Evolution of positive streamers in air over non-planar dielectrics: experiments and simulations

H K H Meyer\textsuperscript{1,}\textsuperscript{*}, R Marskar\textsuperscript{1} and F Mauseth\textsuperscript{2}

\textsuperscript{1} SINTEF Energy Research, Sem Sælands vei 11, 7034 Trondheim, Norway
\textsuperscript{2} NTNU—Norwegian University of Science and Technology, Trondheim, Norway

E-mail: hans.meyer@sintef.no

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Abstract

We study positive streamers in air propagating along polycarbonate dielectric plates with and without small-scale surface profiles. The streamer development was documented using light-sensitive high-speed cameras and a photo-multiplier tube, and the experimental results were compared with 2D fluid streamer simulations. Two profiles were tested, one with 0.5 mm deep semi-circular corrugations and one with 0.5 mm deep rectangular corrugations. A non-profiled surface was used as a reference. Both experiments and simulations show that the surface profiles lead to significantly slower surface streamers, and also reduce their length. The rectangular-cut profile obstructs the surface streamer more than the semi-circular profile. We find quantitative agreement between simulations and experiments. For the surface with rectangular grooves, the simulations also reveal a complex propagation mechanism where new positive streamers re-ignite inside the surface profile corrugations. The results are of importance for technological applications involving streamers and solid dielectrics.

Keywords: streamer, surface profile, high-speed imaging, low-temperature plasma, fluid simulation, dielectric surface

(Some figures may appear in colour only in the online journal)

1. Introduction

Streamer discharges \cite{1} are low-temperature filamentary plasma, driven by electron impact ionization and charge separation in the streamer head. They can appear when the electric field is locally higher than the breakdown field. Once streamers have formed, the self-enhanced field at the streamer tips permits them to propagate in background fields lower than the breakdown field. For example, the breakdown field in atmospheric air is $E_{\text{br}} \sim 30 \text{kV cm}^{-1}$, but positive streamers can propagate in fields down to $\sim 5 \text{kV cm}^{-1}$.

\textsuperscript{*} Author to whom any correspondence should be addressed.

Streamers can propagate in bulk gases but also along dielectric surfaces. Although the governing physics is mostly the same in both cases, there are some differences between the two: (a) dielectric polarization enhances the field between the streamer and the dielectric, and streamers therefore tend to be surface-hugging. (b) Streamers typically propagate faster along a dielectric surface than in the surrounding gas \cite{2–5}. (c) Positive streamers are accompanied by a cathode sheath closest to the dielectric \cite{5–8}. This sheath is analogous to the cathode sheath on electrodes. It appears because secondary electrons from ionization and surface emission are low-energy electrons that move away from the surface and thus do not ionize the gas closest to the dielectric. (d) Streamers can be influenced by emission of secondary electrons from the dielectric surface, but in atmospheric air the overall effect on the...
streamer velocity and range is rather small [8]. (e) Surface charge also affect the streamer behavior, and can for example lead to inception of airborne streamers from the surface [9]. However, charging of dielectric surfaces exposed to positive streamers mainly occurs through ion transport in the streamer wake, i.e. from the channel and onto the surface [8]. Since the ions only move a short distance, surface charging essentially does not affect ionization process in the streamer head [5].

Streamer propagation along dielectrics is important in several research fields. Discharge propagation along gas-dielectric interfaces is often critical for medium voltage (MV) switchgear, which usually contain solid insulating components like supports, shafts, and barriers. Aerodynamic plasma actuators also operate with surface streamers that propagate along the airfoil, usually in the form of a dielectric barrier discharge [10]. Another example is plasma wound healing, in which the dielectric is human tissue [11]. The shape, orientation, profile, or roughness of a dielectric surface are all important factors for streamer propagation along surfaces. Positive streamers in air, for example, have radii on the order of 0.1–1 mm [12], and are thus easily manipulated by modifying the dielectric surface structure on the micron or millimeter scale.

There are several studies that address streamer propagation over planar surfaces [5, 13–15], but studies of streamer propagation over non-planar surfaces are scarce. An investigation of positive streamer propagation over a profile with semi-circular corrugations was presented in [16] by the authors. Comparing both experiments and simulations, we showed that surface profiles reduce both the velocity and range of positive streamers. Moreover, the authors experimentally compared propagation over surfaces with 0.5 mm deep rectangular cut corrugations with a flat surface in [17], and found that positive streamer propagation was more restricted over such surfaces than over semi-circular profiled or flat surfaces. It was also confirmed in [17] that positive streamers follow semi-circular corrugations closely, as predicted by simulations in [16]. Wang et al [18] numerically examined the profile effect for both convex and concave corrugations. Allen [19] found that streamers propagating along dielectrics with various high voltage (HV) insulator shed designs required higher background electric field strengths to sustain propagation than for streamers along plain insulators.

In this paper we perform both computer simulations and high-speed imaging of experiments of positive streamers propagating over various dielectric surface profiles. We extend the analysis in [16] and [17], mainly by including simulations and more experiments of the rectangularly profiled surface, by using more elaborate plasma models, and by using a consistent impulse voltage curve in experiments and simulations. The goal of this article is two-fold. Firstly, we wish to establish a deeper understanding of positive streamer propagation along various surface profiles. Secondly, we wish to take steps towards computational validation of the discharge model through an apples-to-apples comparison with experiments.

The outline of this paper is as follows: in section 2 we outline the experimental setup and procedure. We discuss the numerical approach in section 3, and present our results in section 4. A summary of the paper findings is then presented in section 5.

2. Experimental methods

2.1. Test methods

Figure 1 illustrates the experimental setup, including the dimensions of the electrodes and the surface profile details. Three polycarbonate (Lexan) plate dielectrics of 5 mm × 72 mm × 150 mm and relative permittivity $\epsilon_r = 3$ were used as test objects:

(a) A flat plate.
(b) A plate with semi-circular corrugations as shown in figures 1(a) and (b). This profile is a reproduction of the test object in [16], and has a 20% greater surface area than the plain surface.
(c) A plate with rectangular corrugations. This surface has a 110% larger surface area than the flat plate. This surface profile is shown in blue color in figure 1(c). The rectangular profile restricts streamer propagation along the surface as shown in [17].

For the profiled plates, the surface profiles consist of ~500 µm deep corrugations, which were drilled using a bore head. The dimensions of the profiled surface were measured with a Bruker ContourGT profilometer and averaged, see table 1.

An aluminum casing and a disk-shaped brass electrode were used as ground and HV electrodes. The disk shape was used as its electrical field distribution resembles the 2D planar simulation field, and it provides a small streamer inception region which facilitates imaging.

A voltage impulse was applied to the disk electrode using one stage of a 1.2 MV lightning impulse generator, see figure 3. A resistor in series with the test object limited the discharge energy. The voltage was measured directly on the test object using a North Star PVM-100 HV probe.

Since the computer simulations are sensitive to the applied voltage, we used a simulation voltage similar to the prospective voltage curve in figure 2. The prospective voltage curve was measured with the voltage probe using a charging voltage which was too low to cause inception, and then scaled up based on generator charging voltages. The rise time (10%–90%) of the initial voltage front was 53 ns, while the impulse half-value time was around 50 µs. The short rise time facilitated imaging, but resulted in a voltage overshoot due to oscillations in the circuit, which produced a peak voltage of 48 kV over the test object for a 35 kV charging voltage. The actual voltage measured over the gap depended on the streamer activity as shown in figure 2. With streamers present, the voltage peak value was significantly reduced, possibly due to the series resistor limiting the current to the live electrode.
Figure 1. Electrodes and dielectric test objects. (a) Setup viewed from an angle, showing polycarbonate surface with 0.5 mm semi-circular corrugations outlined in red (A), the HV disk electrode (B) and the grounded aluminum casing (C). (b) Front view, with details showing dimensions of the semi-circular surface profile in red and rectangular surface profile in blue. All indicated dimensions are given in millimeters.

Table 1. Average measured surface dimensions of the profiled test objects (see figure 1). All quantities are given in microns (µm).

| Semi-circular | Rectangular |
|---------------|-------------|
| w_r | w_p | d | r | w_r | w_p | h |
| 1718 | 227 | 459 | 974 | 524 | 491 | 546 |

The actual voltage shape experienced by the test object is an important limitation in the simulations. Since the fluid simulations were not linked to a model of the external circuit, the test object voltage could not be consistently coupled to the simulations, and we therefore used the prospective voltage for the simulations. Several measurements were also made without the probe present, so the probe influence on the voltage is not accounted for. However, the probe input impedance is high (600 MΩ, 15 pF), so the effect is likely minor.

To register light from the streamers, a Philips 56A VP photomultiplier tube (PMT) with a spectral range of 380 nm to 680 nm was used. Both the voltage probe and the PMT were connected to a 1 GHz Tektronix DPO 4104 oscilloscope.

Figure 2 shows the PMT signal and measured voltage (both prospective and with streamers) over the test object. The inset figure shows the events around the rising voltage flank. The estimated inception time and voltage is also shown.

The transit times in cables and the internal PMT delay were compensated for in the post-processing. The inception voltage as registered by the PMT showed a variation of some tens of ns, but the streamer event always occurred on the first rising voltage flank when using a 35 kV charging voltage. Typical instantaneous voltage values at inception were between 20 and 30 kV. When computing the inception voltage using the Townsend–Meek criterion, the resulting value was $U_{\text{inception}} \sim 11$ kV. This deviation between experimental and calculated inception voltage is probably a result of waiting times for a starting electron and possibly non-zero surface charge on the dielectric.

Between each experiment, a grounded metal rod was guided over the surface to neutralize residual surface charge. It is unlikely that this method removed all charge residues. However, the test object will likely itself neutralize some charge during an impulse event: as the voltage pulse decays, reverse discharges between the HV electrode and charged surface occur as can be seen on the PMT signal in figure 2 from around 40 µs. These pulses neutralize some of the charge as shown in [8, 17]. Although we cannot exclude the influence of remnant surface charge in our experiments, the observed streamer behavior was highly reproducible.

2.2. High speed imaging

Different high-speed cameras were used to image the discharges:

(a) A single-frame dual image intensifier camera, Lambert HiCAM 500, with an S20 photo-cathode, with max
The main viewing angle was from the front as shown in figure 1(b), with some variations in tilt to also capture depth variations of the discharge. The images were post-processed by enhancing brightness and contrast and by overlaying an illuminated background picture of the setup. The camera exposure relative to the voltage pulse was controlled with a digital delay generator.

3. Numerical methods

3.1. Streamer dynamics model equations

The numerical simulations were performed using a Cartesian 2D fluid model. Fluid models are often used for simulation of streamer discharges in air, see e.g. [6, 14, 26–29]. The equations of motion are:

$$\frac{\partial n}{\partial t} = -\nabla \cdot (n\mathbf{v} - DN\nabla n) + S, \quad (1)$$

$$\frac{\partial \sigma}{\partial t} = J_\sigma, \quad (2)$$

$$\nabla \cdot (\mathbf{v}\rho) = \frac{\rho}{\epsilon_0}, \quad (3)$$

$$\left[\nabla^2 - (p_0\lambda)^2\right]\Psi_j = -\left(A_4\rho_0^2\frac{p_q}{p_q + p}\xi\nu\right)k_1n_eN_N. \quad (4)$$

Here, $n$ is the particle number density, $\mathbf{v} = \pm\mu\mathbf{E}$ is the drift velocity for positively (+) and negatively (−) charged species, where $\mu$ is the species mobility and $\mathbf{E} = -\nabla \Phi$ is the electric field. Furthermore, $D$ is the diffusion coefficient, and $S$ indicates source terms for the various species. These are discussed further below. The surface charge density is given by $\sigma$ where $J_\sigma$ is the charge flux onto the dielectric surface. The relative permittivity of the dielectric is $\varepsilon_r = 3$ and $p$ is the space charge. Finally, equation (4) describes photoionization in air; we elaborate on this equation below.

3.2. Transport data

For the plasma chemistry we solve for the following eight species: $e$, $N_2^+$, $O_2^+$, $O_2^-$, $O^-$, $O_3^-$, $N_2^+$, $O_3^-$. The electron mobility and diffusion coefficients are computed using BOLSIG+ [20] with the PHELPS database [21], while for the ions we take $\mu = 2 \times 10^{-4} \text{m}^2 \text{Vs}^{-1}$ and $D = 0$. For the source terms we use the reactions given in table 2.

For the photoionization reactions (reactions #14 and #15), we consider the Bourdon et al [30] Helmholtz reconstruction where the photoionization reaction is the sum of three contributions:

$$S_{14} = \sum_{j=1}^{3} \Psi_j. \quad (5)$$

Here, $\Psi_j$ are the solutions to equation (4) where $p_q = 40 \text{mbar}$ is a quenching pressure (and $p = 1 \text{ bar}$ is the gas pressure), $\xi$ is the photoionization efficient and $\nu$ is the relative excitation probability. That is, $\nu k_1n_eN_N$, is the electron impact rate of molecular nitrogen. Spontaneous emission from these can lead to photoionization of molecular oxygen. In this paper we take $\xi\nu = 0.06$. The $\lambda$ and $A$ coefficients are given in table 3.
database have units of m^3 s^{-1} and three-body reactions have units of m^6 s^{-1}. Reactions where the rate coefficient is given as \( k = k(E, N) \) are computed with BOLSIG+ [20] and the PHELPS database [21]. For these reactions the rate is given as a function of the reduced electric field \( E' = E/N \) (in units of Townsend). The electron temperature is obtained as \( T_e = 2\tau / (3k_B) \) where \( \tau \) is the mean electron energy (computed using BOLSIG+). The gas temperature is \( T_g = 300 \text{K} \).

### Table 2. Air reaction mechanism for the simulation model. Note that two-body reactions have units of m^3 s^{-1} and three-body reactions have units of m^6 s^{-1}. Reactions where the rate coefficient is given as \( k = k(E, N) \) are computed with BOLSIG+ [20] and the PHELPS database [21]. For these reactions the rate is given as a function of the reduced electric field \( E' = E/N \) (in units of Townsend). The electron temperature is obtained as \( T_e = 2\tau / (3k_B) \) where \( \tau \) is the mean electron energy (computed using BOLSIG+). The gas temperature is \( T_g = 300 \text{K} \).

| Reaction # | Reaction | Rate | Reference |
|------------|----------|------|-----------|
| 1          | \( e + N_2 \xrightarrow{k_1} N_2^+ + e + e \) | \( k_1 = k_1(E, N) \) | [20, 21] |
| 2          | \( e + O_2 \xrightarrow{k_2} O_2^+ + e + e \) | \( k_2 = k_2(E, N) \) | [20, 21] |
| 3          | \( e + O_2 + O_2 \xrightarrow{k_3} O_2^+ + O_2 \) | \( k_3 = k_3(E, N) \) | [20, 21] |
| 4          | \( e + O_2 \xrightarrow{k_4} O^- + O \) | \( k_4 = k_4(E, N) \) | [20, 21] |
| 5          | \( O_2^- + N_2 \xrightarrow{k_5} O_2 + N_2 + e \) | \( 1.13 \times 10^{-25} \) | [22] |
| 6          | \( O_2^+ + O_2 \xrightarrow{k_6} O_2 + O_2 + e \) | \( 2.2 \times 10^{-24} \) | [22] |
| 7          | \( O^- + N_2 \xrightarrow{k_7} e + N_2O \) | \( 1.16 \times 10^{-18} \exp \left[ -\left( \frac{46.9 \times 21}{n_0T_e} \right)^2 \right] \) | [23] |
| 8          | \( O^- + O_2 \xrightarrow{k_8} O_2^- + O \) | \( 6.96 \times 10^{-17} \exp \left[ -\left( \frac{108.3 \times 21}{n_0T_e} \right)^2 \right] \) | [23] |
| 9          | \( O^- + O_2 + M \xrightarrow{k_9} O_2^- + M \) | \( 1.1 \times 10^{-42} \exp \left[ -\left( \frac{E_e}{n_0T_e} \right)^2 \right] \) | [23] |
| 10         | \( N_2^+ + N_2 + M \xrightarrow{k_{10}} N_2^+ + M \) | \( 5 \times 10^{-41} \) | [24] |
| 11         | \( O_2^+ + O_2 + M \xrightarrow{k_{11}} O_2^+ + M \) | \( 2.4 \times 10^{-42} \) | [24] |
| 12         | \( e + O_2 \xrightarrow{k_{12}} O_2 + O_2 \) | \( 1.4 \times 10^{-12} \sqrt{\frac{\tau_e}{T_e}} \) | [22] |
| 13         | \( e + N_2 \xrightarrow{k_{13}} e + N_2 + \gamma_0 \) | \( 2 \times 10^{-12} \sqrt{\frac{\tau_e}{T_e}} \) | [22] |
| 14         | \( \gamma_0 + O_2 \xrightarrow{k_{14}} e + O_2 \) | | [22] |

### Table 3. Model parameters for the Helmholtz reconstruction.

| \( j \) | \( \lambda \) (m^{-2} Pa^{-2}) | \( A \) (m^{-1} Pa^{-1}) |
|---|---|---|
| 1 | 0.415 | 1.12 \times 10^{-4} |
| 2 | 0.1095 | 2.87 \times 10^{-5} |
| 3 | 0.6675 | 0.275 |

3.3. Discretization

The equations are discretized in space using finite volumes on hierarchical Cartesian grids. We use an embedded boundary (EB) formalism for representing the electrode and dielectrics. EBs add substantial discretization complexity which is not discussed in detail here, see e.g. Adams et al [31] or Marskar [7]. The simulations are performed in planar 2D, with a finest grid resolution of 2.44 \( \mu \text{m} \). For discretization in time we use a Godunov splitting method as in Marskar [32]. The only difference between the current discretization and Marskar [32] is that we here use a semi-implicit coupling to the electric field.

For the rectangular corrugated surface we found that the simulations required extremely fine resolutions when the streamer temporarily halts in the corrugation spaces. In order to stabilize the simulations we used the upwinding suggestions from Villa et al [33] where the source term is computed using the upwinded value of the electron density. In practice, we enforce this by using the face-centered states that are available from the hyperbolic discretization, which thus also includes the effects of slope limiters. For consistency, this modification is done for all the simulations and profiles.

For boundary conditions, the right and bottom edges in the simulation domain are grounded. On the left and top edges we impose a homogeneous Neumann boundary condition, and on the electrode we impose the time-varying prospective voltage shown in figure 2. On the dielectric surface we incorporate the following boundary conditions into the discretization of the Poisson equation:

\[ \epsilon_1 \frac{\partial n_1}{\partial \mathbf{n}_1} \mathbf{\Phi} = \epsilon_2 \frac{\partial n_2}{\partial \mathbf{n}_2} \mathbf{\Phi} = \frac{\sigma}{\epsilon_0}, \quad (6) \]

where \( \sigma \) is the surface charge density and \( \mathbf{n}_1 = -\mathbf{n}_2 \) are unit normals that points away from the surface and into the plasma. The permittivities of the gas and dielectric phases are here represented by \( \varepsilon_1 = 1 \) and \( \varepsilon_2 = 3 \).

3.4. Initial conditions

In the experiments we observed that the streamers started on the rising voltage flank, typically between 20\( \text{kV} \) and 30\( \text{kV} \) instantaneous voltage values. To account for experimental uncertainties as well as natural variations in the statistical time lag in the simulations, we run simulations that start at voltages of 10\( \text{kV} \), 20\( \text{kV} \), and 30\( \text{kV} \) on the voltage curves. These values represent the lowest possible inception voltage (10\( \text{kV} \)) and the typical experimentally observed inception voltages (20\( \text{kV} \) and 30\( \text{kV} \)). The corresponding time lags are shown in figure 4. We do not expect the simulations at 10\( \text{kV} \) to hold much relevance since, at this voltage, the critical volume around the
electrode was extremely small and the probability for inception was therefore also very low.

In all cases we initialize the simulation using a small Gaussian seed of electron-ion pairs near the electrode tip, given by

\[ n_e(x,t) = n_0 \exp \left( -\frac{(x-x_0)^2}{2R^2} \right), \tag{7} \]

where \( n_0 = 10^{16} \text{ m}^{-3}, x_0 \) is the electrode tip and \( R = 100 \mu \text{m} \).

For the ions we used \( n_{O_2^+} = 0.2n_e \) and \( n_{N_2^+} = 0.8n_e \).

4. Results and discussion

4.1. Streamer morphology

Example images of streamer propagation with corresponding plots of voltages, PMT signals, and camera exposure time windows are shown in figures 5–7. The images are 10 ns single-shot frames taken with the HiCAM camera, and each image comes from a different experiment.

Figures 5(b)–(d) show 10 ns snapshots of streamers propagating over a flat surface. Figure 5(b) is taken directly after inception, where the streamer has just crossed the air gap, hit the dielectric surface and started propagating along it. The lower part of the streamer light seen in this image is likely a reflection from the transparent polycarbonate surface of the air gap streamer. The surface streamer is comparatively planar, behaving almost like an ionization wave. However, some branching can be seen in figure 5(c) as the streamer propagates along the surface. In figures 5(c) and (d), air-borne streamers from other parts of the HV electrode start propagating. These do not catch up with the surface streamer, which reach the ground plane in figure 5(d).

Figures 6(b)–(d) show 10 ns snapshots of streamers propagating over a semi-circular profiled surface, with corresponding plots of voltage, PMT signal and camera exposure window, analogous to figures 5(b)–(d). For this surface we found that the streamer descends into the corrugations as predicted by simulations in [16], see figure 6(b), or [17] for a different viewing angle. Another observed effect is the illumination of peaks on the surface profile in the streamer wake, see figure 6(c). Unlike the flat surface in figure 5, the airborne streamers in figure 6 almost catch up with the surface streamer.

Figures 7(b)–(d) show 10 ns snapshots of streamers propagating over a rectangular profiled surface, with corresponding plots of voltage, PMT signal and camera exposure window. It was not possible to conclusively determine whether the surface streamer follows this profile closely, as the profile details are small compared with the imaging resolution. However, the trenches of the profiles are illuminated (figure 7(c)), which suggests that the streamer does interact with the profile. Additionally, illumination of surface profile peaks are again observed in the streamer wake (see figure 7(d)). From long-exposure images shown in [17] we could see that the surface streamer stagnates on rectangular corrugations, and does not reach the ground plane.

4.2. Travel curves

To estimate the streamer velocity we used the SIMX-camera to estimate the location of the streamer head. Since the SIMX camera has 16 channels for single-exposure images, we had up to 16 frames per discharge that we could use for estimating the instantaneous streamer head positions. The streamer horizontal propagation distance in each individual frame was estimated visually from the images with the method described in [16]. Only image series that began with an empty frame were used in the analysis. The temporal uncertainty of the discharge inception is therefore equal to the frame duration, which was varied between 2 ns and 10 ns. We extracted five travel curves for each surface, which are plotted together with the simulation results in figure 8.

Although the SIMX camera provided travel curves with satisfactory temporal resolution, the level of detail in the SIMX images was much lower than for the HiCAM. When analyzing the frames we found that light emission from the surface streamer is strongest close to the electrode, and that it weakens as the streamer propagates along the surface. Comparing SIMX images with the HiCAM images showed that, at least for the rectangular surface profile, some of the empty frames from the SIMX camera contained surface streamers that were too faint to be visible on the SIMX camera. To provide extra data points outside the available range of the SIMX camera, the mean streamer velocity was also estimated from HiCAM images. We measured the surface streamer front position in each image, and estimated the propagation time as the time between the activation of the PMT (which indicates inception) and the closing of the camera gate. These data points are plotted as filled pentagons in figure 8. We point out that the
Figure 5. Example images of streamers on a smooth dielectric surface with corresponding plots of voltage, PMT signal and camera exposure time. Each image is a taken during a different experiment as the HiCAM is a single-frame camera. (a) Sketch of image view. (b) 10 ns camera exposure during streamer inception. (c) 10 ns camera exposure after inception. (d) 10 ns camera exposure towards the last stage of surface streamer propagation.

Figure 6. Streamers on a semi-circular profiled dielectric surface with corresponding plots of voltage, PMT signal and camera exposure time. Each image is a taken during a different experiment as the HiCAM is a single-frame camera. (a) Sketch of image view. (b) 10 ns camera exposure image at inception. (c) 10 ns exposure image during propagation. The PMT was accidentally switched off during this experiment, so no PMT signal is shown. (d) 10 ns exposure when the streamer reaches the end of the plate.

PMT signal has a finite rise time and evaluation of the inception time from this signal has an uncertainty of at least 5 ns. To adjust the accuracy of these measurements we chose the inception time such that the streamer positions for the HiCAM and SIMX cameras were consistent for propagation distances \(d \lesssim 5\) mm. Correspondingly, all the simulation data in figure 8 have a common reference time \((t = 0)\) where the streamers start propagating along the surface.

In general, we found that the streamers propagated faster over the flat dielectric than over the profiled surfaces. In
the experiments with a flat surface the surface streamers propagated with a relatively constant velocity of about \( \frac{2}{\text{mm ns}^{-1}} \), while for the semi-circular profile the mean horizontal velocity was around \( \frac{2}{\text{mm ns}^{-1}} \). For the rectangular-cut surface, the surface streamers did not cross the dielectric and were substantially slower, which is in line with experimental observations reported in [17].

Figure 8 also shows the corresponding velocities obtained from computer simulations. The simulations were performed for streamers starting after time delays \( t_d = 21 \) ns, \( t_d = 33 \) ns, and \( t_d = 44 \) ns to simulate the effect of a first electron time-lag. The curves in figure 8 show the position of the maximum value of the photoionization source term \( \propto k_1 n_e \) for these three simulations. The fluctuation on the simulated travel curves for the profiled surfaces correspond to changes in horizontal streamer velocity as the streamers travel into and out of the surface corrugations.

### 4.3. Propagation mechanism

Next, we discuss the propagation mechanism of the positive streamers over the three surfaces. Figures 9–11 show snapshots of the electric field and the plasma density \( n_e \) for all three surfaces. The data in the figures are taken from the simulation runs that started on 30kV, i.e. a statistical time lag of 44 ns relative to the voltage curve. However, we found that the propagation mechanisms were the same for all three time lags that were investigated for each surface. The largest difference between the different time-lags were the streamer velocities and range, and not overall morphologies. For this reason we do not show corresponding plots for the simulations starting at \( t_d = 21 \) ns and \( t_d = 33 \) ns. We point out that the time labels in the figures indicate the time from the appearance of the starting electron. The temporal location relative to the voltage curve can be inferred from the provided time lags in figure 4. We point out that in all the simulations the maximum electron density was \( \sim 10^{21} \text{ m}^{-3} \), but some figures use a reduced color range for visual clarity.

For the flat surface we find that the streamer propagates in a uniform manner over the surface. As observed in many other computer simulations [5, 7, 16, 17, 34], the streamer is accompanied by a cathode sheath near the dielectric surface. In general, the positive streamer is still driven by ionization processes in the gas, where photoionization provides the majority of seed electrons in front of it. For further details regarding the dynamics of positive streamers over dielectric surfaces, see Li et al [5].

For the semi-circular profile surface we identify the same propagation mechanism as in [16]. The streamer hugs to the surface for the entire propagation, and does not detach from the surface. In addition, propagation from the profile peak and downwards into the pore is generally faster than from the bottom of the pore and towards the top of the profile. For further details on the propagation, see [16] and Wang et al [18].

The propagation mechanism for the rectangular-cut surface differs substantially from the other two surfaces we investigated. Figures 11(a)–(e) show the evolution of the electric field as the streamer propagates from one pore to the next, and figures 11(f)–(j) show the corresponding plasma density. From
these frames we discern two main propagation mechanisms that operate in parallel:

- A primary streamer that propagates upwards out of the initial pore.
- Inception of a secondary streamer, or partial discharge, in the neighboring pore.

In these simulations we find that the secondary streamer fills the pore before the main streamer crosses the profile peak and enters the next pore. This is particularly visible in figures 11(c) and (h). We use the term secondary streamer since this is a new streamer that starts from an initial plasma density that remains well below the threshold for inception. Essentially, the secondary streamer is a partial discharge triggered by arrival of the primary streamer in the preceding pore. Then, as the primary and secondary streamers connect the potential is transferred to the secondary streamer, which continues its propagation as a new primary streamer.

The feasibility of this mechanism depends on the existence of a free electron in the neighboring pore. Unfortunately, our numerical methodology does not allow us to test this in a conclusive way. Our radiative transfer approach is essentially based on a diffusion equation (strictly speaking, an Eddington approximation) [7]. Even when the appropriate absorbing boundary conditions are used [35], the Eddington approximation does not accurately capture shadows. Ionizing
Figure 9. Evolution snapshots for propagation over the flat surface for a time delay $t_d = 44$ ns. Top panel: field distribution around the dielectric surface. (a)–(c) Snapshots of the electric field magnitude $|E|$. (d)–(f) Electron density, clamped to a color map $n_e \in [0, 10^{21}] \text{ m}^{-3}$.

Figure 12 shows the effective ionization coefficient $\alpha - \eta$ for the rectangular profiled surface, clamped to a positive range (i.e. showing the ionization zones). As the primary streamer climbs out of the pore, and the secondary streamer fills it, photo-electrons will appear in the avalanche zone ahead of the primary streamer. These electrons also generate new avalanches and ionizing photons. The ionizing photons are emitted isotropically and their mean free path length is on the order of 500 $\mu$m [36]. Rough geometric evaluations then show that the next pore space is neither completely shielded nor too far away to be reached by ionizing photons. However, we can only conclusively answer this by using discrete photons as in [32], or with a full particle method.

Finally, we conjecture that the re-ignition mechanism is both material and geometry dependent. For example, if the permittivity of the dielectric is raised the field in the dielectric is reduced and an additional voltage drop will occur over the next pore(s), which will facilitate re-ignition. Likewise, increasing the distance between the channels will likely have the opposite effect since the voltage drop over the dielectric increases.

4.4. Modeling uncertainties

Figure 8 shows that velocity trends in both simulations and experiments are in relatively good quantitative agreement. However, exact agreement is not expected since there
Figure 10. Evolution snapshots for propagation over the semi-circular surface profile for a time delay $t_d = 44$ ns. Top panel: field distribution around the dielectric surface. (a) through (e): snapshots of the electric field magnitude $|E|$. (f) through (j): electron density, clamped to a color map $n_e \in [0, 10^{21}]$ m$^{-3}$. 

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Figure 11. Evolution snapshots for propagation over the rectangular surface profile for a time delay $t_d = 44$ ns. Top panel: field distribution around the dielectric surface. (a) through (e): snapshots of the electric field magnitude $|E|$. (f) through (j): electron density, clamped to a color map $n_e \in [0, 10^{20}]$ m$^{-3}$. 
are a number of uncertainties that can affect the computer simulations:

- The simulations are done in Cartesian 2D, but the experiments also exhibit a 3D morphology.
- Streamer branches that start higher up on the disk electrode could affect the surface streamer, but this is not accounted for in the simulations.
- The presence of starting electrons in the various pore spaces is not known.
- In the experiments, the discharge affects the voltage over the test object.

Despite these uncertainties, the agreement between simulations and experiments is quite good. Improvements to our modeling will most likely mandate a fully 3D approach. This is particularly the case if one wants to include the electric circuit into the model, or the secondary streamer branches that initiate from the electrode.

5. Conclusions

In this work, positive streamer propagation over different surface profiles has been investigated. We have performed an analysis consisting of

- High-speed imaging using two different camera systems.
- Fluid simulations in 2D planar coordinates and direct comparison with experiments.

The high-speed imaging showed that we could, at least without introducing drastic modeling errors, approximate the discharges as Cartesian plane waves. We used the imaging to estimate the streamer velocities and ranges for all surfaces, and we observed that the streamers retained their surface-hugging nature also when propagating down into surface corrugations. The streamer discharges were impeded by the surface profiles, where the rectangular cut corrugations restricted the streamer range the most. This surface also had the largest surface area, which could partially explain the result.

We also performed computer simulations which gave comparatively good agreement with experiments. Presumably, part of this agreement arises from the fact that the surface streamers could be approximated as plane waves. Surprisingly, for the rectangular profiled surface the main propagation mechanism was different from the other two surfaces. Rather than finding a single streamer that propagates along the surface, the main propagation mechanism was due to re-ignition of new streamers in the neighboring corrugations.

In summary, we have presented an experimental and theoretical analysis of positive streamer discharges over various types of dielectric surface profiles. Our analysis uses advanced fluid simulations together with experiments, and gives a qualitatively and quantitatively consistent picture of the nature of such discharges. The presented insights on streamer-dielectric interaction over profiled surfaces opens up the possibility to tailor dielectric surfaces for various technological applications involving discharges over solid interfaces.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

H K H Meyer https://orcid.org/0000-0002-9436-6518
R Marskar https://orcid.org/0000-0003-1706-9736

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