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Creeping sparks
stroboscopic imaging of surface streamers

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Creeping sparks - stroboscopic imaging of surface streamers

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Abstract

In order to gain a better understanding of how to prevent sparks creeping along dielectric surfaces - the most common cause of failure in high voltage devices - we have studied the propagation of the preceding streamers along dielectric surfaces. We applied a voltage pulse to a needle a small distance above a dielectric sample - a thin vertically positioned plate - in low-pressure air, and imaged the resulting streamers using a stroboscopic ICCD camera which was positioned so that it imaged the thin side of the sample. We have investigated the chance of at least one streamer branch propagating along the sample surface, as a function of a number of variables: air pressure, sample positioning, voltage pulse amplitude and sample properties, notably relative permittivity. We have found that an increased pressure, more asymmetrical sample placement, smaller voltage pulse, and higher sample relative permittivity all increase the chance of a surface streamer, when other variables are kept constant. We have also investigated the velocity and diameter of surface and gas branches, and found that interactions with the sample cause surface branches to propagate twice as fast, with a diameter thrice as small. We have also investigated two cases of correlation. In the first case we found that the chance of a streamer containing a surface branch increases by about 10% when the previous streamer also contained a surface branch. In the second case we found that when we use a symmetrical geometry with the sample directly beneath the needle, a very strong (99%) preference for discharges on one side of the sample sets in after just a few discharges.
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1. Introduction

In high voltage (HV) devices, the insulation usually consists of a combination of solid and
gaseous insulators. Solid insulators are mainly necessary to provide structural support. The most common insulating gas used is simply air, and its greatest benefit is its ubiquity. The purpose of insulation is of course to prevent the flow of large currents between high and low voltage parts of the device.

Large currents in an insulator do not occur unless a sufficiently large electric field is present. A high electric field can cause dielectric breakdown, increasing the conductivity of the medium greatly. This causes sparks to form, which cause power losses and can even damage devices. As such, HV devices are designed such that the electric field in none of the insulating components exceeds the respective breakdown field.

However, even in devices where the dielectric strength of the insulators themselves is sufficient, dielectric breakdown can still occur on the interface between a solid and a gaseous insulator. While this so-called surface flash-over event is often observed, the physics behind it is still poorly understood. Currently, designs of HV devices are based on empirical ‘trial and error’ methods to prevent creeping sparks along surfaces. As such, it is possible that they are over-designed, and that more efficient design solutions to the surface discharge problem exist. In order to improve HV device designs through fundamental knowledge rather than experience, a better understanding of the physics taking place in these processes is needed.

Sparks are always preceded by streamers and follow the same path as the streamer. In applications, it is extremely difficult to prevent a spark if a streamer has already occurred. Conversely, a spark can always be prevented if streamers can be prevented. For this reason, the present work focusses on the study of streamers along dielectric surfaces. We apply stroboscopic ICCD imaging as well as voltage and current probes to do so.

Chapter 2 of this report discusses the theory of streamers propagating in a single medium as well as possible interfacial effects. Chapter 3 describes the experimental set-up which we have used, and chapter 4 presents the results which we have obtained. Finally, chapter 5 summarises the conclusions which can be drawn from our results and chapter 6 provides an outlook towards possible future research.
2. Theory

2.1 Streamers

Streamers are fast-moving electrical discharges which occur in insulating solids, liquids and gasses. When the insulating medium is exposed to a strong electric field, a streamer discharge can occur. Streamers can extend into regions where the electric field is much lower - below the ionisation threshold of the medium - because their interior consists of a conducting plasma. On the edges of this conducting plasma, electric-field screening occurs. The resulting net space charge in the head of the streamer locally amplifies the electric field, allowing the streamer to propagate.

If a streamer has crossed the ‘gap’ of insulating material and the system can provide sufficient current, a transition from streamer to spark can occur. The difference between these two types of discharges is that in a streamer the electrons have a much higher temperature than the ions, while in sparks the ion temperature and electron temperature are almost the same and can reach thousands of Kelvins. In HV applications, the large currents and temperatures in sparks can cause short-circuiting, power losses and damage to the devices, making sparks undesirable.

In this chapter, we discuss the inception and propagation of streamers in a single medium, as well as the effects of a material interface on streamer propagation.

2.2 Streamer inception

In an insulating medium there are always a few free electrons and ions present - for example due to ionisation from cosmic background radiation. When the medium is exposed to a strong electric field, the electrons and ions are accelerated; positive ions move in the direction of the field, electrons move in the opposite direction. Note that the presence of background ionisation is a requirement; even the strong electric fields used to initiate streamers are not strong enough to cause field ionisation of neutrals. Because of the large difference in mass, electrons are accelerated much faster than ions.

From a certain kinetic energy, the accelerated electrons can ionise neutral atoms or molecules of the medium upon impact (impact ionisation). Impact ionisation creates another free electron and ion, whereupon the two electrons accelerate again and can ionise two more neutrals. Impact ionisation is counteracted by two processes: recombination of free electrons and positive ions into neutrals and attachment of free electrons to neutrals.
forming negative ions. If the ionisation process outweighs these other two effects, the number of free electrons and ions will keep on growing in what is known as an electron avalanche, shown schematically in figure 2.1.

As the avalanche grows, free charges start to influence the electric field. When this effect reaches a significant level, the discharge changes from an avalanche into a streamer. According to the Raether-Meek criterion [18, 19], space charge effects become important when around $10^8$ to $10^9$ free electrons are present under standard conditions.

![Figure 2.1: Schematic representation of an electron avalanche. Electrons are indicated by a ‘-’, Ions (or before collision, neutrals) by a ‘+’.

Figure 2.2: Schematic representation of streamer propagation. ‘+’ indicates positive ions, ‘-’ indicates electrons and negative ions. The left side shows a positive streamer, the right side shows a negative streamer.][1]

2.3 Streamer propagation

The transition from avalanche to streamer takes place because of the large amount of free positive and negative charges created by impact ionisation. These charges act as a conductor and screen themselves from the background electric field. A small layer of space charge forms on the surface of the streamer. This causes the field inside to vanish, but it amplifies the field just outside the streamer. The curvature of the charged region is largest near the head of the streamer, where the surface is (anti-)parallel to the field. Hence, the electric field is enhanced most strongly just in front of the streamer head.

In the small region where the field is amplified, electron avalanches can form more free electrons and ions, increasing the size of the conducting plasma interior. The screening mechanism causes the streamer head to move with the edge of the plasma as it grows.

The mechanism behind streamer propagation is shown schematically in figure 2.2. We differentiate between positive streamers for which the head consists of a layer of positive charge and negative streamers which have a negatively charged head. The negative charge in negative streamer heads consists partly of electrons. Because they are in a region with an amplified electric field, these electrons can form electron avalanches moving in the direction opposite to the electric field, creating free charge in front of the
streamer head and allowing the streamer to propagate in the direction opposite to the field.

However, a positive streamer head consists of positive ions, which are much less mobile than electrons. As such, the ionised region can only grow if there are free electrons directly in front of the streamer head. These are strongly attracted by the electric field enhanced by the positive streamer head and will form electron avalanches towards the head, creating the free charges needed for streamer propagation. This difference in propagation mechanism causes negative streamers to be more diffuse and broad than positive streamers. It also implies that positive streamers need an external source of electrons in order to be able to propagate. These electrons can come from background ionisation and photo-ionisation.

Background ionisation is the ionisation that is already present before the streamer discharge occurs. This ionisation is split into two categories. The first is the constant level of background ionisation caused by e.g. cosmic radiation and radiation from building materials. The second is leftover ionisation from previous discharges. Unlike the first kind of background radiation, the leftover ionisation is time-dependent. For time-scales longer than milliseconds, this ionisation density is inversely proportional to time, so it is proportional to the repetition frequency of the discharge [1]. We can also expect some space-dependence; the ionisation level is initially only high in the previous streamer’s path. However, for slow repetition rates, we expect the effect of diffusion to be considerable in homogenising the ionisation level throughout the vessel [7].

Photo-ionisation is caused by the streamer itself. In the head of a positive streamer, neutrals in an excited state can emit a photon and return to a lower state. If this photon is in the right energy range, it can ionise another neutral some distance away. For example, in air, an excited nitrogen molecule can emit a photon with a wavelength between 92 and 102.5 nm, which can ionise an oxygen molecule [6]. If the photon ionises a neutral in a region where the field is strongly enhanced, the freed electron can form an avalanche towards the streamer head.

2.4 Similarity laws

Similarity laws for gas discharges in gases at different pressures are widely used. They are based on kinetic gas theory, and imply that the mean free path length of electrons ($l_{mfp,e}$) scales inversely with gas density. From an experimental point of view it is convenient to express this dependence in terms of pressure, which scales linearly with gas density under constant-temperature conditions by the second law of thermodynamics. All other streamer length scales (thickness, size of the field enhancement region, etc.) are proportional to $l_{mfp,e}$.

$$l_{mfp,e} \sim p^{-1}$$

At the same time, the velocity of streamers does not scale with pressure, under similarity laws.

$$v \sim p^0$$
2.5. INTERFACIAL EFFECTS

Then, typical time-scales in streamer discharges should also scale inversely with pressure:

\[ \tau \sim \frac{l}{v} \sim p^{-1} \] (2.3)

Deviation from the similarity laws can occur when multi-particle processes or stochastic processes play an important role. Also, the shape and surface properties of solid materials cannot be rescaled with gas pressure. As such, we have to be careful in applying the similarity laws in cases where the streamer interacts strongly with a dielectric sample.

2.5 Interfacial effects

Near the interface between two media, other effects can come into play. Considering a streamer propagating through the air nearby a solid dielectric, there are a few possibilities. We will discuss the most prominent ones: polarisation, photo-emission, secondary electron emission and field emission.

2.5.1 Polarisation

Through polarisation, an electric field will introduce a realignment of the charges on the surface and in the bulk of a dielectric. Generally, this realignment will diminish the field inside the dielectric, and enhance it outside. The realigned charges also act as a mirror charge, attracting the charge that caused the original field [3]. The strength of polarisation is proportional to the electric susceptibility \( \chi_e \) of the medium, which may depend on the electric field magnitude and frequency for non-linear dielectrics. A more widely used parameter is the relative permittivity \( \varepsilon_r = 1 + \chi_e \) of a medium [16].

It has been shown that on a triple junction point - the interface between a conductor and two different dielectrics - polarisation can cause a greatly enhanced electric field in the dielectrics [20]. Applying this to a streamer-dielectric-air interface, we can expect large field enhancement in the air just in front of a streamer moving in air along a dielectric due to polarisation effects.

2.5.2 Photo-emission

When a photon of sufficient energy hits a dielectric surface, it can free one electron from the insulator. This process is akin to the photo-ionisation process that can take place in the bulk of the gas, but the difference is that lower energy photons are required. While oxygen has an ionisation energy of 13.6 eV, most dielectric insulators have a work function of only 5-10 eV. Photons with these lower energies are more commonly emitted by excited neutrals in the streamer head, and they also have a longer mean free path length \( (l_{mfp,\gamma}) \) in air [5].

As electrons are freed, the surface retains a net positive charge. In an insulator, not enough conduction electrons (or mobile holes) are present to quickly restore electroneutrality [14]. If the streamer head is close enough for these electrons to form avalanches,
2.5. INTERFACIAL EFFECTS

It is likely that these freed charges will promote streamer propagation near or at the sample interface. However, if the streamer head is further away, the remaining positive charge may repel the streamer, hampering propagation near the interface. After the discharge, free electrons are likely gradually absorbed. Wild et al. [10] have experimentally investigated the effect of leftover surface charge on a BSO sample after a dielectric barrier discharge (DBD), and found that remaining surface charge facilitates subsequent discharges along their sample, since it enhances the applied electric field. They found that the leftover surface charge dissipated through 2 different decay channels, the slowest of which was on the order of minutes. However, in our own set-up the geometry differs considerably. For example, we know that in our set-up, remaining surface charge can never amplify the electric field since the field lines run parallel to the sample surface. It is also unclear whether decay of remaining surface charge occurs in the same way for the different set-ups.

2.5.3 Secondary electron emission

Secondary electron emission (SEE) takes place when an electron with sufficient energy hits the dielectric’s surface. The electron frees another electron, so that a positive charge remains on the surface. Alternatively, an incident electron can be backscattered, which has no effect on the surface charge, or the electron can be absorbed, contributing a negative charge. In a literature review of experimental investigations of SEE, Chvyreva et al. [9] have found that precious little attention has been paid to incident electrons with energies relevant to streamer phenomena. Monte Carlo simulations of Jorgenson et al. [5] have shown that under streamer experimental conditions, SEE is weak, and the absorption effect is stronger. For a Teflon sample, they find that this sink effect is stronger than the source effect of photo-emission.

2.5.4 Field emission

Electrons from the sample surface may be freed by the electric field itself, also leaving behind positive charge on the surface. The relatively small work function of electrons in the sample coupled with the greatly enhanced field due to triple point field enhancement may cause field emission to become important.
3. Experimental Set-up

In order to study streamer discharges in air and along dielectric surfaces, we have used an experimental set-up consisting of a number of components. The most important of these are a high voltage pulse generator which provides the positive voltage pulse needed to initiate a discharge, a gas-filled vessel containing the anode tip and cathode plate as well as the discharge, the dielectric samples themselves, and the stroboscopic ICCD (intensified CCD) camera coupled with current and voltage probes which allow us to do measurements. These are discussed in the following sections.

3.1 Pulse generator

![C-supply circuit diagram](image)

Figure 3.1: A schematic view of the C-supply circuit. The amplitude of the pulse is determined by the input voltage, 20 kV in this figure but varied between experiments. Resistors $R_2$ and $R_3$ determine the pulse’s rise and fall time respectively.

We have used a C-supply as our high voltage pulse generator. The electrical circuit is shown schematically in figure 3.1. It consist of a 1 nF capacitance which is charged with a negative DC high voltage source. In our case this voltage source is a Kilovolt Company HV power supply, capable of producing a DC voltage of down to -30 kV. A trigger circuit triggers a spark gap which acts as a fast switch with $\sim 50$ ns jitter; sufficiently low for our purposes. When the spark gap fires, the left side of the capacitor is quickly grounded.
through resistor $R_2$, creating a positive high voltage pulse on the right side, at the anode tip. The right side is grounded through resistor $R_3$, which limits the pulse duration, so that the streamer discharge cannot transform into a spark.

To effectively study streamers, pulses with a fast rise time are desirable. If streamers have already originated and propagated before the maximum voltage is reached, they may exhibit properties representative of the lower voltages [1]. This means that ideally $R_2$ is chosen to be small. However, we have found that when $R_2$ is chosen to be too small, large oscillations in the voltage pulse occur, which are also undesirable. Similarly, $R_3$ should be chosen large enough for the pulse to remain high enough during the whole streamer discharge, but it should be small enough to prevent the pulse from eventually causing a streamer-to-spark transition, which can damage the photo-cathode, the sample, or the needle.

### 3.2 Pressurised vessel

It is possible to create streamers and sparks in ambient air of ambient pressure. However, it is much easier to create streamers at lower pressures. Also, similarity laws (section 2.4) imply that decreasing the pressure beneath the ambient value allows us to investigate streamer processes at larger length- and timescales. For these reasons, we conduct our experiments inside a metal vessel filled with low-pressure air ($\sim 25-200$ mbar).

![Figure 3.2: An overview of the used vessel. In the picture, a cut-out has been made so that the electrodes and sample are visible. The left viewport is for the camera.](image-url)
3.3 DIELECTRIC SAMPLES AND PLACEMENT

An overview of the pressurised vessel can be seen in figure 3.2. It is of cylindrical shape, with an inner diameter of 50 cm and a height of 60 cm. At the top of the vessel, a high voltage feed-through is mounted which is connected to the anode tip. The cathode plate is mounted on the bottom of the vessel. The vessel contains two windows: a quartz window (transparent for near ultraviolet light) on the side serving as the viewport for the camera and a regular glass window in front serving as a viewport for the experimenter.

A Pfeiffer vacuum pump is connected to the vessel by means of a manual valve, which we use to pump down the pressure. A manual release valve is also present, allowing quick filling with ambient air.

3.3 Dielectric samples and placement

ABB has provided five different dielectric epoxy samples. The first sample contains a silicon dioxide (SiO$_2$) filler and has a relative permittivity of around $\varepsilon_r = 4$. The second sample contains a barium titanite (BaTiO$_3$) filler and has a relative permittivity of around $\varepsilon_r = 10$. However, $\varepsilon_r$ for BaTiO$_3$-filled samples can depend on magnitude of the electric field [21]. We will refer to this sample as the ‘original BaTiO$_3$ sample’.

The three newest samples are epoxy samples with BaTiO$_3$ filler of mass filling degrees 20%, 40%, and 60% respectively. Their values for $\varepsilon_r$ are around 5, 7, and 11 respectively. We will refer to these samples by their filling degrees.

These values of permittivity are obtained from dielectric spectroscopy data acquired by Lorentz Herrman at ABB. The complete results are presented in Appendix A.

Figure 3.3: A schematic view of the geometry used in the vessel. Not to scale. The vertical distance $h$ between the anode tip and sample was always 16.5 mm, the horizontal displacement $d$ of the sample was usually 0, but was varied in some experiments.
3.4 ICCD CAMERA AND ELECTRICAL DIAGNOSTICS

The dimensions of all the samples are the same: $150 \times 30 \times 2 \text{ mm}$. They were placed in a grounded metal sample holder on the cathode plate, with the shortest side facing the camera, as shown schematically in figure 3.3. For most experiments, the sample was centred directly under the needle, but for some experiments the sample was moved horizontally (in the camera front view) by a distance $d$. The height difference between the top of the sample and the anode tip was always $h = 16.5 \text{ mm}$, and the sample was always centred in the side view.

3.4 ICCD camera and electrical diagnostics

Our main means of measurement was a stroboscopic intensified CCD (ICCD) camera system. Since the streamer head contains excited species, it emits photons in the violet and ultra-violet wavelength range. We have used a LaVision Picostar ICCD camera system to intensify and measure this light.

Since the time between exposures of our camera is much longer than the time-scale of a single discharge, only one picture per streamer can be taken with a standard ICCD set-up. The resulting picture will show the exposure integrated over the entire exposure time; information about where the streamer head was at a particular time will be largely lost. For this reason, we apply a stroboscopic imaging technique in order to obtain both space- and time-resolved information about streamers.

Our method of stroboscopic imaging depends on the fact that the light from the streamer head is too weak to be measured, unless it is amplified. We use a very high exposure time for the camera (several milliseconds), but trigger the intensifier with a signal consisting of a tunable amount of pulses at 50 MHz rather than a block pulse. This timing is summarised schematically in figure 3.4. The result is a stroboscopic image, with several maxima indicating the position of the streamer head at times $20 \text{ ns}$ apart.

![Figure 3.4: A schematic graph of the timing used in stroboscopic imaging of streamers. The different times are not to scale.](image)

The camera system was triggered as shown in figure 3.5. The initial trigger pulse is provided by the programmable timing unit (PTU) inside a PC, controlled by LaVision software. This pulse triggers the CCD array and the Highland P400 delay generator. The P400 immediately sends a pulse to the spark gap, initiating the HV pulse and with it, the discharge. After a short delay (approx. 1600 ns), the P400 also sends a pulse to the Kentech Instruments high rate imager (HRI) controlling the intensifier. This pulse is first converted to a series of pulses by a TU/eDACS HRI intensifier controller unit. The delay is necessary to synchronise the image intensification with the streamer event.

In order to measure the anode voltage, we have used a Northstar PVM1 high voltage probe with a standard divider ratio of 1000:1. Its maximum voltage is 60 kV for pulsed signals, and it can measure frequencies up to 80 MHz.

In order to measure the cathode current, we have used a current shunt. We measure the current by placing a low-resistance resistor (the shunt) behind the discharge (the load). As long as the shunt resistance is much lower than the load resistance, a voltage measurement over the shunt combined with its resistance provide a means of calculating the current though the load. Our shunt is a 60 Ω resistor indicated with $R_4$ in figure 3.1.

In the past, it has been observed that for a shunt of 1 Ω, the measured current signal is dominated by high-frequency noise for measured currents under 1 A, with peaks at 66 MHz and 293 MHz. A FEKO simulation of the electrical cabling has shown that it is likely that the noise is caused by resonances due to the vessel geometry [4], which could be suppressed with a higher shunt resistance. Hence, an increase of the shunt resistance to 60 Ω was implemented. For smaller discharges this still leads to a noisy signal. However, a larger shunt resistance may approach the load resistance too closely, distorting the current measurement in itself. As such, the current measurement was sometimes noisy and only reflected at what times any current at all was flowing.

Figure 3.5: A schematic view of the cabling used to trigger the camera system.
4. Results

In this chapter, we discuss the results obtained in our research. We will first discuss the influence of varying the pressure $p$ inside the vessel. Later we will discuss the influence of sample positioning, voltage pulse amplitude, and sample used.

We distinguish between two types of observation: the observation of streamers consisting only of branches propagating through the gas, and the observation of streamers with some branches propagating along the sample surface while other branches propagate through the gas. In the latter case we often observed precisely one branch propagating along the sample. We will indicate the two cases with ‘gas-only’ (GO) streamers and ‘surface-gas’ (SG) streamers.

4.1 Pressure dependence

4.1.1 A transition

Figure 4.1 shows streamer images at varying pressures, when we apply a 20 kV pulse at a repetition frequency of 1 Hz. The original BaTiO$_3$-filled sample was placed precisely under the needle ($d = 0$). For pressures of 90 mbar or less, we observed only gas-only streamers. For increasing pressure, the chance of observing surface-gas streamers increased. From 140 mbar, we observed only SG streamers. We can view this as a gradual transition between two extreme states in which only one type of streamer occurs.

We investigate the streamer velocity $v$ and reduced diameter $ps$ (product of diameter $s$ and pressure $p$ in figures 4.2 and 4.3, respectively, for both SG and GO streamers.

Note that there is no reason to assume that a surface branch is cylindrically symmetric like we expect from gas streamers. We may in fact expect a surface branch to be compressed in the direction perpendicular to the surface (corresponding to the horizontal thickness observed in the pictures), and stretched in the direction parallel to the surface (depth in the pictures), due to interactions with the sample.

Also note that if our viewing angle is not perfectly perpendicular to the sample, part of a surface branch may be concealed behind the sample’s edge, causing us to measure a lower thickness. Another issue is the fact that our images are actually two-dimensional projections of what is really a three-dimensional phenomena. As such, the velocities are measured as a projection, which is always an underestimate. Especially for surface branches, this projection causes a risk of mistaking two branches for a single, very fast streamer.

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4.1. PRESSURE DEPENDENCE

Figure 4.1: Images of streamers propagating through the gas as well as along the BaTiO$_3$-filled sample, for varying pressures. The black images indicate that no such image is available. I.e., at 90 mbar no surface-gas streamers were observed and at 140 mbar, no gas-only streamers were observed. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$. 

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<th>Pressure (mbar)</th>
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Figure 4.1: Images of streamers propagating through the gas as well as along the BaTiO$_3$-filled sample, for varying pressures. The black images indicate that no such image is available. I.e., at 90 mbar no surface-gas streamers were observed and at 140 mbar, no gas-only streamers were observed. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$. 

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For GO streamers, we calculated the average speed over the last 4 maxima of the left branch, disregarding any maxima where the branch reached the grounded sample holder, as the field and speed increase greatly when a streamer head approaches the ground. For SG streamers, we averaged over the entire path of the surface branch. We ignored branches propagating through the gas for an SG streamer. In both cases, the diameters were measured as the full width at half maximum (FWHM) of a single maximum near the end of the propagation path.

The error bars in figures 4.2 and 4.3 indicate the 95% error range when we average over 5 streamers. Note that both $v$ and $p_s$ are constant under similarity laws. The graphs show that GO streamers obey the similarity laws quite well; both $v$ and $p_s$ seem to be independent of $p$ within the error margin. Surface streamer branches are about twice as fast and thrice as thin as branches in GO streamers. The surface velocity is also independent of $p$ within error margin, but the surface branch diameter seems to decrease more slowly than $\frac{1}{p}$, since $p_s$ slightly increases for increasing pressure.

The generally greater velocity of surface streamer branches may be explained by photo-emission or triple point field enhancement. Due to photo-ionisation, more electrons can be freed than is possible with only photo-ionisation, because of the lower work function involved. More free electrons means that avalanches can form sooner, speeding up the formation of free charge and also speeding up streamer propagation.

Also, triple point field enhancement may cause the field near the head of a surface streamer to be enhanced more strongly than for a gas streamer. This causes free electrons to be accelerated faster, creating free charges more quickly, also speeding up propagation.
4.1. PRESSURE DEPENDENCE

Figure 4.3: Reduced streamer diameter (i.e., product of diameter and pressure) as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$.

The thinner diameters of surface streamer branches can be explained by a strong attraction to the sample. This may be caused by the polarisation mirror-charge effect, photo-emission, or triple point field enhancement. When a streamer branch propagates along the sample interface, polarisation can cause a realignment of charges in the sample which can attract the streamer head, possibly causing the streamer branch to shrink in diameter. Photo-emission may cause the streamer branch to be attracted to the sample by making sure that more free charges are present very close to the sample. Triple point field enhancement may also cause the decrease in diameter, if the enhancement is much higher near the surface. These effects may also cause the surface branch diameter to depend less strongly on pressure than the similarity laws imply, because the interactions with the sample are independent of pressure. The possibly increased thickness in the direction parallel to the surface is caused by these same effects and may also enhance deviations from similarity laws.

We can quantify the transition by introducing the chance of a gas-only streamer $P(GO)$ and the chance of a surface-gas streamer $P(SG)$. If from $N$ streamers, we observed $N_{SG}$ SG streamers and $N_{GO}$ GO streamers (with $N_{SG} + N_{GO} = N$), then $P(SG) = \frac{N_{SG}}{N}$ and $P(GO) = \frac{N_{GO}}{N} = 1 - P(SG)$. We estimate the error in the counts as the 95% certainty interval for a binomial experiment with the same chance: $\sigma_{N_{SG}} = \sigma_{N_{GO}} = 2\sqrt{NP(SG)P(GO)}$. This leads to an error in the chances equal to $\sigma_{P(SG)} = \sigma_{P(GO)} = 2\sqrt{\frac{P(SG)P(GO)}{N}}$. Note that in most cases, these errors are an overestimate of the true 95% error range. Binomial math assumes there is no correlation between the
individual binomial experiments. However, in our experiments there may very well be; as explained more deeply in the next section, leftover ionisation in the gas or leftover charge on the sample surface may depend on previous discharges and influence the next discharge.

When either chance is very small, the presented errors are an underestimate, caused by the assumption in binomial math that the chance is precisely known. However, in our experiments, even though we make the same observation $N$ times, we cannot say with certainty that the chance is 1.

Figure 4.4 shows $P(SG)$ as a function of $p$, when 1024 discharges were recorded at each pressure for the aforementioned settings (20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$). As mentioned before, we observe that $P(S)$ increases from 0 to 1 in the pressure interval between 90 and 140 mbar.

As a side note, it is obvious that counting such a large number of pictures costs a lot of time. We have written a program in Matlab to help decrease this workload. For each image in a series, the program counts how many pixels in a region near the sample surface exceed the maximum pixel value inside a region where only noise was seen. The program then asks for confirmation on what type of discharge is occurring in the most ‘uncertain’ pictures - that is, the pictures with a ‘intense pixel’ count nearest the logarithmic average - from most uncertain to increasingly certain. This continues until the user signals that they are confident all pictures are indexed correctly (typically, after 5-10 subsequently shown pictures are already correctly indexed).

A possible explanation for the transition from GO streamers to SG streamers relies on photo-emission. From kinetic gas theory, we assume that the mean free path of a photon in air scales inversely with $p$, in the same way as the similarity laws argue that $l_{mfp,e}$ and other typical streamer lengths scale inversely with $p$. Furthermore, we assume that the range for photo-emission exceeds the range of active field enhancement since it has been reported that the photo-ionisation range exceeds the range of field enhancement in ambient air [6], and the photo-emission range exceeds the photo-ionisation range [5].

As soon as a streamer head comes in the range for photo-emission, electrons are liberated which drift upwards while the sample retains a net positive charge. The accumulating positive charge repels the streamer head. However, when the streamer comes close enough to the sample for the released electrons to form electron avalanches, these may actually promote propagation along the sample.

As $p$ increases, the range of photo-emission and active field enhancement both shrink (as $\frac{1}{p}$). The distance that the streamer head crosses while positive charge accumulates, i.e., the difference of the two ranges, decreases with increasing pressure. Since the gas branch velocity is independent of $p$, the time over which the positive charge accumulates also decreases with increasing pressure. Hence, photo-emission should cause streamers to be repelled from the sample, with a strength that decreases for increasing pressure.

A possible concern about this explanation is that the electron drift velocity may be much smaller than the streamer velocity. In that case there could be no repulsion by surface charge, since the corresponding negative charges would not have moved by much in the time it takes the streamer head to reach the sample. However, tabulated
4.1. PRESSURE DEPENDENCE

Figure 4.4: Chance of a surface-gas streamer as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$.

values in [15] show that the electron drift velocity in our set-up is around $3 \cdot 10^4$ for the used settings, a tenth of the gas branch velocity. In this calculation we approximated the background field by the quotient of voltage and electrode separation; the effects of the anode tip and the streamer itself are neglected. This sizeable drift velocity implies that electrons should drift away fast enough for surface charges to have an effect on the streamer head. To be more precise, the electron drift velocity decreases from around $3.5 \cdot 10^4$ to $2.5 \cdot 10^4$, as pressure increases from 90 mbar to 140 mbar. This decrease in drift velocity may contribute to the smaller repulsion effect at high pressures by causing electrons to ‘lag behind’ more and counteract the repulsion by positive surface charge.

Aside from surface charge repulsion, the polarisation mirror-charge effect causes streamer branches to be attracted to the sample. Unlike photo-emission, mirror-charge attraction should become stronger for increasing pressure, because then the thickness of the dielectric sample becomes larger compared to length scales in the gas.

That a thicker dielectric exhibits stronger mirror-charge attraction can be understood by comparing the extreme case of an infinitely thin dielectric; which exhibits no mirror-charge attraction, to the extreme case of a semi-infinite dielectric with electric susceptibility $\chi_e$; which exhibits a force $\frac{1}{4\pi\varepsilon_0} \left( \frac{\chi_e}{\chi_e + 2} \right) \frac{q^2}{4\pi d^2}$ on a point charge $q$, a distance $d$ away, when $\varepsilon_0$ is the permittivity of the vacuum [16]. For finite values of sample thickness, we can simply imagine that as sample thickness increases, the opposite-sign charge distribution on the nearer surface remains about the same, while the same-sign charge distribution around the opposite surface is moved further away. An explicit calculation
for a finite thickness requires an infinite series of virtual mirror charges [17].

Because of the dependence of the two effects on $p$, it is to be expected that at low $p$, photo-emission repulsion is strongest and we observe only GO streamers, while at high $p$, mirror-charge attraction is strongest and we observe only SG streamers. Due to stochastic effects, we expect the transition between these two states to be gradual.

4.1.2 Correlation between different discharges

Possibly, there is a correlation between measurements in our experiments. Streamers leave behind a trail of ionisation which does not deionise completely within one second. Leftover ionisation makes it likely for the next streamer to follow the approximate same path as the previous streamer, although diffusion reduces this effect significantly [7]. Still, since we observe that surface branches and branches in gas-only streamers follow quite different paths, leftover ionisation may cause correlation between different discharges.

It is also possible that streamers are affected by surface charge remaining on the sample surface. As mentioned in the previous section, we expect that while the streamer head has not yet reached the sample, positive charge accumulates, repelling the head. Even if some of the free electrons are reabsorbed, the sample can only accumulate positive charge. After an SG streamer, however, a lot of leftover ionisation is present near the sample, partly from gas neutrals. If the electrons are absorbed as strongly as in the simulated nylon sample of Jorgenson et al. [5], the sample could accumulate negative charge after an SG streamer, increasing the likelihood of a subsequent SG streamer.

An easy way to investigate correlation between different discharges is to consider only directly subsequent discharges. E.g., considering only streamers that were preceded by an SG streamer, we can calculate the chances $P(\text{SG} \rightarrow \text{SG})$ and $P(\text{SG} \rightarrow \text{GO})$; the chance that an SG streamer is followed by another SG streamer or by a GO streamer, respectively. $P(\text{GO} \rightarrow \text{GO})$ and $P(\text{GO} \rightarrow \text{SG})$ are defined correspondingly.

If there is positive correlation, i.e., streamers have a tendency to exhibit the same behaviour as the previous streamers, we expect $P(\text{SG} \rightarrow \text{SG}) - P(\text{SG}) > 0$, $P(\text{GO} \rightarrow \text{GO}) - P(\text{GO}) > 0$, $P(\text{SG} \rightarrow \text{GO}) - P(\text{GO}) < 0$ and $P(\text{GO} \rightarrow \text{SG}) - P(\text{SG}) < 0$. In the case of negative correlation we expect the opposites of these inequalities to hold, and in the case of no correlation we expect the equality versions of these inequalities to hold.

In a sense, $P(\text{SG} \rightarrow \text{SG}) - P(\text{SG})$, which can be worded as ‘the increase in the chance of observing an SG streamer caused by the previous streamer being an SG streamer’, is a direct measure for the correlation (like its GO counterpart).

We investigate $P(\text{SG} \rightarrow \text{SG}) - P(\text{SG})$ and $P(\text{GO} \rightarrow \text{GO}) - P(\text{GO})$ in figures 4.5 and 4.6, respectively. For each of the pressures that we have investigated, it seems there is a positive correlation for repeating SG or GO streamers at most pressures. The negative correlations on the edges of the graph are likely due to the overwhelmingly large chance of either measurement. E.g., if only 3 GO events have been observed in 1000 discharges, then the chance of two of those being observed in a row is extremely small, even with a sizeable positive correlation.
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Figure 4.5: Increase in the chance of observing a surface-gas streamer caused by the previous streamer being a surface-gas streamer as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$.

Figure 4.6: Increase in the chance of observing a gas-only streamer caused by the previous streamer being a gas-only streamer as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$. 
Both graphs have a peak at 125 mbar, when $P(SG) \approx 0.7$. $P(SG \rightarrow SG) - P(SG)$ also has a somewhat smaller peak at 110 mbar where $P(SG) \approx 0.3$, but $P(GO \rightarrow GO) - P(GO)$’s 110 mbar peak is much lower. It seems that the errors are small enough to conclude that there is a positive correlation between subsequent discharges, corresponding to an increase in chance of about 10%. However, the errors are too large to draw conclusions about dependence on pressure. For the used settings with a repetition frequency of 1 Hz, it seems both possible causes of correlation mentioned above have only a small effect.

Perhaps we are unable to find a clear dependence on pressure because our measure of correlation is not properly normalised. For example, a 10% increase in chance is much more significant on a 10% base chance than on a 50% base chance. We investigate two different normalisations of our measure of correlation in appendix B.

4.2 Sample placement

It is of interest how the chosen geometry affects the likelihood of observing SG discharges. We have investigated this by varying the displacement $d$ of the sample from the centre of the anode needle (as shown schematically in figure 3.3). First, we will discuss the special case $d = 0$, where the geometry is symmetrical.

4.2.1 Symmetrical geometry

It is of interest how symmetrically the discharge behaves when the geometry used is almost perfectly symmetrical. We might expect that as the geometry approaches perfect symmetry - as shown schematically in figure 4.7 - the discharge will be more symmetrical as well. For example, we may expect that a surface branch on the right occurs as often as a branch on the left when the sample is right under the needle. Of course, we already know from gas streamer experiments that effects like non-linear field enhancement and stochastic availability of electrons severely decrease the symmetry of streamer discharges.

For a particularly symmetrical geometry, some streamer images are shown in figure 4.8. Our other settings were: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample, gas pressure 120 mbar. For these settings $P(GO) \approx 0.3$ so that we observed both SG and GO discharges. For each type, we have selected two pictures. Both GO discharges look quite symmetrical, even though we see small deviations from symmetry in the right image. However, a close look at the SG discharges reveals that in both cases, only a complete surface branch on the right side of the sample is visible.

Actually, in the left SG image, we can also see what looks like the beginning of a surface branch on the left side. In order to see if there are really also surface branches on the left side, and whether these perhaps appear later, or somehow fade away prematurely, we have imaged some other discharges with a smaller amount of stroboscope bursts, at different delays. The images in figure 4.8 used 15 50 MHz strobe bursts and we define their initial delay as 0 ns. Figure 4.9 shows selected images taken from different discharge events with 5 strobe bursts at delays 100 ns apart. They were selected on the criteria...
Figure 4.7: Schematic representation of a symmetrical geometry, zoomed in on the needle and the top of the sample. The sample is placed directly under the needle; with the tip of the needle $h = 16.5$ mm above the centre of the sample.

of showing the same type of discharge as in the left SG discharge from figure 4.8 and having a jitter of approximately the same magnitude. The other settings were: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample, gas pressure 125 mbar.

Figure 4.9 shows that during one discharge event, a surface branch on the right side of the sample occurs first. As this branch reaches the cathode, another surface branch on the left side of the sample occurs, but it propagates more slowly.

The slowness of the second surface branch is possibly caused by the already significantly lower voltage at that time. The fact that we do not observe surface branches on both sides propagating symmetrically at the same time may be caused by the strong electrical repulsion that these two would exert on each other at a distance as small as the sample thickness. It is possible that two branches en route to both sides of the sample surface at the same time simply repel each other horizontally, and both propagate through the gas instead.

However, branches that initiate at different times do not repel each other strongly since only the heads contain a strong concentration of positive charge. In fact, it has been shown that the upper parts of streamer branches may be negatively charged, unlike the positively charged heads [11], in a process that has been compared to the glowing negative trails left behind in the upper parts of sprites [12]. This means that the upper part of a surface branch on the right of the sample may attract a surface branch on the left side.
The first (or sometimes, the only) surface branch often occurred on the same side. For the above settings (particularly symmetric geometry, 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample, gas pressure 125 mbar), out of 128 discharge images, 28 did not show a surface branch, 99 showed that the first surface branch occurred on the right, and 1 showed that the first surface branch occurred on the left.

We also performed similar measurements at some different pressures. While the pressure was being adjusted, no discharge occurred for a few seconds. Even so, all these measurement series showed a similarly strong preference for the right side. However, flushing the vessel with ambient air and pumping it down again caused a seemingly random behaviour for first branch’s side during the first few discharges, and an increasing preference for either left or right surface branches quickly asserted itself.

The large correlation in side of the surface branch between different experiments can be explained by the same mechanisms as the correlation in whether an SG or GO streamer occurs between experiments; leftover ionisation and leftover negative surface charge due to electron absorption. It seems that in this case the correlation is much stronger.
4.2. SAMPLE PLACEMENT

Figure 4.9: Images of surface-gas discharges for a particularly symmetrical geometry using less intensification bursts at different delays, given in the bottom-left corners. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample, pressure 125 mbar.

4.2.2 Influence of sample displacement

Now that we have investigated the (lack of) symmetry for a nearly symmetrical geometry ($d=0$), we consider other values of $d$. Figure 4.10 shows images of some surface-gas streamers for different displacements $d$, with the settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample. For each $d$, it shows an image at the lowest pressure at which a significant chance of a SG streamer was observed ($P(SG) \gtrsim 0.05$).

We observe that as sample displacement from the centre increases, SG streamers can occur at lower pressures. Note that we did not investigate any larger displacements, since for increasing $d$ and meanwhile decreasing $p$, the difference between SG and GO streamers diminished, as streamers became increasingly broad.

In figure 4.11 we present the chance of an SG streamer as a function of pressure for the different displacements shown in figure 4.10. We see that for a larger displacement, the transition from GO to SG streamers takes place at a lower pressure.
4.2. SAMPLE PLACEMENT

Figure 4.10: Images of surface-gas streamers at different sample displacements. The lowest pressure at which there was a significant chance of a surface-gas streamer was used. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample.
4.2. SAMPLE PLACEMENT

The results from figure 4.11 are summarised in figure 4.12, which shows the transition pressure $p_{tr}$ - which we define as the pressure at which $P(SG) = P(GO) = 0.5$ and calculate using a linear interpolation between the nearest two data-points - as a function of $d$. Figure 4.12 shows that $p_{tr}$ decreases from 120 mbar to 40 mbar as displacement increases from 0 to 5 mm.

A possible explanation for the dependence on geometry is the mutual repulsion of symmetrically initiating branches discussed in the previous subsection. For a symmetrical geometry, the repulsion between two gas branches repels both from the sample. If $d$ is non-zero but smaller than half the sample thickness of 2 mm, a branch on one side can reach the sample surface while the other branch is still some distance away. Then, polarisation and triple-point field enhancement could make the one branch stick to the surface strongly, while the other branch is repelled. If $d$ is larger than 1 mm, one of two gas branches is actually repelled towards the sample by the other, which should increase the chance of a SG streamer further. Of course, we can expect stochastic effects to play a role too; even for a perfectly symmetrical geometry, the stochastically greater availability of electrons on one side can cause a branch on that side to reach the sample first and repel the other streamer. Due to this effect we can also create surface-gas streamers for the more symmetrical geometries.
4.3 Voltage pulse amplitude

In order to investigate the effect of the voltage pulse amplitude on streamers, we have performed experiments at 15 kV and 25 kV, as well as 20 kV. We performed these for both our original samples, one BaTiO$_3$-filled and one SiO$_2$-filled, at 1 Hz and $d = 0$. Some of the resulting images with gas pressure 100 mbar are shown in figure 4.13. $P(SG)$ as function of $p$ is shown for the different voltages in figure 4.14 for a BaTiO$_3$-filler and in figure 4.15 for a SiO$_2$-filler.

In figure 4.13, we observe that streamer velocity and diameter increase as we apply increasingly high voltages. From gas-streamer experiments, it is well-known that this is caused by the higher electric field accelerating electrons at a faster rate, in a larger region [1, 2].

Considering the difference between the two samples, figures 4.14 and 4.15 clearly show that for the same settings, SG streamers have a lower chance of occurring along the SiO$_2$-filled sample. A likely cause for this difference is the difference in relative permittivity, which is 10 for the BaTiO$_3$-filled sample and 4 for the SiO$_2$-filled sample. Since polarisation is the only thing that attracts a distant branch to the sample, it is likely that reducing the relative permittivity can have a large effect in reducing the likelihood of SG streamers. However, differences in, e.g., photo-emission may also cause some difference. We will investigate this more deeply in section 4.4.
Another observation is that branches are repelled more strongly from the sample for increasing voltage. For the BaTiO$_3$-filled sample this is clear from figure 4.13, from the fact that at 100 mbar, we observe mostly SG discharges for low voltages and mostly GO discharges for high voltages. For the SiO$_2$-filled sample this is clear from figure 4.13, from the fact that in the 25 kV picture, two streamers are repelled all the way around the long side, to the front and back of the sample. Figures 4.14 and 4.15 show this more completely; for a BaTiO$_3$-filled sample, the transition from GO to SG discharges shifts to higher pressures as we increase $V$. For the SiO$_2$-filled sample, we have not been able
4.3. VOLTAGE PULSE AMPLITUDE

Figure 4.14: Chance of a surface-gas discharge as function of pressure when the original barium titanite-filled sample was used, for some different voltages. Other settings: 1 Hz pulse, $d = 0$.

to sustain the discharge at pressures where $P(SG)$ is above a few percent. Even so, we see that the pressure where $P(SG)$ increases from 0 to at least a small chance, increases for increasing voltage.

The increasing repulsion for increasing voltage is possibly caused by the fact that the repelling effects (surface charge repulsion and symmetric branch repulsion) scale more strongly with electric field than the attracting effects (mirror-charge attraction). Of course, we expect that each of these effects increases for increasing voltage. Since the streamers become larger and electrons are accelerated more strongly, more excitations of neutrals that can emit a photon to cause photo-emission can occur, increasing the effect of surface charge repulsion. Also, the streamer heads should contain more charge for a higher voltage, increasing the other two effects.

However, it is difficult to estimate the exact dependence on voltage or even electric field of these different effects. We can, however, name a few indirect factors for which the different effects should scale differently. For example, it is possible that the difference in scaling is caused by the occurrence of broader streamers for higher voltages. The relative decrease in sample thickness may decrease the effect of mirror-charge polarisation, as discussed in section 4.1.1. The increased voltage may also cause lesser dependency on
4.4 Different samples

In the previous section we saw that for a BaTiO$_3$-filled sample, SG streamers are much more likely to occur than for a SiO$_2$-filled sample. We named the large difference in relative permittivity as a likely cause of this observed difference between our two original samples. However, it may well be that other differences in the characteristics of these samples could have an effect as well. The other BaTiO$_3$-filled samples were used to verify whether the large difference was indeed caused by the difference in permittivity, as we expect only minimal differences in the other characteristics between the samples with different ratios of BaTiO$_3$-filler.

Figure 4.15: Chance of a surface-gas streamer as function of pressure when the original silicon dioxide-filled sample was used, for some different voltages. Other settings: 1 Hz pulse, $d = 0$.

stochastic effects, since free charge can more easily be created anywhere. Then, the stochastic effect that counters symmetric branch repulsion by allowing one streamer to reach the sample before its symmetric ‘twin’. Note that all these effects are counteracted by the increase in streamer velocity brought about by an increased voltage. This increase in velocity allows repelling surface charge to accumulate over a shorter amount of time, reducing its effect.
For all the different samples, we performed experiments for a voltage pulse of 20 kV at 1 Hz, at $d=0$, for different pressures. The observed chance of an SG streamer as a function of pressure is shown in figure 4.16. The different samples are indicated by their value of $\varepsilon_r$ ($\varepsilon_r=4$ corresponds to the SiO$_2$-filled sample, the other values correspond to BaTiO$_3$-filled samples).

Figure 4.16 shows that for the SiO$_2$-filled sample, no surface discharges occur for any of the pressures at which the discharge can be maintained for these settings. For the BaTiO$_3$-filled samples, we find that the transition from GO to SG discharges takes place at a lower pressure, for increasing $\varepsilon_r$. This is underlined in figure 4.17, which shows $p_{tr}$ as a function of $\varepsilon_r$ for the different BaTiO$_3$-filled samples. This confirms that the relative permittivity indeed has a large effect on the surface-streamer interaction.
4.4. DIFFERENT SAMPLES

However, there is a large difference between a BaTiO$_3$-filled sample with $\varepsilon_r = 5$ and a SiO$_2$-filled sample with $\varepsilon_r = 4$. It is possible that a fast transition occurs in this region of relative permittivity, or that the non-linearity in $\varepsilon_r$ of BaTiO$_3$-filled samples means that their permittivity is much higher in our experiments than during the dielectric spectroscopy. It is also possible that differences in other material properties cause even more repulsion from a SiO$_2$-filled sample compared to a BaTiO$_3$-filled sample. Possibly, the latter has a higher work function for photo-emission or a higher tendency for absorption of electrons, both of which would decrease surface charge repulsion and hence promote surface branches along the BaTiO$_3$-filled sample more strongly.

Alternatively, since the relative permittivity of, on the one hand, the two original samples, and on the other hand, the three newest samples, has been characterised in two different measurement series some weeks apart, these may have been performed under circumstances different enough for the results to mismatch. Especially considering the non-linear nature of BaTiO$_3$-filled dielectric samples, it is possible that the difference in the relative permittivity of the 20% BaTiO$_3$-filled sample and the SiO$_2$-filled sample is larger than the dielectric spectroscopy measurements suggest. The spectroscopy results are discussed more deeply in Appendix A.

![Figure 4.17: Transition pressure - the pressure at which the chances of a surface-gas streamer and a gas-only streamer are equal - as a function of relative permittivity of the barium titanite-filled samples.](image)
5. Conclusions

In this chapter we summarise the conclusions that may be drawn from our investigation of surface streamers.

We have found that the occurrence of surface or non-surface streamers depends on a number of factors. Of the ones we have investigated, we have found that the occurrence of surface streamers is promoted by higher gas pressures, lower voltages, a higher sample displacement from the centre, and higher sample permittivity, when other factors were kept constant. We have also found that between BaTiO$_3$-filled epoxy samples and SiO$_2$-filled epoxy samples, there is at least one other difference in properties of the two samples that impedes surface streamers for the latter sample.

We explain the dependence on these different parameters by three processes, considering how changes in the varied parameters affect all three processes. These are surface charge repulsion caused by photo-emission, symmetric repulsion between different streamer branches, and mirror charge attraction due to polarisation of the sample.

We have found that surface streamers are generally faster and thinner than non-surface streamers, twice as fast and thrice as thin for the settings which we used. We explain both these effects by triple-point field enhancement and photo-emission. Mirror charge attraction also plays a role in the decreased surface branches diameters.

We have also investigated correlations between different discharges, both in terms of whether a surface or non-surface discharge occurs and whether a surface streamer propagates along the left or right side of the sample for a symmetrical geometry. We have found that whether or not the previous streamer included a surface branch can influence the chance of there being a surface branch in the next streamer by about 10%. We have also found that despite a symmetric geometry, a 99% chance preference for a surface branch on either side can set in after just a few discharges. We explained both correlations by leftover ionisation in the gas and negative surface charge on the sample due to electron absorption.
In this chapter we present some possible extensions to our research, which may be considered by future researchers.

An interesting parameter which we have not varied in our experiments is the repetition rate. This would likely have a large influence on the correlation between subsequent discharges, and could even influence the chances of surface or non-surface streamers. In our set-up, a repetition frequency of 10 Hz is feasible for continuously repeating experiments. Shorter time-scales could be investigated by using a double-pulse and two ICCD cameras, as applied to streamers in gas mixtures in [8].

By investigating surface streamers in different gas mixtures of nitrogen and oxygen, the effects of photo-ionisation could be investigated more closely. For example, we may expect that at low levels of oxygen concentration, surface streamers are more common since photo-ionisation decreases in magnitude while photo-emission is largely unaltered. However, using a mixture of pure gasses would limit the amount of opportunities to change the sample placement, unless a contraption that could move the sample without having to open up the vessel were installed.

An interesting sample parameter to vary would be the thickness, since it could change the relative impact of true surface effects like photo-emission and bulk dielectric effects like polarisation. Another geometry-related parameter of interest is the distance between the needle tip and the top of the sample. For example, if this were decreased, inception of surface streamers could be studied.

Stereoscopic photography could be used to obtain a better understanding of the paths taken by streamers. For example, in cases where we have assumed that the picture showed us a streamer propagating around the front of the sample, stereo-photography could provide conclusive evidence. Also, from naked-eye observations, we know that surface streamers do not move straight down over the sample surface but instead take winding paths and even branch at times. This could also be investigated with stereoscopic imaging. Another advantage of stereoscopic imaging is that it could provide better estimates of the measured velocities. With the current set-up, we always measure the velocity as projected on a plane, which is always an underestimate.

Furthermore, spectroscopy could perhaps provide information about (chemical) interactions with the sample, and the Pockels method [13] could provide information about the potential - and thus the charge distribution - of surface streamers.
A. Dielectric spectroscopy

Dielectric spectroscopy on our samples was performed by Lorentz Herrman at ABB. His results are summarized in figure A.1. We note that the original BaTiO$_3$-filled sample and the one with 60% BaTiO$_3$ filler are strangely close in reported dielectric constant, since from behaviour in surface streamer experiments as well as colour shading, we estimate the filling ratio of the original to be 50%. It is possible that this is an error caused by different calibration settings at ABB, since the two measurement series were executed weeks apart. This could also explain the large difference in behaviour between our two samples with lowest permittivity in our own experiments. It is also possible that $\varepsilon_r$ of a BaTiO$_3$-filled epoxy sample as a function of filling ratio does not even closely resemble a linear function and instead, the rising behaviour halts for BaTiO$_3$ fillings over 50%, while at the same time our own measurements for the two highest-permittivity samples were faulty due to, for example, imprecise positioning.

![Figure A.1: Relative permittivity as a function of frequency for different sample fillers.](image)

Figure A.1: Relative permittivity as a function of frequency for different sample fillers.
B. Normalisation of correlation

As stated in chapter 4.1.2, defining the measure of correlation as a difference in chances (for example, $P(SG \rightarrow SG) - P(SG)$) means that we neglect the fact that a 10% increase in chance is much more significant when $P(SG) = 0.1$ than when $P(SG) = 0.5$. Possibly, $rac{P(SG\rightarrow SG) - P(SG)}{P(SG)}$ is a better measure of correlation, since we have normalised it by dividing by $P(SG)$.

We investigate $\frac{P(SG\rightarrow SG) - P(SG)}{P(SG)}$ and $\frac{P(GO\rightarrow GO) - P(GO)}{P(GO)}$ in figures B.1 and B.2 respectively. Both graphs only show large correlations near the point where the chances by which we divide approach 0. Apparently this method of normalisation does not provide more insight than the differences in chances themselves.

Perhaps another thing that we should consider is that when $P(SG) = 0.9$, a 10% increase in chance is also much more significant compared to $P(SG) = 0.5$. In order to compensate for both small values of $P(SG)$ and $P(GO)$, we could divide by the product of both the chances and thus consider $\frac{P(SG\rightarrow SG) - P(SG)}{P(SG)P(GO)}$. However, a perhaps more elegant method is to divide by the square root of this product and thus consider $\frac{P(SG\rightarrow SG) - P(SG)}{\sqrt{P(SG)P(GO)}}$. Even though the chances are already dimensionless, this approach guarantees that the result is dimensionless even if the chances were not. Also, $\sqrt{P(SG)P(GO)}$ is the standard deviation in a single binomial experiment with chance $P(SG)$, which holds some mathematical meaning as a normalisation constant.

We investigate $\frac{P(SG\rightarrow SG) - P(SG)}{\sqrt{P(SG)P(GO)}}$ and $\frac{P(GO\rightarrow GO) - P(GO)}{\sqrt{P(SG)P(GO)}}$ in figures B.3 and B.4, respectively. There do not seem to be much differences between these graphs and those presented in figures 4.5 and 4.6 in section 4.2.2. Most notably, a few values near the edges have increased relative to the others, especially making the graph for correlation in repeating SG streamers a little more constant.
Figure B.1: Increase in the chance of observing a surface-gas streamer caused by the previous streamer being a surface-gas streamer, normalised by division over the base chance of a surface-gas streamer, as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$.

Figure B.2: Increase in the chance of observing a gas-only streamer caused by the previous streamer being a gas-only streamer, normalised by division over the base chance of a gas-only streamer, as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$. 

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Figure B.3: Increase in the chance of observing a surface-gas streamer caused by the previous streamer being a surface-gas streamer, normalised by division over the square root of the product of the base chances of gas-only and surface-gas streamers, as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$.

Figure B.4: Increase in the chance of observing a gas-only streamer caused by the previous streamer being a gas-only streamer, normalised by division over the square root of the product of the base chances of gas-only and surface-gas streamers, as function of pressure. Other settings: 20 kV pulse at 1 Hz, original BaTiO$_3$-filled sample at $d = 0$. 

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