Streamer discharge inception in a sub-breakdown electric field from a dielectric body with a frequency dependent dielectric permittivity

Anna Dubinova[1], Casper Rutjes[1], Ute Ebert[1,2]

[1] Centrum Wiskunde & Informatica, Science Park 123, 1098XG Amsterdam, Netherlands
Phone +31205924208 E-mail: a.dubinova@cwi.nl
[2] Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Netherlands

We study positive streamer inception from the tip of an elongated ice particle. The dielectric permittivity of ice drops from 93 to 3 for electric fields changing on the millisecond timescale [1]. We demonstrate that this effect can be important on the nanosecond time scale of streamer discharge development. The effect makes the streamer propagate with only half the velocity it would have for the dielectric permittivity fixed to 93.

1. Introduction

It is well known that dielectrics are polarized by an external electric field; and this polarization is characterized by their dielectric permittivity. However, if the electric field changes fast enough, the dipoles inside the dielectrics cannot follow these changes and their dielectric permittivity drops, eventually to 1 for electric fields that change infinitely fast.

It is also known that the characteristic time scale of streamer discharge development is nanoseconds. On such a short time scale many dielectrics respond to a changing electric field with a smaller dielectric permittivity than to a time independent electric field.

The effect of the frequency dependent dielectric permittivity can be important for example for inception of streamer discharges from ice particles in thunderclouds [2]. Unlike ice, the dielectric permittivity of water changes on sub-nanosecond time scale which can be important for discharges developing in water in electric fields with sub-nanosecond rise-time. Other examples are dielectric barrier discharges or plasma jets, where the dielectric properties of the setup determine the dynamics of the discharge.

2. Model

We simulate the inception of a positive streamer discharge in a sub-breakdown electric field ($0.15E_b$, where E_b is the classical breakdown field) from the tip of a dielectric ellipsoid made of ice, which measures 0.7 cm by 6.0 cm in diameter. The streamer develops in air at 5.5 km altitude with number density $N = 0.6N_0$, where N_0 is the number density of air at STP. We chose these parameters to explain lightning inception from ice particles in thunderclouds [2].

At the tip of the dielectric ellipsoid the external electric field is enhanced to 4 times the breakdown field. However, the field decreases rapidly ahead of the tip of the dielectric, and the area of field enhancement is small. Therefore, the dielectric has to be sufficiently large to allow for a sufficient number of electron multiplications in the area of the enhanced field. Once a streamer starts

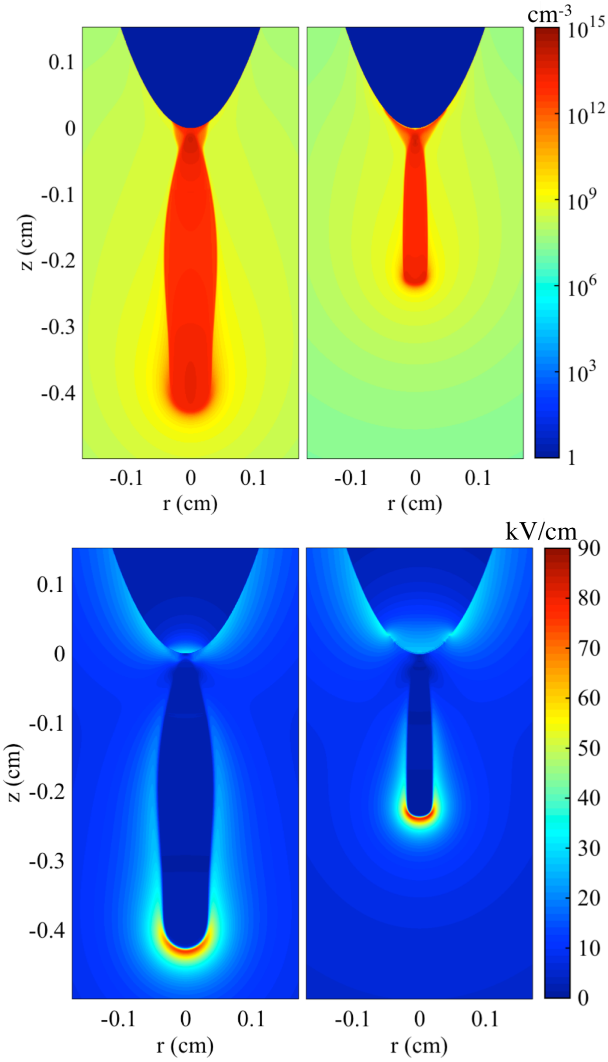

Fig. 1. Electron density (upper panel) and electric field (lower panel) of a positive streamer after 46 ns simulated with constant dielectric permittivity 93 (left), and with the dielectric function of ice $\varepsilon(\omega)$ [1] (right).

developing, the field produced by the charge separation at its head becomes comparable and opposite to the local field, hence it is eventually screened in the interior of the streamer. This dynamics evolves on the time scale of nanoseconds, and the icy dielectric cannot adjust to the changes. Essentially, the dielectric reacts to the field produced by the plasma of the streamer with the dielectric permittivity of 3. At the same time, the dielectric responds to the static external field with the dielectric permittivity of 93.

Due to the linearity of the Poisson equation, the total electric field is the superposition of the rapidly changing electric field and the static electric field. Each of the fields are to be calculated separately with different dielectric permittivities, as illustrated in Fig. 2, where V is the electric potential, and V_0 is the applied potential that generates the static external field.

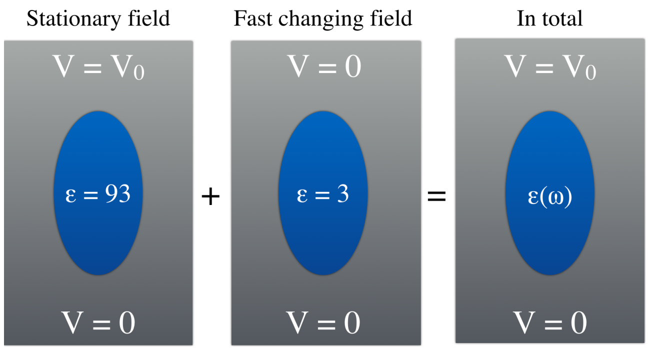

Fig. 2. The total electric field experienced by the plasma in a discharge is the sum of the fast changing electric field and the static background field. When the latter is calculated, the dielectric constant is set to 93, and when the former it is set to 3.

The electric field in our model is calculated with the Ghost Fluid Method [4,5] to capture accurately and fast the discontinuous boundary conditions on the dielectric interface. Neumann boundary conditions are applied in the radial direction and Dirichlet boundary conditions in the axial direction for the electric potential. The Poisson equation is coupled to the transport equation electrons and ions.

We use the diffusion-drift-reaction model from [3] based on local field approximation with photoionization included. The length of the simulation domain is 8.5 cm and its diameter is 4 cm. In the continuity equation for electrons, Neumann boundary conditions are applied on all the boundaries. We assume that initially the density of free electrons and positive ions is 100 cm^{-3}; this number is derived from extended air showers created by cosmic particles with sufficient energy in [3].

3. Results

In Fig.1, we compare the case when the dielectric permittivity of the dielectric is set to 93 with a correct dielectric function $\varepsilon(\omega)$ as described above and illustrated in Fig. 2. In both cases we are able to initiate a discharge. In the case of the correct frequency dependent permittivity, the streamer discharge develops with only half of the velocity and stays much thinner Fig 1 shows as well, that the electric field penetrates deeper into the dielectric, when $\varepsilon(\omega)$ of ice is taken into account.

Acknowledgements

AD acknowledges support by STW project 12119, partly funded by ABB, and CR by FOM-project 12PR3041.

References

[1] V. G. Artemov,, and A. A. Volkov.: Ferroelectrics **466** (2014) 1.

[2] A. Dubinova, C. Rutjes, U. Ebert, S. Buitink, O. Scholten, and G. T. N. Trinh: Phys. Rev. Lett. (2015) to appear.

[3] A. Dubinova, J. Teunissen, U. Ebert, IEEE Trans. Plasma Sci. **42** (2014) 2392.

[4] R. Fedkiw et al., J. Comput. Phys. **152** (1999) 457.

[5] S. Celestin et al., J. Phys. D: Appl. Phys. **42** (2009) 065203.