BACHELOR

Creeping sparks
stroboscopic and stereo imaging of streamers propagating along dielectric surfaces

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Preface

In this preface, I would to say a few words of appreciation. I would like to thank Gijs Akkermans, whose report helped me a lot to get started and further along the way with my own experiments and research. I would also like to thank Sander Nijdam for his advices and insights, which helped me during the project to get a better understanding of processes behind streamer discharges. I also owe a special thanks to my supervisor Dirk Trienekens, who helped me a lot to get started with my project and also helped me further down the road during the entire research. He did this by means of giving me understanding of the different processes in streamers to providing me with the tools needed to perform data analysis and I can go on for quite a bit with other examples. The point is, he was there to help me when necessary. Furthermore, I would like to thank the group of Elementary Processes in Gas discharges for giving me a warm welcome in the group. At last, I would like to thank Monster Energy ® for providing me with the energy necessary to write this report.
Abstract

In medium and high voltage applications (~20 kV – 1 MV), discharges propagating along the interface between a gas and a solid insulator (dielectric) are often observed. These discharges are (potentially) harmful to equipment and are therefore unwanted. Despite the fact that these so-called creeping sparks are often observed, the physical understanding of this phenomenon is lacking. To improve this understanding and to provide for knowledge-based design rules for MV and HV applications, we investigated the streamers preceding these creeping sparks. In this research, we specifically investigate surface streamers. The measurements on surface streamers are performed in a pressurised vessel with a point-plane gap in which we place a dielectric sample. We investigated the chance of surface streamers along dielectric samples and observed that surface streamers occur at lower pressures in nitrogen (~10 – 100 ppm impurity) compared to ambient air. This is probably caused since less photo-ionisation takes place and serves as an electron source for the streamer in nitrogen than in air, making photo-emission a more important electron source in nitrogen. We also measured surface streamer velocity at TiO$_2$-filled samples of varying thicknesses. We found that increasing pressure decreases the velocity and we distinguished a difference in velocity between different sample thicknesses at lower pressures. A combination of bulk dielectric and surface effects may be the cause. We also distinguished a significant difference in surface streamer velocity between air and nitrogen. Our conclusion is not decisive yet for this phenomenon. At last, we investigated the surface streamer path along a dielectric sample. We observed significantly more correlation in subsequent surface streamer paths in air than in nitrogen, probably caused since surface streamers in nitrogen branch a lot more than in air. This correlation, even in nitrogen, appears to be long lasting.
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1 Introduction

For some time, companies in the high voltage industry, such as ABB, have discovered that at some devices unwanted discharges are occurring in medium and high voltages (20 kV to 1 MV). These discharges, were found to often occur at the interface between a solid insulator and a gas insulator. When the current in this discharge is sufficiently high, it can undergo a transition to a spark. These creeping sparks could lead to damage to equipment, such as transformers and cable terminations. So these discharges are unwanted, yet a physical understanding of this phenomenon is lacking. To improve this understanding and to provide for knowledge-based design rules for MV and HV applications, we investigated the streamers preceding these creeping sparks.

For this research, we will mainly focus in getting a better understanding of surface streamers and why streamers tend to travel along a dielectric surface in the first place. We will therefore perform measurements to investigate the occurrence of streamers travelling along a dielectric surface. We will also be investigating the velocity of surface streamers and what role the presence and properties of a dielectric sample have on the velocity of these streamers in both ambient air and nitrogen. We will also study the path that a streamer follows along the surface of a dielectric sample and distinguish between ambient air and nitrogen here as well.

In this report, chapter 2 will give an overview of the theory about streamers needed for this research that is already known. Chapter 3 will describe the set-up and the experimental methods we will use during our experiments in this research. In chapter 4 the obtained results will be presented and discussed. The conclusions of these results will be explicated in chapter 5, whereas chapter 6 will give an outlook on what experiments could be done in following researches based on our conclusions.
2 Theory

This theory is based on the work done by Akkermans [1]. The reason for this is that our research is a follow-up research of his research.

2.1 Streamers

Streamers are rapidly moving discharges, which can occur in insulating gasses, liquids and solids. A high electric field can cause a streamer discharge to occur in these insulating media. Whereas this high electric field is needed for a streamer inception, it is possible for streamers to propagate into regions where the electric field is considerably lower, namely below the ionisation threshold of the medium. This is because the interior of the streamer consists of a conducting plasma. Inside the conducting plasma, the electric field is largely screened. This can only be the fact, if there is a space charge layer on the edges of the conducting plasma. This space charge layer on the front of the streamer is strongly curved, which causes a significant enhancement of the local electric field, allowing the streamer to propagate.

A streamer, that has crossed the gap of an insulating medium, can undergo a transition to a spark, if the system can provide for sufficient current. One of the differences between these two types of discharges is, namely, that a streamer has a higher electron temperature than ion temperature. In sparks, the temperature of ions is roughly the same as the electron temperature, namely in the range of thousands of Kelvins. Next to this thermal and current difference a transition from a streamer also depends on factors such as pressure, gap distance, electrode geometry, the gas type and pulse duration [2]. In HV applications sparks are to be avoided, for the large currents and high temperatures of sparks may cause short-circuiting, power losses and damage to the devices.

Furthermore, this chapter is minded on streamer inception and propagation. Also, the effects of material interfaces on the propagation of streamers will be discussed.

2.2 Streamer inception

For a streamer to initiate, free electrons are needed in the insulating medium. Due to ionisation by cosmic background radiation this is usually the case. Other sources can be ionisation through radiation of radioactive isotopes in building materials or leftover ionisation from previous discharges. Also, external UV sources may provide for free electrons through ionisation of oxygen molecules. This will be described more explicitly in the paragraph 2.3 together with other means of electrons sources. When a medium like air or nitrogen is exposed to a strong electric field, the free electrons (and ions) are accelerated. Positive ions will move in the direction of the field and the electrons will move in the opposite direction. Background ionisation is explicitly required for streamers to incept, for just strong electric fields, normally used to initiate streamer events, will not be strong enough to cause field ionisation of neutrals.

Electrons will be accelerated much faster than ions in the same electric field, because of the large difference in mass. At some point, the accelerated electron will collide with another particle. The average distance that an electron can travel, before it hits another particle is the mean free path \( \lambda_{mfp,e} \). This distance scales inversely with the particle density of the medium in which the electron travels, thus

\[
\lambda_{mfp,e} \propto n^{-1}.
\]  

(2.1)
When considering experiments, it is more convenient to express this dependency in terms of pressure, scaling linearly with the particle density under constant-temperature conditions considering the ideal gas law. Meaning that the mean free path scales inversely with pressure by means of
\[ \lambda_{mf,p} \propto p^{-1}. \] (2.2)

Now, if the mean free path of an electron is long enough, the electron can accelerate enough to reach a certain kinetic energy, high enough to ionise neutral atoms and molecules upon impact. This impact ionisation creates another free electron and ion, whereby this electron and the collided electron again accelerate to ionise two more neutrals. If the obtained kinetic energy of an accelerated electron is not sufficiently high, it could, instead of ionising a neutral, attach to a neutral to form a negative ion or recombine with a positive ion to create a neutral. These two other effects will cause a loss of free electrons. If the impact ionisation, however, outweighs the other two processes, the number of free electrons and ions will keep on growing and an electron avalanche will form. Figure 2.1 gives a schematic representation of this mechanism. Since electrons gain more kinetic energy with a longer mean free path, impact ionisation increases stimulating the occurrence of electron avalanches at lower pressures. This because the mean free path scales inversely with pressure [2].

Now, the free electrons, created by this avalanche, will be accelerated towards the needle, whereas the relatively heavy ions will remain more or less static in time scales of \( \sim 50 - 200 \) ns. In this way the electric field within the streamer will counteract the outside, screening the inside of the streamer and creating a positive space charge at the end of the discharge. From here on, the electron avalanche turned into a streamer. The difference between these stages is that streamers have the earlier mentioned space charge at the head.
Normally, the aforementioned effect will become important when there are around \(10^8 - 10^9\) free electrons present, according to the Raether-Meek criterion [3], [4].

2.3 Streamer propagation

As mentioned earlier, the transition from electron avalanche to streamer occurs when there are enough free electrons and ions. The charges of these particles act as a conductor and screen themselves from the background electric field. The field will vanish by this means inside the streamer, whereas, in case of positive streamers, the streamer edges will consist of positive charges. Moreover, since the positively charged streamer is strongly curved at the streamer head, the electric field will be highly amplified locally, causing further acceleration of electrons towards the head in that region. This principle is shown in figure 2.2. This, of course, leads to the ionisation of more and more neutrals, due to electron avalanches, whereby the streamer can propagate further. Herewith, it has to be noticed, that in the streamer the particles actually are not moving in the direction of where the streamer itself is propagating. This is because the ions, formed due to electron avalanches, are much heavier than electrons, causing them to remain more or less stationary during the streamer propagation. The movement of the streamer can therefore best be interpreted as an ionisation wave, of which only the front is moving. Notice that there are also negative streamers, these will not be discussed, for they were not investigated during this research.

![Diagram of streamer propagation](image)

*Figure 2.2: Electron avalanches near the streamer head. Electrons from here on accelerate further towards the streamer head and even farther towards the needle.*

The fact that the ions in the streamers are not moving in the propagation direction of the streamer, means that, in order for a streamer to propagate, there always already must be electrons present near the streamer head. Otherwise, electron avalanches needed for the streamer to propagate will not occur.
So, in case of a positive streamer in gas, it is necessary to have some sort of an electron source. The two main sources for these means are background ionisation and photo-ionisation.

Background ionisation is ionisation that is already present in the gas before the initiation of the streamer. There can be different sources for this background ionisation. Some of them are constant, like radiation of various sorts such as radon, present in ambient air through building materials and cosmic rays. Another form of background ionisation is leftover ionisation remaining from previous discharges. This is a kind of ionisation that has to be taken into account with repetitive pulsed discharges. The leftover ionisation is proportional to the repetition rate of two subsequent discharges and is found to still be very significant for a repetition frequency of 1 Hz [2]. It could be expected that there is also a certain space-dependency on leftover ionisation. In short time scales we can expect that the ionisation is mainly paled to the streamer path. On longer time scales, thus low repetition frequencies (order of magnitude of 1 Hz), we would expect the ionisation level to be more homogeneously due to diffusion throughout the vessel [5]. There are also some other ways to provide for a certain level of background ionisation, but these methods are inapplicable for the research that is to be discussed.

Another possible electron source for a streamer can be caused by the streamer itself, namely photo-ionisation. If you consider ambient air, the photo-ionisation is induced when an excited nitrogen molecule falls back to its ground state, emitting a UV-photon with wavelengths below 102.5 nm. UV photons with these kinds of wavelengths are able to ionise an oxygen molecule:

\[
\begin{align*}
N_2^+ &\rightarrow N_2 + \gamma_{\leq 102.5\text{ nm}} & \text{(2.3)} \\
O_2 + \gamma_{\leq 102.5\text{ nm}} &\rightarrow O_2^+ + e & \text{(2.4)}
\end{align*}
\]

For this local effect to be a significant contribution as an electron source, the photons have to be created very close to the streamer head, for the travel distance of UV photons is dependent on the density absorbing species, oxygen in this case. In air at atmospheric pressure, this mean free path of the UV photons is about 1.3 mm [7]. However, if the electrons are released too close to the streamer head, they will not be accelerated enough to cause for sufficient subsequent electron avalanches. This means that enough free electrons will be present in front of the streamer head to further propagate. They could then, for example attach to an oxygen molecule, or recombine with a positive ion into a neutral particle.

### 2.4 Similarity laws

Similarity laws, commonly used for gas discharges for different pressures of the gas, hold particularly well for streamer discharges, especially in the propagating head. This is because these processes are fast and dominated by collisions between free electrons and neutrals. Given this fact, it is implied that the mean free path of a free electron compares with the length of the streamer discharge,

\[ l \propto \lambda_{mfp,e}. \] (2.5)

In the paragraph about streamer inception we already discussed that this mean free path of an electron scales inversely with pressure. Furthermore, if electrons gain the same energy while accelerated, the streamers are similar.
This means that the reduced electric field, at constant $T$, is

$$E/n = \text{constant.}$$  \hspace{1cm} (2.6)

Since the number of particles $n$ scales linearly with pressure $p$ the reduced electric field can also be formulated as

$$E/p = \text{constant.}$$  \hspace{1cm} (2.7)

From this fact, it follows that for similar streamers, the velocity does not scale with pressure, meaning that time scales in streamer events should scale inversely with pressure, correspondingly

$$\tau \propto \frac{L}{v} \propto p^{-1}.$$  \hspace{1cm} (2.8)

The described similarity laws only hold for certain conditions. There are, however, processes that have to be taken into account and that have to be corrected for.

For one, there are multiple-particle processes. For this case, the similarity laws will no longer hold, if reactions of two particles or more start to dominate the discharge. If the processes are only significant, but non-dominant, then corrections on the laws can be applied.

Secondly, there are stochastic effects that can have an important role on discharges. This happens mainly when the charge densities are very low in certain media. Stochastic effects will then cause streamers to branch a lot as the discharges tend to follow the free electrons, which are mostly randomly distributed in gasses with low charge densities. Also, a dielectric surface, present near a discharge will break with the similarity laws, as stated above. This is because electrons are likely to collide with the surface and charge it, increasing the chance for a streamer to travel along the surface. This means that we are not dealing with solely a gas discharge, thus breaking the similarity laws. It is mostly these three processes that could break with the described similarity laws in streamer events.

### 2.5 Surface and interfacial effects

Considering a propagating streamer, some other effects, other than the earlier mentioned ones, can come into play at an interface between two media. Some processes in view of streamers propagating in air or nitrogen nearby a solid dielectric tend to be very important and are described in this paragraph.

#### 2.5.1 Polarisation

If an external electric field is applied on a neutral atom, the electrons will be pulled from the nucleus of the atom. When the electric force, induced by the electric field, equals the attractive force between the nucleus and the electrons, a state is reached in which the atom has become fully polarized. Yet, it has to be noticed that lower values of the electric field, thus force, may still cause some polarisation to happen, be it not causing total polarisation. The positive charges will then have been moved in the direction of the electric field, where the electrons will have been pulled towards the opposite direction. The same holds for nonpolar molecules. In a dielectric, these electric field induced dipoles will all realign with the present electric field.
The same will happen when the dielectric consists of permanently polarized molecules. The result is the same: the material gets polarized. This polarization of the material counteracts the electric field inside the material. A measure of the counteraction of the electric field inside the material is given by the relative permittivity of the medium $\varepsilon_r$. This parameter depends on the electric susceptibility $\chi_e$ by means of

$$\varepsilon_r = 1 + \chi_e,$$  \hspace{1cm} (2.9)

which may vary with the electric field strength and frequency if the dielectric is nonlinear [8].

The higher the relative permittivity of the dielectric will be, the more it will decrease the electric field inside the material. However, the overall potential drop in the gap stays the same, meaning that the electric field outside the material will (locally) be enhanced, whereby the field lines slightly bend towards the surface. This effect, of course, depends a lot on the geometry of the set-up, such as the placement of the dielectric sample. Furthermore, it is found that at so-called triple point junctions, points where the conductor, dielectric and surrounding medium are in contact, polarisation in the dielectric can cause a largely enhanced electric field in the surrounding medium [9]. When considering streamers, one could imagine that the triple point junction, in this case formed by the streamer, dielectric and air/nitrogen, the electric field in front of the streamer in air or nitrogen is enhanced due to the polarisation in the dielectric. Also, the relative permittivity and the thickness of the dielectric influence this electric field enhancement [10].

### 2.5.2 Photo-emission

In the paragraph about streamer propagation we discussed how photons can ionise oxygen in air and thereby provide for free electrons. The same can happen, when an excited neutral particle in the streamer head emits a photon near a dielectric. If the mean free path of this photon is long enough to reach the dielectric surface and collide with it, an electron can be freed. This electron then, may cause a new electron avalanche towards the streamer head if close enough to the streamer head. The difference, between both forms of processes, is that the ionisation energy of oxygen is 13.6 eV, whereas most dielectrics have a work function of 5-10 eV. However, the work function of the electrons might be low for dielectrics, the quantum yield at the energies around the work function is very low. Jorgenson et al. simulated and measured this quantum yield and found that, between photon energies of 5-10 eV, the quantum yield is varying a lot, from $10^{-8}$ to about $5 \times 10^{-4}$ for Teflon [11]. Experimental data for other materials is lacking. However, considering the mean free path of electrons needed to increase their kinetic energy, one could imagine that photons with these lower energies are more likely to be emitted than the ones with energies high enough to ionise oxygen. It has to be noted though, that the process of kinetic energy increase of electrons is pressure dependent. Still, a lot of mostly low-energy photons, emitted by the neutrals near the streamer, hit the surface whereby the low yield is compensated for. Furthermore, the mean free path of the lower energy photons is also longer in air and nitrogen than the higher energy photons

$$\lambda_{mf,p,5-10 \text{ eV}} > \lambda_{mf,p,13.6 \text{ eV}},$$ \hspace{1cm} (2.10)

making it more likely for these photons to hit the surface [11].
Electrons emitted from the dielectric leave behind a net positively charged surface. As told before, the freed electrons can provide for streamer propagation, when they create further electron avalanches towards the streamer head. There are two cases here. If the streamer head is close enough to the surface, the remaining charges can support the streamer propagating near or along the surface. However, if too close to the surface, the mean free path of the electrons again becomes too small to cause electron avalanches towards the streamer head. If the streamer head is further away of the surface, though, it may as well be that the streamer will be repelled by the remaining positive charge of the surface.

However, there is another effect that comes into play called secondary electron emission, which will be discussed next.

### 2.5.3 Secondary electron emission

Free electrons can collide with the dielectric surface. What can happen then, is that electrons attach to the surface, charging it negatively. The electrons can also backscatter or release another electron from the surface, leaving it positively charged. All of these effects are referred to as secondary electron emission, however only the latter process can technically speaking be called secondary electron emission. It is found that, when few electrons are present, secondary electron emission causes electrons to attach to the surface, charging it negatively [11]. Now, when a streamer discharge is taking place, the effect of photo-emission still causes electrons to be freed from the surface. These freed electrons can still cause electron avalanches to occur. At the beginning of the electron avalanches, the thermal velocity of the electrons is often still higher than the drift velocity. For this reason, the electrons may collide with the sample surface, charging it negatively due to secondary electron emission. This is described as the sink effect. This sink effect will be reduced when the surface becomes negatively charged to an extent in which the electrons will be repelled from the surface. Hence, this sink effect is also counteracted by the process of photo-emission. However, it is speculated by Jorgensen et al. [11] that the photo-emission effect only will start to have a contribution to electron avalanches promoting streamer propagation near or along the dielectric surface, when the surface is (negatively) pre-charged. Otherwise, the earlier described sink effect of the secondary field emission will dominate over the effect of photo-emission and the subsequently following electron avalanches. Furthermore, Verhaart et al. [12] noted that, in nitrogen, the photo-emission effect was not even observed if the dielectric surface had no net charge or a positively charged surface.

### 2.5.4 Field emission

It may be that a sufficiently high electric field can liberate electrons from the sample surface. The surface will stay positively charged here as well. This field emission is made possible by the fact that the work function of electrons in dielectrics is relatively low. Together with the greatly enhanced field caused by triple point junction where the streamer travels along the surface, this effect might be playing a role in the case where the sample surface is already negatively charged via secondary electron emission.
3 Experimental set-up

At first it must be noticed, that the experimental set-up used to study streamers along dielectric surfaces in air and nitrogen is to a large extent the same as the one Akkermans [1] described in his Bachelor Thesis. Therefore, the experimental set-up that we will describe in this chapter, will be partially based on the experimental set-up that Akkermans described.

We have a high voltage (HV) pulse generator providing for the positive high voltage pulse needed for the streamer to incept. We work with a gap that has a point-plane geometry with an anode needle tip as the point part of the gap and a grounded cathode plate as the plane part of this geometry. Between this plate and the needle we place a variety of dielectric samples. The discharge gap is situated in a pressurised stainless steel, cylindrical vessel (height 60 cm, diameter 50 cm). To image the discharges, a PicoStar HR12 ICCD camera is used. In some of our experiments we applied stereo photography to study streamer behaviour along dielectric surfaces. The complete set-up will be discussed in the following paragraphs.

3.1 C-supply

In our set-up a C-supply is used to provide for the high voltage pulse. Figure 3.1 shows a schematic image of the electrical circuit forming this C-supply. In this C-supply a 1 nF capacitor is charged by a negative DC high voltage source, namely the Kilovolt Company HV power supply. It is capable of producing a voltage as low as -30 kV. In the circuit, a trigger signal is used to ignite a spark gap. As the spark gap ignites, it swiftly grounds the left side of the capacitor through resistor $R_2$, providing for a positive high voltage on that side. This voltage is then transferred to the anode needle tip, hence it is connected to this side of the capacitor.

![Figure 3.1: A schematic image of the electrical circuit of our C-supply. Most of the time the voltage, applied to the needle was 20 kV, as is shown in this figure, however this varied for some experiments. The rise and fall time are determined by the resistors $R_2$ and $R_3$. Image taken from [1].](image)

It is desirable to make sure that the voltage pulse has a short rise time in order to properly study streamer discharges. Nijdam et al. [2] found that streamers may exhibit...
properties of lower voltage, if inception and propagation takes place before the maximum voltage is reached. For this reason $R_2$ is chosen to be small ($R_2 = 100 \, \Omega$). If we choose $R_2 = 0$, however, we will observe large oscillations in the voltage pulse, which is not desirable. The resistance of $R_3$ has to be chosen in such a manner, that the pulse remains sufficiently high for the complete duration of the streamer even, which is $\sim 50 - 200$ ns. Yet, it must be averted that a transition from a streamer into a spark occurs, for sparks could cause damage to the sample or the needle for instance.

3.2 Pressurised vessel

We fill a metal vessel with air or nitrogen at pressures ranging from 40-225 mBar. The reason for measuring at lower pressures, is that we then are able to investigate streamer processes at longer length- and timescales conforming the similarity laws discussed in paragraph 2.4. An overview of the vessel in which we realised these pressures, is shown in figure 3.2. The vessel is cylinder-shaped with a 60 cm height and an inner diameter of 50 cm. A high voltage feed-through is fitted at the top of the vessel and has the anode tip connected to it. The grounded cathode plate is fixed on the opposite side of the vessel which is also grounded. As can be seen in figure 3.2 there are two windows present in the vessel. The front window consists of regular glass, allowing the experimenter to look inside the vessel, while the window on the side of the vessel is a quartz window which is transparent to near ultraviolet light. The camera is positioned towards the latter window. This is because the discharge mainly produces light in the near UV region [2], so in order to properly image the discharges, it is important that this near UV light passes through our window.
Figure 3.2: An image of our vessel made with Autodesk Inventor. In this figure, a quarter of the vessel is cut out to the viewer to see the inside. In this image, an epoxy resin rod sample is placed in the discharge gap. Other samples were used as well.

A gas handling system allowing manual filling and evacuating of the vessel is present. This system allows us to fill the vessels with ambient air or nitrogen at reduced pressures. The impurity of the nitrogen is specified at 10 ppm, indicating the maximum amount of impurities (oxygen, water and other gasses) present. Under ideal circumstances this purity would be the same in our vessel. However, opening the vessel to introduce new samples, inevitably introduces impurities in the vessel.

We use a Pfeiffer Duo 5 Rotary Vane Pump to evacuate our vessel, specified at an ultimate pressure of $2 \times 10^{-2}$ mBar. We first evacuate and flush the vessel with nitrogen to reduce impurities before we perform experiments. Ultimately, we assume that our experiments in nitrogen are performed at $\sim 10 - 100$ ppm impurity.
3.3 Dielectric samples and their placement

ABB has provided for several different dielectric samples. The ones we have are an epoxy resin rod with a relative permittivity $\varepsilon_r = 4$ and epoxy resin slabs with different fillers. Table 3.1 shows what kind of samples we use in our experiments.

Table 3.1: The different kind of samples with their relative permittivities $\varepsilon_r$ and thicknesses $D_{\text{sample}}$.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>$\varepsilon_r$</th>
<th>$D_{\text{sample}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin rod</td>
<td>4</td>
<td>4 Ø x 15</td>
</tr>
<tr>
<td>SiO$_2$-filled</td>
<td>4</td>
<td>2 x 30 x 150</td>
</tr>
<tr>
<td>TiO$_2$-filled</td>
<td>8</td>
<td>2 x 30 x 150</td>
</tr>
<tr>
<td>TiO$_2$-filled</td>
<td>8</td>
<td>4 x 30 x 150</td>
</tr>
<tr>
<td>TiO$_2$-filled</td>
<td>8</td>
<td>10 x 30 x 150</td>
</tr>
</tbody>
</table>

Values for relative permittivities were provided by ABB and measured using dielectric spectroscopy.

The width and the height of the SiO$_2$-filled sample and the TiO$_2$-filled sample are the same, namely 150 x 30 mm. The metal holders of the samples are grounded and placed on the cathode plate in the vessel. In case of the slab-like samples, the vertical distance between the anode tip and the top of the sample is $h = 7.1$ mm. For the epoxy rod this is $h = 8.5$ mm. The rod was always centred directly under the needle as shown in figure 3.2, whereas the other samples were sometimes displaced horizontally with respect to the shortest side of the sample with a displacement $d = D_{\text{sample}}/2$, whereby the displacement $d = 0$ mm corresponds with the centration of the sample directly under the needle, as figure 3.3 depicts.

Figure 3.3: Two possible ways of positioning the sample. The right part of the image shows what the samples look like. On the left is shown how the samples are placed with respect to the needle.
3.4 Stereo photography

Since 2D imaging of streamers inherently leads to a 2D projection of the imaged streamers on the image plane, it can be hard to identify if a streamer is propagating along the surface or if it is moving (partially) normal to the image plane. To exclude false identification of gas streamers as surface streamers, stereo photography is used. By looking at the discharge from two different angles simultaneously, and creating an overlay of these images, we can deduce whether or not a streamer propagates along the dielectric surface. Figure 3.4 gives a schematic overview of this method.

![Schematic diagram of stereo photography set-up.](image)

**Figure 3.4:** A schematic image of the stereo-photography set-up. In this set-up the sample is positioned in such a way that we look parallel to the sample surface, thus facing the shortest side of the sample. The same set-up holds for looking perpendicularly at the sample, however, then the sample will be rotated by 90° counterclockwise.

There are two configurations in this way to think of by means of the positioning of the sample. In one of the configurations the sample is looked upon in a parallel manner, facing the shortest side of the sample, whereas in the other configuration we look to the sample perpendicularly, facing the broadest side of the sample. Figure 3.5 shows both these configurations as observed by the camera. While measuring through stereo-photography, we centred the sample under the anode tip as depicted in figure 3.3 ($d = D_{\text{sample}}/2$).
Figure 3.5: Reference images of the two different stereo photography configurations made with the PicoStar HR12 ICCD camera. The left image (a) shows the sample position in the stereo photography set-up when looking parallel to the sample surface. The same goes for the right image (b), only that the sample is now rotated 90° so that we look perpendicularly at the sample surface.

To accomplish the mentioned configurations, the sample and the mirrors have to be placed under certain angles. To determine these angles, we will now look at only the right side of the set-up, whereas at the left side, the mirror angle will be similar to the right side conforming the bilateral symmetry of the stereo photography part of the set-up. For the first configuration, we made sure that we were looking exactly perpendicularly to the shortest side of the sample. Afterwards, we determined the angle $\alpha$ at which the sample was placed, by measuring the distance from the corner of the sample to mirror 1 and the distance of mirror 1 to mirror 2, after which we took the inverse tangent of these distances and found that the sample angle was about $\alpha \approx 82^\circ$. This angle is with respect to the x-axis, if the optical axis of the camera is chosen to be the y-axis and if the x-axis is the axis perpendicular to the optical axis of the camera. The angle $\theta$, at which the mirror is placed, is found to be $\theta \approx 41^\circ$ with respect to a y-axis. The way we determined the angles is schematically shown in figure 3.4. It has to be noted that the distances, required in determining the sample angle, need to be measured from the same spot of mirror 1.

### 3.5 ICCD camera and pulse triggering

The main diagnostic of our set-up is a stroboscopic intensified CCD (ICCD) camera. Excited neutrals in the streamer head emit photons in the wavelength range of violet and ultra-violet, which can be measured via the LaVision Picostar HR12 ICCD camera. This camera used in these experiments enables us to image the streamers at very short intensifier gate widths (down to 200 ps).

For our experiments we use a repetition rate of 1 Hz, meaning that the time between two discharges is one second. This time is considerably longer than the time-scale of a single discharge. A standard ICCD camera would only be able to make just one picture of a single streamer event, showing image integrated over the entire time that the intensifier input is high, whereby information about the streamer head within the time the intensifier gate was low would be lost. For this reason, we use a stroboscopic ICCD camera.
We use an exposure time for our camera in the order of milliseconds, yet we gate the intensifier with a 50 MHz frequency pulse train of which the number of pulses can be adjusted. Standard ICCD cameras are not capable of doing so. This way of gating the camera will result in stroboscopic images, where the maxima in measured light intensity, each 20 ns apart in time, will indicate the position of the streamer where emission was the highest at this time. Generally, this will be the streamer head.

The triggering of our camera in our set-up is schematically shown in figure 3.6. In our set-up, we trigger our spark gap at first, the voltage pulse will then arise, after which the discharge will follow soon after a short amount of jittered delay. The way the camera exposure is timed, is shown in figure 3.6. Typical exposure times are \(~20\) ms. The intensifier will be triggered together with the spark gap. A delay time is then chosen in such a way that the intensifier signal is high during the discharge. The P400 makes sure that the pulse train, sent to the intensifier, is delayed with this designated delay time. In our experiments, this delay time varies roughly from 1700-1830 ns. The main reason that the delay time needs to be varied over this wide range, is because the jitter on the delay between the spark gap ignition and the voltage pulse, as well as the jitter on the delay between the voltage pulse and the actual discharge may vary a bit (\(~50\) ns). Varying the delay time may therefore prevent data loss, that occurs through jitter by mistiming of the intensifier or camera exposure with respect to the streamer discharge.

![Figure 3.6: The triggering of the ICCD camera. This diagram explains the timing. After the spark gap is triggered, the HV pulse will form after a certain delay time. The delay for the HRI is therefore set to this same delay time. The camera exposure (not to scale here) is chosen to be \(~20\) ms.](image)

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Through LaVision software, we controlled the programmable timing unit (PTU) which provides for the initial trigger for the system. This trigger signal triggers both the CCD array and the Highland P400 delay generator. The P400 has two output signals: one to trigger the voltage pulse and the scope, whereas the second signal is sent to a TU/eDACS HRI intensifier controller unit, which converts the pulse into a pulse train with an adjustable number of gates. This pulse train will arrive at the Kentech Instruments high rate imager (HRI) after the designated delay time, ultimately triggering the intensifier of the camera. A schematic overview is given in figure 3.7.

![Schematic diagram of the camera system](image)

Figure 3.7: A schematic overview of the camera system [1]. In the case of the non-stroboscopic set-up, the TU/eDACS HRI intensifier controller is replaced by a function generator.

In this set-up we also measured the anode voltage and the cathode current. A Northstar PVM1 high voltage probe with a standard divider ratio of 1000:1 is used to measure the mentioned anode voltage, whereas a current shunt with a resistance of 60 Ω ($R_4$ in figure 3.1) is used to measure the cathode current [1].

### 3.5.1 Non-stroboscopic set-up

In most of our experiments we used the above described set-up. However, in some of them we altered the set-up a bit, so that we were able to make non-stroboscopic images with the intention of studying the streamer path along the sample. For this purpose, one gate of 100-170 ns was used to trigger the HRI.
4 Results

The results, achieved in our experiments, will be explained and discussed in this chapter. Firstly, we will discuss the probability for a streamer to travel along a dielectric surface. We will do this for various samples and we will distinguish between air and nitrogen and look at the correlation between subsequent discharges. Then, we will discuss the velocities of streamers along dielectric surfaces of varying sample thickness. We will verify these measurements using stereo photography.

Thirdly, we will investigate the path that a streamer follows on the surface and for this path we distinguish between air and nitrogen. We will also investigate the voltage amplitude dependency of the streamer path.

It has to be noted that, in the case that we see the occurrence of a surface streamer, there still are streamer branches in the ambient gas. However, we will mainly focus on the properties of the streamers propagating along the surface. Furthermore, for all our measurements we have worked with a repetition rate of 1 Hz between subsequent discharges. Also, in all of our measurements the voltage was kept at 20 kV, unless it is explicitly stated differently.

4.1 Surface streamer probability

4.1.1 Probability in air and nitrogen

The first measurements that we performed, were follow-up measurements based on measurements that Akkermans performed [1]. We, for example, measured the probability of streamers travelling along the surface of the SiO$_2$-filled sample, described in table 3.1 of paragraph 3.3. Our experiments we performed in nitrogen, whereas Akkermans performed his in air. In air it turned out that, for a displacement of $d = 0$ mm, no surface streamers were observed [1]. In nitrogen, however, this actually is the case as shown in figure 4.1. The most probable cause for this observation is the fact that in pure nitrogen there is no photo-ionisation serving as an electron source for the streamers. However, the nitrogen in our vessel is no pure nitrogen and has an impurity of ~10$^{-100}$ ppm, as explained in paragraph 3.2. Yet, we still believe that in nitrogen the dielectric sample is a more important electron source through photo-emission than in air. This causes the streamer to deviate more from the electric field lines in nitrogen than it would do in air. Nijdam et al. also found that streamers can deviate from the electric field lines in nitrogen if more electrons are present elsewhere [13].

A small side note has to be made in the comparison with Akkermans’ measurements though, since in his set-up the dielectric sample was placed about 16.5 mm underneath the needle, whereas in our set-up this distance is 7.1 mm. We observed that the vertical distance from the needle tip to the top of the sample does influence the occurrence of surface streamers, although we did not quantify this. However, this can be reasoned since the presence of the dielectric affects the electric field quite a lot and the positioning of it influences the curvature and shape of the electric field lines. So the results we obtained are not completely comparable with the ones Akkermans found. Still, we believe that the outcome of our measurements can be linked and compared with the results Akkermans obtained, because we did observe surface streamers in nitrogen, where they were not travelling along the surface in air.
To quantify the observation of surface streamers in nitrogen, we looked at 500 subsequent streamer images and determined whether a streamer was travelling across the sample surface or not for all of these images. The results of these measurements are shown in figure 4.2. Here, we defined $P_{\text{Surface}}$ to be the chance of it as

$$P_{\text{Surface}} = \frac{n_{\text{surface}}}{n_{\text{total}}},$$

(4.1)

with $n_{\text{surface}}$ the total number of times that a streamer travelled along the dielectric surface and $n_{\text{total}}$ the total number of measured discharges. We also looked at the chance to observe a surface streamer subsequent to an earlier streamer along the surface and called this $P_{\text{ss}}$ and defined it to be

$$P_{\text{ss}} = \frac{n_{\text{subsequent}}}{n_{\text{surface}}},$$

(4.2)

with $n_{\text{subsequent}}$ the number of times that a surface streamer followed up another surface streamer. In figure 4.2 this chance is shown by means of the red dots. As can be seen in the graph, the chances do not differ and when we define a correlation $P_{\text{ss}} - P_{\text{Surface}}$ we see that there is actually almost no correlation. This basically means that the chance of observing subsequent surface streamers is equal to $P_{\text{Surface}}$. Note that $P_{\text{ss}} - P_{\text{Surface}} > 0$ would mean that the occurrence of a surface streamer would influence the behaviour of subsequent streamers, causing an increased chance for them to travel along the surface as well. Another possibility is that $P_{\text{ss}} - P_{\text{Surface}} < 0$, meaning that a streamer propagating along a surface decreases the chance of a subsequent streamer to also travel along the sample surface.
At the Centrum voor Wiskunde & Informatica (CWI) in Amsterdam a model for streamer propagation near dielectric surfaces was developed. Since this model is restricted to cylindrically symmetrical configurations, we repeated the described measurements with an epoxy resin rod sample in both ambient air and nitrogen. Despite the differences in geometry, similar results are obtained. We still do not observe surface streamers along the sample in air, whereas in nitrogen we do observe this, starting from a pressure of 180 mBar. The results of the measurements in nitrogen are shown in figure 4.3. In air we did not observe any surface streamers. Preliminary results from the model developed at CWI pointed out that surface streamers where also observed in nitrogen and also not in air [17].
Some annotations have to be made to these results. We measured up to higher pressures in nitrogen. This is the case, because, in nitrogen, we can still observe streamers at higher pressures for the same repetition rate of 1 Hz. The reason for this is that, in air, free electrons get attached to oxygen molecules, creating $O_2^-$ ions. At a certain pressure, not enough free electrons are present for discharge inception. In nitrogen we still have some contamination, meaning that there are also still some oxygen molecules in the nitrogen gas. So this effect will also play a small role in our set-up in nitrogen. Together with electrons attaching to oxygen molecules, recombination of an ion and an electron into a neutral particle can occur in both air and nitrogen. Kossyi et al. studied these causes of electron loss as well as the ionisation via electrons in a quantitative manner [14]. Starting from a certain pressure, a streamer will not incept anymore since eventually, the mean free path of an electron will become too short for an electron to reach the kinetic energy needed to cause an electron avalanche at a constant voltage. Another thing that stands out in figure 4.3 is the high surface streamer chance in nitrogen at 180 mBar. The cause of this observation is unclear.

4.1.2 Probability for varying sample thickness

We also investigated the surface streamer chance for TiO$_2$-filled samples. Therefore we did the same measurements as described above for these new samples of varying thickness. In this case, we made sure that, for all the samples with varying sample thickness, the surface was at the same position for every measurement. Therefore, the plane of the sample surface was set to coincide with the needle tip of the anode. For each sample, this means a displacement of $d = D_{\text{sample}}/2$, where $D_{\text{sample}}$ is the sample thickness. We performed the probability measurements only for the samples with the thickness of $D_{\text{sample}} = 2, 4$ and $10$ mm. It became clear that for the sample of $10$ mm thickness, surface streamers were always occurring for the entire pressure range. Therefore, we only show the quantitative results of the measurements of the surface streamer chance for the samples with the thicknesses $D_{\text{sample}} = 2, 4$ mm in figure 4.4.

![Figure 4.4: In the left graph, the chance of surface streamers travelling along the TiO$_2$-filled sample with a 2 mm thickness is shown. The similar plot is also shown in the right graph for the TiO$_2$-filled sample with a thickness of 4 mm.](image-url)
4.2 Surface streamer velocities

4.2.1 Different sample thickness

We also compared velocities of the surface streamers in both air and nitrogen at pressures starting from 100 mBar for different sample thicknesses $D_{\text{sample}}$ while displaced so that $d = D_{\text{sample}}/2$. This because the above displayed measurements point out that from 100 mBar surface streamers are always present along the surface in air. Therefore, this must also be the case for nitrogen, since surface discharges are more likely in nitrogen.

At first, we performed measurements in air for samples with varying thicknesses, namely $D_{\text{sample}} = 2, 4, 10$ mm, to study if this would make for significant differences in velocities at different pressures. Figure 4.5 shows images of what the streamers look like for the aforementioned conditions and varying sample thicknesses.

![Figure 4.5](image_url)

*Figure 4.5: In the first row, images are shown of surface streamers moving along the surface of a TiO$_2$-filled sample for different sample thicknesses at 100 mBar. In the second row, the similar images are shown for streamers in 150 mBar of air. The needle and the sample are drawn in the image schematically to give an indication of what their position is in the set-up.*

When the surface streamers of the 2 mm sample and the 10 mm sample are compared, one can see that there is a difference in velocity of the streamer at 100 mBar, where a higher velocity was measured for the 10 mm sample. This is evident from the increased distance between two maxima in intensity.

The velocity was also found to decrease with increasing pressure. The differences observed in these images are quantitatively displayed in figure 4.6.
Figure 4.6: Velocity of the surface streamers in air against pressure for TiO$_2$-filled samples of varying thickness.

The data points in the graph of figure 4.6 represent the average of 50 velocity measurements, whereby the error bars are the standard deviation. We always measured the velocity at the same region of the sample lengthwise. What can be observed from this graph, is that at 100 mBar there is a significant difference in velocity between the 2 mm sample compared to the 4 and 10 mm sample. Also note that there is no significant difference in velocity observed between surface streamers on the 4 mm sample and the 10 mm sample. The observation of surface streamer velocity decrease for increasing pressure is quite remarkable, if compared with the measurements that Akkermans performed, where no substantial differences in the velocity of gas streamers was found when the pressure was increased [1]. However, Briels et al. also performed gas streamer velocities in air and found that the streamer velocity actually is pressure dependent, albeit it that the differences were not large in a wider pressure range [15]. So it is not really clear yet, if the pressure dependency of the gas streamer velocity compares with the pressure dependency of the surface streamer velocity. We also observed the velocity difference between surface streamers for the varying sample thicknesses to decrease or even diminish at higher pressures.

The reason that, at 100 mBar, we observe a difference in velocity between the 2 mm sample and the thicker samples might be due to the fact that the thicker samples have more bulk dielectric material, providing for a higher enhancement in electric field outside the sample. A higher enhancement in electric field can cause a higher velocity of the streamers along the dielectric surface.

However, the 10 mm sample clearly consists of more bulk dielectric material than the 4 mm sample. The surface streamer velocity at the 10 mm sample is not substantially higher than the velocity at the 4 mm sample though. So there tends to be a saturation level of the bulk effect of the dielectric. This saturation is probably caused by the fact that the polarisation of the dielectric counteracts the electric field outside the sample, causing the net electric field to diminish in the sample for a certain thickness. Samples thicker than this do not further increase the electric field outside the sample. An increase in relative permittivity of the dielectric would increase the polarisation and thus decrease the thickness for which the outside electric field is completely counteracted within the sample.
This, however, could only be a partial explanation of the results we obtained, because it does not explain the pressure dependency of the velocity. At lower pressures the reduced electric field is higher conforming formula 2.10, so to completely counteract this field inside the sample by means of polarisation, a thicker dielectric sample would be needed. Whereas, at higher pressures where the reduced electric field is lower the 2 mm sample would suffice. This could be an explanation for the velocity differences for varying sample thicknesses as well as the pressure dependency of the surface streamer velocity. However, saturation of bulk effects may not be the only reason for the rapid decrease in velocities at higher pressures. Surface effects might play a role here as well.

4.2.2 Comparison between air and nitrogen

Besides considering the effects of varying the thickness of the dielectric samples when measuring the velocity of surface streamers, we also investigated the influence of the surrounding gas on the surface streamer velocity. So we measured the velocity for a dielectric of one specific thickness in both ambient air and nitrogen. For this experiment, we placed the 4 mm TiO$_2$-filled sample under the needle at a displacement of $d = D_{\text{sample}}/2$. We used stereo photography to verify whether the streamers were actually travelling along the surface or not. Furthermore, stereo photography also allowed us to differentiate between the streamer branches that are formed along the surface. This means that we are able to measure the velocity of a specific branch of a streamer along the surface, which makes the velocity measurement more accurate. So we placed the sample in such a way that at one side of the image we look parallel to the sample surface as shown in figure 3.5. An image of the measurements in both air and nitrogen is shown in figure 4.7.

![Figure 4.7: In the first row, stereo images are shown of streamer discharges travelling along the surface in air for different pressures, whereas in the second row, the same is displayed in nitrogen. In the first column the anode needle tip and the sample are drawn in the image schematically to give an idea in how they are positioned compared to the discharges themselves. Please note that the dimensions are not completely in proportion to the actual sample position.](image)

At first, we compared the velocity measurements for this sample in air with the measurements described in paragraph 4.2.1. To do this, we determined the velocities at a similar vertical position on the sample as the earlier described measurements. However, the measurements in air did not seem to compare with the measurements for the 4 mm sample we performed earlier. This is probably because of some difference in circumstances, such as a slight increase in sample displacement or a slight increase in voltage or combination of both.
Despite that, we made sure, though, that we performed the velocity measurements in nitrogen under similar circumstances as in air in terms of sample positioning, pressure range and voltage. Also, we measured the velocities at the same vertical position on the sample as the ones in air for the stereo photography set-up used for the measurements depicted in figure 4.7. To get a more accurate estimate of the surface streamer velocity, we measured the velocity at the streamer branch in the middle of the sample on the left side of the image. This is more accurate because the length scales of this part of the sample compare the most with the length scales on the right side of the image. Figure 4.8 provides for a more accurate view of in what area of the sample the velocity is typically measured. The quantitative results of the velocity measurements are shown in figure 4.9.

*Figure 4.8: The area of the sample in which the velocity is measured. The sample is drawn schematically, whereby the area of the sample in which the velocity is actually measured is depicted. The red area on the right side of the image compares with the measuring area shown on the left side of the image.*
Figure 4.9: Surface streamer velocity on the surface of a 4 mm TiO$_2$-filled sample. The black squares depict the velocity of the surface streamers in air, whereas the red dots display the surface streamer velocity in nitrogen.

The data points in the graph of figure 4.9 are the average velocity of surface streamers of 30 different discharges per setting, all measured at approximately the same vertical position of the sample at the same pressure as is already shown in figure 4.8. The error bars represent the standard deviation in the 30 velocity measurements. In the graph of figure 4.9, we observe that streamers travel faster along the surface while surrounded by ambient air than in nitrogen. Nijdam et al. did not find a significant difference when comparing velocities in gas streamers in ambient air and nitrogen at 20 kV [2]. It has to be noted though, that these velocities were determined in another way, so we cannot completely compare our velocity measurements with these results. Furthermore, the observation that the streamer velocities in air and nitrogen differ 20% cannot be excluded from these measurements, because the method used in this work is less accurate. Briels et al. also performed velocity measurements of gas streamers in both air and nitrogen [15]. They also observed a difference in gas streamer velocity in air and nitrogen, namely that gas streamers in air are faster in nitrogen, which is similar to what we observed for surface streamer velocities. Some annotations have to be made here though. Briels et al. determined the gas streamers in a similar way that Nijdam et al. did, so this is not completely comparable and probably not as accurate as the method in which we measured the velocity. Furthermore, Briels et al. compared the gas streamer velocities in air and nitrogen in a larger pressure range than we did. What Briels et al. did observe, was that the gas streamer velocity in nitrogen decreases more with increasing pressure than in air.
We did not observe this for the surface streamer velocities and unfortunately, the images we obtained, did not allow us to also measure the velocity of the streamers travelling only through the gas to compare this. This would have allowed us to determine whether the presence of a dielectric sample also affects the velocity of gas streamers or not.

It would be interesting to see if, in our configuration, the velocity will actually differ for the gas streamers in air and nitrogen in the way that Briels et al. described. Therefore, some extra measurements will also have to be done without the presence of a dielectric sample to verify the earlier obtained results for gas streamer velocities by Briels et al..

Gas streamers in pure nitrogen propagate only via background ionisation, whereas gas streamers in ambient air propagate mostly due to photo-ionisation, since in air background electrons get attached to oxygen molecules fast. Gas streamers are expected to move faster in air than in nitrogen. However, the velocity measurements are not performed in pure nitrogen, meaning that in nitrogen, there is also some attachment of background electrons to oxygen molecules. Also, photo-ionisation will influence the propagation of the streamers in non-pure nitrogen [15].

Wormeester et al. performed simulations to investigate the influence of photo-ionisation on the gas streamer velocity in nitrogen with 1 ppm impurity and compared it with the simulated gas streamer velocity of pure nitrogen. He found that in nitrogen with photo-ionisation gas streamers propagate faster than they would in pure nitrogen [16]. This may explain why gas streamer velocities in air are not a lot higher than they are in nitrogen. So in the case that the gas streamers in air and nitrogen differ with the same percentage in velocity in the presence of a dielectric sample in the gap as the surface streamer velocity in air and nitrogen, it could be explained that gas properties influence the surface streamer velocity the most. Photo-emission would then be less important for the difference in surface streamer velocities in this case.

In the other case, namely where the gas streamers in nitrogen and air do have similar velocities when a dielectric sample is present in the gap, it could be reasoned that the cause for the difference in velocities between surface streamers in air and nitrogen is an interaction effect between the surface and the gas. For this reason, it would be interesting to measure the surface charges on the sample after a streamer event has taken place in both air and nitrogen to see if this may be a cause to this difference in surface streamer velocity.

Yet another possibility may be that in nitrogen there is less leftover surface charge on the sample in nitrogen than there is in air. However, we cannot extract this from our measurements. To test this possible explanation, similar measurements would have to be done in both air and nitrogen for different repetition rates between subsequent discharges to see what influence leftover charge and ionisation has on the velocity of the streamers. As for now it is not yet possible to formulate a conclusive hypothesis of why we observe the measured velocity difference between surface streamers in air and nitrogen.
4.3 Streamer path along dielectric surfaces

4.3.1 Correlation

As mentioned in paragraph 4.2.2, more branching is observed on the sample surface for streamers in nitrogen than for those in air. Considering this, together with the observation that surface streamers propagate faster in air than in nitrogen, the path along which a streamer propagates along the dielectric surface could be an important factor. For this reason, we rotated our sample 90° so that, through stereo photography, we looked perpendicular to the sample surface on the right side of the image. The left image is taken under a slight angle, allowing us to exclude components that travel perpendicular to the image plane. Figure 3.5 (b) of the experimental set-up displays this. Furthermore, we measured the path of streamer along the dielectric surface in a non-stroboscopic manner, since stroboscopic images do not give a clear view on the exact path that the streamer follows. The displacement of our 4 mm TiO$_2$-filled sample was kept at $d = D_{\text{sample}}/2$ and the repetition rate remained at 1 Hz. For these experiments we investigated the effect of the voltage on the streamer path, so we do not only perform experiments at 20 kV. We also made a distinction between surface streamers in nitrogen and in ambient air.

In air, subsequent streamers travelling along the dielectric surface, seem to follow almost the same path along the surface, as can be seen in figure 4.10.

![Figure 4.10: Images of four subsequent surface streamers in air. These images were taken at 140 mBar at a voltage of 20 kV. In the first image, the sample and needle position are schematically drawn in. The samples do actually run down further in the image, but we only compared images in this region.](image)
In the first and second image of the figure, we can observe that the streamers seem to follow the same path across the sample. Even in the third and the fourth image, it can be observed that the main branches of the discharge follow the same path of the previous discharges. At higher pressures, we see more branching along the surface, which can also be observed in figure 4.10. In these images, it could be observed that the main side branch appears to follow a similar path.

An example of what surface streamer paths look like for subsequent surface streamers in nitrogen is shown in figure 4.11.

![Figure 4.11: Four subsequent surface streamers in nitrogen at 140 mBar at a voltage of 20 kV. The sample and the needle are drawn in.](image)

It could be observed immediately, that the discharge along the surface in nitrogen is a lot more branched than the ones in air. Gas streamers in nitrogen exhibit more stochastic behaviour than gas streamers in air, however, this does not explain why this is also observed along the surface, since photo-emission also plays a role here. It could be seen that there appears to be less correlation between subsequent discharges than in air, although this does not appear to disappear altogether. When comparing the first and second image of the figure the main branch seems to follow a similar path in those subsequent discharges. Even the main side branch appears to follow a similar path. Also, when we look at the second and the third image, the right main branch of the third image seems to have a similar pathway as the main branch in the second image. Furthermore, the left main branch of the third discharge even tends to follow the path of the main side branch in the second image. Although there appears to be overlap in paths between subsequent streamers in nitrogen, this is not the case for every subsequent surface streamer events. This can be observed when we compare the fourth image with the third image of figure 4.11.

So we can observe in both figure 4.10 and 4.11, that in both air and nitrogen, there appears to be some sort of correlation between subsequent discharges. To be able to create overlays of subsequent discharges, a MATLAB script was used. These overlays ease identification of similar streamer paths.
In the resulting images streamer $i$ is made purple (p), streamer $i+1$ is made green (g). If an overlap is observed between streamer $i$ and $i+1$, the channel of the streamer will appear white (w) in the image. The resulting images are displayed in figure 4.12.

![Figure 4.12](image1.png)  
![Figure 4.12](image2.png)

Figure 4.12: Two subsequent surface discharges are overlain for both air (a) and nitrogen (b) at 20 kV at 140 mBar. The first streamer event is made purple and the second one green. Where both discharges overlap, the streamer path is observed to be white in the image.

As can be observed in figure 4.12 there appears to be quite some overlap for subsequent surface streamers in air. In nitrogen this appears to be a lot less, although we still see overlap at some branches. The results of this overlaying in images provides for a similar outcome of what we expected from just looking at the different images like we did in figure 4.10 and 4.11. Now we have mapped in what way the streamers appear to follow similar paths along the sample surface, we also quantified this correlation in streamer paths. So we calculated the correlation between the images via

$$ r = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2)(\sum_m \sum_n (B_{mn} - \bar{B})^2)}}. $$

In formula 4.3, $r$ is the correlation between image $A$ and $B$, where $A_{mn}$ and $B_{mn}$ are the intensities of pixel $(m,n)$ for image $A$ respectively image $B$ with $\bar{A}$ and $\bar{B}$ the average intensity of all pixels of image $A$ respectively image $B$. So the way in which the correlation is calculated between image $A$ and $B$ is to multiply the difference between the intensity of each pixel with the average intensity of all pixels from one image with the other, after which there will be summated over the whole array of the selected pixels. The correlation is then normalised by dividing by the term that can be seen in the denominator, which is the square root of the correlation of image $A$ with itself multiplied by the correlation of image $B$ with itself. This is then done for all images in a data set of 100 images at each pressure. All the obtained values of the correlation at each pressure are then averaged and provided with an error bar being the standard deviation.

It has to be noted that, at 20 kV, we calculated the correlation between image $i$ and $i+1$, $i$ and $i+10$, $i+50$. The results that this gave in both air and nitrogen at a voltage of 20 kV, are shown in figure 4.13.
Figure 4.13: The correlation between discharges at different pressures in both air and nitrogen at 20 kV. The data points with a high correlation depict the correlation between discharges in air, whereas the data points with lower correlation depict the same in nitrogen.

In figure 4.13, 1 step correlation means correlation between image $i$ and $i + 1$, where the 10 step correlation stands for the correlation between image $i$ and $i + 10$ with the 50 step correlation standing for the correlation between image $i$ and $i + 50$. The reason why we distinguish between these is to determine the timescale of correlation. If there is a significant difference between the 1 step correlation and the 10 step correlation, or the 50 step correlation, then we could determine a timescale for this correlation. However, from figure 4.13 it becomes obvious, that this is not the case. It might be the case that we seem to see a long lasting correlation in the streamer path because the streamer has a preferred path along the surface as soon as the first discharge has taken place. However, perhaps the path the streamer follows is not dependent on any of the previous streamers, but simply determined by other parameters. In both air and nitrogen, this seems like a plausible explanation.

A second reason may be that the correlation in surface streamer paths actually does last as long as 50 steps or even more. In air this could be the case, although, at higher pressures, also surface streamers in air tend to branch more than at lower pressures. Still, in air, even the path that separate branches follow seems to be similar for subsequent discharges, so it is possible that there just is a long lasting correlation between surface streamers in air. In nitrogen this is less likely due to the branching of the surface streamers that was mentioned earlier. This still may be a possible explanation, though, since some parts of the main branches and also some side branches do overlap for surface streamers in nitrogen.

It should be noted that the streamer channels we imaged are quite broad, leading to higher correlation.
What does stand out in these measurements is that there actually is significantly more correlation in the surface streamer paths in air than there is in nitrogen. This difference is probably caused by the extensive branching of the surface streamers in nitrogen. As for to determine the cause of the correlation itself, it might be interesting to measure the actual surface charge after a streamer event has taken place along the sample. In addition to this, it might as well be worth measuring at what time interval this surface charge is reduced by half for instance to see how large the influence of the repetition rate and leftover surface charge is at the correlation.

### 4.3.2 Different voltages

Having performed the experiments described under the previous sub header at 20 kV, we investigated if the voltage pulse we provided for the streamer, would have an influence at the correlation between the paths that subsequent streamer discharges follow along the sample surface. So we performed the same measurements we did at 20 kV in air and nitrogen at respectively 18 and 23 kV. The results of these measurements are shown in a similar manner in figure 4.14.

![Figure 4.14](image)

*Figure 4.14: The correlation between different streamer discharges in air and nitrogen at 18 kV (a) and 23 kV (b). The upper data points represent the correlation in streamer paths in air and the lower ones depict the correlation in nitrogen.*

For measurements at the voltages of 18 and 23 kV we only investigated the 1 step and the 10 step correlation. Another annotation that has to be made is that there seem to miss some data points for the correlation in air at 18 kV. This is, because in our configuration, the streamers did not incept at 18 kV in air at pressures of 150 and 160 mBar. Again we observe a distinction at both voltages in the correlation between surface streamer paths in air and nitrogen.

At different voltages there appears to be a difference in the correlation between surface streamer paths at 18 and 23 kV in nitrogen and also in air. Although, a distinction can be made between the correlation for the streamer paths at both the voltages, the error margins overlap at all pressures, except for the correlation at 120 mBar in nitrogen. At this pressure in nitrogen, there is a significant difference in correlation between streamer paths at both the voltages.
However, the observed correlation at 120 mBar in nitrogen at 23 kV is found not to be accurate, since we only measured the correlation at a small part of the sample. This is due to the fact that the gate width of our intensifier turned out to be too short during these measurements. It is found that the beginning of the surface streamer paths have a high correlation, explaining the large difference in correlation between surface streamer paths in nitrogen at 120 mBar at respectively 18 and 23 kV.

If we take a further look at the images of the surface streamers themselves and distinguish between discharges at 18 and 23 kV the increase of branching appears to be a lot less than expected as can be observed in figure 4.15. Moreover, the little difference in branching for different voltages might actually be a reason for the fact that, in most of the cases, the difference in correlation is non-significant or at least small. Still, it is remarkable that the correlation seems to be higher at higher voltages, in nitrogen especially. It has to be noted though, that the increase of voltage may cause an increase in the channel width of the surface streamer path, which may lead to a higher correlation.

Figure 4.15: Four subsequent images of surface streamers at the surface of a TiO2-filled sample at 130 mBar in nitrogen, for 18 kV (first row) and 23 kV (second row).
5 Conclusions

In this chapter the most important conclusions of the obtained results in this research will be summarised.

5.1 Surface streamer probability

In the experiments in nitrogen (~0.1% impurity), surface streamer probability for a SiO$_2$-filled sample, was measured. We observed that there is an increased chance for surface streamers to occur in nitrogen with respect to air. The most probable cause for this observation, is the fact that in nitrogen the contribution of photo-ionisation to form free electrons is much lower than it is in air. For this reason, the streamer tends to deviate from the electric field lines at lower pressures in nitrogen towards the sample surface. The surface will then probably become a more important electron source for the streamer in this case through photo-emission. Experiments with an epoxy resin rod, instead of the SiO$_2$-filled sample, gave similar results. Surface streamers are more likely to occur in nitrogen at lower pressures than in air.

5.2 Surface streamer velocity

5.2.1 Different sample thickness

At a pressure of 100 mBar, we observed that there was a significant velocity difference for the streamers along the surface of a 2 mm sample and the streamers along the 4 and 10 mm samples in air. A probable cause for this, is the fact that the 4 and 10 mm samples are thicker and therefore have more dielectric material. This provides for a higher local electric field enhancement, hence a higher velocity. However, there is a saturation level in this, since there was no significant difference in surface streamer velocity between the 4 and 10 mm sample. We expect this saturation level to exist, because of the fact that the polarisation of the dielectric completely counteracts the outside electric field, starting from a certain thickness of the dielectric sample. We also observed a decrease in surface streamer velocity when we increased the pressure. Earlier experiments were not conclusive on this [1], [15]. Furthermore, at higher pressures we also observed no significant difference between the surface streamer velocities along the samples of different thickness. A possible explanation for this may be that at higher pressures the reduced electric field outside the samples is lower in such a way that the 2 mm sample suffices to counteract this reduced electric field within the sample through polarisation.

5.2.2 Comparison between air and nitrogen

We found the surface streamer velocity to be significantly higher in air than in nitrogen. Nijdam et al. [2] did not find any significant differences in velocities of gas streamers in air and nitrogen without the presence of a dielectric sample. Briels et al. observed that gas streamers do propagate faster in air than in nitrogen on a large pressure range. Briels et al. discusses here that this difference in gas streamer velocities is caused by the fact that there is a lot more photo-ionisation in air than in nitrogen with an impurity [15]. This difference in velocity between gas streamers in air and nitrogen would also probably be larger, if measured in pure nitrogen, than in contaminated nitrogen, as can be explained from the simulations Wormeester et al. performed [16].
The reason, however, of why we observe the velocity difference in surface streamers is not understood yet. We discussed possible explanations. It could be the case that the velocity difference between nitrogen and air is similar for gas streamers compared to surface streamers. In this case, gas properties may influence the difference surface streamer velocities more than photo-emission. In the case that gas streamers have similar velocities in the presence of the dielectric, the difference in surface streamer velocity might be caused by an interaction effect between the surface and the gas. Furthermore, it could also be that in nitrogen, there is less leftover surface charge after a discharge than in air.

5.3 Streamer path along dielectric surfaces

5.3.1 Correlation

Investigating streamer paths along a dielectric sample, we observed that subsequent surface streamers in air seem to follow similar paths most of the time. In nitrogen, we also observe some correlation between subsequent streamer discharges along the surface. However, we conclude that this correlation is significantly higher for surface streamers in air than in nitrogen. This is probably due to the fact that the surface streamers in nitrogen branch a lot more than they do in air. The observed correlation seems to be long lasting, which can mean two things. One is that the streamer has a preferred path along the dielectric surface, which might be the case in air. The other may be, that there actually is a really long lasting correlation from the moment on that the first discharge has taken place. Even for nitrogen, this might hold, since, despite branching a lot, some branches do follow similar paths when looking at subsequent discharges.

5.3.2 Different voltages

Finally, we also investigated what the influence was of changing the voltage pulse on the surface streamer path. So we investigated the correlation between subsequent surface streamers at voltages of 18 and 23 kV. We found an increase in correlation for increasing voltage. We found this remarkable, because at higher voltages streamers tend to branch more. These differences, however, were not significant within the error bars.
6 Outlook

In this chapter, we will discuss further research that can be done following from the results we obtained.

By terms of follow-up measurements for the surface streamer velocity, the following experiments could be performed:

- Researching the bulk dielectric effects versus the surface effects on the surface streamer velocity. This could be done by measuring velocities for samples of varying thicknesses for both higher and lower pressures than we measured at in our experiments.
- It remains unclear why we observe the difference in surface streamer velocity when comparing surface streamers in air and nitrogen. Possible experiments to clarify this are:
  - Performing the experiments in such a way that also the gas streamer velocities can be measured in the presence of a dielectric sample;
  - Measuring the surface charge of the dielectric sample after a streamer event has taken place, to observe if this has any influence on the surface streamer velocity.

For surface streamer paths, we observed that, especially in air, but also partially in nitrogen, the subsequent surface streamers seem to follow similar paths along the dielectric sample. The correlation between subsequent surface discharges seems long lasting, the reason why this occurs is not clear though. So follow-up experiments could be:

- Repeating measurements on surface streamer paths for different repetition rates, to see what the influence is of leftover surface charges on the path of the streamer in both air and nitrogen;
- Measuring surface charges after surface streamers and looking at what happens with these surface charges over time to determine to what extent this will influence the surface streamer path.
Bibliography


[17]  Private communications with A. Dubinova, CWI Amsterdam