

Modeling of negative streamer propagation in a weak uniform electric field

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The results of numerical simulations of negative streamers in air at atmospheric pressure in a weak and uniform electric field are presented. Streamer development was considered between a protrusion on a plane cathode and a plane anode separated by a distance of 3.3 cm. The region with an enhanced field near the protrusion tip, where streamer inception took place, was ~0.3 cm long and the propagation region with a uniform background field covered ~3 cm of the gap length. The parameters of the streamers were studied for different magnitudes of the background field strength: 5, 6, 7 and 8 kV/cm at constant magnitude of the field strength at the tip of the protrusion aiming to determine minimal field required for stable propagation. Internal and integral characteristics of streamers developing in different background fields are discussed and analyzed.

1. Introduction

Electrical discharges in high-pressure gases are usually associated with formation and development of filamentary plasma channels (streamers), which propagate in an ambient neutral gas. A streamer is a self-adjusting object. Since it has been formed, it produces charged particles in a high field region at the front, needed to maintain high plasma conductivity in the channel. In its turn, the electric field at streamer tip is controlled by the produced space charge. This property allows streamers to develop in weak fields, much lower than the ionization threshold of the gas. However, there is a minimum background electric field strength E_{\min} , so-called stability field, required to support stable streamer propagation (*i.e.* with constant velocity). For cathode directed (positive) streamers in air it is $E_{\min} \approx 5 \text{ kV/cm}$. This value was found in experiments [1] and was confirmed by numerical simulations for short (~0.6 cm) [2] and for intermediate (~3 cm) [3] streamers. For long channels (of order of tens of cm) the magnitude of ~8.5 kV/cm was obtained in [4]. Data regarding negative streamer stability field in air are very rare and ambiguous. One could refer to [5], where the range of 8-16 kV/cm was mentioned on the basis of available experimental data, and to the results of modeling [2], from where the values of 10-15 kV/cm could be found for short streamers.

In the present paper results of computer simulations of negative streamers in air in weak uniform fields are presented. The parametric study was performed in order to determine the minimal field strength required for a stable propagation. The conditions for simulations were similar to ones used in [3]. Streamer advancement was considered between two plane cylindrical electrodes, which provided a uniform background field E_0 . A thin protrusion was introduced on the cathode surface in order to create a region with locally strong field needed to trigger the streamer discharge. The gap length was 3.3 cm. The field strength at the tip of the protrusion was approximately 200 kV/cm and fell down to a constant value of E_0 a few millimeters from the tip.

Thus, the streamer propagated ~ 3 cm in a weak and uniform background field after the initiation in the region of enhanced field near the cathode.

2. The model

In this study, a quasi two-dimensional model of the streamer known as 1.5-D model was used. The streamer was considered as a cylindrical channel of fixed radius $R_c = 200 \mu\text{m}$. It was supposed that the charge was distributed uniformly over the cross section of the channel. The ionic diffusion was not taken into account, as it does not play significant role in the time scale of streamer propagation. The system of continuity equations for densities of electrons, positive and negative ions (n_e , n_p and n_n respectively) was as:

$$\begin{aligned} \frac{\partial n_e}{\partial t} + \text{div} (n_e \vec{w}_e + D_e \nabla n_e) &= K_e \\ \frac{\partial n_p}{\partial t} + \text{div} (n_p \vec{w}_p) &= K_p \\ \frac{\partial n_n}{\partial t} + \text{div} (n_n \vec{w}_n) &= K_n \end{aligned} \quad (1)$$

Here, t is the time; w_e, p, n are the drift velocities of electrons, positive ions and negative ions respectively; D_e is the diffusion coefficient for electrons; K_e, p, n are the rates of production and losses of electrons, positive and negative ions respectively. The rates of the following processes were taken into account: collision ionization by electrons, two- and three-body attachment of electrons to oxygen molecules, electron-ion and ion-ion recombination, photoionisation. All coefficients in the equations (1) are functions of the local electric field strength, which was obtained from the solution of Poisson's equation (cylindrical co-ordinate system):

$$\frac{\partial^2 \varphi}{\partial z^2} + \frac{\partial^2 \varphi}{\partial r^2} + \frac{1}{r} \frac{\partial \varphi}{\partial r} = -R(z, r), \quad (2)$$

where $\varphi(z, r)$ is the potential; z is the axial co-ordinate, with its origin at the anode surface, directed along the symmetry axis of the electrode gap; r is the radial

co-ordinate ($r = 0$ on the symmetry axis); $R(z, r)$ is the space charge density, $R = e(n_p - n_e - n_n) / \epsilon_0$ (e is the elementary charge and ϵ_0 is the dielectric constant). The axial and radial components of the electric field strength $E(z, r)$ were found as derivatives of the potential along corresponding directions. The details about the choice of coefficients and rate constants, boundary and initial conditions, methods for solving equations (1) - (2) and procedure of calculating integral streamer parameters can be found in [3].

3. Results of simulations

Computed temporal variations of distributions of electron density along the streamer channel developing in different background fields are shown in Fig. 1. As it can be seen, streamer inception takes place in the high field region ($z > 3$ cm), where the electron densities reach $\sim 10^{14}$ cm $^{-3}$. Different behavior is observed when plasma front is approaching the weak field region. If the background field is lower than 7 kV/cm, streamer termination takes place in the middle of the gap and the length of the channel is ~ 1.9 cm and 2.9 cm for $E_0 = 5$ and 6 kV/cm respectively. The streamer is able to cross the gap in the background field $E_0 = 7$ kV/cm, however the electron density is decreasing with time. The density is kept constant if the field strength is equal to 8 kV/cm. In this case losses of electrons in plasma are compensated by the high rate of their production, which is dependent on the local electric field strength at the streamer front. One can see in Fig. 2 that this field is rapidly decreasing when streamer termination is observed (upper graphs) because the density of space charge produced at the channel front is not high enough. However, for $E_0 = 8$ kV/cm the electric field associated with the streamer head is ~ 200 kV/cm and almost constant during propagation. Similar behavior was obtained for positive streamers [3] with the peak field strength ~ 170 kV/cm. Constant field strength at plasma

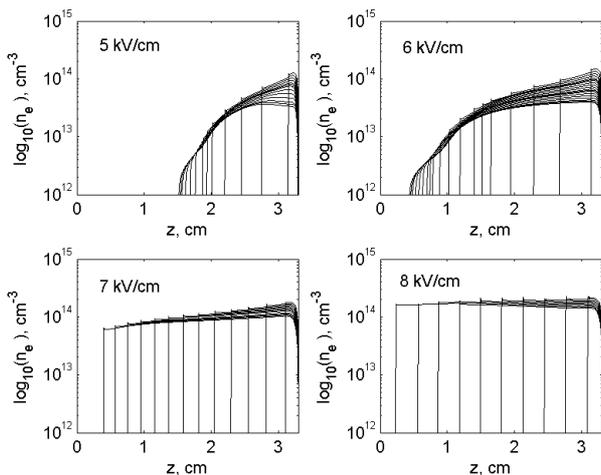


Fig.1. Electron density profiles for streamers propagating in different background fields E_0 (indicated on the graphs). Time difference between the profiles on the upper graphs is 2 ns, on the lower graphs - 1 ns. The cathode is located at $z = 3.3$ cm.

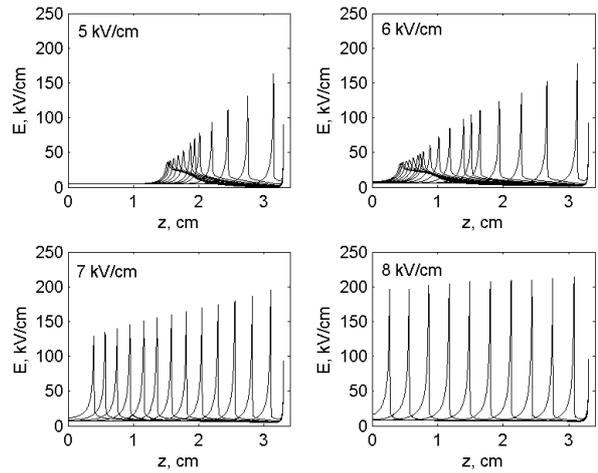


Fig. 2. Electric field distributions along the streamer channel in different background fields. Time moments correspond to Fig. 1.

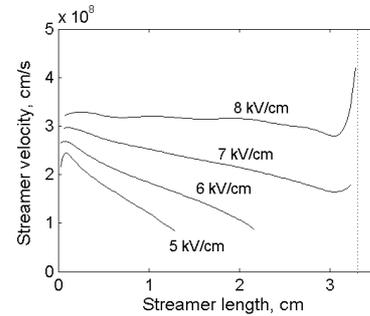


Fig. 3. Streamer velocity in different background fields.

front causes its steady advancement with the velocity $\sim 3.2 \cdot 10^8$ cm/s (Fig. 3), which is 2 times higher than the velocity of a positive streamer in its stability field of 5 kV/cm [3]. Acceleration is observed at the very late stage when streamer head approaches the anode surface. For the background fields $E_0 = 5, 6,$ and 7 kV/cm, the velocity decreases linearly with channel length and a termination takes place if it is less than $\sim 7 \cdot 10^7$ cm/s.

4. Conclusion

The numerical simulations of negative streamers in air in weak uniform fields have shown that the minimum field strength required for stable propagation is 8 kV/cm. The computed magnitudes of the field strength at the streamer front and streamer velocity were higher than corresponding values for a stable positive streamer.

5. References

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