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Journal of Atmospheric Science Research
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ARTICLE

On the Formation of a Bead Structure of Spark Channels during a Discharge in Air at Atmospheric Pressure

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ARTICLE INFO

Article history
Received: 6 May 2020
Accepted: 22 May 2020
Published Online: 31 June 2020

Keywords:
Discharge in air
Formation of sparks
Bead structure
ICCD camera
Point-to-plane gap
Bead lightning

ABSTRACT

The conditions for the formation of spark channels with a bead structure in an inhomogeneous electric field at different polarities of voltage pulses are studied. Voltage pulses with an amplitude of up to 150 kV and a rise time of ≈1.5 μs were applied across a 45-mm point-to-plane gap. Under these conditions, spark channels consisting of bright and dim regions (bead structure) were observed. It is shown that when current is limited, an increase in the rise time and the gap length does not affect the formation of the bead structure. It was found that an increase in the amplitude of voltage pulses leads to an increase in the length of beads. The appearance of the bead structure is more likely at negative polarity of the pointed electrode. The formation of spark channels was studied with a four-channel ICCD camera.

1. Introduction

In recent years, interest in studying atmospheric discharges has increased significantly, see, for example, [1–7]. Attempts are also being made to reproduce atmospheric discharges under laboratory conditions [8-20]. This is facilitated by the improvement of equipment for recording fast processes and the development of various models of discharges. Interesting results on the observation of blue jets and red sprites in the upper atmosphere are presented in [1,2,5-7]. So, in [1], images obtained from the international space station are presented. They demonstrate the appearance of blue jets over an area with thunderstorm activity. Images of red sprites observed at altitudes of up to 100 km are given in [2]. Lightning and lightning protection was studied in [3,4].

Bead lightning is one of the rarest and insufficiently studied phenomena [8-10]. In [8], it is noted that many researchers deny the very existence of such types of discharges. However, in recent years, new data on the development of bead lightning under conditions close to nature [11] and on the observation of its analogue in laboratory spark discharges [12-16] were obtained.

In [11], bead lightning was observed in an initiated atmospheric discharge. The discharge was shot at with an exposure time of 1 ms. It was found that at the first stage, an uniform bright channel is observed. Further individ-

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 DOI: https://doi.org/10.30564/jasr.v3i1.1858

ual beads are appeared in the channel. Then, when the brightness of lightning decreased, dim regions between the beads were clearly visible. The length of one bead was about 50 cm under these conditions. After a return stroke, the glow of lightning channel again became uniform and intense.

In [12], bright filaments (unformed spark) in the center of an 18-mm point-to-plane gap filled with air were observed on the background of emission of a diffuse discharge. The amplitude of voltage pulses was ≈200 kV. Such unformed spark channels were observed in pulse-periodic discharges, when nanosecond voltage pulses with amplitudes of 10–15 kV were applied across a 6-mm point-to-plane gap. It was assumed that the discharge observed is similar to bead lightning.

An analogue of bead lightning was also observed in a spark discharge in a gap of several meters in length [13]. At the beginning, loops formed by several thin channels were observed in the discharge channel. The radiation intensity of the loops decreased faster than the intensity of a single channel due to the rapid cooling of the loops. This led to the formation of the bead structure. It was suggested that under natural conditions, there are loops in the lightning channel, and as a result, when lightning fades, the bead structure is observed. Note that X-ray radiation was recorded during such spark discharges [17,18].

The results of our studies, begun in [12], are presented in [14-16]. In new studies, a four-channel ICCD camera was used. In air and nitrogen, spark channels with the bead structure were observed. No loops were observed in [12,14-16], and a diffuse discharge preceded the spark stage. In the prebreakdown stage of these discharges, the current of a runaway electron beam passing through the foil anode was measured. Collective monographs [21-23] are devoted to the study of runaway electron generation in laboratory discharges. In [15,16], the length of a gap did not exceed 8.5 mm, and the rise time of voltage pulses was 200 ns.

This work presents the results of studies of the conditions for the formation of the bead structure during spark discharges in a point-to-plane gap with a length of up to 45 mm. Voltage pulses of both polarities with a rise time of the order of a microsecond were applied across the gap.

2. Experimental Setups and Measurement Technique

Two experimental setups were used. A home-made generator (Figure 1) based on a pulse transformer that produces voltage pulses with an amplitude of up to 200 kV with a step front was used in the first setup.

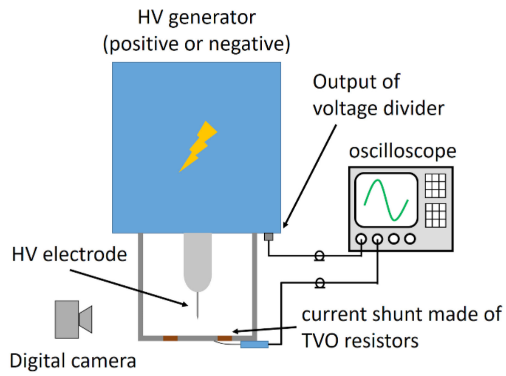

Figure 1. Experimental setup 1

Voltage pulses were applied to a cylindrical conductor with a diameter of 7.5 cm and a length of 14 cm. A 7-cm long electrode (needle or cone) with a small radius of curvature were installed at the end of the cylindrical conductor. A cone electrode had a base diameter of 5 mm, a cone angle of 68°, and a radius of curvature of ≈0.1 mm. The second electrode was made of a needle that had the base diameter of 3 mm, the cone angle of 36°, and the radius of curvature of ≈0.05 mm. Both electrodes were made of a stainless steel. The opposite electrode was flat. It was connected to the grounded case of the generator through a current shunt made of TVO resistors. The interelectrode distance d was 45 mm.

The generator produced pulses of both negative and positive polarity. The rise time of the voltage pulse, which had two steps, was ≈1.5 µs. Waveforms of negative voltage pulses in idle mode and during the formation of a diffuse discharge are shown in Figure 2.

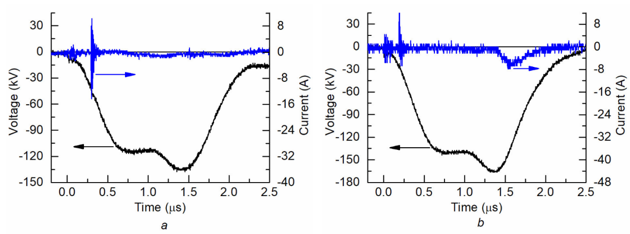

Figure 2. Waveforms of negative voltage pulses in (a) idle mode and (b) during the formation of a diffuse discharge. Setup 1

The amplitude of the voltage pulses varied due to a change in the charging voltage of a capacitor C_1 (65 nF) in a primary circuit of the transformer in the range of 7–10 kV. Voltage was measured using a resistive voltage divider. Signals from the current shunt and the voltage divider were recorded on an TDS-2020 oscilloscope (300 MHz, 5 GS/s).

In the second setup, a high-voltage generator was also home-made-produced. It formed voltage pulses with an amplitude of up to 36 kV and with a rise time of 0.2 µs.

  DOI: https://doi.org/10.30564/jasr.v3i1.1858

In this work, in contrast to the previous ones [15,16], the experiments were carried out not only with negative polarity, but also with positive one. The full width at half maximum (FWHM) of voltage pulses in the idle mode was ≈300 ns, and the rise time was ≈200 ns. The generator was connected to a discharge gap via a 60-cm long coaxial cable with a wave impedance of 75 Ω. A high-voltage electrode was made of a sewing needle. The electrode length, diameter, and curvature radius of the tip were 5 mm, 1 mm, and 75 μm, respectively. The opposite electrode was flat. The interelectrode distance *d* was 8.5 mm. A discharge chamber was equipped with a capacitive voltage divider and a current shunt. When using the mesh anode and collector, it was possible to measure a current of runaway electrons [24]. A collector could be installed instead of the current shunt for measuring the current of runaway electrons that came out of the gap at negative polarity of the high-voltage electrode.

On the setup 2, the dynamics of the development of a discharge was studied using a four-channel ICCD camera. The block diagram of the setup 2 is presented in Figure 3.

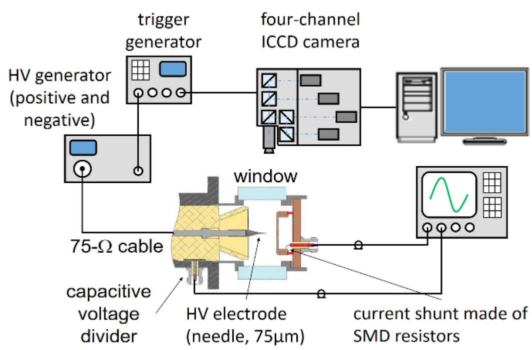

Figure 3. Experimental setup 2

On the setup 2, the current shunt was made of SMD resistors. Unlike TVO resistors, they are more broadband. Signals from the capacitive voltage divider, the current shunt as well as the clock signal from the first channel of the ICCD camera were recorded on the Tektronix TDS3054B oscilloscope. As a result, this made it possible to synchronize the ICCD images with the waveforms of voltage and discharge current.

Gas discharge chambers in all setups were filled with air at a pressure of 100 kPa. The generators operated in a single pulse mode. Images of the discharge plasma emission were taken with a Sony A100 digital camera.

3. Experimental Results

3.1 Setup 1

In contrast to previous studies on discharges with the bead structures [12,14-16], in this study, experiments were carried out at applying microsecond voltage pulses (Figure 2). The gap length was 45 mm instead of 8.5 mm or less in [12,14-16]. Breakdown voltage and discharge form varied from pulse to pulse due to the instability of discharge initiation. This is typical for many types of discharge, including both lightning [2-4] and sparks in meter-long gaps [17-18]. The image of the cone-to-plane gap and the images of a discharge plasma emission in this gap are presented in Figures 4 and 5.

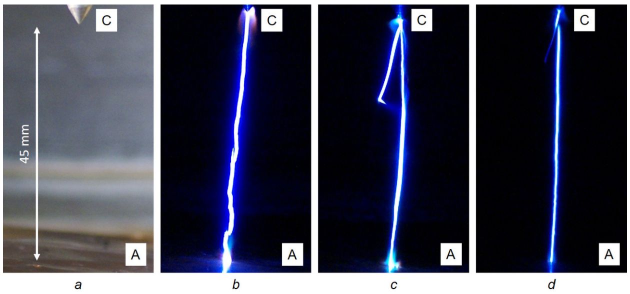

Figure 4. Image of the cone-to-plane gap and images of a discharge plasma emission. Setup 1. Negative polarity

Negative voltage pulses were applied across the gap with *d* = 45 mm. Bends of the spark channel are observed in Figure 4b. Similar bends were described in [25], where nanosecond voltage pulses were applied across a point-to-plane gap. The spark leader, which has not crossed the gap, and the spark channel are observed in Figure 4c. At the same time, the spark leader apparently closed on the spark channel. This area is characterized by a diffuse glow (Figure 4c). A break in the spark channel and diffuse glow are observed in Figure 4d.

The obtained images allow us to make the assumption that the spark leader can transform into a diffuse channel at negative polarity. In general, the formation of a diffuse discharge at atmospheric pressure of various gases is provided by the preionization of the gas by runaway electrons generated in a high electric field [21-24,26].

A zigzag spark channel and a spark channel with a bead structure are observed in Figs 5a and 5b, respectively.

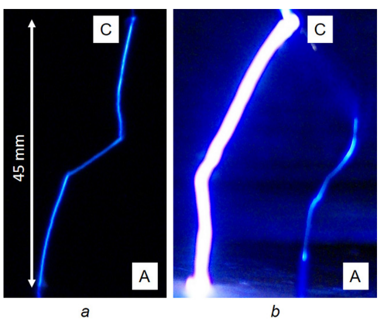

Figure 5. Images of the discharge plasma emission in the cone-to-plane gap. Setup 1. Negative polarity

 DOI: https://doi.org/10.30564/jasr.v3i1.1858

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 were 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.

The image of the needle-to-plane gap with the same *d* and the images of a discharge plasma emission in this gap are presented in Fig 6. A diffuse discharge (Figure 6b) was observed in a number of implementations when the needle electrode was used instead of the conical one. The needle electrode has a larger enhancement of the electric field strength due to the smaller radius of curvature.

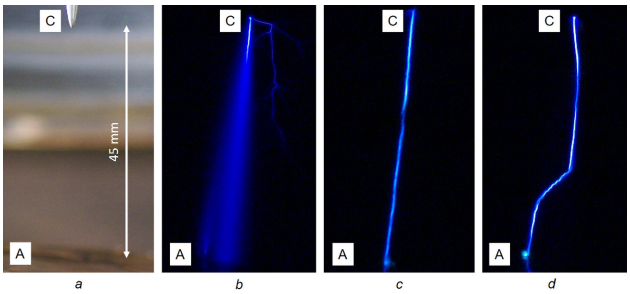

Figure 6. Image of the needle-to-plane gap and images of a discharge plasma emission. Setup 1. Negative polarity

A bright spark leader that did not cross the gap per pulse is observed against the background diffuse emission in Figure 6b. In [12,14–16], 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 1 at breakdown delay times of an order of magnitude more than in [15-16]. 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 [15,16] at breakdown voltages of tens of kV.

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

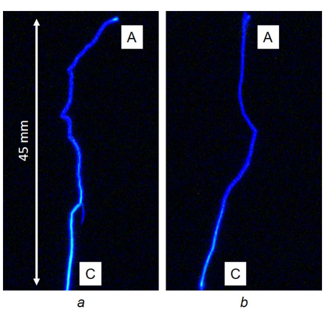

Figure 7. Image of a discharge plasma emission in (a) cone-to-plane and (b) needle-to-plane gaps. Setup 1. Positive polarity

The spark channel at positive polarity of cone or needle electrodes was often single, diffuse and had many bends. The beads could only be observed from the side of the grounded flat electrode. They had less brightness and length. Spark channels 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 [15,16] were observed only at negative polarity of an electrode with a small radius of curvature.

In the experiments, the waveforms of voltage and discharge current were also recorded. The waveforms of voltage and current in idle mode, as well as during diffuse discharge (Figure 6b) are presented in Figure 2. 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 the voltage pulse. In those cases, when a spark discharge with and without bead structure were observed, the breakdown occurred earlier. The waveforms of voltage and discharge current at negative and positive polarities when sparks were observed (Figure 5b and Figure 7a, respectively) are presented in Figure 8.

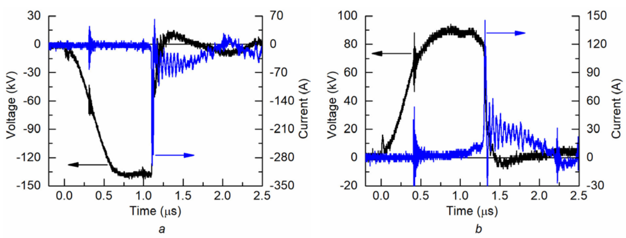

Figure 8. Waveforms of voltage and discharge current at both polarities when sparks are formed. Setup 1

It is seen that the breakdown occurred 1–1.3 μs after applying the 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.

3.2 Setup 2

The development of a discharge with spark channels having a bead structure was studied on setup 2 using the four-channel ICCD camera with a minimum exposure time of 3 ns. Similar studies with negative polarity were carried out in [15,16]. It was shown that in a point-to-plane gap filled with air at a pressure of 100 kPa, a diffuse discharge is first formed, and then a spark channel consisting of separate beads is formed. Channels with the bead structure were observed in each pulse. Their number and length varied from pulse to pulse. No studies were carried

  DOI: https://doi.org/10.30564/jasr.v3i1.1858

out at positive polarity.

Figure 9 shows ICCD images of discharge development as well as corresponding waveforms of voltage and current obtained on setup 2 at negative polarity.

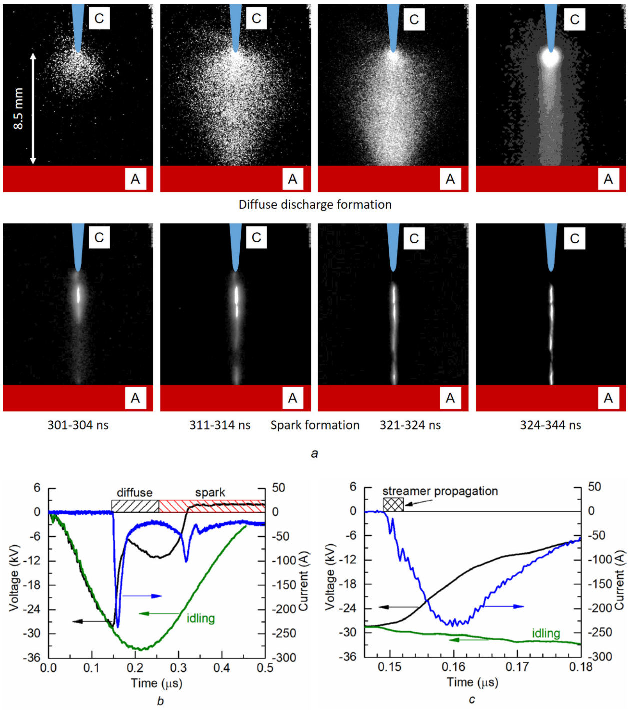

Figure 9. (a) ICCD images of a discharge in the point-to-plane gap filled with air at a pressure of 100 kPa. C – cathode, A – anode. (b, c) Waveforms of voltage and discharge current pulses. Negative polarity. Setup 2

It is seen that at the initial stage a diffuse discharge is formed (Figure 9a). The discharge 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 was switched on before the breakdown. The discharge formation time was determined from the waveforms of current. As shown in our previous paper [27] the formation of a streamer is accompanied by the flow of a current, which we call the dynamic displacement current (DDC). The fact is that the formation of a streamer is accompanied by a redistribution of the electric field strength in 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 easy to find on the waveforms of current. DDC increases sharply when a streamer starts and when it approaches the opposite electrode. These features are clearly distinguishable in Figure 9c, and the corresponding time interval is designated as streamer propagation. Such streamers with a large diameter (Figure 9a) are typical for nanosecond breakdown of point-to-plane gaps [19,27,28].

The spark formation lasted several tens of ns (Figure 9a, spark formation). Under the experimental conditions, the length of beads and their number changed from pulse to pulse. The maximum number of beads reached 8, as in [15,16]. 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.

When polarity was changed to positive, the discharge slightly changed. The corresponding ICCD images and waveforms of voltage and current are presented in Figure 10.

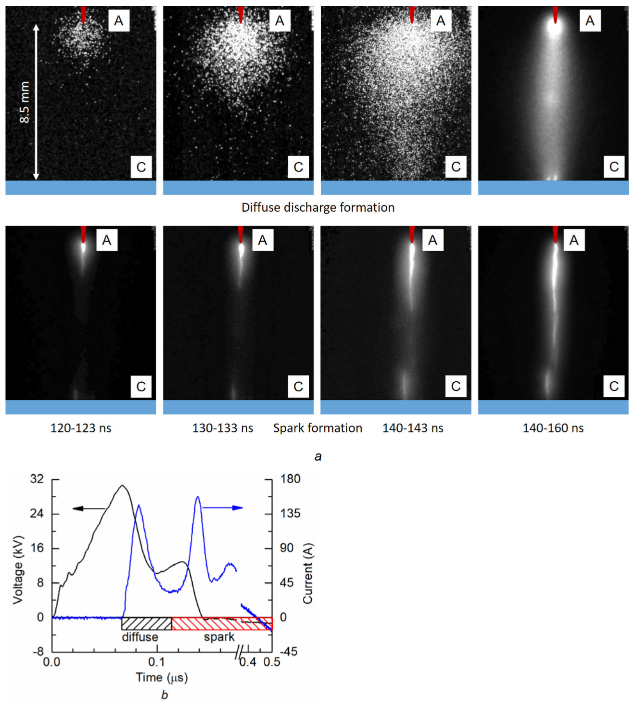

Figure 10. (a) ICCD images of a discharge in the point-to-plane gap filled with air at a pressure of 100 kPa. C – cathode, A – anode. (b, c) Waveforms of voltage and discharge current pulses. Positive polarity. Setup 2

It is seen that at the initial stage a diffuse discharge is also formed (Figure 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.

4. Discussion

The studies showed that an increase in the gap length from 8.5 to 45 mm and an increase in the rise time of voltage pulses from 0.2 µs to 1 µs did not affect the formation of bead structures of spark channels in air at atmospheric pressure in an inhomogeneous electric field. We assume that the bead structure forms due to changes in the electric field strength in the spark leader head that is caused by changes in its size.

It is known (see, for example, [21,26]) that, in air at atmospheric pressure, a diffuse discharge is formed in gaps with an inhomogeneous electric field due to runaway electrons. As was found in [12,14–16] and confirmed in the present work, beads are formed when current decreases in the diffuse stage of the discharge. With a sufficient pulse duration, beads 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 experimental conditions: the length of beads and the distance between them on the setup 1 were greater than on the setup 2.

At the beginning, a diffuse discharge is formed (Figure 6b, Figs 9 and 10) due to the development of a streamer or several streamers (an ionization wave) [19,24,27]. At high overvoltages, the diameter of the streamer can be comparable with the distance between the electrodes [19]. This is common for nanosecond discharges in an inhomogeneous electric field. This is ensured 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 a streamer [28]. As shown in this work, a discharge forms in diffuse form under conditions when microsecond voltage pulses are applied across gaps. 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 [29]. X-ray radiation caused by runaway electrons in lightning was detected experimentally using sensors mounted on an airplane [30].

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 [31] 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. Then, 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 are taking place. In laboratory conditions, a sequence of beads having a weak radiation intensity that do not reach the opposite electrode is often observed [16]. 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 [31].

With sufficient duration and magnitude of 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. In atmospheric discharges, bead lightning is very rare [8]. It is likely that the bead structure of lightning disappears due to return stroke, during which the main current flows [11,31]. We assume that bead lightning can be observed under conditions when several channels develop, as well as at relatively low magnitudes of current.

5. Conclusions

The spatial structure of discharges formed in an inhomogeneous electric field at different polarities and durations of voltage pulses was studied in air at atmospheric pressure 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 bead lightning were observed: images taken with a digital camera showed that there are 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 spark channel is non-uniform. The dim regions follow the bright ones. The results of this work confirm the hypothesis expressed in [15,16] about the effect of electrons in runaway mode on the formation of inhomogeneities in lightning channel during its development.

DOI: https://doi.org/10.30564/jasr.v3i1.1858

Acknowledgments

The work is performed in the framework of the State task for HCEI SB RAS, project #13.1.4.

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  DOI: https://doi.org/10.30564/jasr.v3i1.1858