the streamer front. After crossing the gap, the CVR recorded the conduction current.

![Figure 4](image)

**Figure 4.** (a) Waveforms of the voltage and current pulses for a discharge in air. The amplitude of the incident wave is 24 kV. (b) Images of a plasma glow taken with the HSFC-Pro four-channel ICCD camera during formation of the streamers in air. Ch1, Ch2, Ch3, and Ch4 are the ICCD camera channels. The lengths of the rectangles correspond to the exposure times of the channels.

A single streamer was observed in nitrogen upon applying voltage pulses with an amplitude of 24 kV. There was no qualitative difference compared to using air (Figure 4b vs Figure 5b). Some differences in the current rise time in air (Figure 4a) and nitrogen (Figure 5a) were observed. From the comparison, we conclude that the streamer velocity in nitrogen was lower than in air.

![Figure 5](image)

**Figure 5.** (a) Waveforms of the voltage and current pulses for a discharge in nitrogen. The amplitude of the incident wave is 24 kV. (b) Images of a plasma glow taken with the HSFC-Pro four-channel ICCD camera during formation of the streamers in nitrogen. Ch1, Ch2, Ch3, and Ch4 are the ICCD camera channels. The lengths of the rectangles correspond to the exposure times of the channels.
4. Discussion
These experimental data show that the formation of streamers in air and nitrogen under threshold conditions is qualitatively different. A single streamer formed in air. The streamer had the shape of a ball near the pointed electrode where the electric field strength was amplified. After crossing half of the gap, the ball streamer transformed into a cylindrical streamer. The transformation was due to the low electric field strength in the front of the ball streamer when it reached the maximum size, $R_{\text{max}}^\text{air}$. In nitrogen, the ball streamer also formed near the pointed electrode. Branching of the streamer was observed when it reached a certain size, $R_{\text{max}}^\text{N_2}$. However, $R_{\text{max}}^\text{N_2} < R_{\text{max}}^\text{air}$. Consequently, the branching of the streamer in nitrogen occurred at a higher electric field strength than the transformation of the ball streamer into the cylindrical streamer in air. This is likely due to the difference in the mechanisms of pre-ionization of gas ahead of the streamer front. As known, photoionization occurs in air [2, 3]. What happens in pure nitrogen? Runaway electrons are likely generated due to a very high (~$1 \cdot 10^5$ V/cm) electric field strength near the pointed electrode and at the streamer front (~$1 \cdot 10^5$ V/cm) until it reaches a certain size. Runaway electrons produce a characteristic X-ray radiation, which pre-ionize the gas ahead of the streamer front. When $R_{\text{max}}^\text{N_2}$ was reached, the electric field strength at the streamer front became lower than the critical electric field strength for generation of runaway electrons. As a result, the streamer branched. Upon applying voltage pulses with an amplitude of 24 kV, $R_{\text{max}}^\text{N_2}$ reached higher values than at 8 kV, and we observed a single streamer. The present and previous [4] results show that there is qualitatively no difference in the formation of streamers in atomic and molecular gases at a high overvoltage and both polarities. In refs. [4, 5], runaway electrons were registered at a negative polarity of the pointed electrode.

5. Conclusion
Experimental data on the formation of streamers in a point-to-plane gap filled with air or nitrogen under threshold and overvoltage conditions were compared. In nitrogen and under threshold conditions, the streamer branched after reaching a certain size. In air, branching was observed very rarely. Usually, the ball streamer formed in air, and after crossing half of the gap, transformed into a cylindrical streamer. This difference is likely due to the mechanism of pre-ionization of gas ahead of the streamer front. Photoionization provides effective pre-ionization of the gas in air under threshold conditions. In nitrogen, the characteristic X-ray radiation produced by runaway electrons provides pre-ionization of the gas. However, a high electric field strength is required for generation of runaway electrons. This requirement is fulfilled near the pointed electrode and until the ball streamer reaches a certain size. At a high overvoltage, this size can be comparable and can exceed an interelectrode distance. As a result, a single streamer forms. During streamer formation, a dynamic displacement current caused by a fast redistribution of the electric field strength is recorded.

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