Modelling of Streamer Discharges in Air-filled Sub-millimetre Needle-Plane Electrode Gaps Under Fast-rising Field Conditions

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Research Summary

Streamer discharges are fast ionisation fronts generated under intensive electrical stress. They are a crucial stage in the evolution of an electrical breakdown in gas and also important to a range of industrial applications.

In this work, streamers in sub-millimeter needle-plane gaps in atmospheric air and under fast-rising ramp voltages are modelled using a hydrodynamic approach, using the finite element framework demonstrated previously in [1,2].

The plasma model used in this study is considerably more advanced than before, now including:

Plasma chemistry for air - 7 species involved in 18 total reactions including photoionisation

The local mean energy approximation to ensure model validity over a wider range of electric field

The study of streamers in short gaps and fast-rising voltages helps to inform the design and understanding of HV pulsed power systems, including:

The design of plasma closing switches

Understanding of electrical breakdown in gas-insulated systems in divergent fields

Design of HV diagnostics and discharge detection equipment

Study the impact of impulsive fields on plasma composition for chemical processing applications

Introduction To Streamer Modelling

Streamer discharges in gases are fast-propagating ionisation fronts, generated under intensive electrical stress. Accelerated electrons above the ionisation threshold leads to rapid production of space-charge. When the space-charge induced electric field becomes sufficiently strong compared to the external applied field, a streamer discharge may form and rapidly propagate forward, fuelled by impact ionisation. One approximation which may be used to simulate streamer discharges is the **hydrodynamic** approach, which assumes that the concentration of charged species is sufficiently high to be considered a continuum, and therefore may be described similarly to fluids which are controlled by **advection, diffusion, and reaction** processes.

Hydrodynamic Model

Drift-Diffusion Equations

$$\frac{\partial n_i}{\partial t} - \nabla \cdot (\operatorname{sgn}(q_i) n_i \mu_i \nabla \varphi)) - \nabla \cdot (D_i \nabla n_i) = S_i$$

Poisson Equation

$$-\nabla \cdot (\varepsilon \nabla \varphi) = \sigma_s + \sum_i q_i n_i$$

Helmholtz Approximation for Photoionisation

$$\nabla^2 S_{ph,j} - (p_{O_2} \lambda_j)^2 S_{ph,j} = -\left(A_j p_{O_2}^2 \frac{p_q}{p + p_q} \xi \frac{\nu_u}{\nu_i} \right) S_{im}$$

$$S_{ph} = \sum_j S_{ph,j}$$

Electron Energy Balance Equation

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \mathbf{\Gamma}_\varepsilon = -e \mathbf{\Gamma}_e \cdot \mathbf{E} - \sum_{m=1}^{N} \Delta E_m k_m \prod_{j=1}^{R} n_j$$

Plasma Chemistry

$$S_i = \sum_{m=1}^{N} k_m \prod_{j=1}^{R} n_j$$

In this work...

Using a plasma modelling package we developed and benchmarked in [1,2], positive and negative streamers have been modelled in the domain shown in Fig. 1.

The model features a simplified set of reactions for air chemistry [3] involving **e^-, O_2^+, N_2^+, O_4^+, N_4^+, $O_2^+N_2$, and O_2^-** charged species, photoionisation using Zheleznyak's model [4], and the use of the local mean energy approximation (LMEA).

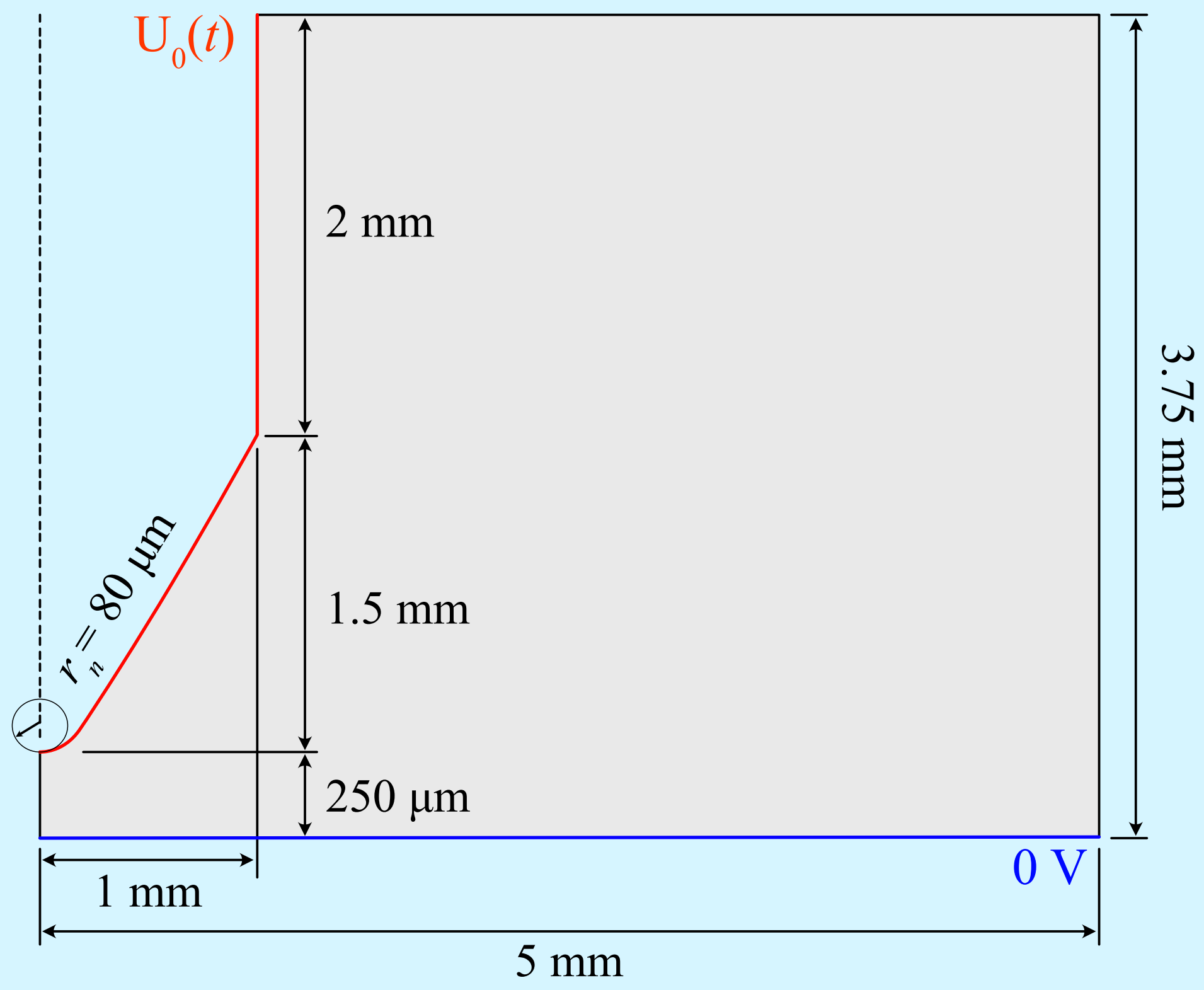
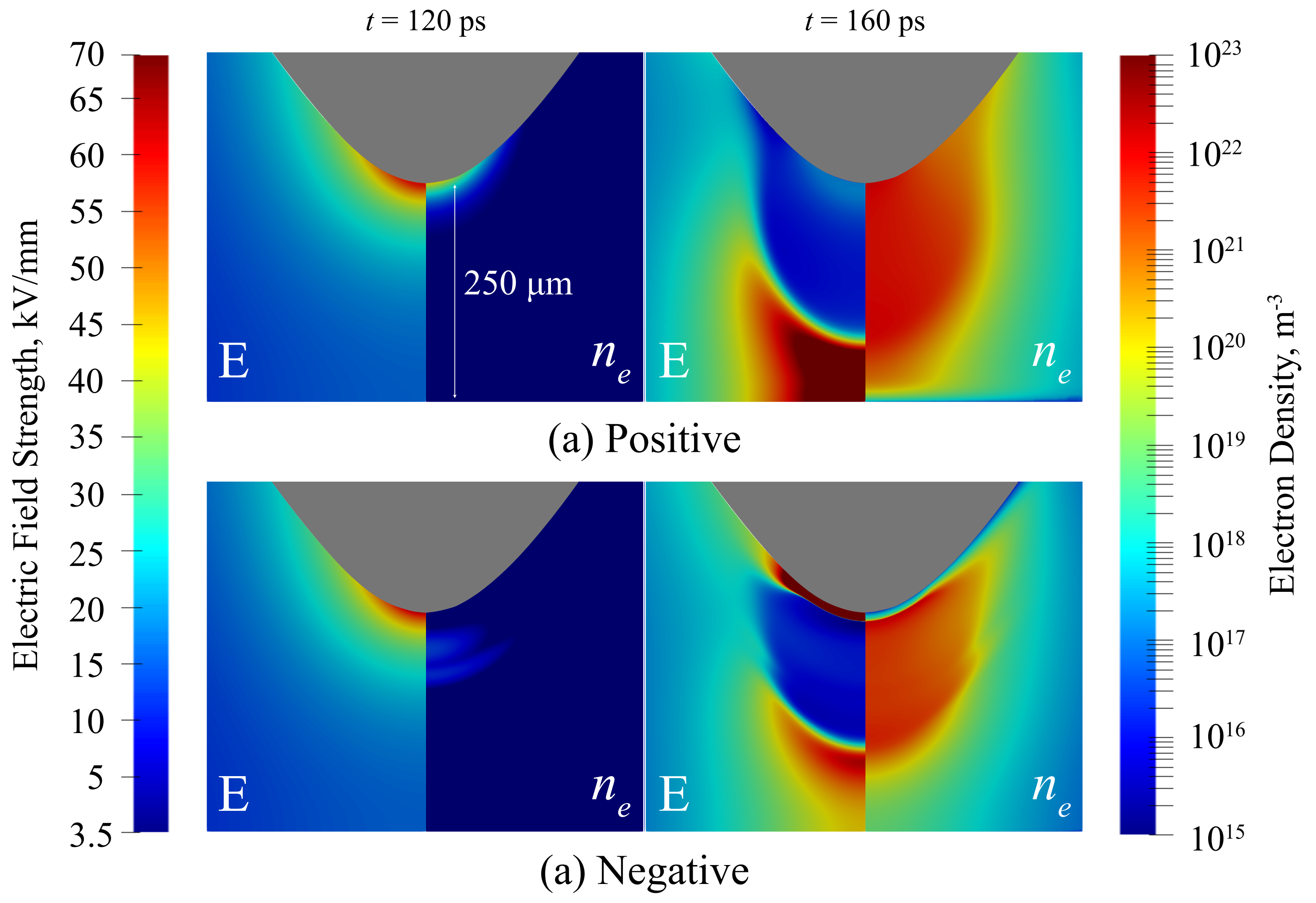


Fig. 1. Computational Axisymmetric Needle-Plane Domain

Streamer Modelling Results



(a) Positive

(a) Negative

Fig. 2. The electric field and electron density for (a) positive and (b) negative streamers at t = 120 and 160 ps.

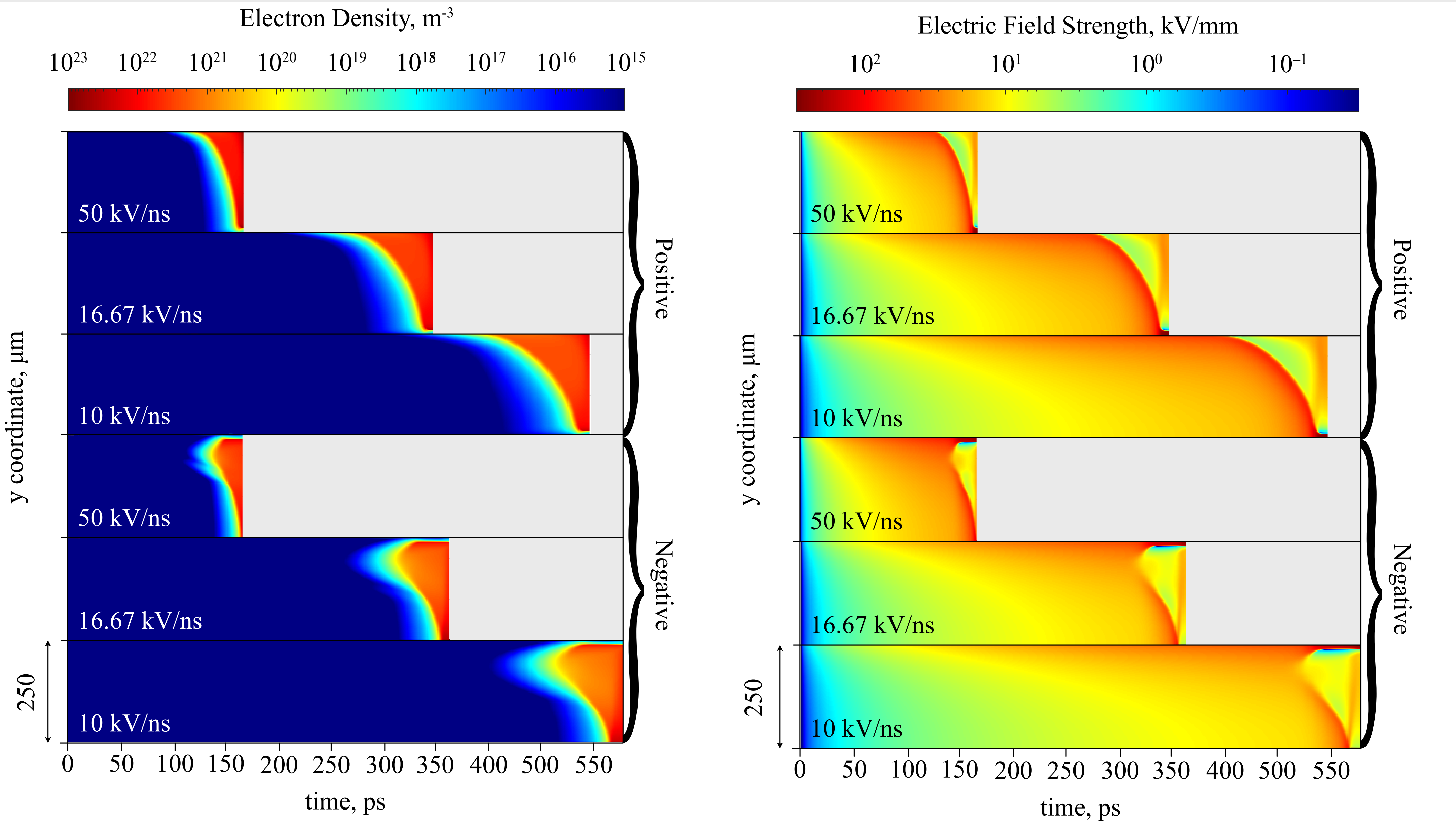


Fig. 3. Time evolution of the (left) electron density, and (right) electric field for voltage rise rates of 50, 16.67, and 10 kV/ns, down the axis of symmetry of Fig. 1.

Discussion & Points of Interest

Figure 2

- Differences at initiation between positive and negative streamers. An initial ionisation wave is observed in the negative case, before a secondary wave is generated and becomes dominant.
- Formation of the cathode sheath with low electron density, but intensive electric field in the negative case.
- Positive streamer crosses gap first, despite negative streamers typically accelerating more rapidly. Possibly due to insufficient time to accelerate in such short gaps.

Figure 3

- Negative streamer initiates some distance away from the needle, in contrast with the positive streamer.
- Streamer velocity is reduced with decreasing rate of voltage rise, for both polarities.
- The electric field in the streamer channel begins to rise after the streamer head has passed, for both polarities.
- As before, negative streamer (instantaneous) velocity is significantly higher than that of positive streamers, but positive streamers bridge the gap first due to earlier initiation.

Future Work

It is intended to extend this modelling work to different gases relevant to pulsed power equipment, possibly CO_2 or air-CO_2 mixtures.

Inclusion of solid dielectric interfaces with the needle electrode embedded would also be of high interest, to study the dynamics of streamers at gas-solid interfaces using this advanced plasma model.

[1] T. Wong, I. Timoshkin, S. MacGregor, M. Wilson, M. Given, "A Python-based Adaptive Mesh Solver for Drift-Diffusion Modelling of Streamer Discharges," IEEE Pulsed Power Conference, CO, USA, 2021.

[2] T. Wong, I. Timoshkin, S. MacGregor, M. Wilson, M. Given, "Simulation of Streamer Discharges Across Solid Dielectric Surfaces Using the Open-Source FEniCS Platform," IEEE Pulsed Power Conference, CO, USA, 2021.

[3] S. Pancheshnyi and A. Starikovskii, "Two-dimensional numerical modelling of the cathode-directed streamer development in a long gap at high voltage," J. Phys. D: Appl. Phys, vol. 36, pp. 2683-2691, 2003

[4] M. Zheleznyak, A. Mnatsakanyan, S. Sizykh, "Photo-ionisation of nitrogen and oxygen mictures by radiation from a gas-discharge," High. Temp., vol. 20, pp. 357-362, 1982.