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Spark Discharge in Atmospheric-Pressure Air and Bead Structure of Its Channel

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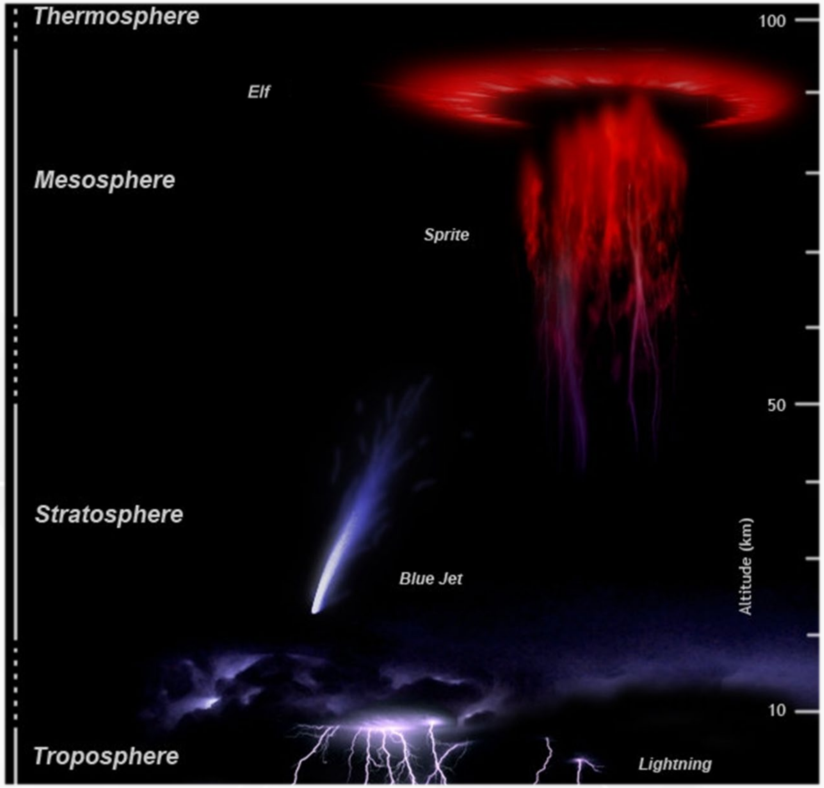
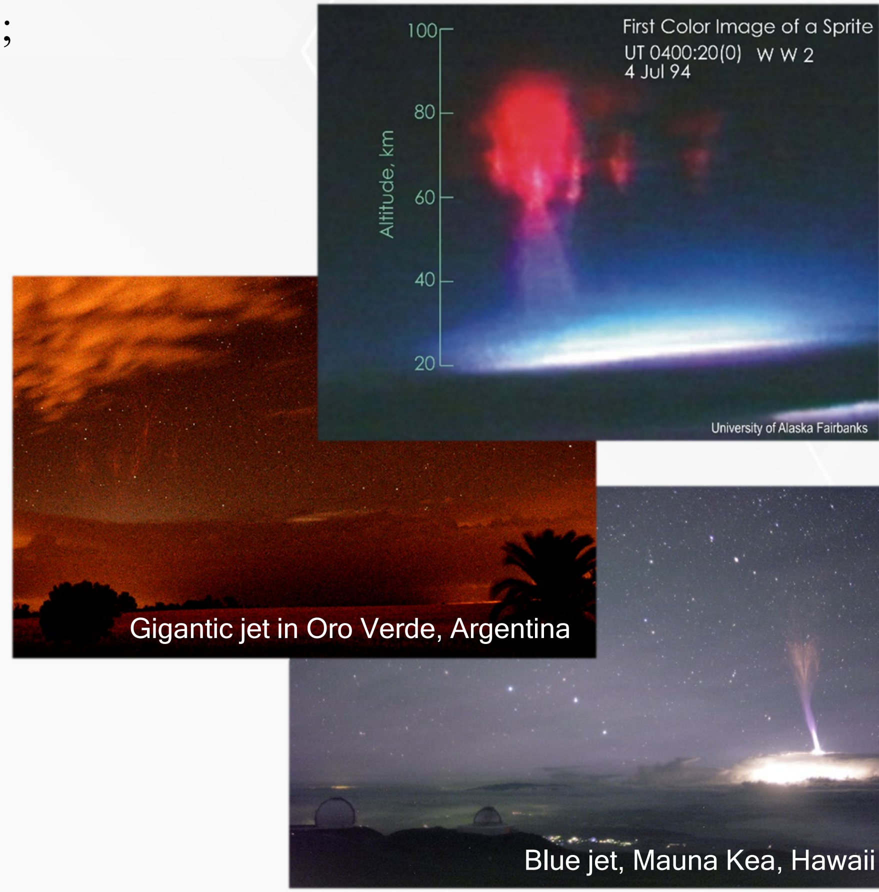
Introduction

In recent years, interest in studying atmospheric discharges has increased significantly.

Attempts are being made to reproduce various types of atmospheric discharges in laboratory conditions:

- blue jets over an area with thunderstorm activity [1];
- red sprites at altitudes up 100 km [2];
- lightning and lightning protection [3-4].





Different types of atmospheric discharges. Source: Wikipedia.

[1]. O. Chanrion, T. Neubert, A. Mogensen, Y. Yair, M. Stendel, R. Singh, & D. Siingh. Geophysical Research Letters, **44** 496 (2017).
[2]. M. Füllekrug, E.A. Mareev, & M.J. Rycroft (Eds.). Sprites, elves and intense lightning discharges (Vol. 225). Springer Science & Business Media, 2016.
[3]. R. Zeng, C. Zhuang, X. Zhou, S. Chen, Z. Wang, Z. Yu, & J. He. High Voltage, **1** 2 (2016).
[4]. W. Lu, Q. Qi, Y. Ma, L. Chen, et al. High voltage, **1** 11 (2016).

Introduction

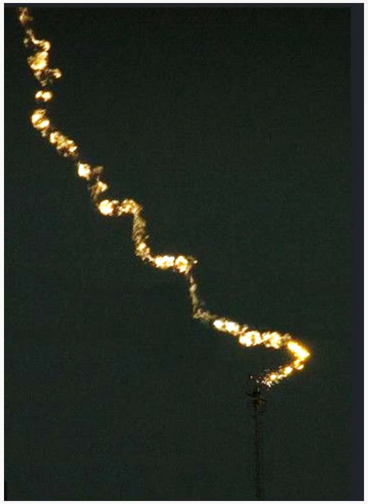
Bead lightning is one of the rarest and insufficiently studied phenomena [5].

Many researchers deny the existence of this type of discharge.

In recent years, new data on the development of the bead lightning under conditions close to nature [6], and on the observation of its analogue in the laboratory spark discharge [7-9] were obtained.

From many studies at different conditions it follows that:

- at the first stage an uniform bright channel is observed;
- further individual beads in the channel are appeared;
- then the brightness of the lightning decreases and dim regions between the beads is clearly visible.



Bead Lightning.

Main objective: to study conditions for the formation of the bead structure during spark discharges in a "point-plane" gap with a length of up to 45 mm at both polarities of a voltage pulse with a rise time of the order of a microsecond.

[5]. V. Cooray, An Introduction to Lightning (Springer, 2015).
*[6]. G.O. Ludwig, M.M.F. Saba, Phys. Plasmas, **12** 093509 (2015).*
*[7]. S.P.A. Vayanganie, V. Cooray, M. Rahman, et al., Phys. Lett. A, **380** 816 (2016).*
*[8]. D.V. Beloplotov, V.F. Tarasenko, Phys. Lett. A, **383** 351 2019.*
*[9]. D.V. Beloplotov, A.M. Boichenko, V.F. Tarasenko, Plasma Physics Reports, **45** 387 2019.*

Experimental Setup No. 1

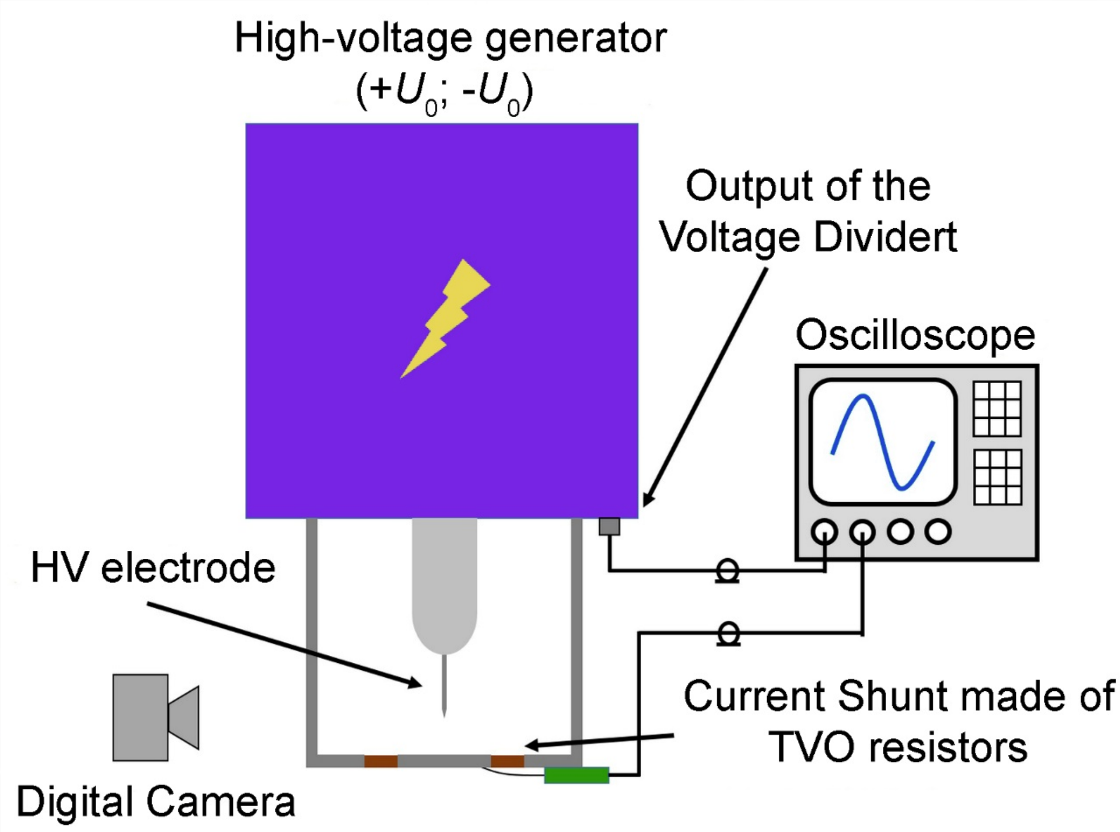


Fig. 1. Sketch of the experimental setup No. 1.

The generator operated in a single pulse mode.

The diode was filled with atmospheric-pressure air.

Integral images of the discharge were taken with digital camera.

Home-made high-voltage generator based on pulsed transformer:
two-step pulse
$U_0 = 200$ kV
$\tau_f = 1.5$ μs

7-cm long HV electrodes with a small radius of curvature made of stainless steel:

- cone (base diameter – 5 mm; apex angle – 68°; $r_{curv} = 100$ μm);
- needle (base diameter – 3 mm; apex angle – 36°; $r_{curv} = 50$ μm).

Flat grounded electrode was connected to the generator case through a current shunt made of TVO resistors.

Gap width: $d = 45$ mm

$p_{Air} = 100$ kPa

Tektronix TDS-2020 (300 MHz; 5 GSa/s)
SONY A100 digital camera

Experimental Setup No. 1

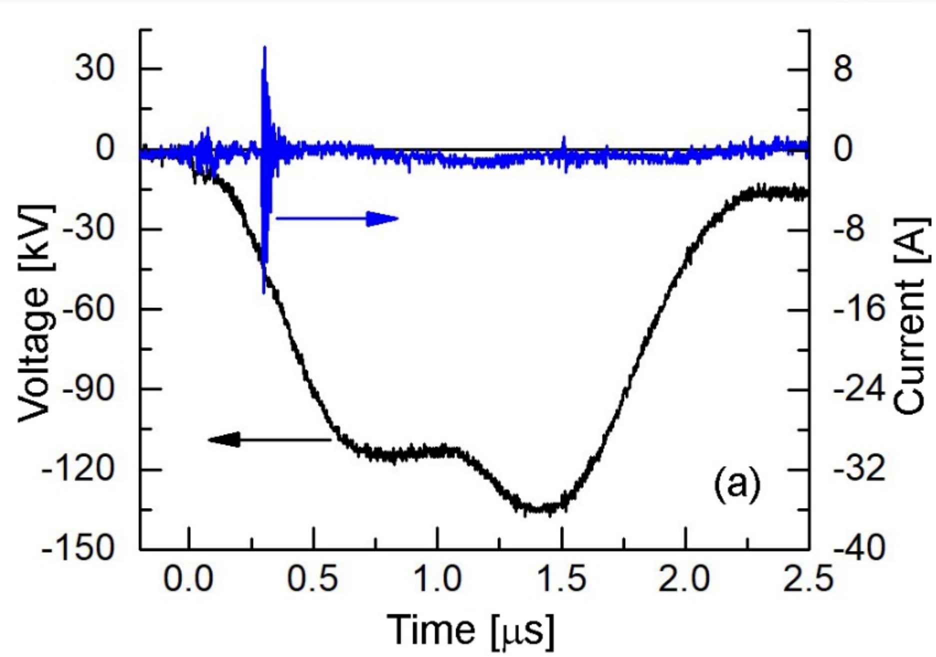


Fig. 2a. Waveforms of negative voltage and current pulses. Setup No. 1. Idle mode.

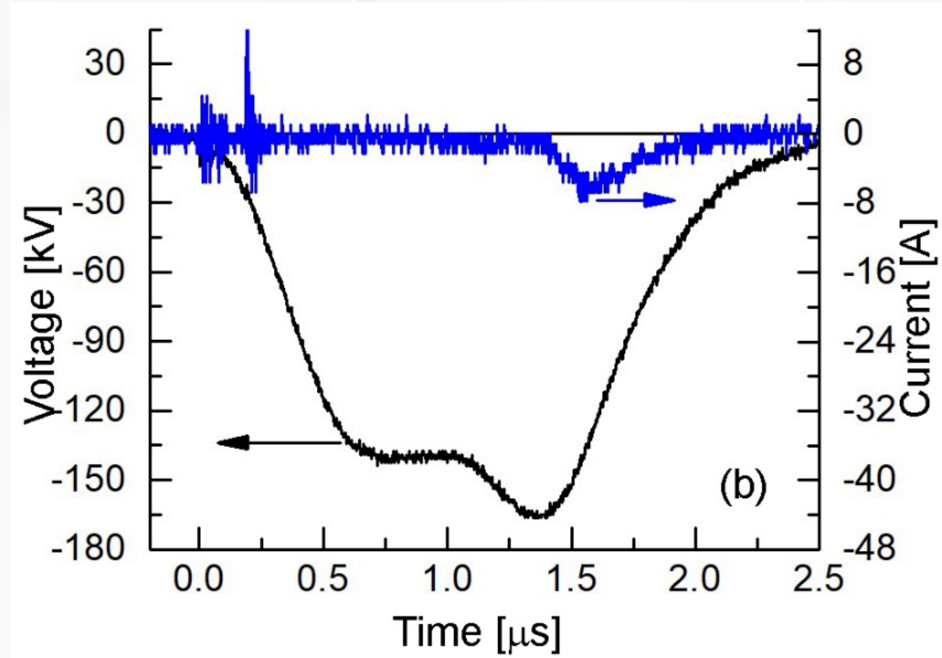


Fig. 2b. Waveforms of negative voltage and current pulses. Setup No. 1. Formation of a diffuse discharge (see Fig. 6b).

The current through the gap was absent in idle mode, as it should be. When diffuse discharge occurred, a current pulse with an amplitude of ≈ 3.5 A was observed on the falling edge of voltage. In those cases, when a spark discharge with and without the bead structure were observed, the breakdown occurred earlier.

Experimental Setup No. 2

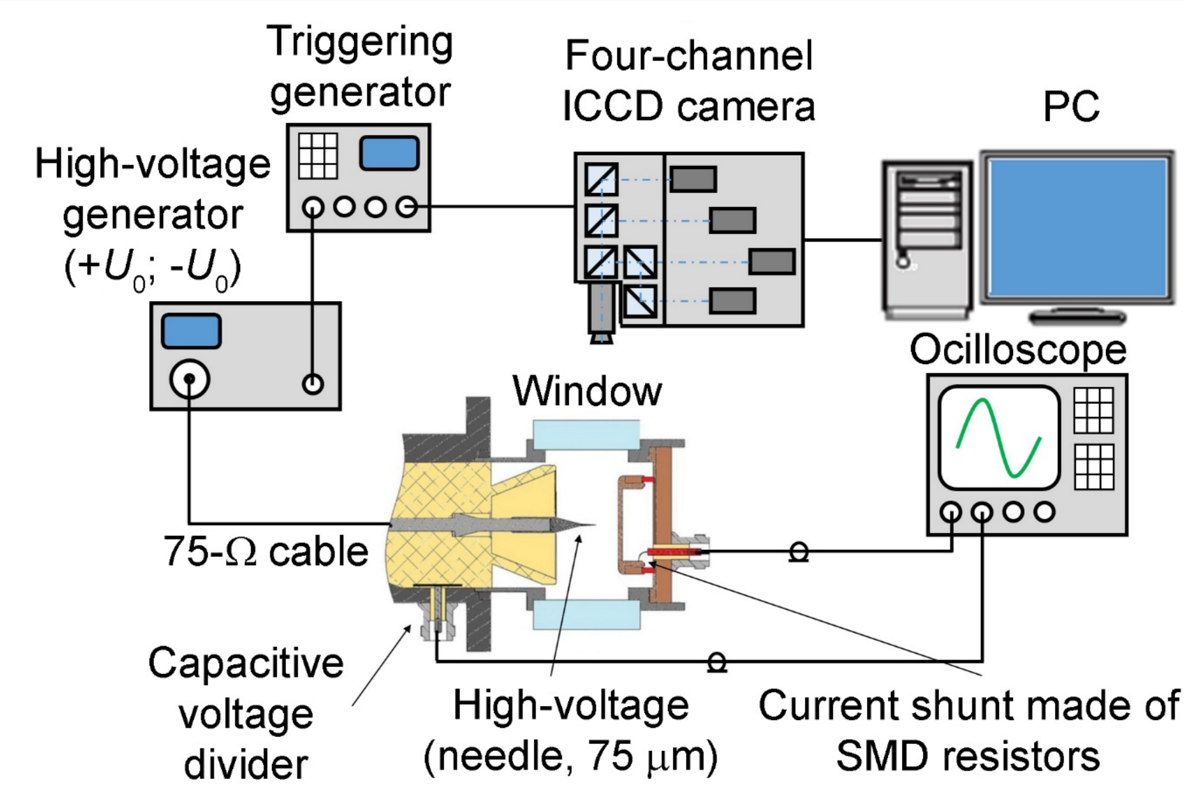


Fig. 3. Sketch of the experimental setup No. 2.

The development of the plasma glow at the breakdown stage was recorded with a four-channel ICCD camera HSFC Pro (minimal gate – 3 ns).
SMD resistors are more broadband than TVO ones. It was possible to synchronize the ICCD images with the waveforms of voltage and discharge current.

Home-made high-voltage generator:
$U_0 = 36$ kV
$\tau_f = 0.2$ μs
$T_{0.5} = 0.3$ μs

HV electrode with a small radius of curvature made of stainless steel:

- sewing needle (base diameter – 1 mm; length – 5 mm; $r_{curv} = 75$ μm).

Flat grounded electrode was connected to the generator case through a current shunt made of SMD resistors.

Gap width: $d = 8.5$ mm

$p_{Air} = 100$ kPa

Tektronix TDS-3054B (500 MHz; 5 GSa/s)
SONY A100 digital camera

Experimental Results. Setup No.1. Negative polarity

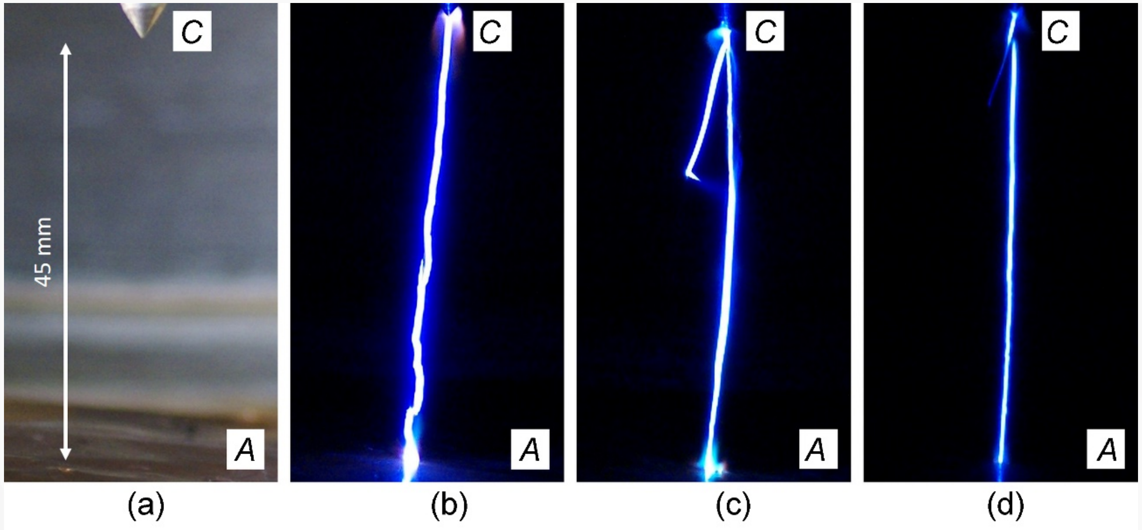


Fig. 4. Image of the cone-to-plane gap and integral images of the discharge plasma glow in this gap at various implementations. Setup No. 1.

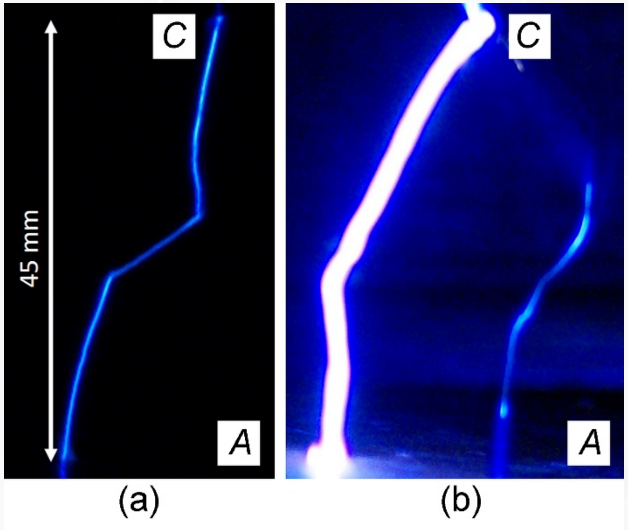


Fig. 5. Integral images of the discharge plasma glow in the cone-to-plane gap at various implementations. Setup No. 1.

Breakdown voltage and discharge form varied from pulse to pulse due to the instability of initiation. Bends of the spark channel are observed (like in [10]). A spark leader, which has not bridged the gap, and a spark channel are observed in Fig. 4c. At the same time, the spark leader apparently closed on the spark channel. This area is characterized by diffuse glow. A break in the spark channel, apparently related with the formation of two spark leaders, and diffuse glow are observed in Fig. 4cd.

The images allow us to make the assumption that the spark leader can transform into a diffuse channel at negative polarity.

A zigzag spark channel and a spark channel with a bead structure are observed in Figs 5a and 5b. The brightness of the zigzag spark channel is not uniform. A pronounced bead structure is observed when two spark leaders cross the gap. Such discharge implementations occur quite rare. The largest current flows through the bright channel. The spark channel with the bead structure is characterized by the presence of diffuse regions.

*[10]. C. Zhang, V.F. Tarasenko, T. Shao, et al., Physics of Plasmas, **22** 033511 (2015).*

Experimental Results. Setup No.1. Negative polarity

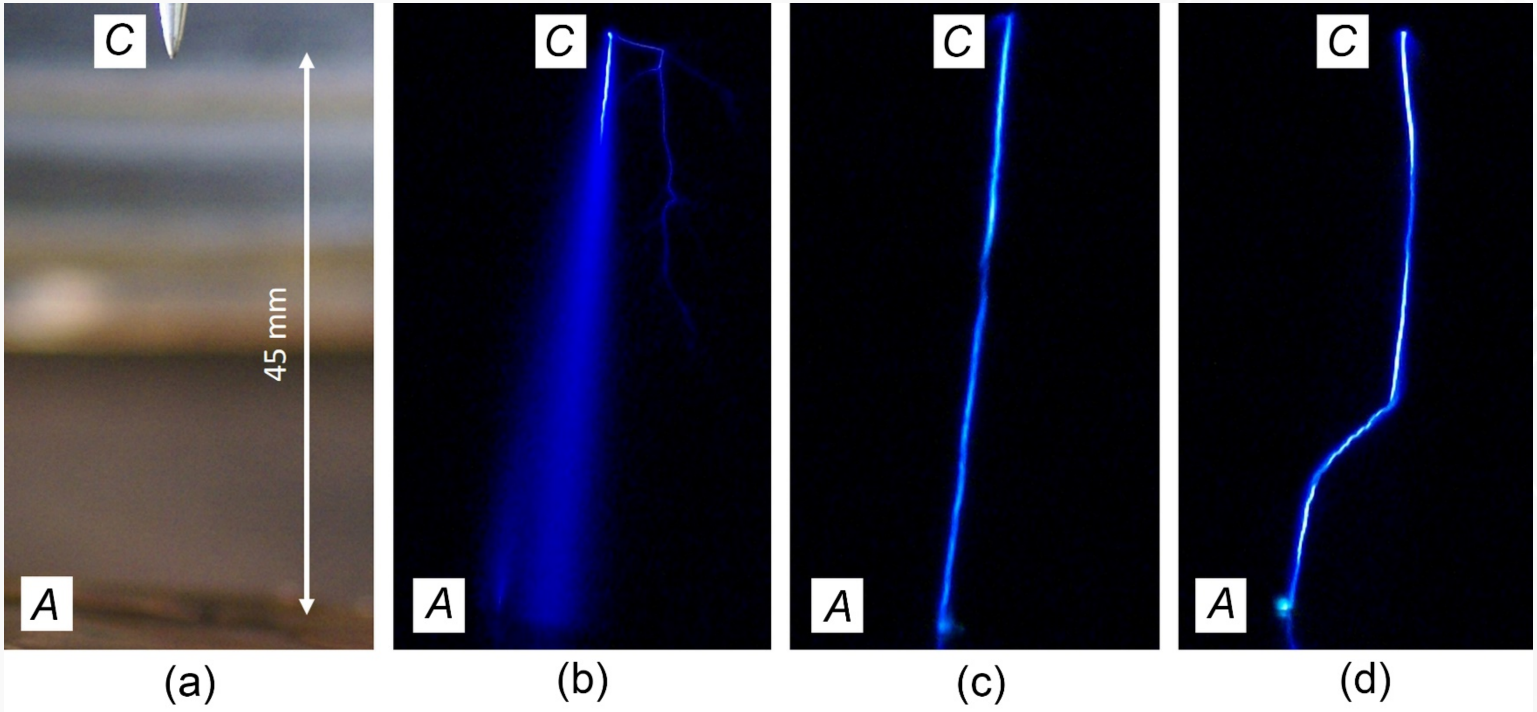


Fig. 6. Image of the needle-to-plane gap and images of the discharge plasma glow in this gap at various implementations. Setup No. 1. Negative polarity. d = 45 mm.

A diffuse discharge was observed in a number of implementations when the needle electrode was used instead of the conical one (Fig. 6b). The needle electrode provided a larger electric field strength enhancement due to the smaller radius of curvature. A bright spark leader that did not cross the gap per pulse was observed against the background diffuse emission in Fig. 6b. In [8, 9], the formation of a spark channel with a bead structure followed the diffuse stage of a discharge. The diffuse discharge stage was observed in experiments on Setup No. 1 at breakdown delay times of an order of magnitude more than in [8, 9]. Spark channels of various form (linear and zigzag) with a bead structure are observed in Figs 6c and 6d. It is seen that the brightness periodically changes along the channel length. These images were obtained under conditions when the breakdown occurred earlier than on average. The length of individual beads is longer than that observed in [8, 9] at breakdown voltages of tens of kV.

Experimental Results. Setup No.1. Both polarities

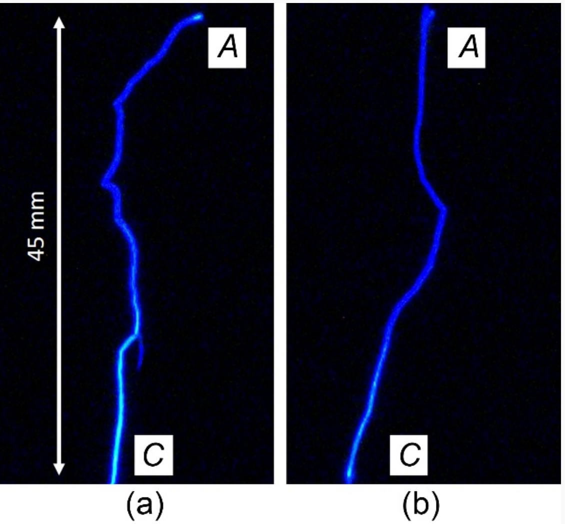


Fig. 7. Image the discharge plasma emission in (a) cone-to-plane and (b) needle-to-plane gaps at various implementations. Setup No. 1. Positive polarity. d = 45 mm.

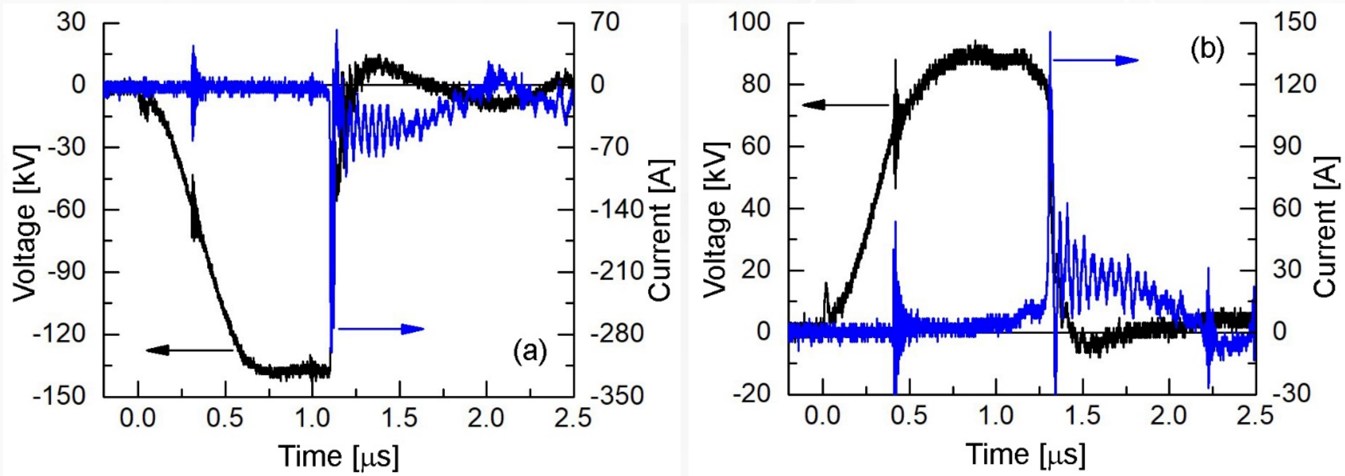


Fig. 8. Waveforms of voltage and current pulses when sparks were observed. Setup No. 1. Negative polarity (a) (corresponds to Fig. 5b), Positive polarity (b) (corresponds to Fig. 7a). d = 45 mm.

The structure of spark channels changed when voltage pulses of positive polarity were applied across the gap (Fig. 7).

The observed characteristic features of the spark channel with the positive polarity of cone or needle electrodes are that it was often single, diffuse and had many bends. The beads could only be observed from the side of the flat grounded electrode. They had less brightness and length. At positive polarity, sparks with bead structure over the entire length of the discharge gap were not observed in any of the order of hundreds of implementations. Note that the bead structures in [8, 9] were observed only at negative polarity of an electrode with a small radius of curvature.

It is seen from the Fig. 8 that the breakdown occurred 1–1.3 μs after applying voltage pulse across the gap. In this case, typical for spark discharges, a rapid voltage drop due to the high conductivity of a spark channel is observed.

Experimental Results. Setup No.2. Negative polarity

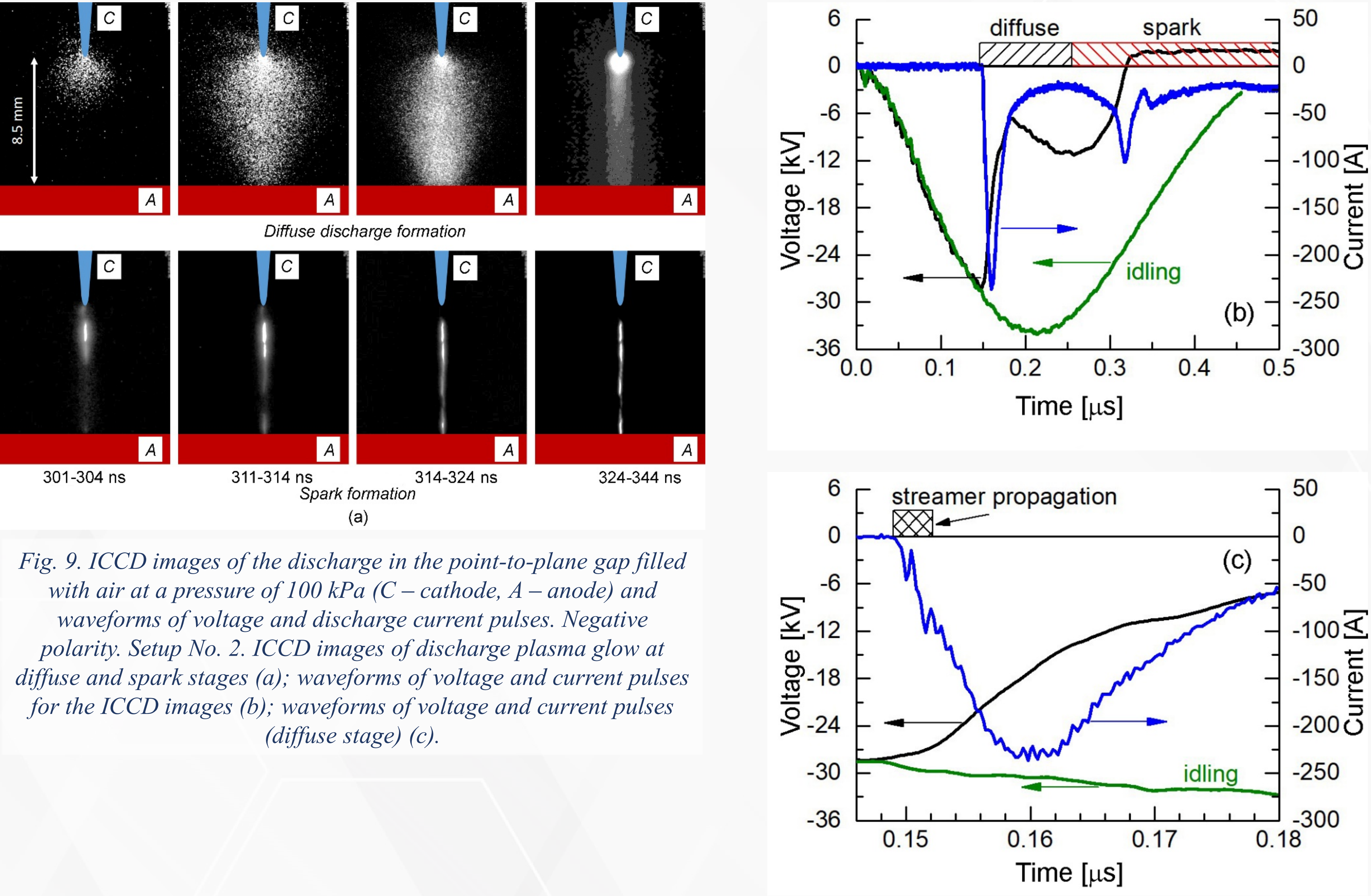


Fig. 9. ICCD images of the discharge in the point-to-plane gap filled with air at a pressure of 100 kPa (C – cathode, A – anode) and waveforms of voltage and discharge current pulses. Negative polarity. Setup No. 2. ICCD images of discharge plasma glow at diffuse and spark stages (a); waveforms of voltage and current pulses for the ICCD images (b); waveforms of voltage and current pulses (diffuse stage) (c).

Experimental Results. Setup No.2. Negative polarity

At the initial stage a diffuse discharge is formed (Fig. 9a). The formation time did not exceed 1.5 ns.

In this case, in order to study the initial stage of the discharge, the ICCD camera channels were switched on before the breakdown. Channels 1–3 were switched simultaneously. However, due to the imperfect hardware of the ICCD camera, there is a jitter between the channels (<1 ns). Despite this, the imperfection played in a positive direction. This made it possible to observe the development of a streamer, which crossed the gap in less than 1.5 ns.

The discharge formation time was determined from the waveforms of the discharge current. As shown in our previous papers the formation of a streamer is accompanied by the flow of a dynamic displacement current (DDC) caused by a redistribution of the electric field strength due to the formation and propagation of the streamer, which ensures the breakdown of the gap. A time-varying electric field induces a displacement current. The magnitude of DDC depends on the streamer velocity and therefore has characteristic features that are easily found on the current waveform. DDC increases sharply when the streamer starts and it approaches the opposite electrode. These features are clearly distinguishable in Fig. 9c, and the corresponding time interval is designated as streamer propagation. Such streamers with a large transverse dimensions are typical for nanosecond breakdown of "point-plane" gaps [11].

The spark formation lasted several tens of ns (Fig. 9a, spark formation). Therefore, the channels 2 and 3 of the ICCD camera were switched on with delays of 10 and 20 ns relative to the channel 1. Under these conditions, the length of beads and their number changed from pulse to pulse. The maximum number of beads reached 8, as in [8, 9]. The position of beads in space can also vary from pulse to pulse. In general, these experiments confirmed the stable formation of bead structures of the spark channel at negative polarity of the electrode with a small radius of curvature.

[11]. D.V. Beloplotov et al.. Streamers at the subnanosecond breakdown of argon and nitrogen in nonuniform electric field at both polarities // Tech. Phys. 63 793 (2018).

Experimental Results. Setup No.2. Positive polarity

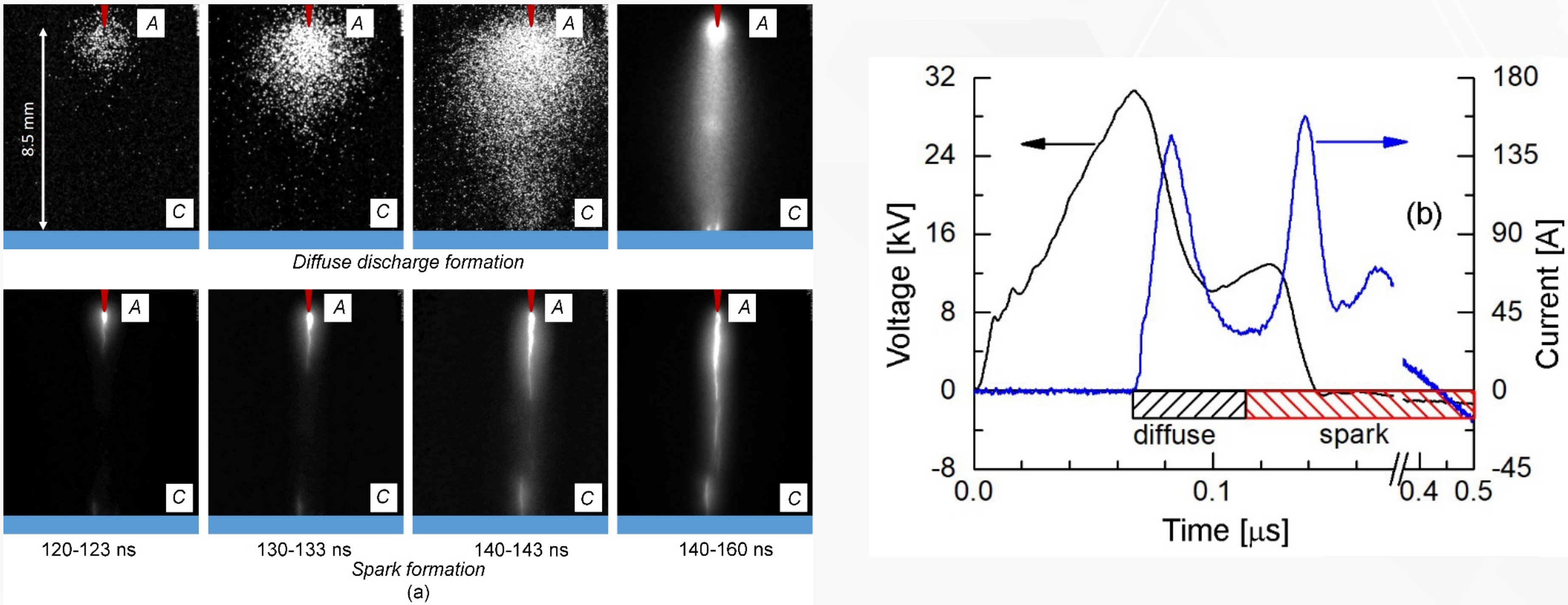


Fig. 10. ICCD images of the discharge in the point-to-plane gap filled with air at a pressure of 100 kPa (A – anode, C – cathode) and waveforms of voltage and discharge current pulses. Positive polarity. Setup No. 2. ICCD images of discharge plasma glow at diffuse and spark stages (a); waveforms of voltage and current pulses for the ICCD images (b).

At positive polarity of the pointed electrode, the discharge slightly changed. The corresponding ICCD images and waveforms of voltage and current are presented in Fig. 10. It is seen that at the initial stage a diffuse discharge is also formed (like in Fig. 9a). The change in polarity did not have a qualitative effect on the formation of a diffuse discharge in air. However, the discharge formation time increased up to 2 ns. This means that the average velocity of a positive streamer was less than that of the negative one.

Discussion

An increase in the gap length from 8.5 to 45 mm and rise time of voltage pulses from 0.2 μs to 1 μs did not affect the formation of the bead structures of the spark channel in atmospheric pressure air in an inhomogeneous electric field. We assume that the bead structure forms due to changes in the electric field in the spark leader head that is caused by changes in its size. It is known, see, that, in air at atmospheric pressure, a diffuse discharge is formed in the gap with an inhomogeneous electric field owing to runaway electrons. It was confirmed in this study, that beads are formed in the gap with a decrease in the current in the diffuse stage of the discharge. With a sufficient pulse duration, they are "smoothed" when a strong current flows. The probability of the appearance of beads, their length and quantity, as well as the dynamics of their formation, vary from pulse to pulse and depend on the experimental conditions, in particular, on the voltage across the gap.

At the beginning, during the breakdown of the gap, the diffuse discharge is formed (Fig. 6b, Figs 9 and 10) due to the development of a streamer or several streamers (an ionization wave). At high overvoltages, the diameter of the streamer can be comparable with the distance between the electrodes. This is common for nanosecond discharges in an inhomogeneous electric field and for negative polarity of the electrode with a small radius of curvature. This is provided by the generation of fast (with energies of hundreds of eV — units of keV) and runaway (with energies of tens – hundreds of keV) electrons that preionize the gas ahead the streamer. As shown in this work, the discharge can be diffuse form under conditions when microsecond voltage pulses are applied across the gap. There is no data on the formation of a diffuse discharge during the development of lightning in the Earth's atmosphere. We assume that during the development of lightning a diffuse discharge can form in the vicinity of the leader due to runaway electrons, as well as due to cosmic rays, which produce preliminary ionization of air. Ionization of air by cosmic rays is a long-established fact, see, for example, the monograph [12]. X-ray radiation caused by runaway electrons in lightning was detected experimentally using sensors mounted on an airplane [13]. At the stage of discharge constriction, the appearance of a clot of plasma with a high concentration of electrons and ions is necessary to start the bead formation processes. It can be a cathode spot and a spark leader or a negative step leader, which is responsible for the formation of the lightning channel [14], under natural conditions. The electric field is redistributed and concentrated in the vicinity of the leader head (spark leader head). In a high electric field, some electrons can go into runaway mode. They can ensure the formation of a diffuse region in front of the leader or improve uniformity and increase the diameter of the channel. The diffuse region 'screens' the tip of the leader (bead) due to the redistribution of the electric field. The electric field strength at the front of the leader decreases, the number of high-energy (fast and runaway) electrons decreases or they disappear completely. The electric field strength at the front of the diffuse region is also small because of its relatively large diameter. In addition, the conductivity of the diffuse channel is generally less than that of the spark channel or the channel formed by the leader due to the lower electron concentration. A narrow channel forms from the front of the diffuse region. Constriction provides heating of this region. As a result, a bead is formed. The electric field strength at the front of this narrow channel increases again due to the geometric factor. The process is then repeated. A new high-energy electron generation cycle and the formation of a diffuse region taky place. In laboratory conditions, a sequence of beads having a weak radiation intensity that do not reach the opposite electrode is often observed [9]. A periodic stop of the leader is observed in spark discharges in large gaps with a negative rod electrode [3], as well as during lightning development [14]. With sufficient duration and magnitude of the current, the brightness of the channel can be aligned and the bead structure disappears. The bead structure can exist for a long time if a shunt spark channel appears through which most of the current will flow. In atmospheric discharges, the bead lightning is very rare. It is likely that the bead structure of lightning disappears due to return stroke, during which the main current flows [6, 14]. We assume that the bead lightning can be observed under conditions when several channels develop, as well as at relatively low magnitudes of current.

[12]. Yu. P. Raizer, Gas Discharge Physics (Springer, 1991).
*[13]. P. Kochkin, A.P. Van Deursen, A. De Boer, et al., Journal of Physics D: Applied Physics, **48** 425202 (2015).*
[14]. E.M. Bazelyan, Yu.P. Raizer, Lightning physics and lightning protection'(CRC Press, 2000).

Conclusions

- The spatial structure of discharges formed in an inhomogeneous electric field at different polarities and durations of voltage pulses in air at atmospheric pressure was studied at gap width of up to 4.5 cm.
- At negative polarity of the electrode with a small radius of curvature, spark channels with a bead structure similar to a bead lightning were observed: images taken with a digital camera showed that there are alternating bright and dim regions along spark channel.
- The emission of dim regions was similar to that of a diffuse discharge, and the emission of bright ones was similar to that of a spark discharge. Using a four-channel ICCD camera, it was possible to observe the development of such structures.
- It was found that the formation of the spark channel begins from the region of the electrode spot, which is characterized by a high concentration of ions and electrons as well as a high temperature. However, the channel is formed non-uniform in length. The dim regions follow the bright ones. The results of this work confirm the hypothesis expressed in [8, 9] about the effect of electrons in runaway mode on the formation of inhomogeneities in the lightning channel during its development.

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