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# Ignition different mode of corona discharge in air at atmospheric pressure

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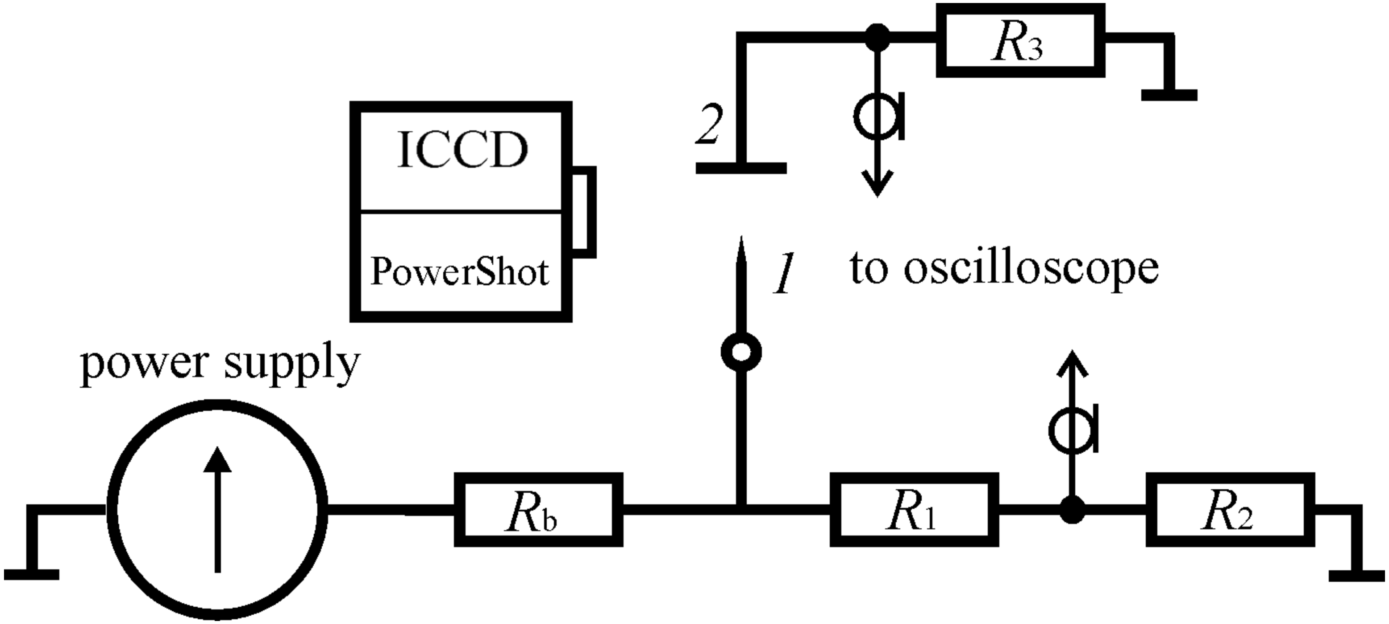
A corona discharge in air at atmospheric pressure is intensively studied and applied. The appearance of a corona in the transmission lines of electric energy and other devices results in energy loss. There is a wide spectrum of applications of corona discharge. It is known that various corona discharge regimes, including a stationary corona, are implemented on conductors with a small radius of curvature. At negative voltage polarity on the tip electrode, a nonstationary corona occurs and current pulses (Trichel pulses) are recorded with the repetition rate increasing with the voltage. At positive polarity on the tip electrode, a corona discharge occurs at higher voltages than at negative polarity. Some authors attribute the recorded current pulses to the formation of streamers.

**The purpose of this work is to study the ignition of different mode of a corona discharge in the air at atmospheric pressure at low voltages and high electric field strengths, to achieve which a tip with a small radius of curvature was used.**

# Experimental Setup:

## $R_b$ = 18 MOhm, $R_1$ = 2.5 MOhm, $R_2$ = 2.5 kOhm, $R_3$ = 1 kOhm.




**To study the corona discharge, the setup shown in the Fig. 1 similar to that used earlier. This scheme was traditional for studies of a corona discharge with a point-to-plane gap. As a high-voltage electrode, "bead" needles with a diameter of 0.32, 0.64, 1.04 mm and with a radius of curvature of the tip 11 (No. 1), 30 (No. 2), 100 µm (No. 3), respectively, were used. The discharge was ignited between the point and the plane electrode both with negative and positive voltage polarity.**

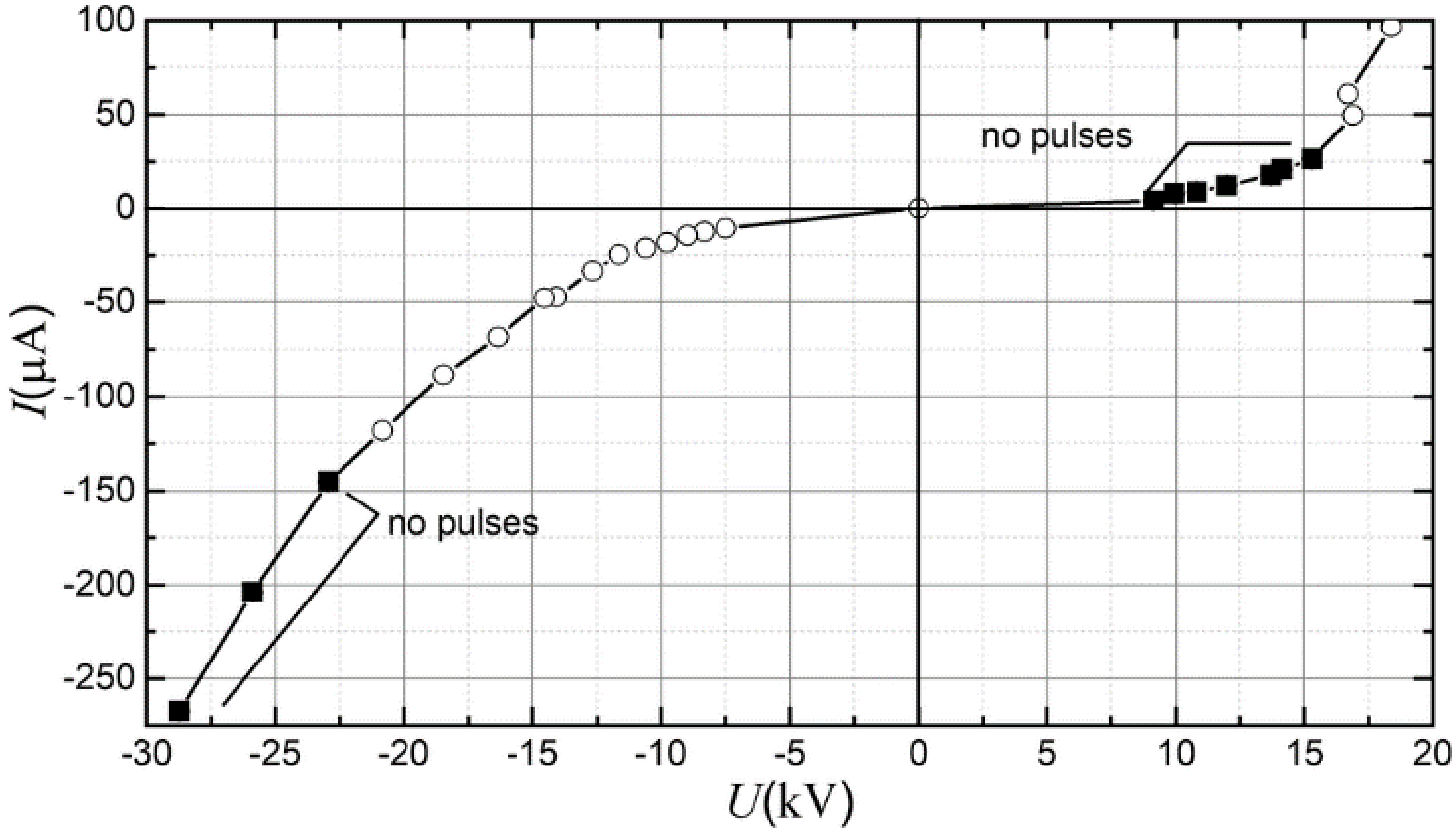
# Needle parameters

| Size | Diameter, mm | Tip radius, μm |
|---|---|---|
| No. 1a | 0.32 | 11–13 |
| No. 1b | 0.32 | 40 |
| No. 2 | 0.61 | 30 |
| No. 3 | 1.04 | 100 |
| No. 4 | 3 | 200 |

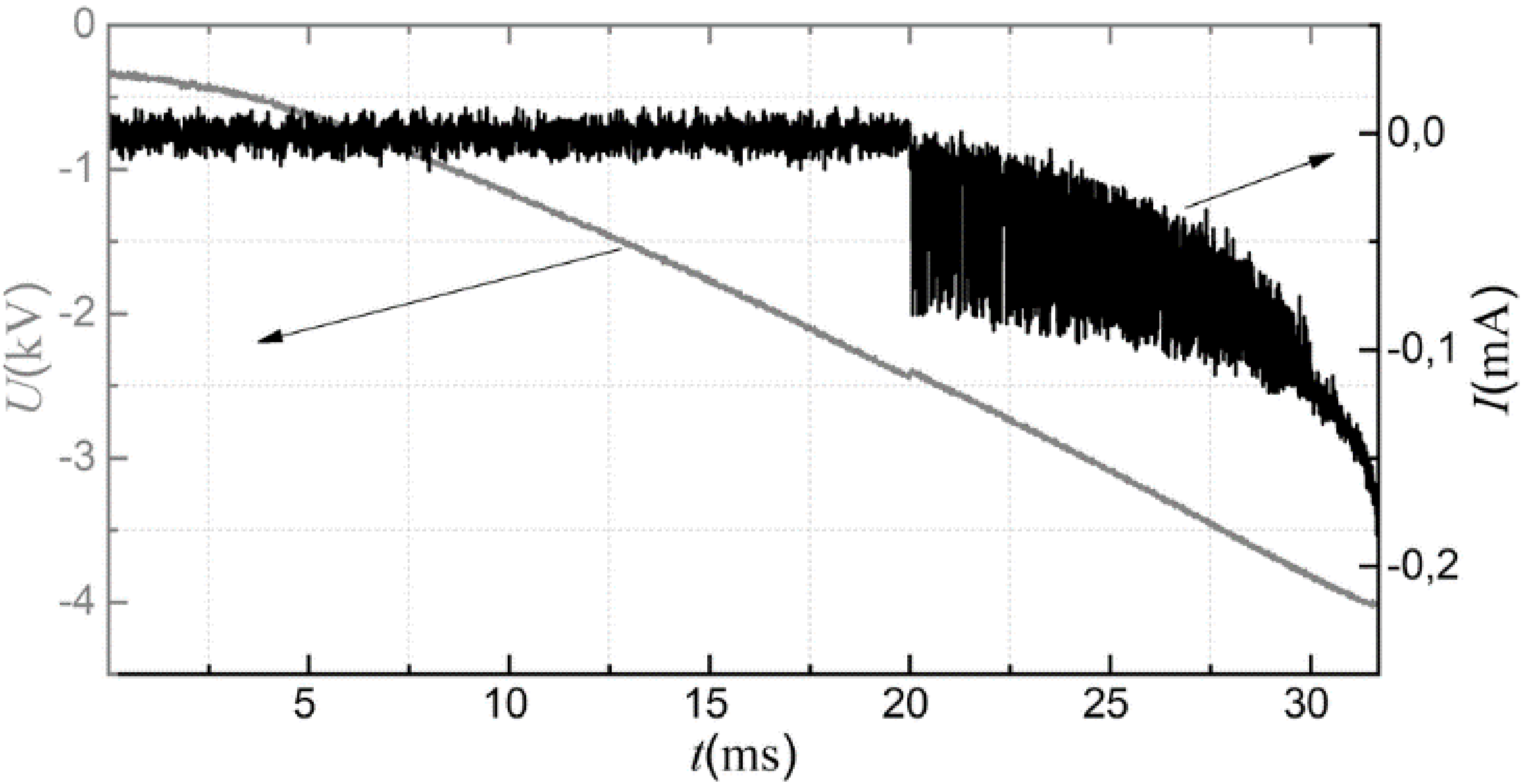
Three voltage sources were used. The first source worked in the range $U$ = 0.4-5 kV and the pulse amplitude could deviate by no more than 0.2%. The rate of voltage increase in the gap was no more than 0.2 kV/ms. The second power source with a voltage of up to 36 kV also provided its growth rate of no more than 0.2 kV/ms. The third source was pulsed. It generated sinusoidal voltage pulses with a front of ≈500 ns and a half-height duration of ≈500 ns as well with a frequency of 1 to 50 kHz. To determine the minimum discharge initiation voltage, we used a high-voltage source with high voltage stability and long needles (55 mm) with a small curvature radius of the tip.

A photograph of the integral corona glow was obtained using a Canon PowerShot SX 60 HS digital camera in single-shot shooting with an exposure time of 15 s. Corona plasma glow was recorded using a four-channel HSFC PRO ICCD camera, which had a minimum duration of one frame of 3 ns.

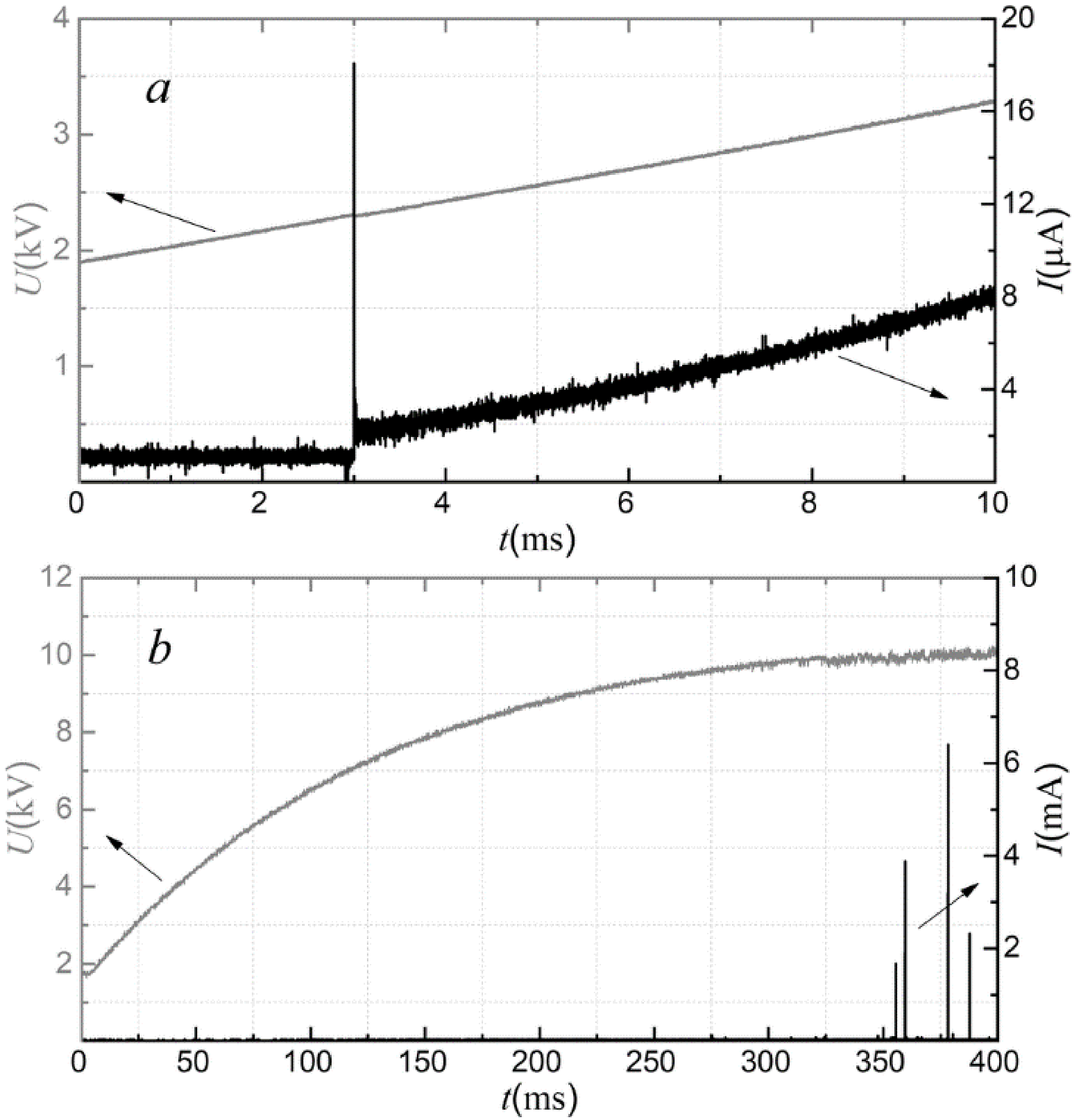
Using a TDS 3034 digital oscilloscope (Tektronics, Inc.) and a high voltage probe, the time course of the voltage was determined. The pulses of the discharge current from a high-resistance current shunt ($R$ = 1 kΩ) were also recorded by an oscilloscope at a time resolution of about 5 ns. This made it possible to measure both the pulsed and component of the direct current through the gap. The experiments were carried out in a laboratory room in atmospheric air at a temperature of ≈20 degrees and a humidity of not more than 60%.




**Average discharge current versus negative and positive polarity voltage with needle No. 4 spaced from plane electrode by 20 mm.**

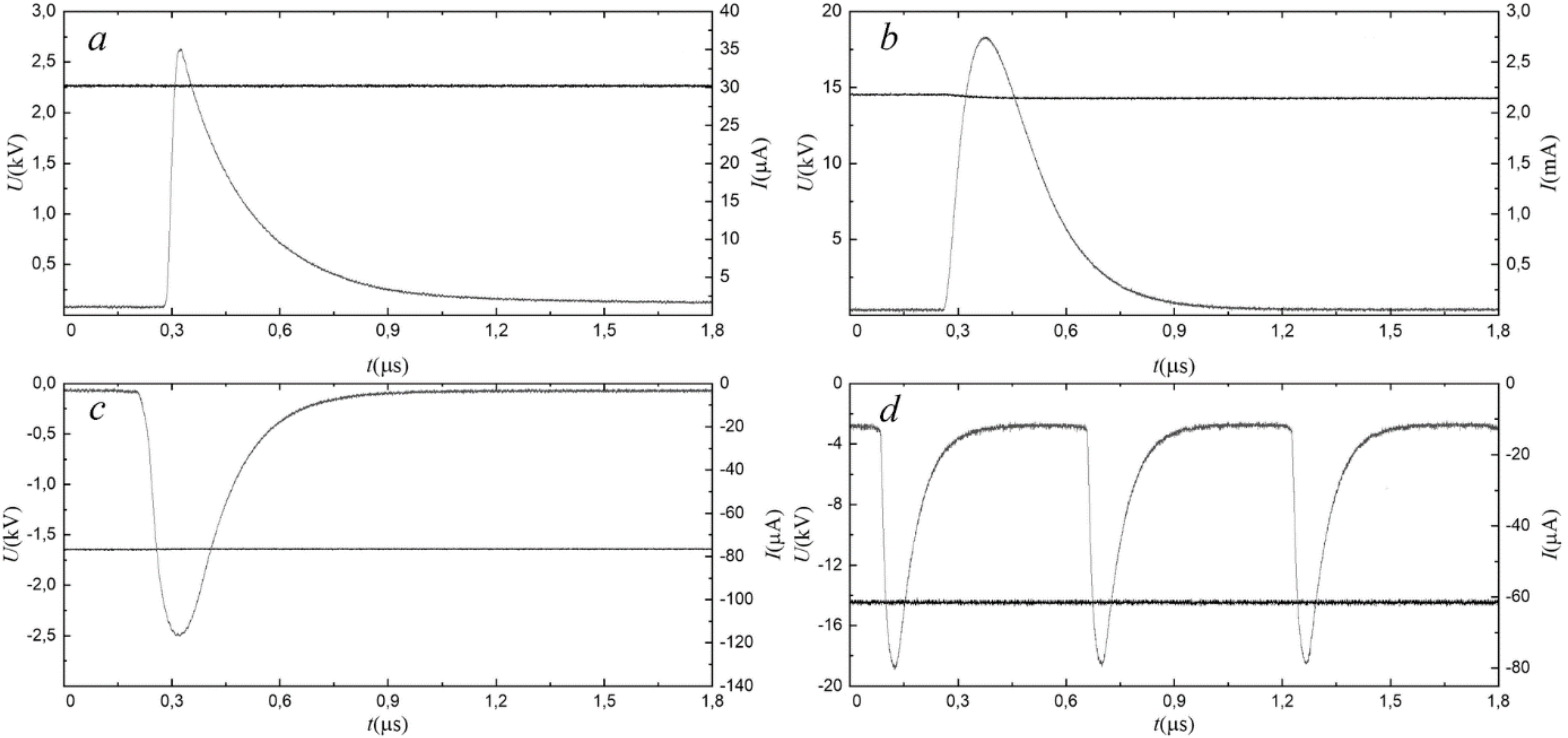



**Waveforms of voltage and current of negative corona recorded from within ~35 ms. Needle No. 1b. Length of gap 3 mm.**



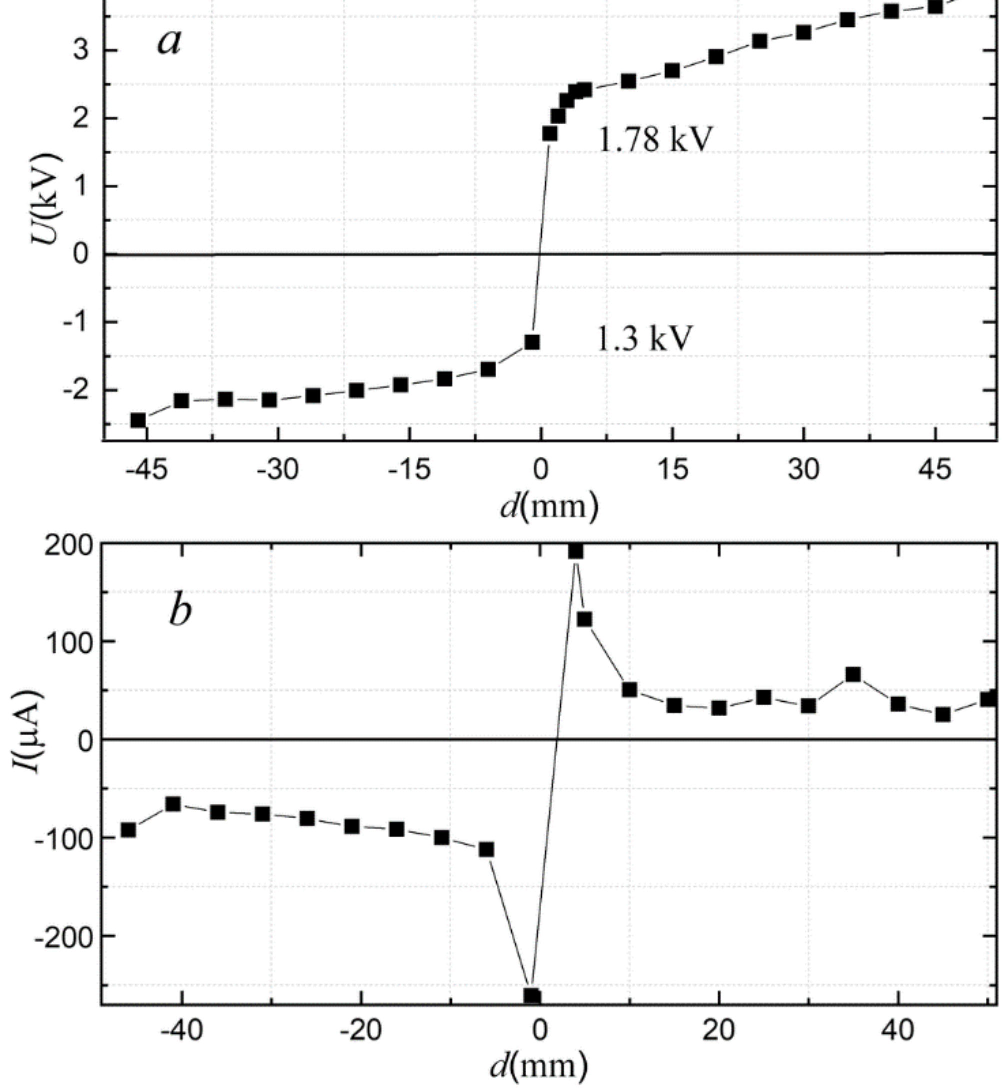

**Waveforms of voltage and current of positive corona when applying needle No. 1b. Length of gap 10 mm.**

**To determine the point in time that corresponded to the initiation of a corona discharge, a signal from a shunt was used, and the value of the shunt was chosen to be sufficiently large (1 kΩ).**




**First current pulses (a, c) and pulses in mixed modes (b, d) at different voltages (straight lines) at positive (a, b) and negative polarity (c, d). Gaps 5 (a, c) and 40 mm (b, d). Needle No. 1b.**

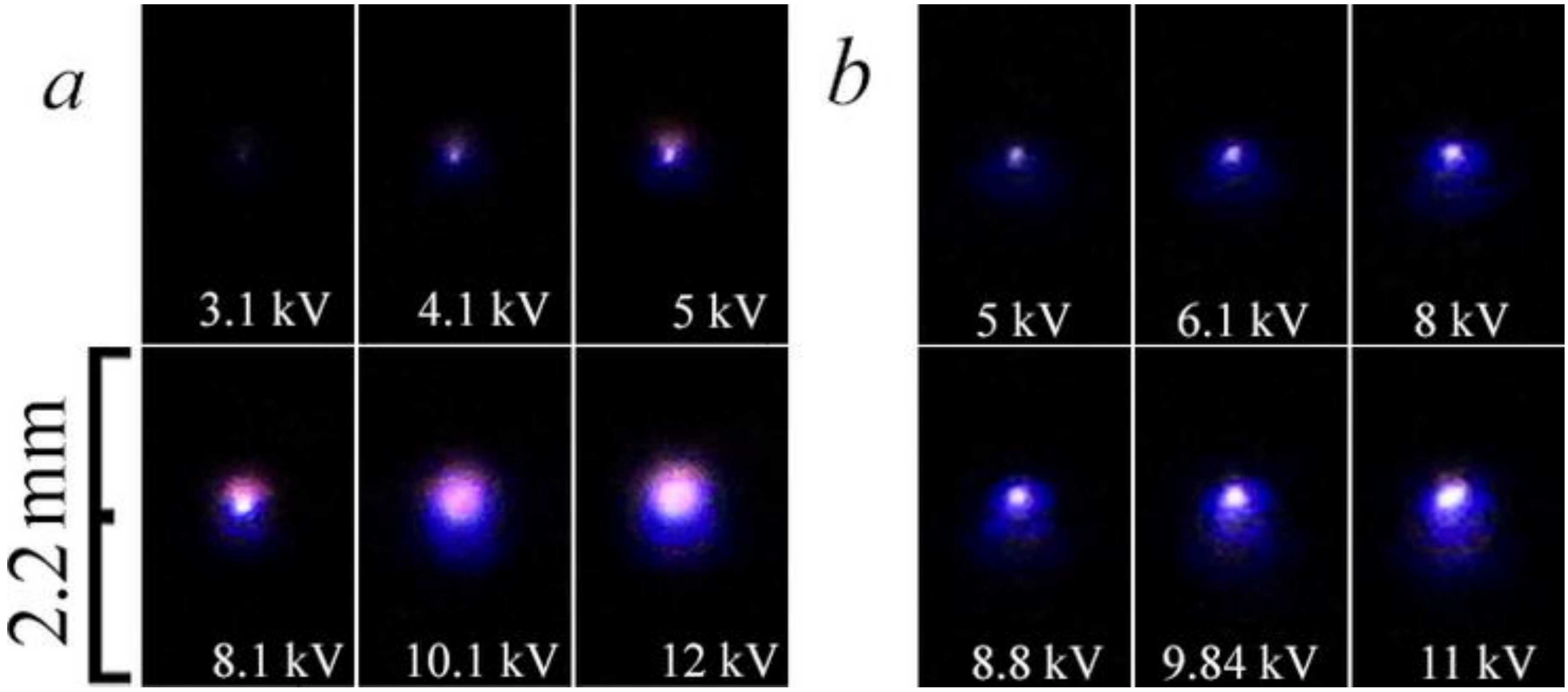
Before the appearance of the first pulses, a dark current was recorded, the value of which was less than 1 μA. The current pulses had a half-maximum duration of about 200 ns. The front of the current pulse was shorter with positive polarity, but the duration of this pulse at 0.1 was greater. A decrease in the radius of curvature of the tip, the diameter of the needle, and the gap led to a decrease in the voltage of initiation of the corona discharge. Depending on the radius of curvature of the tip of the point electrode at which the corona discharge was ignited, the voltage could vary by more than 1 kV. So, when negative polarity voltage was applied, the starting voltage of the corona discharge in the case of a pointed needle with a radius of curvature of 11 μm and with an gap of 1 cm was ≅ 2.2 kV. Wherein the starting voltage when using a needle with a radius of curvature of 30 μm and an gap of 3 cm was ≅ 3.6 kV.




**Start voltage of first current pulses (a) and their amplitude (b) versus gap *d* between needle No. 1a and plane electrode. Negative *d* values are for negative voltage polarity.**

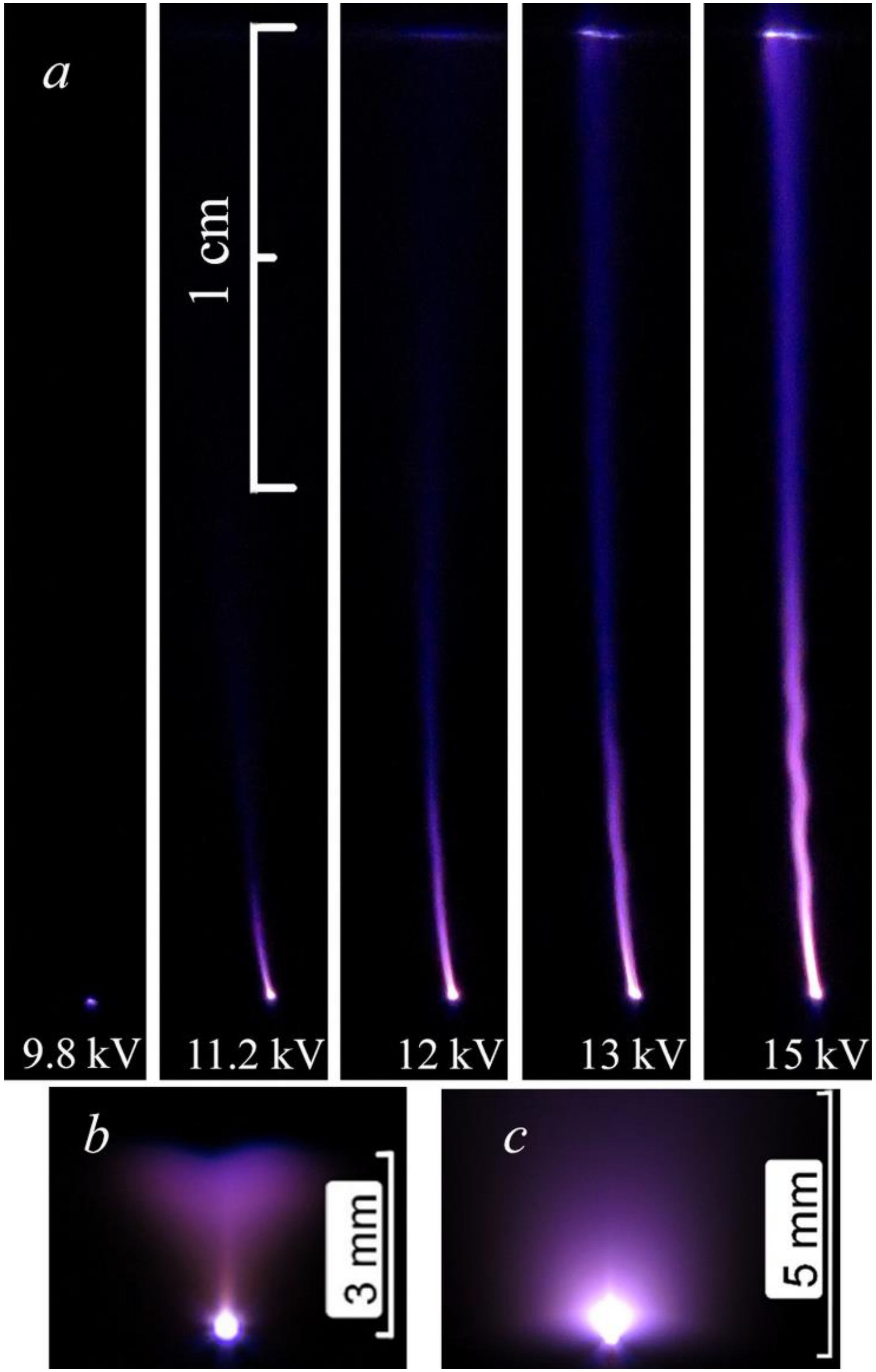
**To prove the hypothesis about the formation of ball streamers at both polarities of the voltage pulse under the conditions of corona discharge, the plasma glow was recorded using an ICCD camera. However, at a low rate of voltage increase in the gap (0.2 kV/ms or less), the first current pulses appeared at voltages of a few kilovolts. The plasma glow intensity (of the first streamers) under these conditions was small and, with a frame duration of several hundred nanoseconds or less, plasma glow was not recorded. Therefore, for recording, a pulsed corona discharge initiation mode with a third voltage source was used. Due to the relatively short front of the voltage pulse (≈500 ns), the formation of streamers occurred at high voltage, which also depended on the interelectrode gap and the needle used. An increase in voltage increased the amplitude of the current of the initiating pulse and the intensity of the plasma glow. Photo of the plasma glow for individual frame with a negative and positev voltage pulses are shown in next Figs.**

When a voltage of the direct current was applied to the electrodes at its tip appeared plasma structure of ball shape.



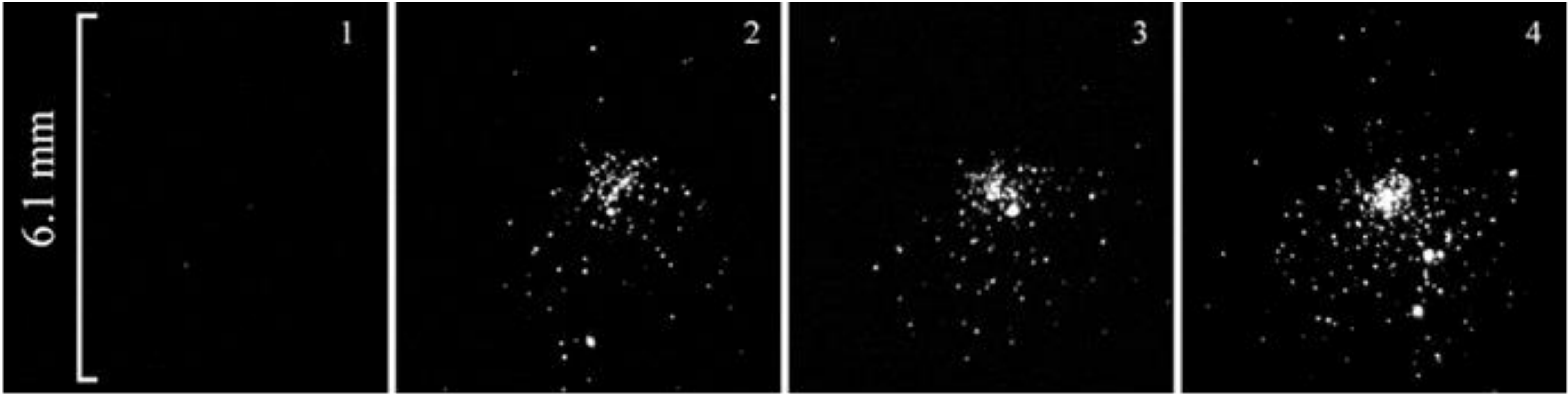

Images of corona discharges near needle No. 1a at negative (a) and positive polarity (b).

Length of gap 2 cm. Exposure time 15 s.

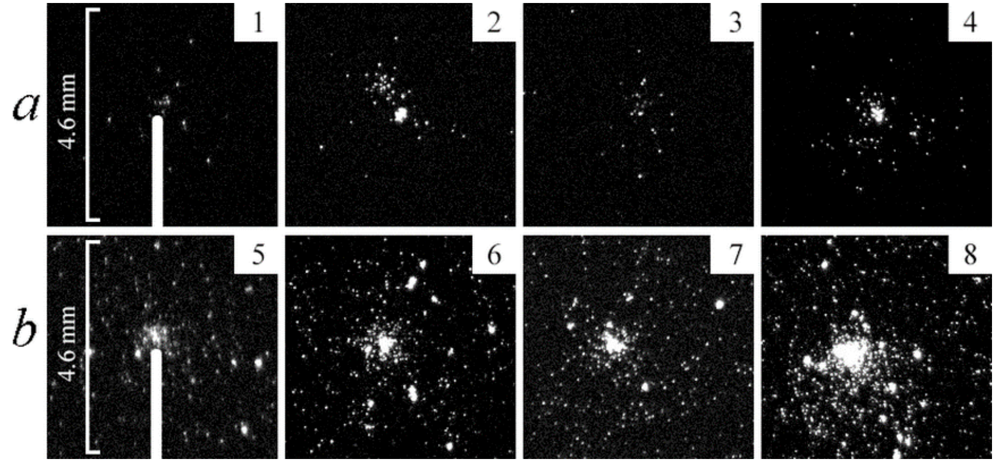



**Images of discharges from positive needle No. 2b at *d* = 20 mm (a) and from negative needle No. 1b at *d* = 10 mm, *U* = 3.8 kV (b) and negative needle No. 4 at *d* = 10 mm, *U* = 16.9 kV (c). Exposure time 15 s.**

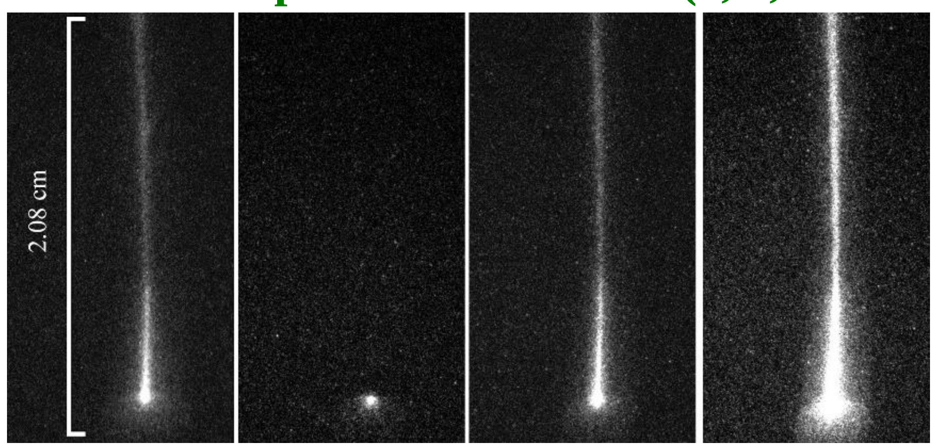
ICCD images of the corona discharge at the negative tip. The frame 1, 2, 3 durations are 50 ns, and 4 is 140 ns. Delays of frames from the start of shooting 0 ns for frames 1 and 4, 50 ns for frame 2 and 100 ns for frame 3. Pulse high voltage source. The maximum voltage in the gap is $U_m$ = 19.2 kV. $d$ = 20 mm.




**There is no radiation in the first frame, and in the second frame, a glow cloud of plasma is visible, the size of which does not change significantly at frames 3 and 4.**

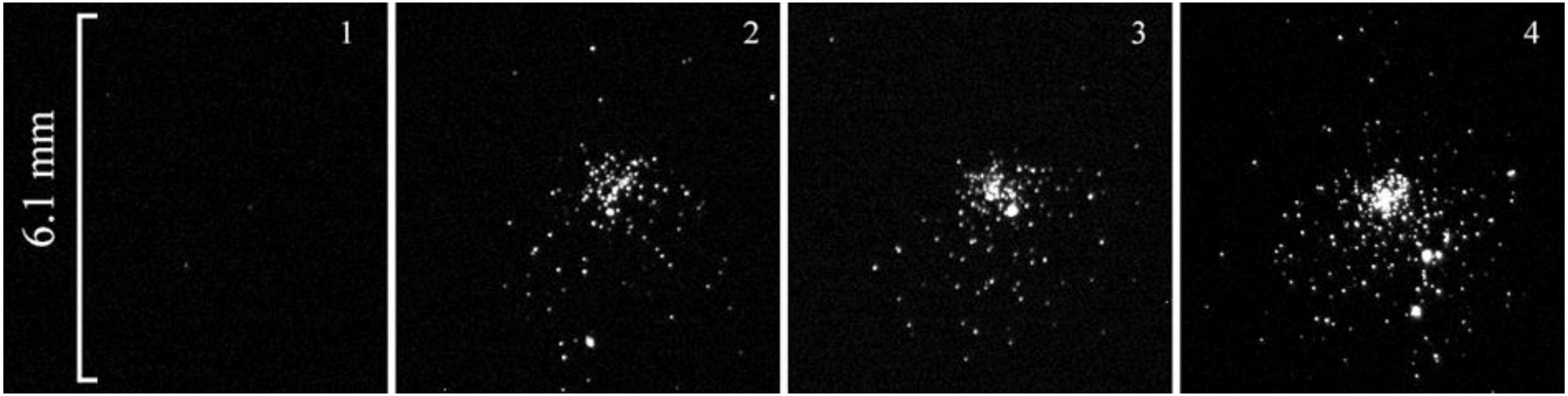



**ICCD images of negative coronas near needle No. 1b with *d* = 9 mm at maximum gap voltages 13 kV (*a*) and 6 kV (*b*). The needle is shown only in frames 1 and 5. Frame duration 200 ns (*1, 2, 3*), 600 ns (*4*), 20 μs (*5, 6, 7*), and 60 μs (*8*) with no time delay between first (*1, 5*) and second frames (*2, 6*) and between second and third (*3, 7*). Last frames (*4, 8*) are for coronas within respective first frames (*1, 2, 3* and *5, 6, 7*).**




**ICCD images of cylindrical positive streamer from needle No. 1b with *d* = 21 mm at maximum gap voltage 17.3 kV. Frame durations 100 μs (*1, 2, 3*) and 300 μs (*4*) with no time delay between first (*1*) and second frame (*2*) and between second and third (*3*). Last frame (*4*) is for discharge within first three frames.**

**ICCD images of a positive-polarity corona discharge with a pulse power supply. The durations of frames 1, 2, and 3 are 3 ns and for frame 4 are 10 ns. Frame delays from the start of shooting 0 for frames 1 and 4, 3 ns for frame 2 and 6 ns for frame 4. $U_m$ = 17.3 kV. $d$ = 20mm.**




**The start delay of the ICCD camera was chosen so that there was no glow on the first frame. In other frames, a glow plasma cloud is visible whose size does not change significantly.**

After the first pulse, a quasi-stationary component of the discharge current was observed and repeated pulses were recorded. The frequency of current pulses with a negative voltage polarity (Trichel pulses [G.W. Trichel, "The Mechanism of the Negative Point to Plane Corona Near Onset," Physical Review, vol. 54, pp. 1078-1084, December 1938]) was significantly higher than with a positive, and at low voltages, this difference reached several orders of magnitude. The duration of repeated pulses did not change significantly with an increase their frequency. The amplitude of the quasi-stationary component of the discharge current and the frequency of the repeated pulses increased with increasing voltage.

We believe that the observed first current pulses are due to the formation of cathode- and anode- directed streamers in the high-field area near the tip of electrode. Moreover, as before shows, at minimal voltages, the plasma had a shape close to a ball one, and it can be assumed that the tip has ball streamers, as in [V.F. Tarasenko, V.S. Kuznetsov, V.A. Panarin, V.S. Skakun, E.A. Sosnin, and E.K. Baksht, "Role of Streamers in the Formation of a Corona Discharge in a Highly Nonuniform Electric Field," JETP Letters, vol. 110, pp. 85-89, September 2019].

It follows that, over 50 ns, the ionization of air near the tip occurred with a velocity of motion of the glow front of at least 0.02 mm/ns. Such a high speed can be provided under given conditions only due to the formation of a streamer [Y.P. Raizer, "Gas Discharge Physics," Springer-Verlag Berlin Heidelberg, 1991]. From waveforms of current shows that even with a lower voltage, the front of the current pulse is also about 50 ns. Accordingly, under these conditions, the velocity is determined by the velocity of the streamer front (~0.02 mm/ns).

With a positive voltage polarity, a shorter front of the current pulses during corona discharge is recorded, see Fig. 2. In addition, with increasing voltage, the amplitude of the current with a positive polarity increases faster than with a negative. This made it possible to register the formation of a streamer from a positive tip with a minimum ICCD camera frame duration of 3 ns, Fig. 5.

# Conclusion

**It has been shown, that the ignition of a corona discharge in air at atmospheric pressure in a nonuniform electric field occurs at both polarities owing to the formation of ball streamers. Moreover, a streamer from the positive polarity tip starts at a higher voltage across the gap than from the negative polarity tip. With the same voltage across the gap, the larger average corona discharge currents in the mode of ball streamers are recorded at the negative tip polarity.**

**The increase in the average current of the corona discharge is achieved at the negative tip because the repetition frequency of the individual pulses is much (two or more orders of magnitude) higher than that at the positive tip polarity. The formation of cylindrical streamers from the positive tip, with an increase in the voltage leads to a significant increase in the current pulse amplitudes, and they become higher than current pulse amplitudes from the negative tip for the same voltage.**

**These data are consistent with our results obtained previously [1, 2].**

**1. V. F. Tarasenko, V. S. Kuznetsov, V. A. Panarin, V. S. Skakun, E. A. Sosnin, E. Kh. Baksht, "Role of streamers in the formation of a corona discharge in a highly nonuniform electric field," JETP Letters, v. 110, no. 1, pp. 85-89, 2019.**

**2. V. S. Kuznetsov, V. F. Tarasenko, E. A. Sosnin, "On Pulsed Modes of the Glowing Corona Region," Russian Physics Journal, v. 62, no. 5, pp. 893-899, 2019.**