04

Periodic inhomogeneities in the glow of a diffuse plasma jet during a discharge in low-pressure air

© V.F. Tarasenko, V.A. Panarin, V.S. Skakun, N.P. Vinogradov

Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia
E-mail: VFT@loi.hcei.tsc.ru

Received June 25, 2024
Revised August 26, 2024
Accepted August 26, 2024

Experimental data on the inhomogeneous glow of pulsed discharge plasma at air pressures of 0.4 and 1 Torr were obtained. The breakdown was carried out in quartz tubes with internal diameters of 1.8 and 8.4 cm, which were arranged in series. A transition from the regime of plasma diffuse jets (PDJs) with a uniform distribution of radiation intensity to a regime with the formation of a periodic structure has been discovered. It is shown that the second mode is caused by the appearance of additional peaks of microsecond duration on the main voltage and current pulses of the discharge.

Keywords: plasma diffuse jets, low pressure air, periodic radiation structures, analogs of columnar sprites.

DOI: 10.61011/TPL.2025.01.60134.20036

Atmospheric discharges in the stratosphere and the mesosphere are fairly diverse and attract a considerable amount of research attention [1–4]. Column red sprites are the most well-studied at present. However, high-speed photography data from terrestrial laboratories, aircraft, satellites, and the International Space Station revealed that they also have a complex structure [3–5]. It was established that column sprites are normally initiated from the lower part of the halo by streamers directed toward the Earth's surface. The region of the sprite's primary column adjacent to the halo has the greatest radiation intensity. Regions of bright glow (beads) arranged periodically in linear chains are observed in the lower part of streamer channels [5,6]. However, the physical nature of their formation has not yet been established unambiguously.

The aim of the present study is to create red plasma diffuse jets (PDJs), which are miniature equivalents of column red sprites and consist of streamers, with a periodic structure during propagation in air.

Note that reports on miniature equivalents of red sprites [7–10], atmospheric pressure discharges with a bead structure [11,12], and low-pressure glow discharges with striations [13,14] have already been published.

The experimental setup shown in Fig. 1, *a* was constructed for the planned research.

The capacitor capacitance, charging resistance R_3, and the air pressure were varied to probe different glow modes. Dielectric (left) and metal (right) flanges were installed at the ends of tube *6* to fit thin quartz tubes *3*. Capacitor C charged from DC voltage source U through resistance R_3 was used for excitation. The duration of the interval between breakdowns of the gap with electrodes *2–7* could be adjusted from 30 ms to 1 s by varying the capacitor capacitance and (or) R_3 and supply voltage U. The variation of capacitor capacitance, resistances R_3 and R_4, and the pressure also allowed one to alter the duration of the discharge current pulse. Tubes *3* and *6* were filled with air to a pressure of 0.4 or 1 Torr.

The voltage across the discharge gap was measured by an AKTAKOM ACA-6039 divider, and the discharge current was measured by a shunt constructed from TVO resistors. Signals from the shunt and the divider were fed to a Tektronix MDO 3104 oscilloscope (bandwidth: 1 GHz; sample rate: 5 GS/s). The discharge was photographed with a Canon 2000D camera.

Typical oscilloscope records of discharge voltage and current pulses in the pulse-periodic steady-state mode are shown in Fig. 1, *b*. A different breakdown voltage was recorded when source U was switched on for the first time; therefore, the discharge was photographed in the steady-state mode. When the breakdown voltage was reached, a discharge in the form of a PDJ formed in tube *6*, the voltage at electrode *2* decreased, and the discharge current was interrupted. Capacitor C was then charged again, which led to subsequent breakdown between electrodes *2–7*.

The measurement results revealed that PDJs may be produced in tube *6* in a wide range of experimental conditions. With short current pulses ($\sim 50\,\mu$s at the level of 0.1 or shorter), the plasma jet had a uniform glow (Fig. 2, *a*).

The discharge was photographed in the steady-state mode. The repetition rate of discharge current pulses was ~ 40 Hz. The intensity of plasma jet emission and its distribution along the length of tube *6* depended on the capacitance of capacitor C, resistance R_3, the air pressure, and the U source voltage. The breakdown of air was initiated in tube *3* by a single-barrier capacitive discharge between electrodes *2* and *4*, the latter being at a floating potential. Metal electrode *7* was the cathode. Therefore, the glow at electrode *7* was purple (PG). Just as in [8–10], the PDJ was colored red, and its length in tube *6* exceeded

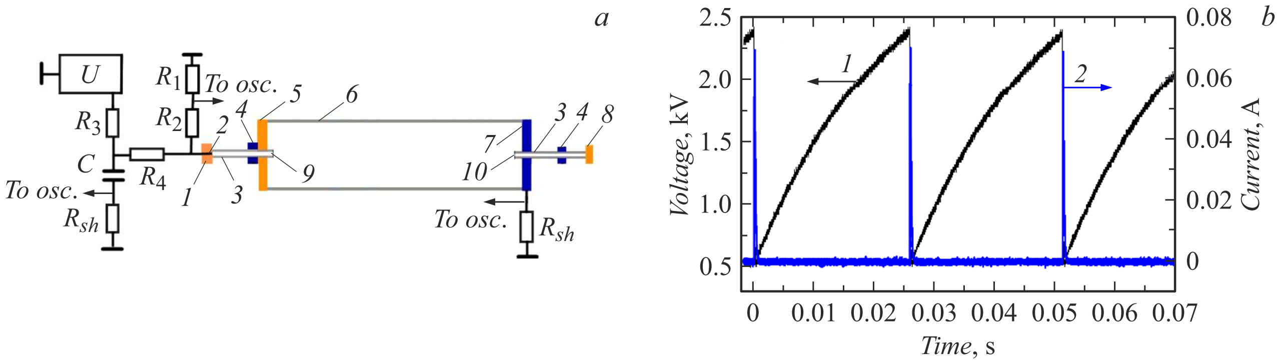

Figure 1. *a* — Diagram of the setup for PDJ generation in low-pressure air with a half-amplitude duration of discharge current pulses varying from 1 μs to 20 ms. *1*, *8* — End flanges made of caprolon; *2* — steel electrode with a small radius of curvature (~ 0.5 mm); *3* — quartz tubes with an internal diameter of 1.8 cm; *4* — 1-cm-wide ring electrodes made of stainless steel; *5* — end flange made of caprolon with an aperture for the first tube *3*; *6* — KU quartz tube 28 cm in length with an internal diameter of 8.4 cm; *7* — end flange made of duralumin with an aperture for the second tube *3*; and *9* and *10* — open ends of quartz tubes *3* that protruded a distance of 1 cm into tube *6*. *U* — Positive-polarity DC voltage source; R_1 and R_2 — voltage divider resistances; R_3 — charging resistance of 1, 18, or 43 MΩ; R_4 — 10 kΩ resistance limiting the discharge current; *C* — capacitor with a capacitance of 10, 65, or 238 nF; and R_{sh} — shunt resistances of 24 Ω. *b* — Oscilloscope records of discharge voltage (*1*) and current (*2*) pulses from the right (relative to the reader) shunt at a capacitor capacitance of 10 nF, $R_3 = 1$ MΩ, and pressure $p = 1$ Torr.

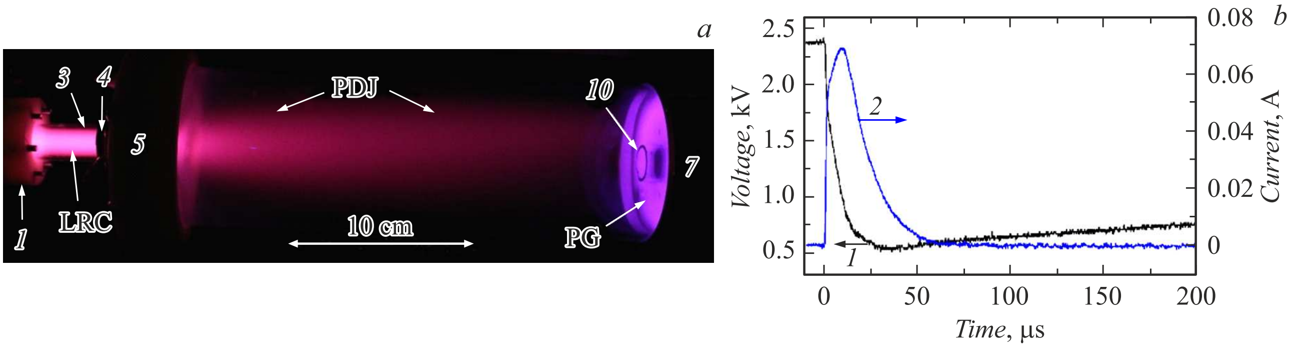

Figure 2. *a* — Photographic image of discharge glow at a capacitor capacitance of 10 nF, $R_3 = 1$ MΩ, and pressure $p = 1$ Torr. Designations *1*, *3*, *4*, *5*, *7*, and *10* are the same as in Fig. 1, *a*. LRC — discharge in tube *3*, PDJ — plasma diffuse jet in tube *6*, and PG — purple glow of discharge plasma near electrode *7*. The frame exposure time is $\Delta t = 0.5$ s. *b* — Oscilloscope records of discharge voltage (*1*) and current (*2*) pulses from the right shunt obtained in the same conditions as in panel *a*.

20 cm. The discharge in thin left tube *3* was also red, but the color was more intense.

Figure 2, *b* presents the oscilloscope records of voltage and current pulses of the discharge from Fig. 2, *a* plotted with a higher time resolution than in Fig. 1, *b*. It is evident that air breakdown occurs when a voltage of ~ 2380 V is reached at electrode *2*. The discharge current amplitude was ~ 66 mA, and its half-amplitude duration was 20 μs. The minimum voltage across the gap at which the discharge current decreased to zero was ~ 550 V; within ~ 26 ms, it increased again to ~ 2380 V (Fig. 1, *b*). This mode was a quasi-steady-state one and persisted for a long time (in the present case, for several minutes at the least). There were no additional short peaks in the oscilloscope records of current and voltage.

Figure 3, *a* shows the photographic image of discharge glow obtained with the duration and amplitude of discharge current pulses increased due to the use of capacitor *C* with a capacitance of 65 nF.

The discharge glow pattern has changed. A periodic structure of bright and dark bands emerged in the PDJ. Short peaks *P* with a duration of $< 1\,\mu$m, which is similar to that of current pulses observed in the formation of streamers in a PDJ [8], were found in the oscilloscope records of discharge current and voltage (Fig. 3, *b*). The length of the time interval between these peaks depended on several parameters (primarily on the discharge current in the main pulse) and was $\sim 30\,\mu$s at the maximum current magnitude. Air breakdown occurred in this mode when a voltage of ~ 3000 V was reached at electrode *2*. The voltage across the gap decreased to ~ 660 V and then increased smoothly to ~ 3000 V within 32 ms. The amplitude of the main discharge current pulse increased to ~ 167 mA, and its FWHM was ~ 0.68 ms. Thus, the photographic

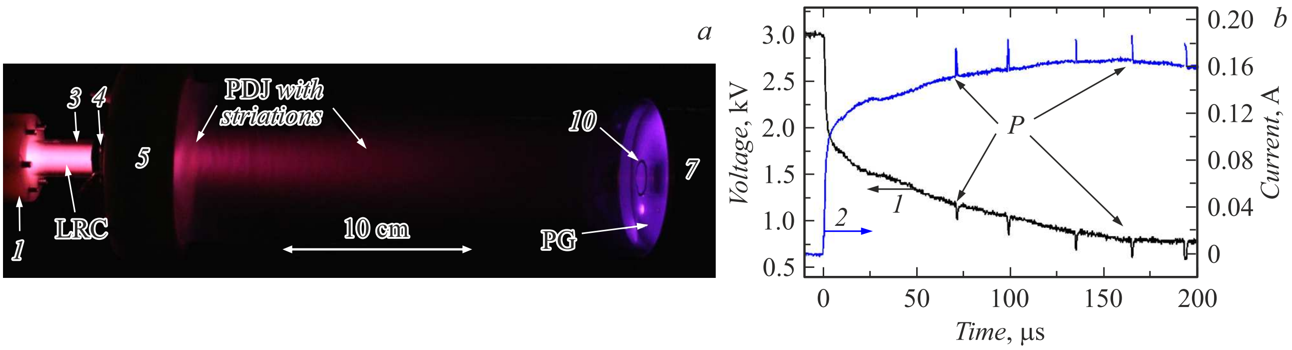

Figure 3. *a* — Photographic image of discharge glow at a capacitor capacitance of 65 nF, $R_3 = 1\,\mathrm{M\Omega}$, and pressure $p = 1$ Torr. Designations *1*, *3*, *4*, *5*, *7*, and *10* are the same as in Fig. 1, *a*. LRC — bright discharge column, PDJ *with striations* — plasma diffuse jet with a periodic glow structure in tube *6*, PG — purple glow of discharge plasma near electrode *7*. $\Delta t = 0.8$ s. *b* — Oscilloscope records of discharge voltage (*1*) and current (*2*) pulses from the right shunt obtained in the same conditions as in panel *a*.

image in Fig. 3, *a* was obtained within three current pulses. The photographic image in Fig. 2, *a* was obtained within 20 current pulses.

As the current in the main pulse decreased, the pause between peaks *P* became several times longer. When the current in the main pulse was reduced to ~ 20 mA, short peaks *P* in the oscilloscope records vanished. They were also lacking at the front of the main current pulse within $\sim 70\,\mu$s of the onset of breakdown (Fig. 3, *b*). This suggests that the emergence of a periodic structure in PDJ glow is associated with the formation of short discharge current peaks on the main pulse. Peaks of current and voltage and the periodic structure in discharge emission were also recorded at a reduced air pressure of 0.4 Torr,. The reason for the increase in breakdown voltage compared to the experiment with a capacitor capacitance of 10 nF (Figs. 1, *b* and 2, *b*) will be investigated in future studies. The breakdown voltage in our experiments depended on a number of parameters. For example, it decreased when the pressure was reduced to 0.4 Torr, but the breakdown voltage obtained with a capacitor capacitance of 65 nF was greater than the one corresponding to 10 nF. When the power supply was switched on, the breakdown voltage of the first pulse was lower than that of the second one (with the rate of voltage rise across the gap remaining unchanged). Therefore, the measurements of electrical parameters and photographic recording of the discharge were performed in the steady-state pulse-periodic mode. The energy input into the discharge with a capacitor capacitance of 65 nF is greater than the one with 10 nF. The repetition rate of current pulses and the shape and duration of voltage decay across the gap differed in these cases.

Having analyzed the conditions of PDJ formation, we found that a periodic structure in discharge glow emerges with an increase in amplitude and duration of the discharge current pulse. When microsecond and nanosecond voltage and current pulses were used, the PDJ glow lacked a periodic structure. However, when two opposite streamers with different front polarities were initiated and collided, isolated bright glow regions were observed even with microsecond voltage pulses [9,10]. We believe that with an increase in duration and amplitude of the discharge current, these experiments established the conditions for formation of subsequent streamers from electrode *2*, which is evidenced by the presence of coincident short peaks of current and voltage. The propagation of secondary streamers and their collision with previous ones led to the emergence of a periodic structure of red glow regions in the PDJ. The presence of bright spots (beads [5]) in propagation of column sprites to the Earth's surface may also be attributed to the formation of secondary streamers and their collision with primary ones.

Thus, the transition from uniform glow of plasma diffuse jets, which are miniature equivalents of column red sprites, to the emergence of a periodic structure in them was observed. It was found that this mode is associated with the emergence of short (with a half-amplitude duration of $< 1\,\mu$s under the examined conditions) peaks, which are apparently induced by the formation of secondary streamers, in the oscilloscope records of current and voltage.

Funding

This study was carried out as part of project No. 24-29-00166 of the Russian Science Foundation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] C.-L. Kuo, T.-Y. Huang, C.-M. Hsu, M. Sato, L.-C. Lee, N.-H. Lin, Atmosphere, **12** (8), 1000 (2021). DOI: 10.3390/atmos12081000

[2] C. Xu, X. Qie, Z. Sun, J. Yang, H. Zhang, A.B.C. Chen, J. Geophys. Res.: Atmospheres, **128** (8), e2022JD037292 (2023). DOI: 10.1029/2022JD037292

[3] A. Jehl, T. Farges, E. Blanc, J. Geophys. Res.: Space Phys., **118** (1), 454 (2013). DOI: 10.1029/2012JA018144
[4] J. Qin, S. Celestin, V.P. Pasko, S.A. Cummer, M.G. McHarg, H.C. Stenbaek-Nielsen, Geophys. Res. Lett., **40** (17), 4777 (2013). DOI: 10.1002/grl.50910
[5] A. Luque, H.C. Stenbaek-Nielsen, M.G. McHarg, R.K. Haaland, J. Geophys. Res.: Space Phys., **121** (3), 2431 (2016). DOI: 10.1002/2015JA022234
[6] R. Marskar, Plasma Sources Sci. Technol., **33** (2), 025024 (2024). DOI: 10.1088/1361-6595/ad29c0
[7] A. Robledo-Martinez, A. Garcia-Villarreal, H. Sobral, J. Geophys. Res.: Space Phys., **122** (1), 948 (2017). DOI: 10.1002/2016JA023519
[8] V.F. Tarasenko, E.K. Baksht, V.A. Panarin, N.P. Vinogradov, Plasma Phys. Rep., **49** (6), 786 (2023). DOI: 10.1134/S1063780X23601736
[9] V.F. Tarasenko, N.P. Vinogradov, E.Kh. Baksht, D.S. Pechenitsyn, Plasma Phys. Rep., **50** (1), 130 (2024). DOI: 10.1134/S1063780X23601736
[10] V.F. Tarasenko, N.P. Vinogradov, E.Kh. Baksht, D.A. Sorokin, D.S. Pechenitsin, Atmos. Oceanic Opt., **37** (4), 547 (2024). DOI: 10.15372/AOO20240405
[11] S.P.A. Vayanganie, V. Cooray, M. Rahman, P. Hettiarachchi, O. Diaz, M. Fernando, Phys. Lett. A, **380** (7-8), 816 (2016). DOI: 10.1016/j.physleta.2015.12.039
[12] D.V. Beloplotov, V.F. Tarasenko, Phys. Lett. A, **383** (4), 351 (2019). DOI: 10.1016/j.physleta.2018.11.004
[13] E. Williams, M. Valente, E. Gerken, R. Golka, in *Sprites, elves and intense lightning discharges* (Springer, Dordrecht, 2006), p. 237–251. DOI: 10.1007/1-4020-4629-4_11
[14] M.M. Tahiyat, J.C. Stephens, V.I. Kolobov, T.I. Farouk, J. Phys. D: Appl. Phys., **55** (8), 085201 (2021). DOI: 10.1088/1361-6463/ac33da

Translated by D.Safin