Propagation of Cathode-Directed Streamer Discharges in Air

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Outline

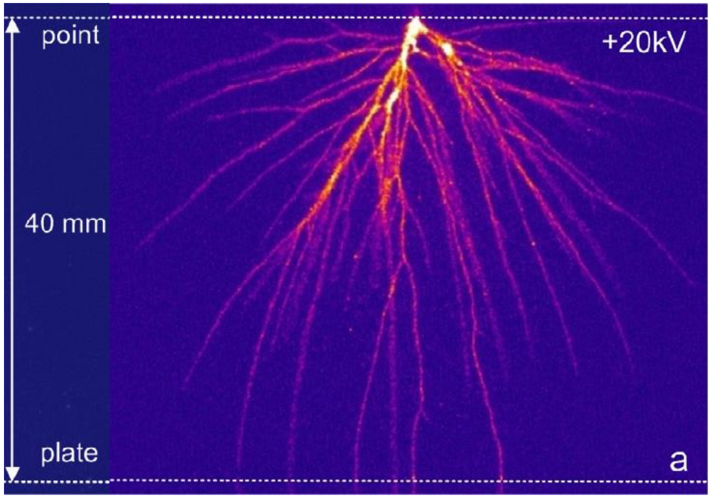
- Introduction
- Drift-diffusion model of streamer discharges in air
- Model implementation
- Simulations of positive streamers
- Concluding remarks

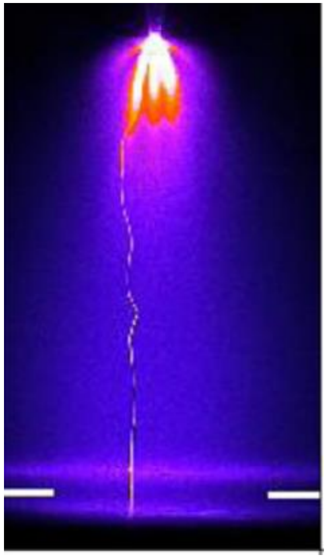
Electrical gas discharges

- Phenomena associated with transport of electrical charges through neutral gas due to applied electric fields.
- Transport processes are usually strongly dominated by space charge effects.
- Examples of non-thermal discharges: electron avalanches, streamers, coronas, stationary glow discharges, dielectric barrier discharges (DBD).
- A streamer discharge is a self-sustained ionization wave propagating in neutral gas.

Positive streamers in air

- Streamers develop as thin plasma channels sustained by production of electrons in the strong field region at the head.
- Depending upon conditions (pressure, length, power input, overvoltage, etc.) they may experience branching.





Transition from glow to streamer:

needle-plane gap, length 20mm, U_{app} = +21 kV, exposure 5 s.

T. M. P. Briels et al.,” Positive and negative streamers in ambient air: measuring diameter, velocity and dissipated energy”, J. Phys. D: Appl. Phys., 2008, **41**, 234004.

T. Czech et al., ” Optical emission spectroscopy of point-plane corona and back-corona discharges in air”, Eur. Phys. J. D, 2011, **65**, 459–474

Drift-diffusion model of air discharges

- Charge carriers are represented as electronic and ionic “fluids” and are characterized by averaged properties.
- Mass conservation equations for electrons and ions:

$$\partial n_e / \partial t + \nabla \cdot (-n_e \, \mu_e \, \mathbf{E} - D_e \nabla n_e) = S_e(E)$$
$$\partial n_p / \partial t + \nabla \cdot (n_p \, \mu_p \, \mathbf{E} - D_p \nabla n_p) = S_p(E)$$
$$\partial n_n / \partial t + \nabla \cdot (-n_n \, \mu_n \, \mathbf{E} - D_n \nabla n_n) = S_n(E)$$

- Poisson equation for electric potential ϕ:

$$\nabla \cdot (\varepsilon_0 \varepsilon \, \nabla \phi) = -q(n_p - n_e - n_n) , \quad \mathbf{E} = -\nabla \phi$$

- Appropriate (problem dependent) boundary and initial conditions are to be provided for all the PDEs.

Incorporating photoionization in air

- Mechanism:

$$e + N_2 \rightarrow N_2^* + e \Rightarrow N_2^* \rightarrow N_2 + h\nu\,(98 \div 102.5\,nm) \Rightarrow O_2 + h\nu \rightarrow O_2^+ + e$$

- Non-local ionization: electrons are created by photons at a distance from a source of radiation.
- The photoionization rate is included as $S_{ph}(\mathbf{r}) = \sum_j S_{ph}^j(\mathbf{r})$ where the terms $S_{ph}^j(\mathbf{r})$ satisfy Helmholtz equations(*)

$$\nabla^2 S_{ph}^j(\mathbf{r}) - (\lambda_j\, p_{O_2})^2 S_{ph}^j(\mathbf{r}) = -A_j\, p_{O_2}^2\, I(\mathbf{r})$$

- Two exponential fit is used with the parameters λ_j and A_j .

(*) A. Bourdon et al., “Efficient models for photoionization produced by non-thermal gas discharges in air based on radiative transfer and the Helmholtz equations”, Plasma Sources Sci. Technol., 2007, **16**, 656-78.

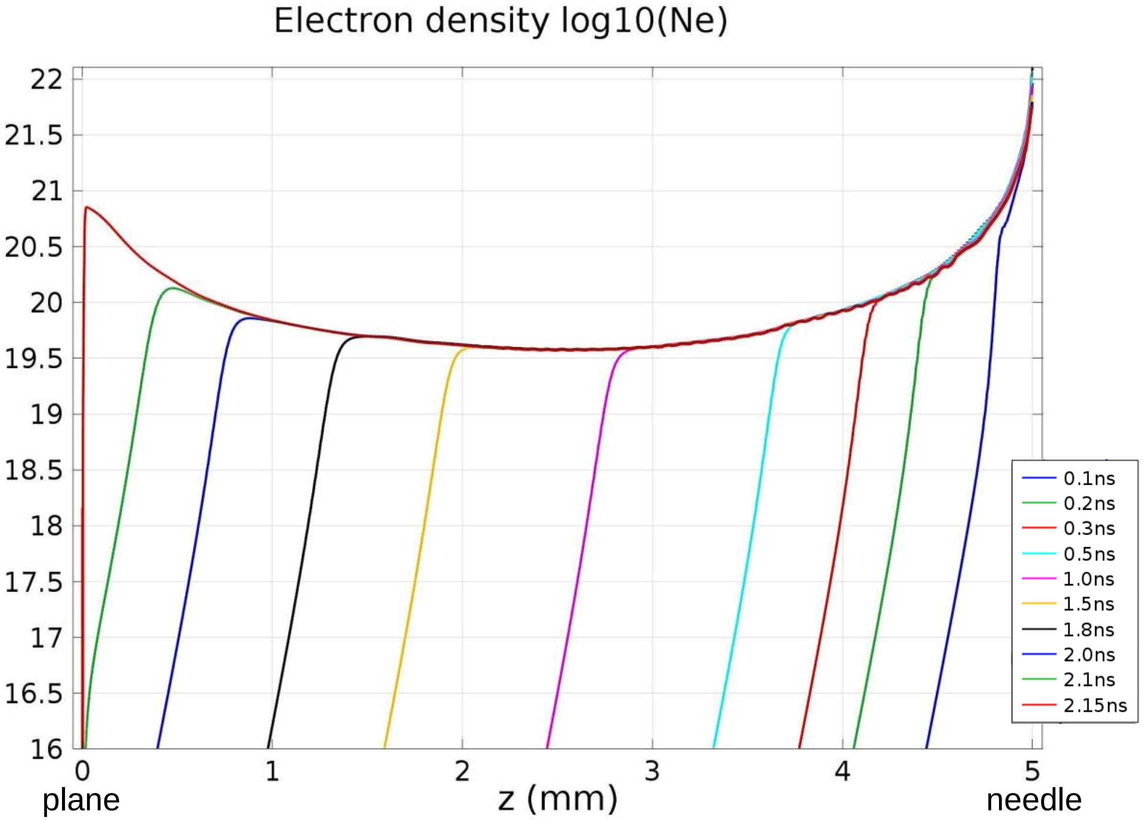
Model implementation

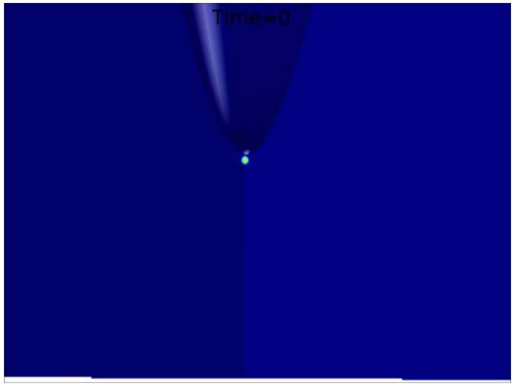
- Set of PDEs: three drift-diffusion, Poisson’s, two Helmholtz.
- Source term stabilization is implemented for the DD PDEs.
- Mesh size at streamer front is ~10 µm, within the plasma channel ~70 µm and larger in the rest of the domain.
- The mesh was refined manually.
- Solver: direct, segregated (two steps) with continues Jacobian update.
- Time stepping: BDF with variable order.

Simulations of streamers in air

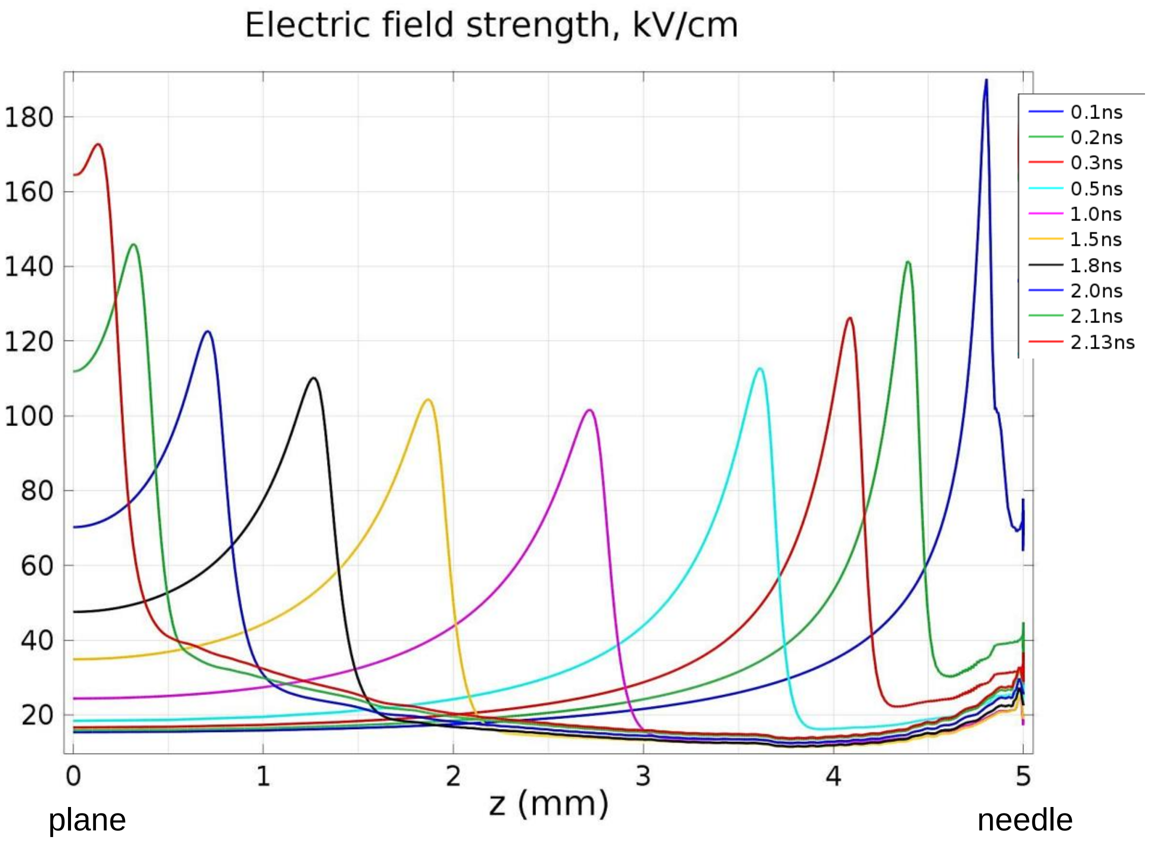
- Hyperbolic needle-plane electrodes, pressure 760 Torr, temperature 293 K, voltage rise time 0.1 ns.
- A single discharge is considered and the model is implemented in 2D utilizing axial symmetry.
- The discharge is initiated from a seeding charge spot of Gaussian shape ($n_e = n_p = 10^{20}$ m^{-3}, σ = 30 µm) located at 0.1 mm from the needle tip.
- Drift of ions is neglected due to the short duration of the discharge.
- Two study cases:
  - gap length 5 mm (applied voltage +15 kV dc)
  - gap length 30 mm (voltage +40 kV dc).

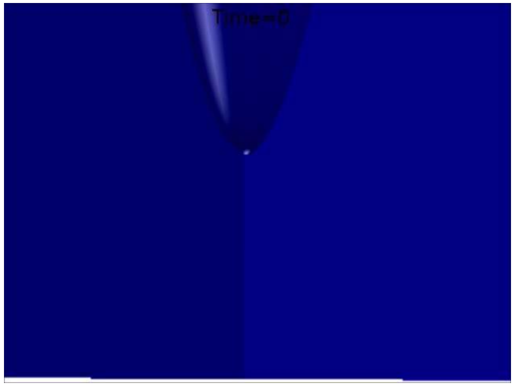
Short streamer: dynamics of electrons



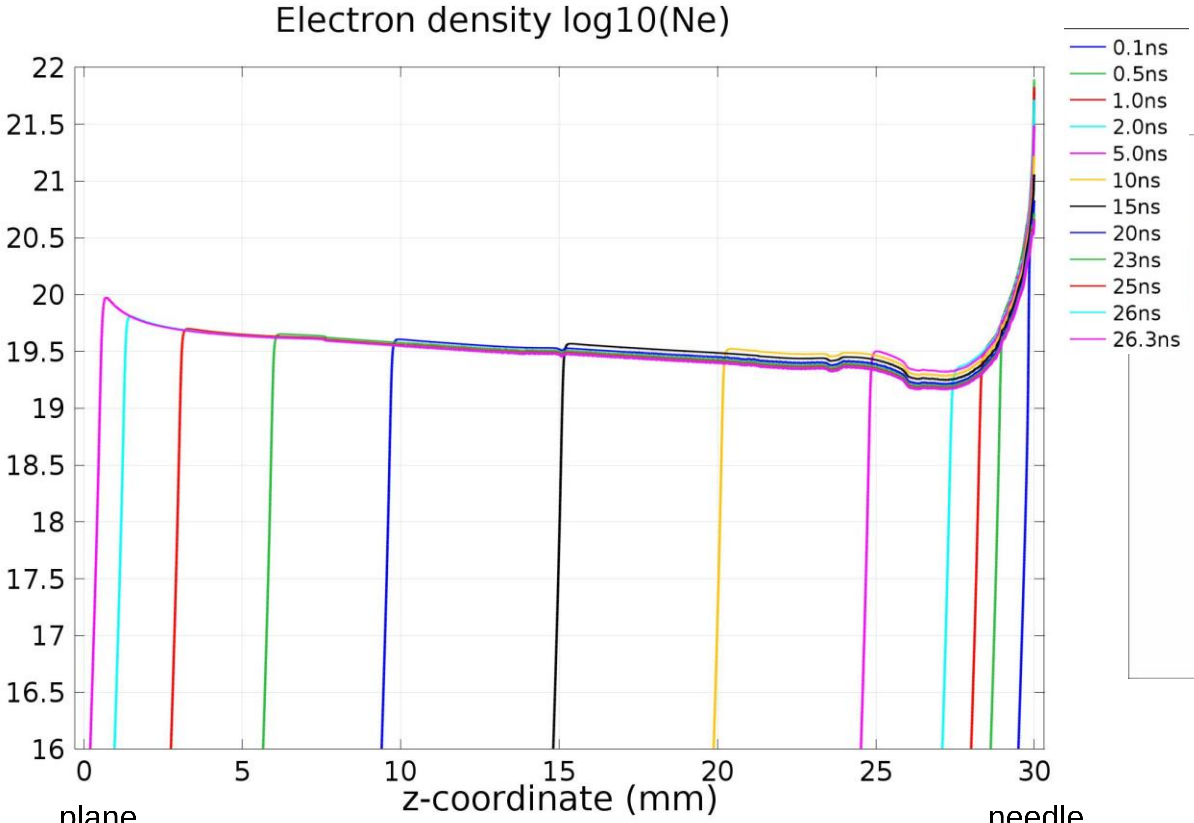


Short streamer: electric field



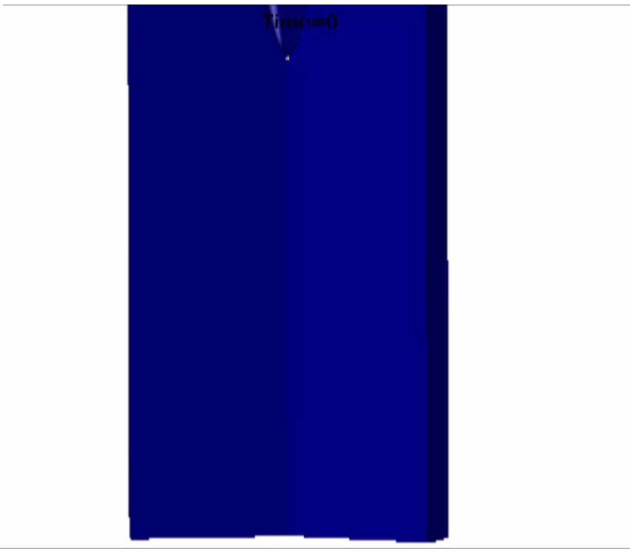


Long streamer: dynamics of electrons

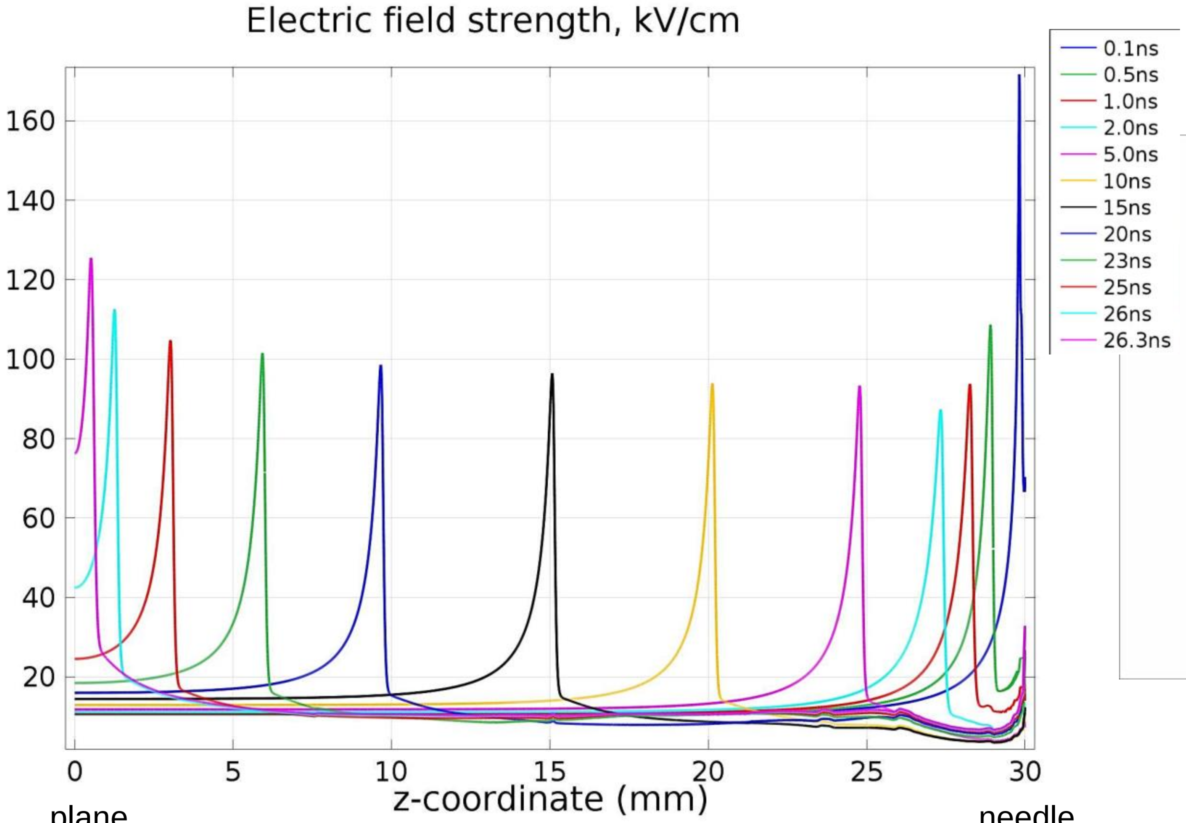


plane

needle

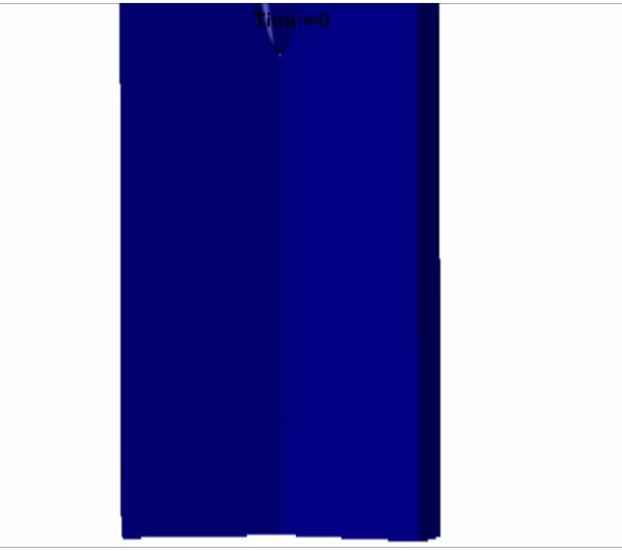


Long streamer: electric field



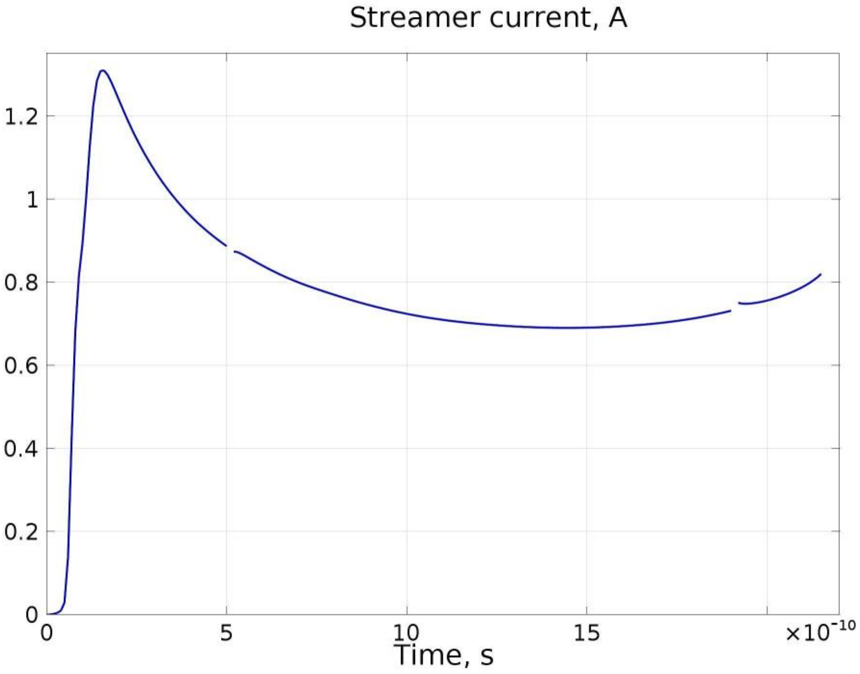
plane

needle

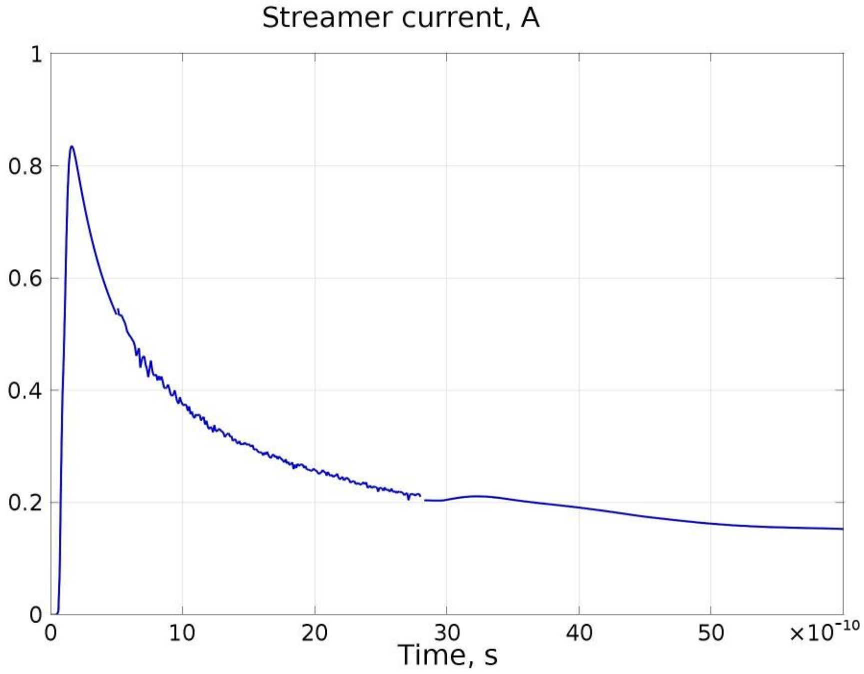


Calculated discharge current

Streamer 5 mm



Streamer 30 mm



Calculated parameters of streamers

- Velocity at stable propagation:

5 mm streamer - ~$1.8 \cdot 10^6$ m/s

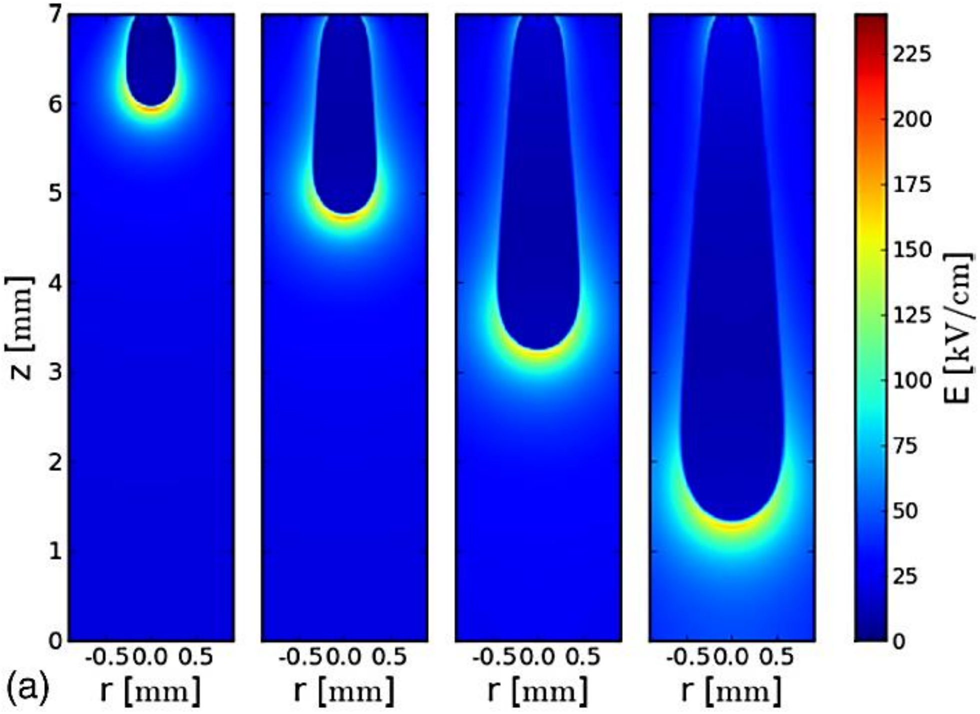
30 mm streamer - ~$1.0 \cdot 10^6$ m/s

- Channel radius at stable propagation :

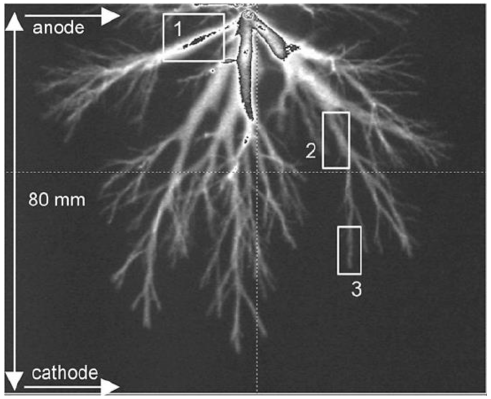
5 mm streamer – 600-700 µm (strongest field)
400-500 µm (strongest S_{ph})

30 mm streamer – 500-600 µm (strongest field)
200-300 µm (strongest S_{ph})

Typical parameters of streamers



A. Luque et al., “Positive and negative streamers in ambient air: modelling evolution and velocities”, J. Phys. D: Appl. Phys. **41** (2008) 234005.



- Type 1 streamers are very thick with a diameter of about 2.5 mm; their velocity is just over 1 mm ns^{-1} and they carry currents of up to 25 A.
- Type 2 streamers are thick with a diameter of about 1.2 mm, a velocity of 0.5 mm ns^{-1} and currents of the order of 1 A.
- Type 3 streamers are thin; their diameter is 0.2 mm which can only be properly determined by zooming in sufficiently with the camera (cf table 1), their velocity is $\sim$0.1 mm ns^{-1} and their current $\sim$10 mA.

T. M. P. Briels et al., “Circuit dependence of the diameter of pulsed positive streamers in air”, J. Phys. D: Appl. Phys. **39** (2006) 5201–5210

Concluding remarks

- The drift-diffusion (fluid) model of non-thermal discharges in air has been implemented.
- Lessons learnt: meshing, numerical stability, setting proper boundary conditions, optimizing solver properties, etc.
- “Wish list” :
    - implementation of a moving frame with a fine mesh for resolving gradients at streamer front;
    - implementation of a high order numerical scheme or technique allowing for flux correction;
    - implementation of finite volume approach for drift-diffusion equations (to preserve positivity).

Thank you for your attention!!