Streamer propagation along profiled insulator surfaces under positive impulse voltages

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Abstract

Controlling discharge growth on insulator surfaces is important in high voltage gaseous insulation systems. In this study, the effect of small-scale surface profiles on streamer discharge propagation is examined experimentally. The experimental test objects were 5x72x150 mm polycarbonate plates with and without machined surface profiles. One test object had a surface with 0.5 mm deep semi-circular corrugations, while the other profile had 0.5 mm deep rectangular corrugations. The semi-circular profile increased the surface area with 20 %, while the rectangular profile increased the area with 110 %. A plain surface was also examined as a reference. Positive impulse voltages were applied to a 1 mm thick disk electrode placed 2 mm above the insulator. The insulator was placed in a grounded aluminium casing. The streamer development was imaged with a light-sensitive high-speed camera. Surface charges left on the surface after the impulse were examined using an electrostatic probe and simulations of saturation charge. The rectangular surface profile reduced the streamer range significantly, which suggests an effect of added surface area. Imaging indicated that the wavelike surface streamers follow the profiles closely. Surface potential measurements showed a saddle-shaped distributions, with values in line with saturation charge computations.

1. Introduction

Medium voltage (MV) metal-enclosed switchgear cabinets include several solid insulating surfaces such as supports, shafts and barriers. Discharge behaviour at the gas-dielectric interfaces are often critical for the impulse withstand voltage of these devices. Therefore, replacing the powerful greenhouse gas SF_6 in MV switchgear requires innovative designs for the gas-dielectric interfaces. Discharge propagation near and along insulators is challenging to model, and surface charging of the dielectric surfaces introduces a memory effect that can affect results.

Streamer discharges can result in breakdown of gaseous insulation systems. Streamers form when an electron avalanche reach a critical size, resulting in a self-sustaining discharge mechanism. The space charge from the initial avalanche creates an electric field distortion which results in new electron avalanches. The streamer channel advances as the avalanches in front of it leave behind new space charge closer to the counter-electrode. The condition for streamer inception can be expressed with the integral

$$\int_0^d \alpha_{\text{eff}}(|\mathbf{E}|, P)\mathrm{d}\mathbf{x} \geq \ln(N_{\text{c}}), \tag{1}$$

where α_{eff} is the field- and pressure dependent effective ionization coefficient. Equation (1) is evaluated along a path $\mathbf{x}$ (e.g. a field line) where $\alpha_{\text{eff}} > 0$, starting from the point of maximum field strength and ending where $\alpha_{\text{eff}} = 0$. The streamer constant $\ln(N_{\text{c}})$ is related to the number of electrons N_{c} required for streamer inception. From engineering experience, $\ln(N_{\text{c}}) \approx$ 9-10 can be assumed, see [1] and references therein.

In previous work, the authors showed that small-scale corrugations can delay and inhibit streamer growth on dielectric surfaces [2]. Other researchers also examined the effect for both convex and concave corrugated surfaces of various scales [3]. The simulations in [2, 3] revealed local variations in streamers such as radius and propagation velocity as a result of the surface profile. A semi-circular surface profile with 0.5 mm deep corrugations significantly reduced the range and velocity of streamers in both experiments and simulations in [2]. However, it was shown that the increased surface area does not fully explain the observed streamer suppression. The local geometry of the surface profile played an imporant role in the propagation dynamics. It is also known that streamer discharges are attracted to dielectric surfaces, and that surface streamers are faster than streamers in the surrounding gas [4].

Furthermore, surface charging phenomena affect the surface streamer propagation. Earlier streamer simulations by the authors [2, 5] predicted residual surface charge distributions that were in agreement with charge saturation, i.e. zero normal electric field on the air side of the air-dielectric interface [6, 7].

Streamer ranges are typically estimated with an empirical

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stability field rule: a necessary average field strength required for propagation, typically $E_{st,+} \approx 0.4 - 0.6$ kV/mm for positive streamers along insulating surfaces in air [8]. For negative streamers, $E_{st,-} \approx 1 - 1.5$ kV/mm can be used [9]. Results from [2] demonstrated that the stability field rule is not accurate for profiled dielectric surfaces. The impact of the added area of profiled surfaces on streamer ranges has not yet been systematically investigated.

The aim of the present work is to extend the analysis in [2]. Higher resolution images will be used to examine propagation in the corrugations in detail. Furthermore, a surface profile with a different geometry and greater surface area will be studied. Moreover, the present work will also discuss surface charging aspects based on experiments using an electrostatic probe and surface charge simulations.

2. Methods

2.1. Setup

Figure 1 illustrates the experimental setup, including dimensions of the electrodes and the surface profile details.

Four polycarbonate (Lexan) plate dielectrics of 5x72x150 mm were used as test objects. Surface profiles with 0.5 mm deep corrugations were drilled using a bore head. One profile type had semicircular corrugations as shown in red color in figure 1a and b. This gave a 20 % greater surface area than the plain surface, hypothetically a longer path for the streamer. On another surface, a rectangular surface was machined which had a 110 % larger surface. This surface profile is shown in blue color in figure 1c.

The dimensions of the profiled surface were measured with a Bruker ContourGTK profilometer and averaged, see table 1. Gold sputtering was used to increase the surface reflectivity for these measurements.

An aluminium casing and a disk-shaped brass electrode were used as ground and high voltage (HV) electrodes respectively.

Table 1 – Average measured surface dimensions in figure 1 of the profiled test objects. All units are given in μm.

Semi-circular				Rectangular		
w_c	w_p	d	r	w_t	w_b	h
1718	227	459	974	524	491	546

A voltage step pulse was applied to the disk electrode using an impulse generator which was charged to 35 kV, see figure 2. A resistor in series with the test object limited the discharge energy.

The applied voltage was measured with a capacitive divider a few meters from the test object during the imaging experiments. However, later measurements with a North Star PVM-100 100 MHz 600 MΩ, 15 pF

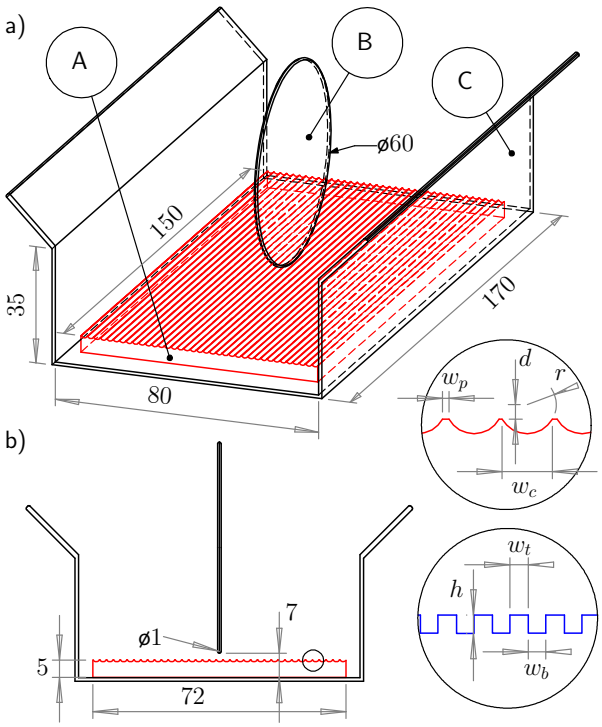

Fig. 1 – Electrodes and dielectric test objects (a) Setup viewed from an angle, showing polycarbonate surface with 0.5 mm circular corrugations outlined in red (A), the HV disk electrode (B) and the grounded aluminium casing (C). (b) Front view, with details showing dimensions of the semi-circular surface profile in red and rectangular surface profile in blue. All indicated dimensions are given in millimeters.

voltage probe close to the test object revealed a fast, ringing overshoot of 48.5 kV_{peak} which was not correctly registered by the capacitive divider. The overshoot is suspected to originate from stray inductances and capacitances from the long lead connections. The rise time (10 to 90 %) was 53 ns, while the impulse half-value time was around 50 μs. The applied voltage shape for the experiments is shown in figure 4. Using a photo-multiplier tube it was also observed that the discharge event led to a small temporary voltage drop of up to a few kV. The surface potential experiments (see subsection 2.3.) were performed in a different lab, where the measured voltage was 35 kV_{peak} and the rise and half-value times were 0.5 and 50 μs respectively.

2.2. High speed imaging

A dual image intensifier camera (Lambert HiCAM 500) with a 300 mm/f2.8 Nikkor lens was used to image streamer propagation along the dielectric surface. The image intensifier was controlled with a gate pulse over a fiber optic link, see figure 2. The on-time of the intensifier was varied from 10 ns up to 1 ms, and was recorded on the oscilloscope via a fiber optic link to the camera. The intensifier gain was also varied, depending on the discharge brightness and intensifier on-time.

The main viewing angle was from the front as shown

in figure 1b and c, with some variations in camera axis inclination. The camera focus plane was set to the part of the disk electrode closest to the dielectric surface. The images were post-processed by enhancing brightness and contrast and by overlaying an illuminated background picture of the setup.

For imaging experiments, the test object was stressed with lightning impulses as shown in figure 2. The discharge initiation was regular, with a variation of a few tens of ns.

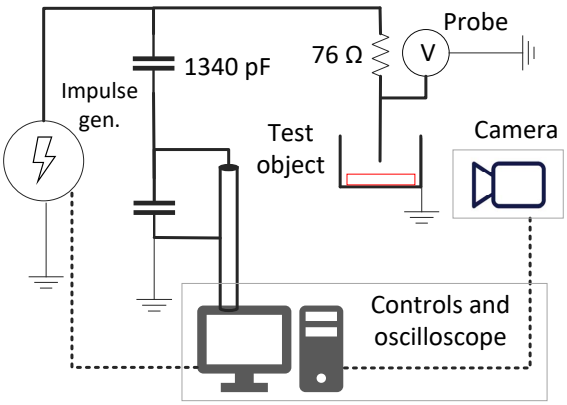

Fig. 2 – Streamer imaging setup. Voltage impulses were applied with a impulse generator to the test object in figure 1. The dielectric surface is highlighted in red. The voltage shape was measured both with a capacitive divider and a high voltage probe. The probe was not connected during the imaging experiments. The broken lines are fiber optic links.

2.3. Surface potential measurement

A Trek 3455ET probe with a 20 kV Trek 341B HV amplifier was used to measure surface potential after a discharge. After the applied impulse, the HV electrode was removed, and the surface potential probe was introduced.

Removing the electrode and placing the probe was done on one side of the dielectric, and the surface charge distribution was likely disturbed by these operations. When the probe was in place, it was moved along the center line of the dielectric plate as shown in figure 3. The probe-to-surface distance was 2 mm. The probe did not scan the entire surface, only around 66 mm, as the probe is operated at high potential and must keep a clearance to grounded parts. The positioning errors were in the range of 2-3 mm.

To remove the residual surface charge after an impulse, a grounded rod was moved along the surface before each impulse for both the imaging and surface potential experiments. For surface potential measurements, the surface was also cleaned with isopropyl alcohol.

2.4. Surface charge calculations

A commercial Finite Element Method (FEM) software (COMSOL) was used to estimate surface charge

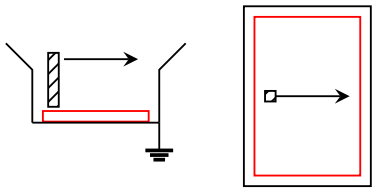

Fig. 3 – Surface potential measurement. A surface probe was placed over the surface and moved with a robot stage along the center line, 2 mm above the surface. Left illustration: front view. Right illustration: top view.

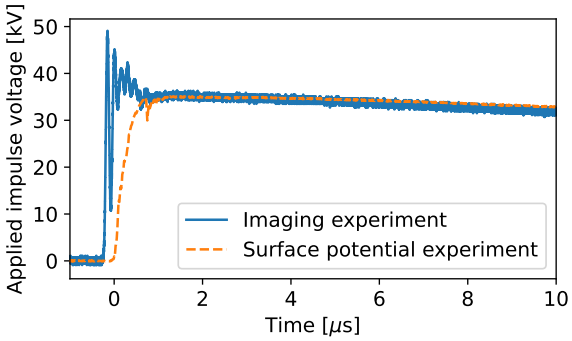

Fig. 4 – Imaging experiments and surface potential experiments were performed in different labs, with different impulse voltage shapes. Note the steep, ringing overshoot in the imaging experiment.

distributions in 2D, see figure 5. Homogeneous Neumann electrical boundary conditions were placed on the left and top side of the domain in figure 5, whereas the bottom and right hand side were electrically grounded. The methodology described in [6, 7, 10] was used to calculate surface charges, while the methodology used for streamer inception (equation (1)) calculation is described in [11]. The approach is summarized below:

1. Calculate saturation charge distribution σ_{sat} (zero normal electric field at air side of the dielectric boundary) at applied voltage peak.

2. Keep σ_{sat} on the surface while reducing the applied voltage until there is streamer inception between the HV electrode and charged surface. The potential difference between the rod and the surface is then U_{res}.

3. Assume that a restrike is initiated and covers a portion of the surface A_{res} given by the empirical streamer range $U_{\text{res}}/E_{\text{st,-}}$

4. Iteratively reduce and redistribute the surface charge on A_{res} so that the normal air-side E-field is constant, until there is no longer streamer inception between the rod and the surface

5. Remove the electrode and extract the surface potential for comparison with experiments

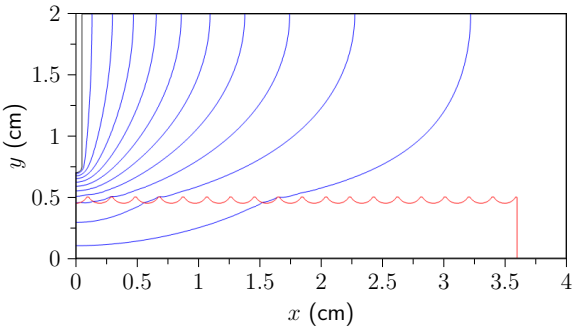

Fig. 5 – Potential distributions in 2D planar FEM simulations, with the high voltage electrode in black, dielectric surface in red, and equipotential lines in blue.

3. Results and discussion

3.1. Streamer propagation

Images of streamer propagation are shown in figure 6, figure 7 and figure 8. All images are separate voltage impulses, as only one image was taken for each impulse. The camera axis inclination was varied as indicated with schematics in figure 6, figure 7 and figure 8.

Streamer propagation on the smooth reference surface is shown in figure 6. Figure 6a is a long-exposure image showing the entire optical activity during the impulse. Figure 6b and figure 6c are 10 ns exposure images at different stages of propagation. In figure 6b, the streamer starts from the HV electrode and starts propagating along it. The streamer crosses the final air gap to the grounded wall in figure 6c. Surprisingly, the surface streamer does not branch, resulting a ring-like symmetric illumination on the surface for short exposure times, as in figure 6c. Streamers in atmospheric air gaps without dielectrics typically show heavy branching, which can also be seen in the airborne streamers near the top of figure 6a. The wavelike streamer behaviour in figure 6 may explain the relatively good correlation with 2D planar simulations that was seen in [2].

In figure 7, the streamer propagation on the semi-circular profiled surface is shown. A more direct front view was used in figure 7a than in figure 7b and c. Figure 7a shows a long-exposure 1 ms image, while figure 7b shows a 50 ns exposure image of the first propagation span and figure 7c shows a 10 ns exposure image of the last propagation span. Figure 7a reveals that the streamer descends in the corrugations, following the surface profile. This finding supports the hypothesis that the reduced surface streamer range on profiled surfaces is an effect of elongated streamer channels. Similarly to figure 6c, a ring-like surface illumination is seen in figure 7c. However, the ring is thinner in figure 7c than in figure 6c as the streamer is slower and stagnating.

The streamer was most strongly restricted by the rectangular surface, figure 8, likely because of the greater surface area of this surface. It was difficult to check optically whether the streamer propagated down in the corrugations for this surface, as the corrugations are small.

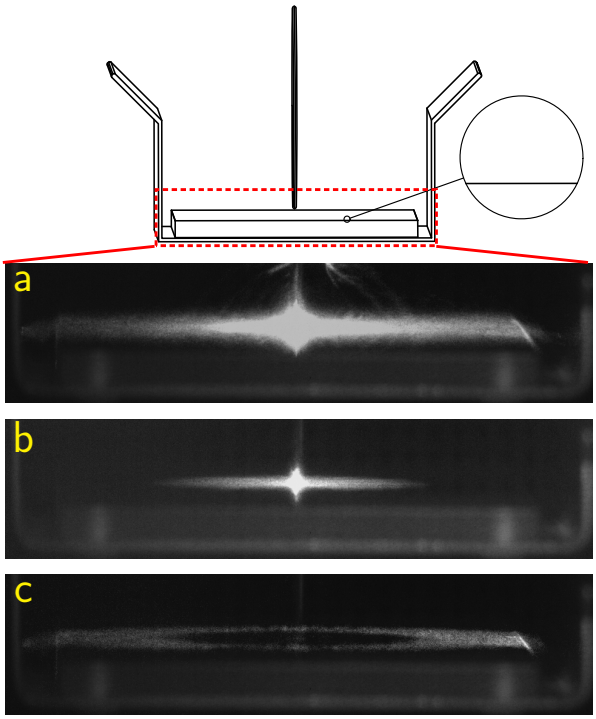

Fig. 6 – Streamers on a smooth dielectric surface. The camera viewing angle is slightly inclined as indicated in the schematic. a) 1 ms camera exposure. b) 10 ns camera exposure at inception. c) 10 ns camera exposure of the last propagation span.

Table 2 – Streamer range estimates from images taken with 35 and 14 kV charging voltage on the different test objects.

	Applied impulse charging voltage	
Profile	35 kV	14 kV
Plain	$\geq$ 40 mm	28 mm*
Semi-circular	31.5 - 40 mm	14 mm*
Rectangular	28.3 mm	-

*values from [2]

The range of the streamer on various profiles was estimated from images, see table 2. Values from [2] are also included. It can be seen from table 2 that both semi-circular and rectangular profiles have a restricting effect on the streamer range.

All the images showed both surface streamers and airborne streamers going out from the HV electrode. However, high speed imaging in [2] showed that the primary discharge event is the surface streamer. The airborne streamers likely come at a later stage, and could come from different parts of the electrode.

3.2. Residual surface potential

Figure 9 shows measured surface potential distributions after applied impulses on barriers with flat profile and semi-circular profile. The surface potential distribution

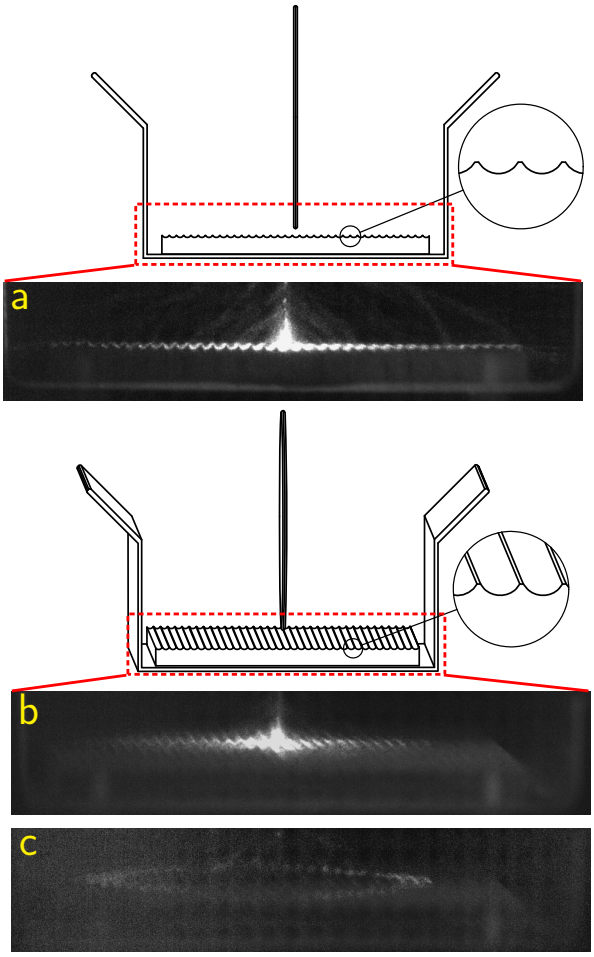

Fig. 7 – Streamers on different dielectric surface with semi-circular corrugations. Two different camera viewing angles were used as indicated in the schematics. a) 1 ms camera exposure, front view. b) 50 ns camera exposure, inclined view. c) 10 ns camera exposure, inclined view.

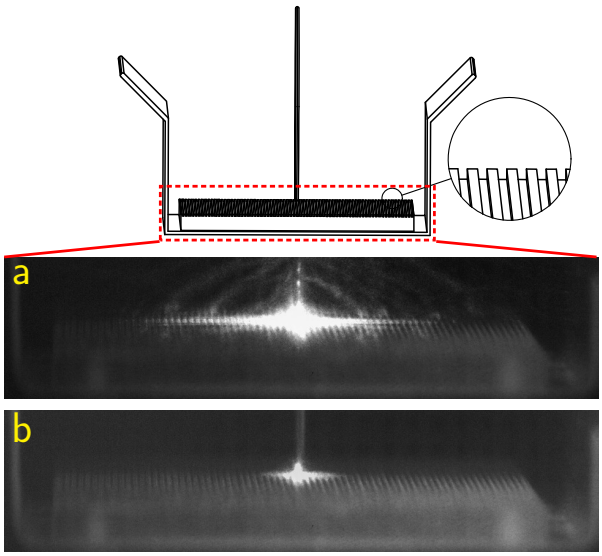

Fig. 8 – Streamers on dielectric surfaces with rectangular corrugations. The camera viewing angle is slightly inclined as indicated in the schematic. a) 1 ms camera exposure. b) 10 ns camera exposure.

is positive with a depression at the center position, which indicates reverse discharges occurring at the tail of the voltage impulse. The simulated surface potential at saturation charge and after a restrike for the surfaces are also shown. The authors have previously investigated this reverse dischage effect with both experiments, electrostatic and electro-hydrodynamic simulations [5, 6, 10].

Streamer simulations in [2] predicted a surface charge distribution for the circular profile with accumulation of surface charges in the corrugations. In figure 9, the surface potential measured on the semi-circular profile does not differ from the measurements on the plain surface. However, the spatial resolution of the probe is probably insufficient to observe the effect of the corrugations. Removal of the HV electrode and positioning the probe likely disturbed the surface charge distribution on the left side, which explains the asymmetry in figure 9.

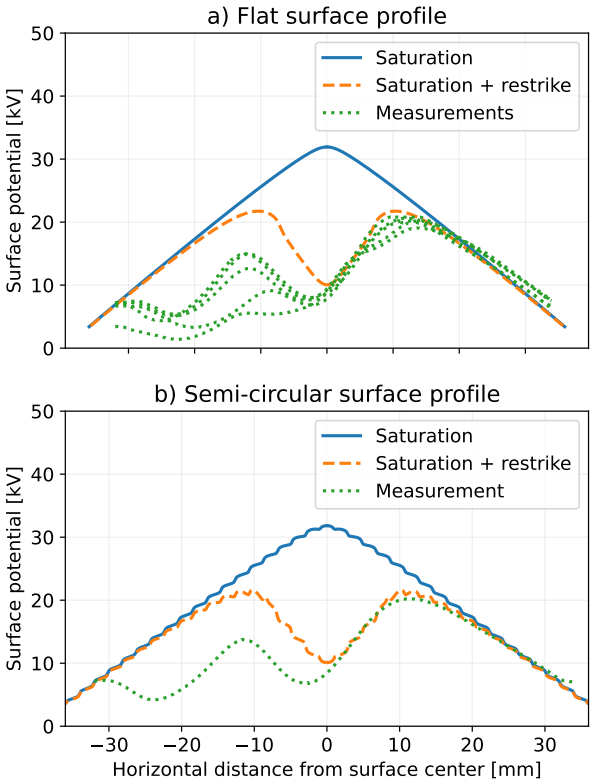

Fig. 9 – Surface potential measurements and calculations after a 35 kV_{peak} impulse on a) plain and b) semi-circular profiled dielectric surfaces. The probe was scanned along the surface from the left to the right. Removal of the HV electrode and positioning of the probe likely disturbed the surface charge distribution on the left side.

The measurements fit relatively good with the restrike calculation for the undisturbed side of the surface. However, there are several error sources:

- Positioning errors of up to 2-3 mm.
- The computations are 2D, while the experiments are

three-dimensional. However, the experimental setup was designed to imitate a 2D field at the center, so the error is expected to be small. This is also supported by the observations of symmetrical, non-branching surface streamers as discussed above.

- Removing the electrode and setting up the surface probe likely disturbed the surface charge distribution in the region where the probe was inserted.
- Time lag of a few minutes between the applied impulse and the measurement, giving time for surface charge relaxation.
- Probe influence on the potential distribution. It was assumed in simulations that the probe is electrically invisible to the surface, as it is driven to the same potential as the surface. The effect of the finite resolution of the probe was also not examined.

4. Conclusion and outlook

In this work, positive streamer propagation and surface charging over different surface profiles has been investigated. The streamers are impeded by different profile shapes. Rectangular cut corrugations with 0.5 mm depth restrict streamer propagation along the surface strongest. This surface had by far the greatest surface area, which could explain the result. Imaging indicates that streamers follow the profiles closely. Moreover, the imaging showed no streamer branching over the plain surface. Surface potential measurements showed a typical saddle-shaped surface potential distribution, with values that agreed well with saturation charge and restrike computations. The saddle-shape was expected, and is a result of reverse discharges between the HV electrode and charged surface at the impulse tail.

The results shown provide new insights to streamer-dielectric interaction, applicable for e.g. engineering high voltage insulation systems.

Acknowledgment

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