Ordering of the flame track in the ring mode of the Trichel pulse negative corona discharge

R H Amirov¹, S A Barengolts²,³, E V Korostylev⁴, N V Pestovskii³,⁴, A A Petrov³,⁴, I S Samoylov¹, S Yu Savinov³,⁴
¹ Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya str. 13 Bd.2, Moscow, 125412, Russia
² A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilova str. 38, Moscow, 119991, Russia
³ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninskij Pr. 53, Moscow, 119991, Russia
⁴ Moscow Institute of Physics and Technology (State University), Institutskiy per., 9 Dolgoprudny, Moscow Region, 141700, Russia
E-mail: amirovravil@yahoo.com

Abstract. The ring mode of the Trichel pulse negative corona discharge was studied in atmospheric air. The localization of the discharge flame track in the stable self-organized regular pattern of 3, 4, 5 and 6 – pointed star was found at the cathode surface. This phenomenon was observed at mean currents in the range 100-115 µA at the conditions of the experiment, when the modes with one or two rings are not stable. The conclusion was made that the ring mode of the discharge, which is caused by the symmetrical distribution of the volumetric charges in the conditions of the symmetrical electric field, may be unstable. This instability results in the spatial self-organization of these parameters and causes the organization of the discharge flame track at the cathode surface in the regular patterns.

1. Introduction
Negative corona discharge in the point-to-plane electrode configuration is a classical research object of plasma physics. This is caused by the wide range of technical applications of negative corona, and by the interest of studying of the processes involved in the discharge mechanism, which is currently unclear.

Negative corona discharge in ambient air in the point-to-plane configuration typically operates in the Trichel pulse mode at currents 1-100 µA and in glow mode at 100-200 µA [1]. In the Trichel pulse mode the discharge current is a consequence of pulses with typical amplitude 1 mA, duration at half magnitude 20 ns, pulse time separation 1 µs and width of leading edge 2 ns. Each pulse is caused by propagating ionization wave formed due to accumulation of positive volumetric charges near the cathode surface [2]. The light radiation of the discharge flame is also a consequence of light pulses with duration 10 ns [3]. The diameter of the discharge flame near the cathode surface is ~10 µm at atmospheric pressure and typically is smaller than the cathode pin diameter.

After each current pulse in the Trichel regime the discharge flame is formed at the cathode surface in the most favorable place where the electric field has the maximum value; also this region should have sufficient size (more than 1 µm). Microfields in smaller regions cannot influence sufficiently the
discharge formation and may be responsible only for emission of electrons. The electric field distribution at the cathode surface is determined by the voltage and depends sufficiently on the volumetric and surface charges. Negative corona discharge causes the erosion of the cathode surface with specific erosion rate $10^{-6} – 10^{-4}$ g/coul with formation of micro and nanocraters [4]. Erosion processes in the region of discharge flame localization, formation of microcraters, formation and charging of dielectric layers, recycling of erosion products, accumulation of volumetric charges cause change of electric field distribution and wandering of the discharge flame at the cathode surface [1].

So in the Trichel pulse mode at cathodes with diameter less than 500 µm there are three regimes of the discharge flame dynamics: stable, unstable and stochastic [5]. Stable regime is realized at cathodes with diameter less than 100 µm and weakly susceptible to oxidation. Stable regime is characterized by constant values of Trichel pulse amplitude and pulse time separation. In the stable regime the discharge flame may keep its point of localization at the cathode surface for more than 1 s. Unstable regime is caused by formation of oxide layers at the cathode surface. In this regime the change of discharge position at the cathode surface causes change of Trichel pulse amplitude and pulse time separation. The linear dependence between amplitude and pulse time separation takes place at constant mean current. In unstable regime the discharge flame may be localized in one point of the cathode surface for $10^{-6} – 1$ s. The stochastic regime is observed at cathodes completely covered with oxide layer. In this regime the discharge flame changes its position at the cathode surface after each current pulse. The Trichel pulse parameters may also be changed after each current pulse, there is no any dependence between amplitude and pulse time separation [6].

In the glow mode of discharge a stable cathode layer is formed, and the dynamics of the discharge flame is sufficiently affected by the field of the positive space charges. As result the discharge flame moves smoothly over the cathode surface without frequent jumping from one point to another as occurs in the Trichel pulse mode.

At cathodes with tip diameter more than 500 µm the Trichel pulse negative corona discharge may be realized in the ring mode [7]. In this form the points of the discharge flame localization are distributed at the cathode surface along the coaxial rings. This mode is caused by the accumulation of the volumetric negative charges near the cathode surface in the conditions of symmetry of electric field [8].

In this work, the negative corona discharge is studied in ambient air in the point-to-plane configuration in the Trichel pulse regime in the ring mode. To exclude the action of the surface charges on the flame wandering, graphite cathodes are used.

2. Experimental setup

Negative corona discharge is studied in air at atmospheric pressure in the point-to-plane configuration. Experimental setup scheme is shown in the figure 1. Cathodes used in this work are made of MPG-6 polycrystalline graphite. Graphite cathodes were used to prevent formation of charged dielectric layers at the cathode surface. Also on the graphite cathodes the microstructures are not formed as result of recycling of erosion material [9]. These oxide layers and microstructures may influence the distribution of electric field and wandering of discharge flame. Initially the point has the form of a rod with diameter 1 mm, but in few minutes after the voltage is on, the tip gets a hemispherical shape because of erosion processes [10]. A copper plane with diameter 10 cm was used as anode, the gap was 12 mm. The discharge flame is observed with use of long-focus microscope MBS-9 and camcorder Casio EX-ZR100.

Cathode surface was observed through a 1-mm hole in the anode plane. There was no positive corona on the edges of a hole. The presence of a hole in the anode plane does not influence the discharge regimes and patterns. Discharge current was measured with use of microammeter M-906. Voltage was measured with use of C-196 electrostatic voltmeter. The average current is 10-120 µA, the voltage is 10 – 30 kV. Oscillograms of discharge current were registered with use of 1 MOhm oscillograph Tektronix TDS-410A (bandwidth 200 MHz) witch was connected across a 50-Ohm resistor between the anode and the ground. Air humidity is 50-70 % and does not influence the
discharge. Duration of discharge was 20 – 40 minutes. Typical images (side view) of Trichel pulse corona in unstable regime and in ring mode made with exposition 40 ms are shown in figures 2 and 3 correspondently.

![Diagram of experimental setup](image1)

**Figure 1.** Experimental setup: 1 – cathode pin, 2 – anode plane, 3 – corona discharge, 4 – high voltage supply, 5 – voltmeter, 6 – microammeter, 7 – resistor 50 Ohm, 8 – Oscillograph Tektronix TDS – 410A, 9 – microscope MBS-9 with camcorder Casio ex-zr100.

![Trichel pulse corona in unstable regime](image2)

**Figure 2.** Trichel pulse corona in unstable regime. I = 50 µA.

![Trichel pulse corona in the ring mode](image3)

**Figure 3.** Trichel pulse corona in the ring mode. I = 100 µA.

3. Results and discussion

According to results presented by Loeb [1], the ring mode of the discharge may be observed when the ratio of the gap length to cathode tip radius is h/r < 20. This ratio characterizes the uniformity of the electric field distribution near the cathode surface.

After the voltage is supplied to the electrodes at mean current less than 50 µA, the discharge is realized in the unstable form of Trichel pulses. In this form the discharge flame is localized at the cathode surface is some region for some milliseconds and then it disappears in this place and appears in another one. When the graphite cathodes are used, this behaviour of the discharge flame is explained by the change of the local geometry due to erosion processes, and by accumulation of the negative space charge in the region of the discharge flame localization. When the current reaches the values 50 µA, the discharge falls into the ring mode, which was described by Greenwood in 1951 [7, 8]. The ring mode of the discharge is shown in the figure 4. In this form the regions of the flame localization are distributed along the ring, and the distance between the localization points of the flame of this ring is approximately 50 µm.
The further increase of the voltage follows the increase of the electrical current. This causes the increase of the ring radius. In the ring mode with one ring the Trichel pulses operate in stable regime. When the mean current reaches 100 µA, the self-organization of the discharge flame track appears in form of regular patterns. So at ~100 µA the track is localized along the line which has the form of 3-pointed star (figure 5), at ~105 µA it has the form of 4-pointed star (figure 6), at ~110 µA it has the form of 5-pointed star (figure 7) and at ~115 µA – the form of 6-pointed star (figure 8). The further increase of the voltage and current causes the appearance of the second ring, which is shown in the figure 9. The ring discharge with two rings was reported by Loeb [1]. Trichel pulses in the ring mode at mean current I > 100 µA appear in unstable regime.

The material, the cathode is made from, has some influence on the possibility of formation of the self-organized discharge tracks. So, when the metal cathodes are used, the surface oxidation and charging occurs. Then the dynamics of the discharge flame is governed by the electric field of the surface charges, and the self-organization is difficult to observe. The transition of the discharge into the pulseless mode causes the formation of erosion cells with diameter 60 µm (at atmospheric pressure) on the graphite cathodes [11]. This disturbs the condition of the symmetry of the electric field and makes difficult the self-organization of the discharge track in Trichel regime after reduction of current.

**Figure 4.** The ring mode of the Trichel pulse negative corona discharge. Current I = 60 µA. Voltage U = 13.5 kV.

**Figure 5.** Discharge track at I = 100 µA, U = 16.5 kV.

**Figure 6.** Discharge track at I = 105 µA, U = 16.7 kV.

**Figure 7.** Discharge track at I = 110 µA, U = 17 kV.
4. Conclusions
In this work the ring discharge was studied in the Trichel pulse negative corona in ambient air. To conclude, it was found that the ring mode of the negative corona discharge, which is caused by the peculiarities of the distribution of the negative space charge in the conditions of the symmetry of the electric field, may be unstable. This instability is caused by the self-organization of distribution of the volumetric charges near the cathode surface and causes the organization of the discharge flame track at the cathode surface. The track has the stable form of regular three, four, five and six-pointed stars. The observation of these self-organized structures in the ring mode of Trichel pulse corona is reported in this paper for the first time.

Acknowledgments
The work was made under financial support of the Russian Science Foundation, grant 14-12-00784. One of authors (AAP) would like to thank Dr. Evgenii Anokhin from MIPT for useful discussion of this work.

References
[1] Loeb L B 1965 Electrical Coronas. Their Basic Physical Mechanisms. (Berkeley, CA: Univ. California Press)
[2] Hoder T, Cernak M, Paillol J, Loffhagen D, and Brandenburg R 2012 Phys. Rev. E 86 055401(R)
[3] Amin M R 1954 J. Appl. Phys. 25 627
[4] Petrov A A, Amirov R H, Samoylov I S 2009 IEEE – Transactions on Plasma Sciences 37 1146
[5] Amirov R H, Petrov A A, Samoylov I S 2009 Int. J. of Plasma Environmental Science and Technology 3 35
[6] Brunt R J, Kulkarni S V 1990 Phys. Rev. A. 42 4908
[7] Greenwood A 1951 Nature 167 41
[8] Greenwood A 1952 J. of Appl. Physics 23 1316
[9] Petrov A A, Amirov R H, Asinovskii E I, Samoylov I S 2009 J. Plasma Fusion Res. Ser. 8 780
[10] Asinovskii E I, Petrov A A and Samoylov I S 2007 JETP Letters 86 302
[11] Petrov A A et al. 2014 XXIX International Conference on Equations of State for Matter 183