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ICCD-imaging of a plasma glow during the prebreakdown stage of nanosecond discharges at both polarities in nitrogen, air, and argon

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Abstract. Dynamics of a plasma glow during the prebreakdown stage of a nanosecond discharge in the «cone-to-plane» gap with length of $d = 3$ mm was investigated with a HSFC PRO 12-bit four-channel ICCD camera. The gap was filled with nitrogen, air, argon. Gas pressure was ranged from 12,5 to 400 kPa. Voltage pulses of negative ($U = 25$ kV, $\tau_{0,5} = 3$ ns, $\tau_{0,1-0,9} = 0,7$ ns) and positive ($U = 25$ kV, $\tau_{0,5} = 10$ ns, $\tau_{0,1-0,9} = 3$ ns) polarities were applied across the gap. Images of the plasma glow at different stages of streamer formation are presented. It was established that a diffuse discharge is formed due to formation of a large streamer. It was found that plasma appears at a certain distance from the conical electrode at both polarities. These and other features of streamer formation are discussed.

1. Introduction

Great attention has been given to study of nanosecond discharges in different gases. This is due to wide possibilities of applications of nanosecond discharges to create sources of spontaneous and stimulated radiation [1,2], as well as sources of low-temperature non-equilibrium plasma [3]. Such plasma is applied in airflow control systems, ignition fuel systems, as well as for a treatment of liquid and solid materials [4–6].

Currently, the problems of formation and propagation of streamers are being studied. As is known, parameters of a streamer depend on the value of the product of gas pressure by gap length, as well as on the gap geometry, kind of gas and the overvoltage rate. The last one is determined by the rate of voltage rise (dU/dt). For relatively long gaps (~ 10 cm) filled with nitrogen at atmospheric pressure and dU/dt of $\sim 10^{12}$ V/s, a streamer has a branching structure [7]. Moreover, there is significant effect of the polarity of voltage pulse. As compare to a cathode-directed streamer, an anode-directed one can disappear after crossing a half of the gap at the same amplitude of voltage pulse. Oxygen admixtures lead to a decrease in the branching frequency of the streamer and to the breakdown of the gap at negative polarity.

A large number of experimental data shows that in gaps having the length of ~ 1 cm and dU/dt of $\sim 10^{13}$ – 10^{14} V/s a diffuse discharge is formed [8–10]. From some theoretical studies it follows that the diffuse discharge under such conditions is the result of the formation of a streamer having a transverse



size comparable with the gap length [11,12]. However, there is no exhaustive experimental data on the structure of the streamer under such relatively extreme conditions.

The objective of present work is to study the structure of the streamer during the phase of the diffuse discharge formation at positive and negative polarities in nitrogen, air, and argon at in the pressure range of 12.5–400 kPa.

2. Experimental setup

The block-scheme of the setup is presented in figure 1. Two FID pulsers of negative (GIN-100-1, $U \approx 25$ kV, $\tau_{0.5} \approx 3$ ns, $\tau_{0.1-0.9} \approx 0.7$ ns) and positive (GIN-50-1, $U \approx 25$ kV, $\tau_{0.5} \approx 10$ ns, $\tau_{0.1-0.9} \approx 2$ ns) polarities were used. Voltage pulses were applied across the «cone-to-plane» gap placed into a vacuum chamber. The solution angle at the apex of the cone-shaped electrode was 30° . The gap length d was 3 mm. The chamber was equipped with a capacitive voltage divider (CVD), a current-viewing resistor (CVR) based on chip-resistors as well as a collector allowing to register runaway electron beams (RE beams). Waveforms from CVD, CVR, and collector were recorded with a LeCroy WaveMaster 830Zi-A oscilloscope (30 GHz, 80 GS/s). Design of the discharge chamber allowed to register simultaneously voltage and discharge current or the voltage and current of a RE beam.

The images of plasma glow were registered with a HSFC PRO 12-bit four-channel ICCD camera. Its minimum exposure time is 3 ns. However, discharge processes shorter than 1 ns could be registered due to the precise synchronization and running the ICCD camera 2–3 ns before the moment of arrival of a voltage pulse to the high-voltage electrode. Both a jitter of the synchronization system and a jitter of the breakdown allowed to observe a streamer on different stages of its formation from pulse to pulse. As a result, dynamics of streamer development was reconstructed from the instant of its appearance to the instant of bridging the gap. Note that in this case there is no time reference between separate images.

Additionally, to estimate a streamer velocity in nitrogen, a Hamamatsu C10910-05 streak camera equipped with an Acton SpectraPro SP-2300 monochromator (Princeton Instruments) was used. The streak camera allowed to register the time dependence of the discharge plasma radiation intensity from different zones along the gap with high temporal resolution (time-base sweep was 5 ns per 1024 pixels). Time-resolved radiation intensity of 0-0 band of the second positive system of a nitrogen molecule (peak wavelength 337.1nm) was registered. It is well known that the second positive system of nitrogen is effectively excited during the prebreakdown stage of nanosecond discharges [13]. About 300 pulses were registered from each zone. The streamer velocity was estimated as a propagation velocity of the light front along the gap.

The chamber was pumped out with a forevacuum pump and then filled with nitrogen, air, and argon. Pressure was ranged from 12.5 to 400 kPa.

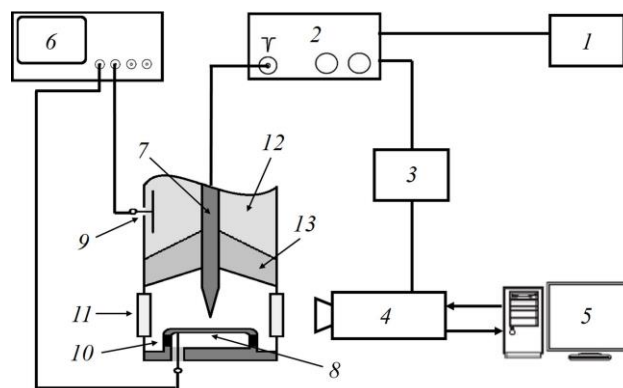


Figure 1. Block-scheme of the experimental setup. 1 – triggering pulser, 2 – high-voltage pulser, 3 – delay pulser, 4 – ICCD camera or streak camera, 5 – computer, 6 – oscilloscope, 7 – high-voltage electrode, 8 – grounded electrode, 9 – capacitive voltage divider, 10 – current viewing resistor, 11 – window, 12 – transmission line, 13 – insulator.

3. Results

3.1. Waveforms

Waveforms of voltage, discharge current, as well as RE beam current pulses are presented in figure 2. Note that a RE beam was registered in individual series of experiments as described in Section 2. It was found that a RE beam is registered at the maximum voltage (before the voltage drop) when lengths of registration paths were equal. At conditions under the study a duration of the RE beam current was ≈ 70 ps that corresponds to the pulse response of the collector. The increase in pressure led to a decrease in the RE beam current amplitude.

Figures 2a,b show how unstable the breakdown is. The duration of the prebreakdown stage varies from 1 to 2 ns. A RE beam is also unstable relative to the voltage pulse onset. Instability of the breakdown can be caused by the appearance of initial electrons (statistical lag). In such conditions (nanosecond voltage pulses, negative polarity, «cone-to-plane» gap), the field emission should provide initial electrons ensuring breakdown stability. However, conical electrode surface condition, dielectric inclusions, relatively low electric field ($dU/dt \sim 10^{13}$ V/s) affect the stability of the field emission. Stability of the discharge increases when values of dU/dt reach 10^{14} – 10^{15} V/s providing significantly higher values of the electric field [8]. In addition, it can be seen, the earlier start of ionizations processes leads to a slower voltage drop (figure 2a).

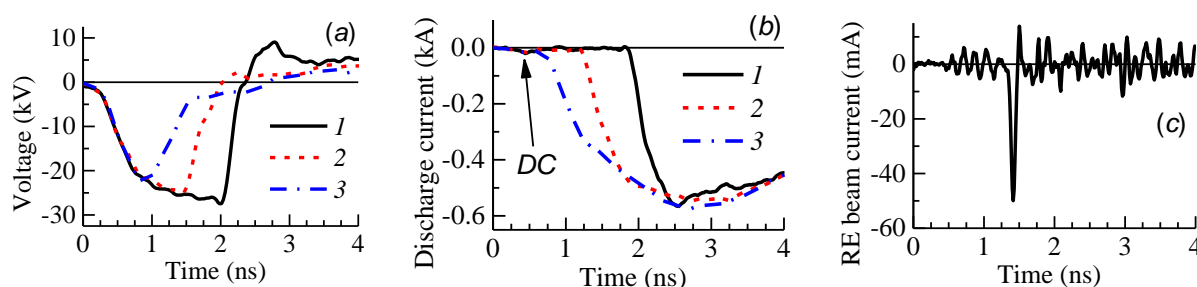


Figure 2. Waveforms of voltage (a), discharge current (b), as well as RE beam current pulses (c). A RE beam was registered behind the 10- μ m-Al anode. Nitrogen pressure is 100 kPa. d is 3 mm. 1, 2, 3 – different discharge implementations. Positive surges on the voltage pulses are caused by the insufficient value of RC -constant of CVD. DC – displacement current.

3.2. ICCD-imaging

At conditions under the study, a diffuse discharge was formed in the gas pressure range of 12,5–400 kPa. The formation of a large streamer was observed with the ICCD camera (figure 3). The transverse size of the streamer was equal to the longitudinal one at pressure up to 50 kPa. The increase in pressure led to the expected reduction in its transverse size. Sometimes formation of two streamers was observed at pressure of 400 kPa. Formation of the explosive center on the cathode was observed after bridging the gap by the streamer. Rarely ($\sim 1/1000$), the formation of the explosive center was observed before.

It was found that the plasma appears at some distance from the cathode tip at the initial stage (figure 3). The distance depends on the gas pressure. The higher pressure, the shorter the distance. The plasma appears on the cathode surface at a pressure of 400 kPa. On the one hand, the reason for the observed dynamics is the optimal value of the reduced electric field E/p for the impact ionization coefficient α . Due to enhancement of electric field strength near the cathode tip, E/p takes very high values at low pressure and α reaches maximum value at some distance from the cathode. The increase in pressure leads to a decrease in value of E/p and the zone with the largest α is displaced towards cathode tip. On the other hand, an electron avalanche should pass a certain distance until it transforms to a streamer and creates enough (threshold) number of excited nitrogen molecules whose radiation intensity will be enough to register by the ICCD camera. However, at positive polarity electron

avalanches move toward the conical anode and we should have observed the plasma on the anode surface, but experimental data show that the same dynamics of the streamer formation is observed at positive polarity of the voltage pulse, as well as with other gases.

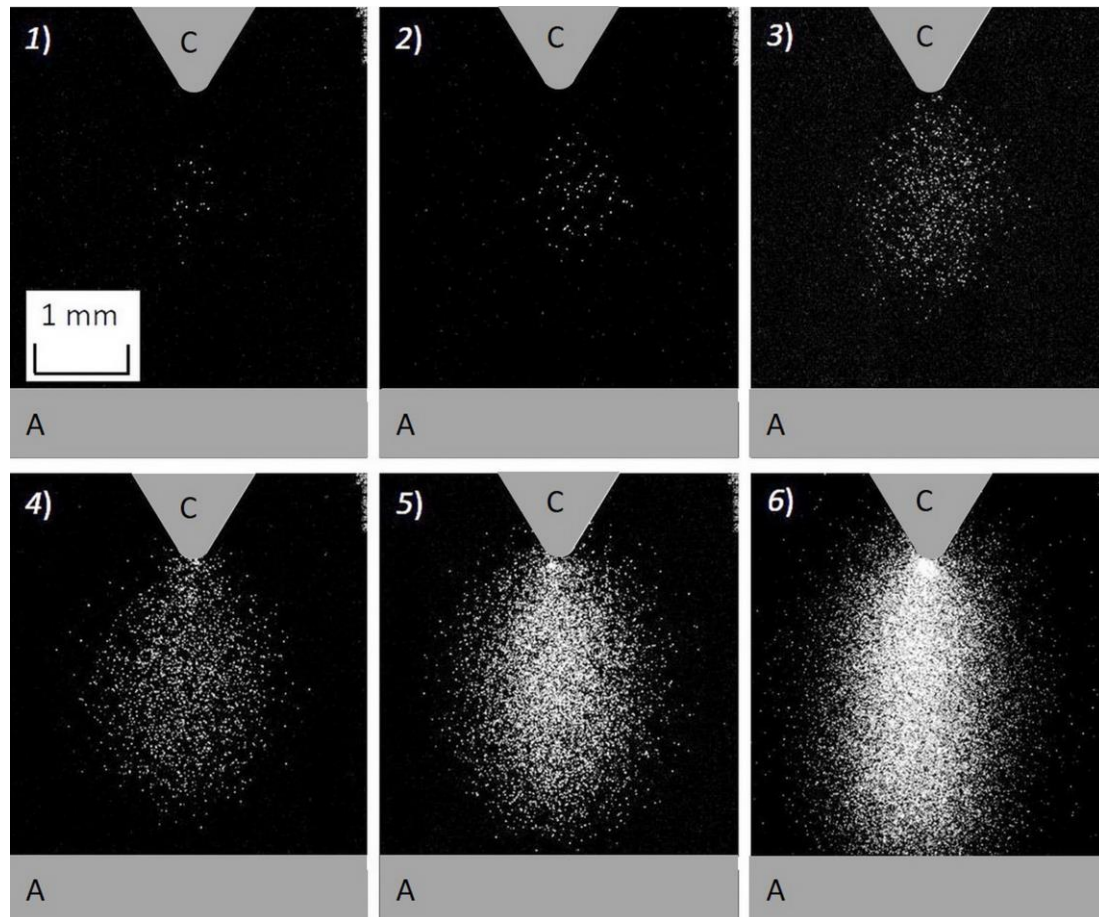


Figure 3. Images of the discharge plasma glow taken with the ICCD camera. Nitrogen pressure is 100 kPa. GIN-100-1, negative polarity. C – cathode, A – anode.

3.3. Streamer velocity

Experimental data obtained with Hamamatsu C10910-05 streak camera show that an average velocity of the anode-directed streamer is $(2\div 4)\cdot 10^9$ cm/s at atmospheric pressure of nitrogen. This value increases up to $6\cdot 10^9$ cm/s at nitrogen pressure of 50 kPa. Unfortunately, there is no data at pressure above 100 kPa.

4. Discussion

From the experimental results it follows that at applying of nanosecond voltage pulses of both polarities across a gap with a non-uniform electric field strength distribution the diffuse discharge is formed in different gases in a wide range of pressures. ICCD-imaging of a glow of the discharge plasma during the prebreakdown stage showed that a streamer with large (2–3 mm at $d = 3$ mm) transverse sizes develops. It is well known that at a breakdown of a gap in a quasi-static electric field, the diameter of a streamer is ~ 100 μm . At high overvoltage an electric field strength on the streamer head is high enough and can be higher than the critical value for generation of runaway electrons. Runaway electrons moving ahead an anode-directed streamer pre-ionize a gas. Electron avalanches forming from seeded electrons overlap and provide moving of the plasma front. In the case of a cathode-directed streamer, runaway electrons move towards the streamer head. In this instance, a

characteristic radiation generated as a result of the interaction of runaway electrons with molecules of a gas pre-ionizes the gas [14]. Note that bremsstrahlung can be generated at the initial stage and participate in a preliminary gas ionization. Moreover, the radial component of the electric field at the streamer front can become significant. Together, this creates conditions for the formation of a streamer having large transverssize.

5. Conclusion

The obtained experimental data show that the diffuse discharge occurs at applying nanosecond voltage pulses of both polarities across the «cone-to-plane» gap due to formation a large streamer. At conditions under the study, there was no significant influence of the polarity of voltage pulses and kind of gas on streamer dynamics.

We assume that a large streamer is formed due to generation of runaway electrons on the streamer front, where electric field is enhanced. Runaway electrons and characteristic radiation pre-ionize a gas and create conditions for the formation of a large-size streamer.

In the very beginning, the plasma appears at a distance from the conical electrode. Increase in pressure leads to displacement of the zone in which the plasma appears towards the conical electrode. It was assumed that a reduced electric field strength near the conical electrode is very high and maximum value of impact ionization coefficient α is reached at some distance. The higher pressure, the shorter the distance from the conical electrode, where the plasma appears.

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