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## Streamer, plasma diffuse jet and glow discharge during breakdown in low-pressure air by a voltage pulse with a front of ~20 ms

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*Formation of diffuse plasma in tubes with inner diameters of 8.4 and 14.2 cm at voltage growth rate  $V \sim 35$  kV/ $\mu$ s and  $\sim 100$  V/ms is investigated. Photographs of discharge glow in different modes are presented. It is shown that at  $V \sim 100$  V/ms and air pressures  $p$  0.4 and 1 Torr, breakdown of the gap is initiated by streamer propagation from a flat electrode of positive polarity. It is established that after the streamer passes the gap plane – tip and forms a red diffuse plasma jet, a glow discharge is formed, which can be maintained both in pulsed and in stationary mode. It is shown that the greatest radiation power from the discharge plasma under these conditions is given by the streamer front, and the greatest radiation energies of the first and second positive nitrogen systems are achieved by increasing the excitation pulse duration during the transition to the glow discharge mode. It is confirmed that at  $p = 0.4$  and 1 Torr the radiation spectrum of the positive column of the glow discharge corresponds to the radiation spectrum of red columnar sprites.*

*Keywords:* plasma diffuse jet; low-pressure air; collision of two jets; capacitive discharge.

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### Introduction

There are different shapes of high-altitude discharges (red sprites, blue jets, halo, elves and other, for example, see review [1]). The most of publications are devoted to red sprites, which study is conducted from ground-based laboratories [2], planes [3], satellites [4] and International Space Station [5]. However, studying high-altitude discharges require large material costs and expensive equipment. Moreover, although the appearance of red sprites is observed above thunder clouds, they appear spontaneously, and their dimensions, shape and place of appearance always differ. Therefore, experimental and theoretical works where main properties of high-altitude atmospheric discharges, mainly red sprites are conducted. At the same time, the used various discharge modes can be conditionally divided into two

groups. The first group includes the discharges between metal electrodes are used [6–9]. In the second group analogues of red sprites are formed without contact with metal electrodes [10–14].

One of the issues that requires study is the appearance of a bright luminous area (glow) in red columnar sprites [15]. This area appears in the “column” of sprite after a passage of positive streamer starting from “halo” formation in the mesosphere which has an increased concentration of discharges [1, 15]. As the glow area forms, the streamer’s front continues to move down to the thunder clouds and radiation increases. At the same time, the location of glow area practically does not change.

The purpose of this work is to experimentally simulate a bright glow area similar to the one observed in red columnar sprites and analyze the conditions necessary for its appearance. Well-known works did not set

tasks on the experimental simulation of red sprites glow area.

### Setup and measurement method

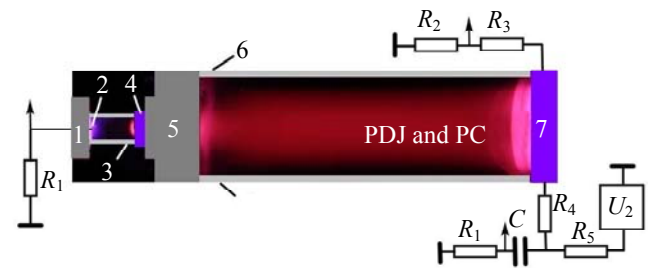
To study the shape and luminosity of the discharge at low air pressure, two setups were used the simplified diagrams of which together with discharge photos are shown in fig. 1 and fig. 2.



**Fig. 1.** Experimental setup diagram No. 1 with an inserted photo of the plasma diffusion jet (PDJ) glow obtained at an air pressure of 0.4 Torr and exposure of 0.25 s. 1 and 6 – capron flanges; 2 – tube made of ESALUX TX polycarbonate with an outer diameter of 15 cm and wall thickness of 4 mm; 3 – grounded electrode made of duraluminum with a hole for quartz tube 4 with an outer diameter of 21 mm and wall thickness 1.5 mm; 5 – external ring electrode made of steel foil with a width of 10 mm;  $U_1$  – pulse generator with a voltage pulse amplitude at a load of  $U = +7$  kV and frequency  $f = 21$  kHz connected to electrodes 3 and 5

Installation No. 1 shown in fig. 1 used a tube made of ESALUX TX polycarbonate with an internal diameter of 14.2 cm which was transparent in the visible spectrum area. Axis tube was located at a distance of 24 cm from the metal plate of experimental bench. Large tube diameter allowed to create plasma diffusion jets (PDJ) far from its inner wall. The tube length was equal to 55 or 147 cm. Plasma diffusion jets were formed from plasma generated by a capacitive discharge limited by one barrier between electrodes 3–5 to which voltage pulses were fed from the  $U_1$  generator. Voltage pulses came with a repetition frequency of 21 kHz with an amplitude of  $\approx 7$  kV in operational mode. Duration of pulses at half height was  $\approx 1.3$   $\mu$ s and their edge and falling edges was  $\approx 0.4$   $\mu$ s. Since the red columnar sprites are initiated by positive streamers [1, 15], voltage pulses of positive polarity were often used during the experiments with which PDJ was initiated by positive streamers [11, 12].

Installation No. 2 shown in fig. 2 used a CU quartz tube with an external diameter of 9 cm.



**Fig. 2.** The diagram of experimental setup No. 2 with an inserted photo of the plasma diffusion jet (PDJ) and positive column (PC) of a glow discharge at air pressure of 0.4 Torr. The photo was obtained at exposure of 3.2 s and the setup was turned on once. In the photo, capron flanges 1 and 5 cover electrode 2 and discharge glow respectively. 1 and 5 – capron flanges with holes; 2 – grounded electrode made of steel with curvature radius of 0.5 mm; 3 – quartz tube with external diameter of 21 mm and wall thickness of 1.5 mm inserted into the through hole of the flange 5; 4 – external ring electrode made of steel foil with a width of 10 mm which covers the discharge glow; 6 – quartz tube made of CU quartz with an external diameter of 9 cm and wall thickness of 3 mm; 7 – high-voltage plane electrode made of duraluminum.  $U_2$  – DC voltage source.  $R_1$  – shunts,  $R_2$  and  $R_3$  – voltage divider,  $R_4$  – resistance to limit the discharge current,  $R_5$  – charging resistor of capacitor C

Axis of tube 6 was located at a distance of 30 cm from the metal plate of experimental bench. Capacitor  $C = 10$  nF which was connected to high-voltage electrode 7 was charged from the constant adjustable voltage source  $U_2$  with positive polarity and amplitude up to 10 kV through resistance  $R_5 = 1$  M $\Omega$ . The second output of capacitor C through metal plate of the experimental bench and shunts  $R_1 = 20$   $\Omega$  were connected to additional electrode 2 installed in the center of flange 1 made of dielectric. Electrode 4 was under floating potential. Break down voltage at its rate of increase of  $\sim 100$  V/ms at electrode 7 was in kilovolt units. It should be noted that fig. 2 uses a photo of discharge in a dark room, so the flanges 1, 5 and electrodes 4 and 7 were originally black. These flanges and electrodes were colored in different colors for better focus. Moreover, it should be kept in mind that electrode 4 and flange 5 cover the discharge glow in holes.

The shape of the voltage pulses was measured using AKTAKOM ACA-6039 divider. The divider resistance was 900 k $\Omega$  (low-

voltage arm) and 900 M $\Omega$  (high-voltage arm). Discharge current was defined using shunts with a resistance of 20  $\Omega$ . Signals from the divider, shunts and PMT were fed to the MDO 3104 oscilloscope (1 GHz, sampling frequency 5 samples/ns). Optical radiation from the discharge plasma was registered with Canon 2000D digital camera and through HR2000+ES spectrometer lightguide (range 200–1150 nm; optical resolution  $\approx 0.9$  nm). Spectrum sensitivity of HR2000+ES and lightguide were known. The radiation pulse shape was determined using a silicone PMT (Si-PM) as part of MicroFC-SMA-10035 module. Rise time of the PMT transfer characteristic was 0.3 ns, the recovery time of cells was 180 ns, The PMT has maximum sensitivity at a wavelength of 420 nm and it gradually decreases in both direction from the maximum, at the same time, at the edges of the range (320–800 nm) the sensitivity was equal to  $\approx 15$  % of the maximum value. 3–5 radiation pulses were recorded during measurement the shape and amplitude of which were repeated with a deviation from average pulse not exceeding 10 %. PMT registered radiation from discharge areas with a width of  $\approx 1$  cm. Center of such areas was in setup No. 2 on its central axis at distances of 2, 12.5 and 27 cm from the left surface of electrode 7. The remaining part of the tube was covered with black screen. Radiation spectra at this setup were determined in the same areas were radiation pulses from PMT were registered. Photographing the discharge, recording radiation pulses using PMT and measuring of spectra was conducted without external lighting. Relative air humidity in the laboratory room was  $\approx 24$  % and the temperature was 23  $^{\circ}\text{C}$ .

## Results and their discussion

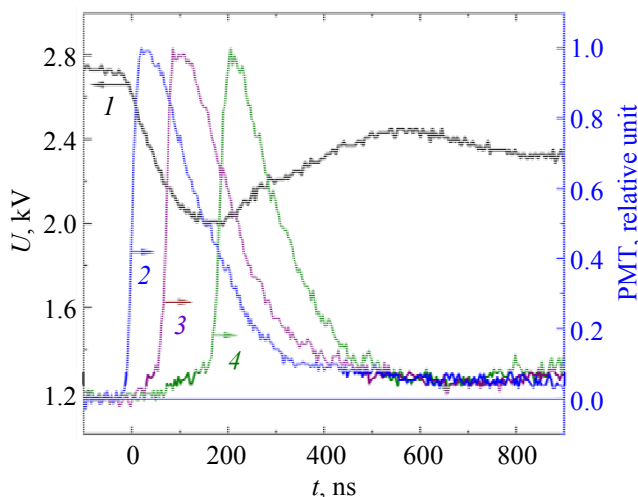
Fig. 1 shows photo of the discharge obtained at atmospheric air pressure of 0.4 Torr and pulse repetition frequency of 21 kHz. It shows the integral glow of 5250 PDJ of red color with blue shade. When increasing the pressure up to 1 Torr, the PDJ glow intensity and its length decreased. PDJs under these conditions appear due to positive or negative streamers the initiation of which was studied in previous works [11, 12]. At low air pressures and voltage pulse from the first generator  $\approx 0.4$   $\mu\text{s}$  (voltage growth

rate of  $\approx 35$  kV/ $\mu\text{s}$ ) streamers were formed due to the creation of dense plasma and quick increase in the reduced electric field strength at its boundary. However, specific density of the PDJ radiation energy to which the streamer front and its afterglow contribute was relatively small. Amplitude of the discharge current and its duration at setup No. 1 were limited due to the dielectric barrier formed by the wall of quartz tube 4. Therefore, for photographing the discharge it was necessary to use the pulse-periodic mode for PDJ generation.

To increase radiation intensity of the discharge in the studied analogs of red columnar sprites, the following scheme was used, see fig. 2. In this scheme, capacitor  $C$  which was connected to electrodes 2 and 7 via resistance  $R_4$  was used to increase the current pulse duration. Moreover, DC voltage source  $U_2$  was also connected to electrode 7 via resistance  $R_5$ . A current pulse with a greater amplitude and duration than when using  $U_1$  generator was formed with the capacitor. Due to the use of  $C$ , two electrodes 2 and 7 without dielectric barriers, as well as source  $U_2$ , it was possible to ignite a glow discharge at setup No. 2 after formation of PDJ both in single pulse and continuous modes. Discharge at setup No. 2 turned into a flowing one with positive column in tube 6. In this mode the discharge radiation energy increased significantly, see photo of the discharge per one pulse in fig. 2. In the area near electrode 2 which is a cathode, the radiation color changed as it should be in case of glowing discharge. Application of resistance  $R_4$ , as well as the optimization of the capacitor  $C$  capacity allowed to exclude the formation of strata in positive column of glowing discharge which was observed in work [13]. An important result obtained at this setup in the single pulse mode was initiation of discharge due to positive streamer at voltage rise rate of  $V \sim 100$  V/ms and its edge of  $\sim 20$   $\mu\text{s}$  and more. At voltage rise rate of 35 kV/ $\mu\text{s}$ , as was established before, see, for example, work [12], streamers are steadily formed and initiate plasma diffusion jet. Proofs of streamer formation from plane electrode at  $V \sim 100$  V/ms are shown in fig. 3.

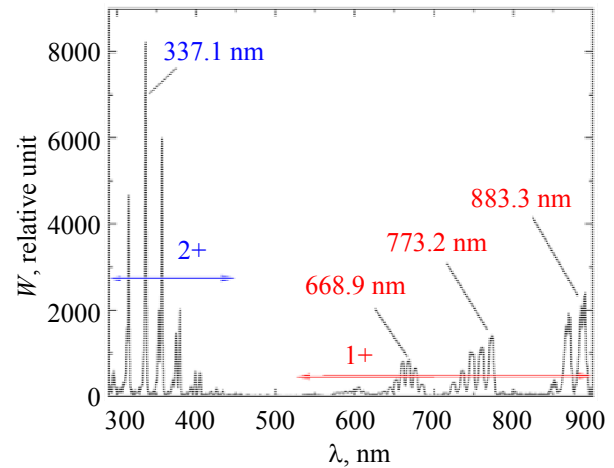
The glow of the streamer edge appeared at electrode 7 (oscillogram 2), then was registered in the central part of tube 6 (oscillogram 3) and then near flange 5 (oscillogram 4). The pulse duration

at half height was  $\sim 100$  ns which complies with measurements in work [12]. The propagation speed of streamer edge was 1.8 mm/ns in the first section from electrode 7 and 1.1 mm/ns in the section of passing the central part of tube 6. Thus, it was established that at low air pressure and low voltage rise rate,  $\sim 20$  ms for oscillogram 1 in fig. 3, discharge initiation occurs due to a positive streamer, which forms a PDJ, which switches to the glow discharge mode. Discharge duration, as well its mode, in this case depend on values  $C$ ,  $R_4$ ,  $R_5$  and air pressure. Change of values  $C$ ,  $R_4$ ,  $R_5$  and voltage of source  $U_2$  allows to change excitation pulse duration and, respectively, radiation pulse duration. Increase of resistance  $R_5$  to 18 M $\Omega$  for setup in fig. 2 resulted in limitation of current from source  $U_2$  and the discharge stops in  $\sim 10$  ms. With a tube with a diameter of 15 cm at setup No. 2 we also registered initiation of breakdown by positive streamer starting from electrode 7.



**Fig. 3.** Oscillograms of voltage pulses  $U$  (1) and streamer radiation from areas at distances 2 (2), 14.5 (3) and 27 cm (4) from the left surface of electrode 7 which had positive polarity.  $C = 10$  nF,  $R_3 = 1$  M $\Omega$ ,  $R_4 = 10$  k $\Omega$ ,  $p = 0.4$  Torr. Setup No. 2. The photo of discharge glow in this mode is given in fig. 2

From a comparison of discharge color in fig. 1 and fig. 2 it can be seen that at the same air pressure, the blue discharge shade disappeared and in the second case the discharge color began to match better the radiation of red columnar sprites, see, for example, photos in figures under No. 1 in works [13, 16]. Radiation spectrum obtained at setup No. 2 with the main contribution of glowing discharge column is shown in figure 4.



**Fig. 4.** Radiation spectrum for the conditions in fig. 3 from the area located at a distance of 14.5 cm from the left electrode 7 surface. Exposure time – 30 seconds

The bands of the second (2+) and first positive (1+) systems of molecular nitrogen provided the main contribution to the radiation spectrum. At the same time, the spectral density of radiation energy of three bands 2+ of nitrogen system was significantly higher than in bands of 1+ system that defined the red color of PDJ. A feature of the studied mode is the absence of bands of the first negative system (1-) of molecular nitrogen ion obtained for the glow area during measurement of red sprite radiation spectra [17]. Moreover, a high intensity of radiation from the 1+ bands of the nitrogen system was recorded in the bands with wavelengths of 869.5 and 888.3 nm in the nearest infrared area of the spectrum. In the modes implemented at setup No. 1 with microsecond voltage pulses durations, as well as in works [11–13, 16], the spectral energy density of these bands is lower than of the bands with the maximum  $W$  at wavelengths of 668.9 and 773.2 nm. It should be noted that a powerful radiation in the infrared area of the spectra [18] was also recorded in the radiation of red sprites.

## Conclusion

The conducted studies have shown that it is necessary to change the discharge mode by introducing an additional energy source to increase the intensity of radiation in the red sprite column. It was conducted in the laboratory experiments by to the connection of the capacitor and increasing the duration of excitation pulse. At the same time, the initial breakdown of low-

pressure air was carried out due to the positive streamer which formed the plasma diffusion jet transforming into the positive glowing jet column. According to our hypothesis, a bright luminous glow area is formed in red columnar sprites due to the negative discharges accumulated at altitudes of 60–70 km above the sea level by the ice particles, see work [19]. These discharges provide an additional contribution of energy to the sprite column radiation after passing through the streamer and forming glow area. Moreover, the passage of

current in this area can be affected by vapors of burnt meteorites from elements with low ionizing potential the impact of which was discussed in work [20].

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