# FINAL STAGE OF CATHODE DIRECTED STREAMER PROPAGATION

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The numerical simulations of the cathode directed streamer propagation in the atmospheric air at the constant voltage applied to the discharge gap are carried out. It is found an explanation of the streamer stopping possibility at the given distance from electrodes achieved in experiment. For the streamers, which cross the gap, it is obtained the transverse ionization wave propagation, which gives a contribution to the second maximum of the total current time dependence.

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## INTRODUCTION

At the constant applied voltage, the positive corona in atmospheric air usually operates in pulse mode, through the cathode directed streamers. Experiments show that in positive corona the energy expense on one ozone molecule forming is less than in negative corona. Positive streamer propagation is widely studied [1] and its study is continued [2, 3]. In the present work, a final stage of streamer propagation is studied.

Dependently on the discharge parameters, the streamer can either cross the gap between electrodes or stop somewhere in the gap. Experiments show that in the first case there are two peaks in the total current time dependence, whereas in the second case there is one peak.

The streamer stopping in the gap far from electrodes itself at first sight seems surprising phenomenon. Indeed, if an ionization zone ahead of streamer has moved sufficiently far from the needle anode after the beginning of streamer propagation, but it has not come to a very short distance on the plane cathode, then some further streamer propagation does not change considerably the electric field in the ionization zone. And it may be supposed that all streamers, which have passed the considerable part of the gap, will come to cathode. But in the experiments, the ability is demonstrated to stop the streamer in any position, not very near to electrodes.

To find out the causes of phenomena observed when a streamer stops in the gap or comes to cathode, the numerical simulations were carried out. In the calculations, there were taken into account drift and diffusion of electrons and ions, positive and negative, and the reactions of ionization, recombination, ion-ion and electron-ion, and attachment. The equations and some details of calculations are given in [4]. For the source of electrons necessary to begin the avalanches, it was taken electron emission from cathode under different assumption about photon distribution. Namely, it was uniform over cathode, or it was formed by flow without absorption parallel to the axial symmetry axis, or by spherically symmetric flow with absorption.

## 1. STREAMER STOPPING IN THE GAP

As one of the causes of the streamer stopping in the discharge gap with a needle anode (together with the field non-uniformity), it is sometimes proposed the streamer channel conductivity decrease through electron attachment. But in [5], there is detailed substantiation of formal possibility of the stationary streamer propagation in the unbounded space with an attaching gas and uniform external field. The characteristic length of the well conducting part of such streamer is determined with the product of the streamer velocity and the characteristic time of a free electron motion before the attachment. Farther from the streamer head, the streamer channel is filled with the positive and negative ions, which density decrease with time through recombination. But all streamer characteristics in the frame of reference moving together with such streamer and the streamer propagation velocity are constant. In the real bounded discharge gap with non-uniform field, the intensive attachment to a certain extent may to promote the streamer stopping through the conductivity decrease in the space near the needle anode. The field strengthening here (caused by the decrease of the medium conductivity and the ability to screen the field) leads to the potential drop increase on the streamer channel and to its decrease on the rest part of the gap, and so, to the field weakening in the ionization zone. But if such potential redistribution takes place at the stage of the streamer propagation when the distances from the ionization zone to anode and cathode are the values of the same order then the tendencies, in the ionization zone, to the field weakening (due to the conductivity decrease) and strengthening (due to the streamer movement to cathode) are the factors of the same order, and so, the streamer channel conductivity decrease caused by electron attachment hardly may be decisive circumstance for the streamer stopping far from electrodes.

One of the possible causes of such stopping is suggested by the following experimental fact: it is comparatively easy to stop the streamer in the given point of the gap by the decrease of the applied voltage from the values, at which the pulsed mode of discharge with the streamers crossing all gap had been already stated, whereas the increase of voltage from the small values at once gives the streamers, which cross the whole gap. So, it is natural to pay attention to the different conditions of the propagation of the first and next streamers.

Before the first streamer start the distribution of free electrons and negative ions in the discharge gap is determined by external sources. If the sources are uniform then in the gas with low intensity of attachment the distribution of free electrons is near to linear one and

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the value of electron density near cathode is very small (in connection with electron drift), whereas in the gas with high intensity of attachment the similar distribution is characteristic for the negative ions.

The next streamers are propagating in the gas with the particles, formed by the previous streamers. There are exited particles and negative ions, which may be ionized due to interaction with other exited particles or by photons or electrons having comparatively small energy. In the time intervals between streamers, the drift and recombination make the negative ion distribution in the gap non-homogeneous along the field direction. Nearer to anode the negative ion density is greater, and here, the more favorable conditions for the streamer propagation are formed. At such distance from anode, where the negative ion density is too small, so that relevant source of free electrons is too week, the streamer stops. The dependence of the quasi-stationary streamer propagation velocity on the average field strength for the different background electron density is shown in the Fig. 1. Streamers cannot propagate with too small velocity.

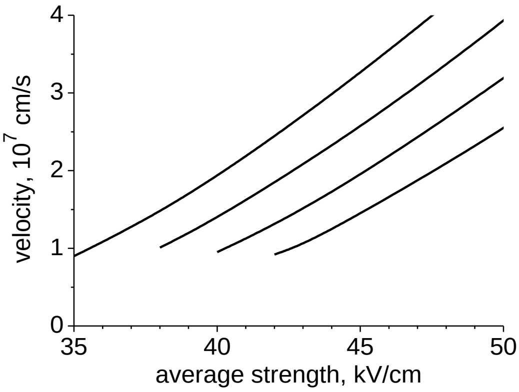


*Fig. 1. Quasi-stationary streamer propagation velocity for the different background electron density ($10^3 \ldots 10^6$ $cm^{-3}$, from right to left)*

For the streamer, propagating in the bounded gap, the electric field strength in ionization zone has a tendency to increase, as the charge of the streamer head is gathered with aid of charge displacement on the increased streamer length. But the transverse streamer dimension is not fixed. The approximately determined quantity is the electric field strength value in ionization zone. It is determined with the characteristic type of the dependence of the ionization coefficient on the field strength. Namely, the strength in ionization zone approximately corresponds to such values, the decrease from which leads to considerable decrease of ionization coefficient, whereas increase from which leads to only small ionization coefficient increase. And the value of transverse streamer dimension, for the given potential of the streamer head with respect to cathode, should give the required field strength value in ionization zone. As a result, with the increase of the streamer length at the beginning of its propagation, the transverse streamer dimension increases, with approximately constant values of the field strength and the densities of electron current, leading to the increase both the displacement current and the conductance current. The streamer stopping gives the decrease of the total current for a few orders. The total current time dependence for the streamers stopping in the discharge gap far from electrodes has one maximum.

## 2. STREAMER STOPPING NEAR CATHODE

If the voltage applied to the gap is sufficiently large then the pulsed mode of positive corona takes a form of streamers, which cross the whole gap. The streamer approach to cathode is accompanied with increase of the field strength in ionization zone and with intensification of impact ionization and radiation of photons able to cause ionization in gas or electron emission from cathode. The conductivity and displacement currents considerably increase. But subsequent movement of the streamer head to cathode leads to decrease of dimension of ionization zone. Though this decrease is accompanied with the field strengthening, the local intensity of photon radiation and electron multiplication almost does not enhance, as relevant coefficients for radiation and ionization are almost independent on the field strength at such strength level. So, the total rate of ionization decreases, leading to the conductivity current decrease. Also, due to ionization and the charged particle drift, in the space very near to cathode, the density of positive ions non-compensated by electrons is increased, enhancing the tendency to the potential redistribution, accompanied with some decrease of the rate of near-cathode field strengthening, and so, with the displacement current decrease.

The described processes give maximum in the total current time dependence. But after the total current decrease, its new increase takes place. It is connected with the going out of large amount of positive ions to cathode and with transverse ionization wave propagation over the cathode surface. Usually, the number of electrons knocked out from cathode by photons generated in gap by one electron is much less than the number of ionization acts made by the same electron. Also, the ion-electron emission coefficient is usually small. As a result, the total positive charge going out to cathode is only slightly less than the total negative charge going out to anode. Positive ion distribution formed by avalanches near cathode is characterized by so small distance of density doubling, that the ion going out may give nanosecond time of the total current doubling.

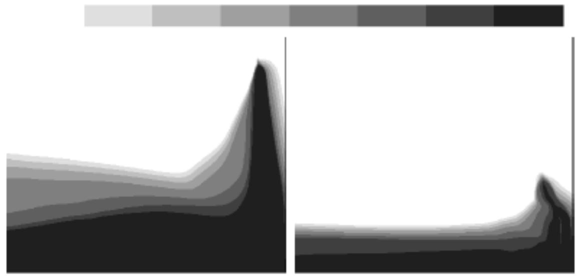

*Fig. 2. Electron density distribution in the near-cathode space at the time near maximum of total current for the different variants of photoemission (in the text)*

Further positive ion density increase in the space very near to cathode leads to further potential redistribution with the field strengthening in the streamer channel, field weakening near cathode, and with end of the transverse ionization wave propagation (as potential values in the different points of the near-cathode space become approximately equal to one at cathode). The electron density distribution in the near-cathode space at the time near maximum of total current is shown in the Fig. 2 for the cases of photoemission based on the photons non-absorbing in gas with uniform distribution over cathode (left) and on the photons with absorption length 10 μm (right); the right boundaries are cathodes, the horizontal pictures dimensions are 0.5 mm, the color range (at the top, from white to black) corresponds to $(10^8…10^{16})$ $cm^{-3}$ (in logarithmic scale, with taking the color for the nearest lesser value). Having passed the second maximum, the total current begins to decrease.

Positive ions go out comparatively quickly from the space, where the field strength is large. In the case when the ionization intensity is not sufficient to keep the positive ion number in the gap, the boundary of quasi-neutral plasma is moving from cathode. Electrons and negative ions also go out from the gap, but the field near anode remains sufficiently strong for intensive ionization. An accidental ionization enhancement here leads to weakening of the field and ionization intensity, and this end of the streamer channel stays near anode. Through recombination and attachment, the channel conductivity decreases and the potential drop on the channel increases. So, at this stage, the field near the cathode end of the channel is weaker than one at the stage of streamer propagation, and it is not sufficient to renew the propagation. The channel destruction or the considerable decrease of its conductivity gives the possibility for the near-anode ionization to form the space charge, sufficient for new streamer development.

In the other case (for the sufficiently large applied voltage), when the ionization process is quasi-stationary, the gas heating usually leads to the spark formation.

## CONCLUSIONS

In positive corona the cathode-directed streamers may cross the discharge gap or stop in it. The possibility of the streamer stopping at the given (not too small) distance from cathode is connected with the presence of negative ions and exited particles, which have remained after the previous streamers and play a role of additional source of electrons on the way of new streamer. The streamer stopping here is connected with the considerable decrease of negative ion density nearer to cathode.

When the streamer crosses the whole gap, there are two maximums of the total current. The first maximum is connected with the stopping of ionization wave. The second maximum is connected with the positive ion going out of the gap and with the ionization wave over the cathode surface. The characteristics of this wave are dependent on the intensity of electron emission from cathode. The time of its propagation is bounded with the time of the considerable increase of the positive ion density near cathode, which leads to essential potential redistribution.

## REFERENCES


1. Yu.P. Raizer. *Gas discharge physics*. Springer: “Verlag”. 1991.
2. O.V. Bolotov, V.I. Golota, B.B. Kadolin, et al. Similarity laws for cathode-directed streamers in gaps with an inhomogeneous field at elevated air pressure // *Plasma Physics Reports*. 2010, v. 36, № 11, p. 1000-1011.
3. O.V. Manuilenko, V.I. Golota. Computer simulation of positive streamer dynamics in strongly non-uniform electric fields in air. Effect of applied voltage on a streamer velocity for different needle radii // *Problems of Atomic Science and Technology. Series “Plasma Physics” (20).* 2014, № 6(94), p. 187-190.
4. O. Bolotov, B. Kadolin, S. Mankovskyi, et al. Quasi-stationary streamer propagation // *Problems of Atomic Science and Technology. Series ”Plasma Electronics and New Methods of Acceleration” (9).* 2015, № 4, p. 185-188.
5. M.I. Dyakonov, V.Yu. Kachorovsky. Stationary propagation of streamers in electronegative gases // *Sov. Phys. JETP*. 1990, v. 71, № 3, p. 498-505.


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### КОНЕЧНАЯ СТАДИЯ РАСПРОСТРАНЕНИЯ КАТОДОНАПРАВЛЕННОГО СТРИМЕРА

***О. Болотов, Б. Кадолин, С. Маньковский, В. Остроушко, И. Пащенко, Г. Таран, Л. Завада***

Выполнено численное моделирование катодонаправленного стримера в атмосферном воздухе при постоянном напряжении, приложенном к разрядному промежутку. Найдено пояснение возможности останавливать стример на данном расстоянии от электродов, достигнутой в эксперименте. Для стримеров, которые пересекают промежуток, получено поперечное распространение волны ионизации, которое даёт вклад во второй максимум зависимости полного тока от времени.

### КІНЦЕВА СТАДІЯ ПОШИРЕННЯ КАТОДОСПРЯМОВАНОГО СТРИМЕРА

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Виконане числове моделювання катодоспрямованого стримера в атмосферному повітрі при постійній напрузі, докладеній до розрядного проміжку. Знайдене пояснення можливості зупиняти стример на даній відстані від електродів, досягнутої у експерименті. Для стримерів, які перетинають проміжок, отримане поперечне поширення хвилі іонізації, яке дає внесок у другий максимум залежності повного струму від часу.