Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Fredrik Leonardie Bratland

New Environmentally-friendly Insulation Gases

Pre-breakdown Mechanisms under Impulse Voltage in Synthetic Air and AirPlus

Master's thesis in Electrical Power Engineering
Supervisor: Frank Mauseth
Co-supervisor: Hans Kristian Hygen Meyer
June 2022

NTNU
Norwegian University of
Science and Technology

Fredrik Leonardie Bratland

New Environmentally-friendly Insulation Gases

Pre-breakdown Mechanisms under Impulse Voltage in Synthetic Air and AirPlus

Master's thesis in Electrical Power Engineering
Supervisor: Frank Mauseth
Co-supervisor: Hans Kristian Hygen Meyer
June 2022

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

With an increasing focus on environmentally friendly solutions in the energy industry, there is a desire to reduce the current use of SF_6 as an insulation gas. It has excellent dielectric properties, making it nearly perfect as an insulation gas. However, it has a global warming potential of approximately 23,900 times that of CO_2, meaning it is an incredibly potent greenhouse gas. However, to reduce the use of SF_6, there must be some other insulation gas to take its place. A mixture of ketones and synthetic air called AirPlus is an up-and-coming alternative. This thesis aims to investigate and experiment on AirPlus, specifically how pre-breakdown mechanisms act in AirPlus compared to synthetic air. This is done at pressures of 1.0, 1.3, and 1.5 bar, with positive and negative impulses, in a very inhomogeneous rod-plane gap of 53 mm. A needle is inserted into the rod to increase the inhomogeneity further.

Ketones, or C5-FK ($C_5F_{10}O$), have a boiling point at 26.9°C, meaning it has to be mixed with a carrier gas to lower the boiling point to below 0°C. For AirPlus, this carrier gas is synthetic air. Synthetic air is a mixture of 80% nitrogen and 20% oxygen. AirPlus is a mixture of 7.5% ketones and 92.5% synthetic air.

The simulations performed with COMSOL and a python script showed that for both synthetic air and AirPlus, the inception voltage should increase with increased pressure. The increase in inception voltage from synthetic air to AirPlus was calculated to be around 28-29% for all pressures with positive polarity.

The experimental tests showed different results, however. The inception voltages from the up-and-down tests showed that the negative polarity in 1.5 bar synthetic air was just above half the voltage of 1.3 bar. Several other cases like this imply that the up-and-down method might not be a good way of finding the 50% inception voltage, even with a wait time of 180 seconds between shots.

A high-speed camera was used to capture images of the streamers in the different configurations. In synthetic air, the images show that increasing the pressure to 1.5 bar will stop the negative streamers from propagating all the way to the plane, while the positive streamers will still propagate over the whole gap. Increasing the pressure to 1.5 bar results in short leader-like discharges for both polarities. None of the streamers in AirPlus are even close to propagating all the way to the plane, regardless of pressure and polarity, even with higher voltage than in synthetic air.

As a proof of concept, stereoscopic 3D imaging was tested with a simple mirror setup. A digital 3D model of a steel wire formation was made using a python script with only a stereoscopic image as input.

Sammendrag

Med økende fokus på miljøvennlige løsninger i energi-industrien er det et ønske om å redusere den nåværende bruken av SF_6 som isolasjonsgass. SF_6 har utmerkede dielektriske egenskaper, noe som gjør det til en nær perfekt isolasjonsgass. Ulempen er at den har et globalt oppvarmingspotensial (GWP) på omtrent 23,900 ganger så mye som CO_2, som betyr at det er en utrolig sterk drivhusgass. For å redusere bruken av SF_6 må det være en annen isolasjonsgass som kan ta over. En blanding av ketoner og syntetisk luft ved navn AirPlus er et veldig lovende alternativ. Målet med denne oppgaven er å undersøke og eksperimentere på AirPlus, spesifikt hvordan prenedbrytningsmekanismer virker i AirPlus sammenlignet med syntetisk luft. Dette gjøres ved trykk på 1,0, 1,3 og 1,5 bar, med både positive og negative impulser, i et meget inhomogent stang-plate gap på 53 mm. En nål settes inn i stangen for å øke inhomogeniteten ytterligere.

Ketoner, eller C5-FK ($C_5F_{10}O$) har et kokepunkt på 26,9°C, som betyr at det må blandes med en bæregass for å senke kokepunktet til under 0°C. For AirPlus er denne bæregassen syntetisk luft. Syntetisk luft er en blanding av 80% nitrogen og 20% oksygen. AirPlus er en blanding av 7,5% ketoner og 92,5% syntetisk luft.

Simuleringene utført med COMSOL og et python-skript viste at for både syntetisk luft og AirPlus bør tennspenningen øke med økt trykk, uavhengig av spennings-polaritet. Økningen i tennspenning fra syntetisk luft til AirPlus ble beregnet til å være rundt 28-29% for alle trykk med positiv polaritet.

De eksperimentelle testene viste imidlertid andre resultater. Tennspenningene fra opp-og-ned tester viste at negativ polaritet i 1,5 bar syntetisk luft hadde rett over halvparten av spenningen på 1,3 bar. Det var flere andre tilfeller som dette, noe som antyder at opp-og-ned-metoden kanskje ikke er en god måte å finne 50% tennspenning, selv med en ventetid på 180 sekunder mellom spenningspåtrykkene.

Et høyhastighetskamera ble brukt til å ta bilder av streamerne i de forskjellige konfigurasjonene. I syntetisk luft viser bildene at å øke trykket til 1,5 bar vil stoppe negative streamere fra å forplante seg helt til platen, mens de positive streamerne fortsatt vil forplante seg over hele gapet. Ingen av streamerne i AirPlus er i nærheten av å forplante seg hele veien til platen, uavhengig av trykk og polaritet, selv med høyere spenning enn i syntetisk luft. Å øke trykket til 1,5 bar resulterer i korte leader-lignende utladninger for begge polaritetene.

Som et prinsipp ble det også tested stereoskopisk 3D fotografi med et enkelt speil-oppsett. En digital 3D modell av en ståltråd-figur ble laget ved hjelp av et python-skript, hvor kun et stereoskopisk bilde var input.

Preface

First, I would like to thank my supervisor, Frank Mauseth, and co-supervisor Hans Kristian Hygen Meyer for all the help and guidance and for being available when needed.

The laboratory setup would not be possible without Morten Flå and Dominik Häger. Also, thanks to Dag Linhjell at SINTEF for all the inputs and expertise.

Thank you to Fanny Skirbekk for being a great lab partner and for helping with countless improvements to the thesis, and Stian Nessa for working countless hours in the lab to assemble and disassemble the lab setup. And finally, I would like to thank all my fellow students in F452 for all the good times.

Contents

Chapter 1

Introduction

For several decades, sulfur hexafluoride, or SF_6, has been the preferable insulating gas in medium voltage (MV) and high voltage (HV) gas-insulated systems. SF_6 is an excellent insulation gas with very good dielectric properties, making it incredibly useful in smaller compact insulated systems. However, SF_6 comes with a considerable disadvantage regarding environmental damage. It has a global warming potential (GWP) of approximately 23,900 times that of CO_2, meaning that if 1 kg of SF_6 is released into the atmosphere, it is the equivalent of 23,900 kg of CO_2. This creates the need for other more environmentally friendly alternatives. One of the new alternatives is C5-fluoroketones, or C5-FK (chemical formula $C_5F_{10}O$). It is chemically stable, is not toxic, and is not flammable. One of the downsides of C5-FK is the dew point at 26.9°C, which is too high for regular MV and HV applications, which require a dew point at least below 0°C. Because of this, it needs to be mixed with a carrier gas. The carrier gas needs to lower the dew point enough and not affect the GWP or the dielectric properties in a negative way. Nitrogen was first seen as the best choice as the carrier gas, but oxygen also had some good properties for the final mixture. Hence, synthetic air was chosen as the carrier gas, which is 80% nitrogen and 20%. The final mixture ended up being a mixture of 7.5% fluoroketones and 92.5% synthetic air, called AirPlus. AirPlus has great dielectric properties, almost comparable to SF_6. But because the gas mixture is relatively new, more research is required to determine in what applications it can replace SF_6.

In the MV to HV system range up to 230 kV, fast front overvoltages such as lightning impulses are the most severe overvoltages. For the electrical equipment in this range, streamer discharges produced from fast front voltages must be considered.

Using a marx impulse generator, pre-breakdown mechanics in technical air and AirPlus are investigated. Both positive and negative polarities are tested in 1.0, 1.3, and 1.5 bar pressure. The goal is to understand better how discharges propagate in AirPlus compared to synthetic air in very inhomogeneous fields and how increased pressure affects how both positive and negative streamers behave and propagate. To compare theory with practical experiments, numerical simulations will also be conducted.

1.1 Scope of Work

The scope of this project can be defined by the following parts:

- To calculate and simulate the inception voltage of the different configurations presented in Table 5.1. This will be done using COMSOL to model the plane-rod gap and a python script developed by Hans Kristian Hygen Meyer at SINTEF Energy. The field lines from the COMSOL simulations are then imported to the script, which will use the streamer integral to calculate the minimum possible inception voltage for that model. The results will then be compared to the experimental inception voltage tests. The experimental inception tests are done using the up-and-down method with a photomultiplier tube (PMT) to confirm the presence of light in the gap. The simulations are expected to show lower values than the experimental results, as there is a time lag before a free electron is available to start the first electron avalanche. Also, the resulting inception voltages for AirPlus are expected to be significantly higher than those in synthetic air.
- To create a visual understanding of how streamers behave in both synthetic air and AirPlus in the different configurations. By capturing a large amount of images for each of the configurations, a general understanding of the streamer behavior can be made. There will be captured at least 15 images for each configuration, in addition to images of the inception voltage tests. These images will then be analyzed and compared to understand what effects AirPlus has on the streamers, in regards to length and number of branches, compared to synthetic air. The pressure of the gas will also be considered, as higher pressures will decrease the distance at which the electrons can accelerate from the field in the gap.
- As more of a side-project, stereoscopic 3D imaging will be researched and tested. A single camera can produce a 3D image or model of the streamers by using mirrors and prisms. This can possibly provide better and more reliable imaging, as a single 2D image is more prone to be misread. What is meant by this is that the dimensional aspect is not present in a 2D image, and it can be challenging to be certain if something, a streamer branch, for instance, is moving towards or away from the camera view. A simple test setup will be made and tested on both a steel wire model and streamers. A python script is also made to create the 3D model of the steel wire model.

1.2 Spesialization project

A specialization project was written in the previous semester, with a similar theory and laboratory setup. The project is not a published document, so the whole text will be copied, except for some fixed errors. Hence, some of the information written in the projects is still valid and useful, and will be quoted in some occasions in this thesis.

Chapter 2

Theory

2.1 Insulation gases

The following section is taken directly from the specialization project. In Gas Insulated Switchgear (GIS) and medium- and high-voltage circuit breakers and switches, some insulation gas must be used. SF_6 is the gas most used today, as this is an excellent insulation gas. It has great dielectric strength, low boiling point, is non-toxic, not flammable or corrosive, and has good thermal conductivity compared to air [1]. It is also relatively inert, has high heat transfer capabilities, and combined with the dielectric strength, it is very suitable for arc extinction capabilities. These are generally all essential properties for any gas to be used as an insulation medium. Another important aspect is the environmental requirements, which is why SF_6 should be replaced. It has a global warming potential (GWP) of approximately 23,900 times that of CO_2 [2].

When considering a gas to replace SF_6, Cigre WG D1.67 has defined three main technical requirements [3]:

- **The dielectric strength**

  The voltage an insulating material can withstand before it loses its insulating properties. This should be significantly better than atmospheric gases like N_2, CO_2, and air. It is preferred to be in the vicinity of that of SF_6 at the same pressure.

- **The dew point**

  The temperature where a gas is turned to its liquid state. This has to be below the minimum use temperature of the product or application in which the gas is to be used. As with the electric strength, this is linked with the operating pressure of the gas.

- **The chemical stability**

  The gas has to be relatively inert, meaning there should be no extensive decomposition, polymerization, or carbon generating during high temperatures, partial discharges, or because of surrounding materials.

2.1.1 Synthetic air

Synthetic air, also called technical air or pure air, is a gas mixture of nitrogen and oxygen, with a ratio of 80-20, respectively. This is gas close to that of atmospheric air, but without the impurities, such as water vapor, CO_2, and Argon. These impurities are usually considered to be around 1% of the air.

2.1.2 AirPlus

AirPlus is a gas mixture of synthetic air and fluoroketones (C5-FK). 3M developed the product C5-FK, also named 3M™Novec™5110 Dielectric Fluid, and is shown in Figure 2.1. AirPlus is usually considered to have a ratio of 7.5% C5-FK and 92.5% synthetic air. The reason for the mixture instead of pure C5-FK is the dew point. The C5-FK has a relatively high dew point of 26.9°C, meaning it would be liquid for most applications around 20°C. The dew point is significantly lowered by using synthetic air as a carrier gas to below 0°C. The lowest temperature for indoor MV primary GIS is typically -5°C, while -25°C is a typical requirement for compact secondary substations.

When testing for different gasses to use as the carrier gas, pure nitrogen was first viewed as the most prominent [4]. It proved to have dielectric and chemical advantages when adding oxygen, and dry synthetic air was chosen as the best carrier gas.

Ketones alone have shown excellent dielectric performance. The toxicity of ketones is in the same range as SF_6, which is very low. The GWP is also below that of CO_2.

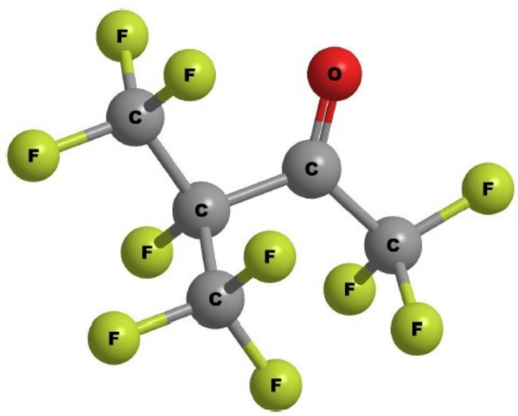


Figure 2.1: C5 fluoroketone 3M Novec 5110 Fluid [4]

2.2 Streamer Inception

When a strong positive electric field is applied to a gas in an inhomogeneous gap, an electron avalanche may occur. A discharge process will begin if this electron avalanche reaches a number of electrons above a critical value. The avalanche will leave behind a positive space charge which turns into a filamentary discharge. This discharge is what's called a streamer. The field strength needed to initiate streamer inception can be calculated using the streamer inception integral

$$\int_{\Gamma} \alpha_{\text{eff}} dx = \ln(N_c) \tag{2.1}$$

The field-dependent effective ionization coefficient is represented with α_{eff}, and N_c is the critical number of electrons needed in the electron avalanche to form a streamer head capable of self-propagation. Γ is the critical field line, typically starting where the field strength is highest, and following the field line where $\alpha_{\text{eff}} > 0$, until a critical background field E_c is reached, where $\alpha(E_c) = 0$. For atmospheric air, this critical background field is $E_{c,air} = 2.5$ kV/mm. When the critical number of electrons in the avalanche is reached, typically around $N_c = 10^8$, inception will occur. It is worth noting that even though inception occurs, it does not necessarily lead to a breakdown.

It has also been found a phenomenon where the positive discharge from a needle is not directly forming a streamer branch but rather a transition stage where the discharge is cloudy or diffuse [5, 6]. This was called *inception cloud*, and can also be observed in negative discharges [7]. An example of an inception cloud is shown in Figure 2.2. In this example and others, light is emitted in almost all directions around the electrode, growing outwards. The second stage is shown in the middle image in Figure 2.2 and is the light emitted from a thin shell, expanding from the cloud. The third stage shown on the right side is the shell breaking up and forming separate streamer branches.

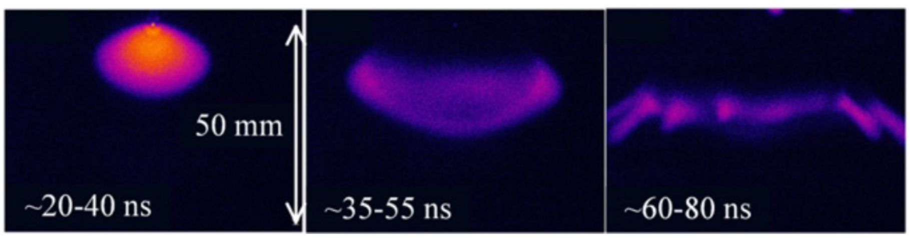


Figure 2.2: Inception cloud to the left, the shell in the middle and the destabilization of the shell to the right. The voltage applied here is a 130 ns +35 kV voltage pulse in 200 mbar synthetic air. Figure from [8] and [7].

Several sources has seen this phenomena, and it has been called different things, such as diffuse discharge [9–11], spherical streamer [12, 13] or an ionization wave [14]. The second phase, the shell phase, is a nonlinear structure with a propagating ionization front. The electric field is screened from the inside of the streamer, like the left image in Figure 2.3, but closer to semi-spherical and not yet lengthened. The ionization front of the streamer is indicated by the local light emission. The maximum radius of the cloud corresponds with the premise that the shell's interior is electrically screened, and the electric field on the boundary is approximately the breakdown field E_k. The radius R of a conducting sphere with the electric potential U and surface field E is $R = U/E$, meaning the maximum radius of the inception cloud is

$$R_{max} = \frac{U}{E_k} \tag{2.2}$$

Here, U is the applied voltage on the electrode, and E_k is the breakdown field.

2.3 Streamer Propagation

As mentioned, streamers can be of both positive and negative polarity. A schematic comparison is shown in Figure 2.4. A positive streamer will typically propagate towards the cathode against the drift direction of the electrons. It carries a positive charge surplus at the streamer head. A negative streamer will propagate towards the anode. Positive streamers in air propagate faster and further than negative and have been observed to start more easily. Around a negative streamer, an excess of electrons forms the space charge layer. These drifts away from the streamer body and the enhancement of the electric field at the streamer tip will be decreased due to the lateral drift. This happens even if the lateral field is below the breakdown threshold. On the other hand, a positive streamer will only grow where the field is high enough for a large number of approaching avalanches to develop. An excess of positive ions forms their charge layers. These ions move significantly slower than the electrons. This means that for positive streamers, the field enhancement ahead of the streamer is better sustained.

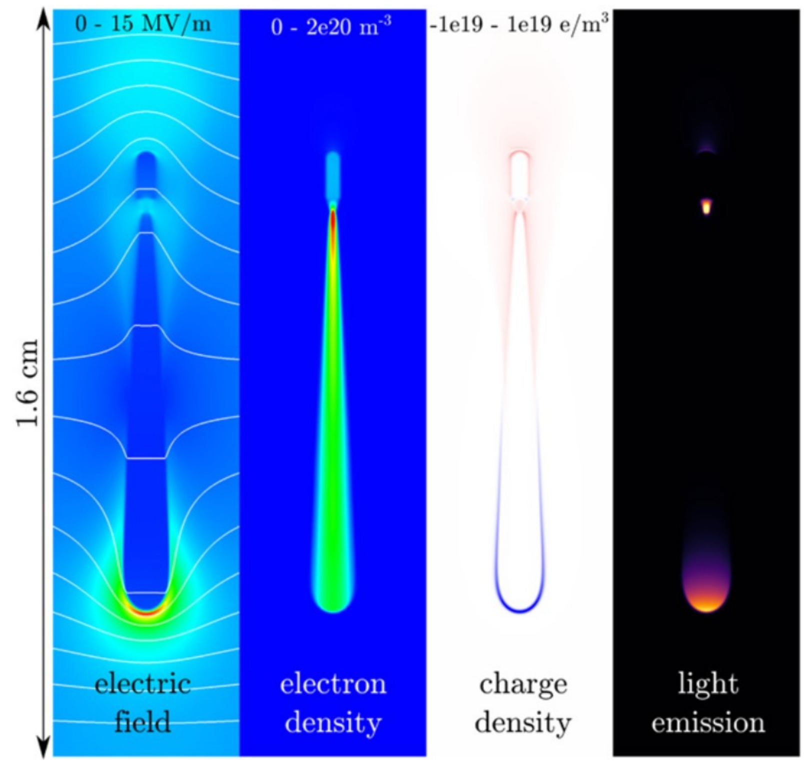


Figure 2.3: A simulation of the cross-section of a positive streamer propagating downwards. In image one from the left, a strong electric field is present at the streamer tip. In image three from the left, the charge density can be seen. A charge layer surrounds the streamer body, the blue at the tip represents the positive charge, and the red at the tail represents the negative charge.

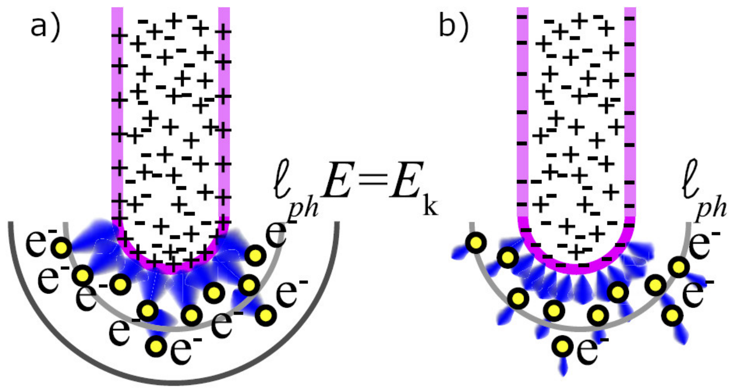


Figure 2.4: A schematic of how streamers propagates. a) shows positive streamers in air and b) shows negative streamers in air. The blue electron avalanches starts from the yellow electrons, ℓ_{ph} indicates the range of the photoionization, and $E = E_k$ shows the active region. From [15]

2.4 Gas particles in electric fields

For currents to flow and both breakdown and pre-breakdown mechanisms to occur, charge carriers must be present in the gas. These are electrons and ions created from ionizing the gas molecules. Ideally, an insulation gas does not allow any currents to flow at all, but when a weak electrical field is applied over a gap, a very small current will flow. This is because of free electrons and ions. Increasing the temperature of the gas or the electrical field will increase the number of charge carriers. From natural radiation, additional charge carriers may occur. In confined spaces such as inside a steel tank or GIS chambers, however, the appearance of charge carriers may be more stochastic. This can be artificially generated with, for instance, UV radiation.

The most essential ionizing mechanisms are photoionization, collision-ionization, and thermal ionization. Photoionization is when a photon with some frequency ejects one or more electrons from a molecule, creating an ion. The energy of a photon can be calculated with the equation

$$W_f = h \cdot f \tag{2.3}$$

where f is the photon frequency, and h is the Planck constant. This means that a photon with a higher frequency has more energy, increasing the chance of photo ionizing the gas molecules. In air, this is the most dominant ionization mechanism.

Collision-ionization can happen when two molecules collide. Suppose the resulting kinetic energy of the colliding molecules exceed the ionization-energy of the gas molecules. In that case, one or more electrons will eject, creating a free electron and a positive ion. In an electric field, the electron and ion will accelerate in opposite directions. This can lead to new collisions, more often for the electrons than the ions. This is because the electrons are accelerated more than the ions due to the lower mass of the electrons.

When the temperature in the gas increases, the movement of the molecules are increased and can lead to ionization, but for air and SF_6, the temperature has to be above 1000°C for this to happen.

2.5 Electron delay

When looking at discharges during a longer time, where the voltage is increased gradually over time, there cannot be observed any delay effects. This effect must be considered when studying impulse voltages, or fast rising voltages. It means the inception isn't necessarily occurring at the exact time the voltage exceeds the inception voltage threshold V_0. Inception cannot occur unless there is a free electron present. The time lag t_s until this electron occurs is the *ignition delay*, and is a statistical time lag. In Figure 2.5, it can be seen that the minimum inception voltage V_0 is much lower than when the inception occurs after the time lag t_s.

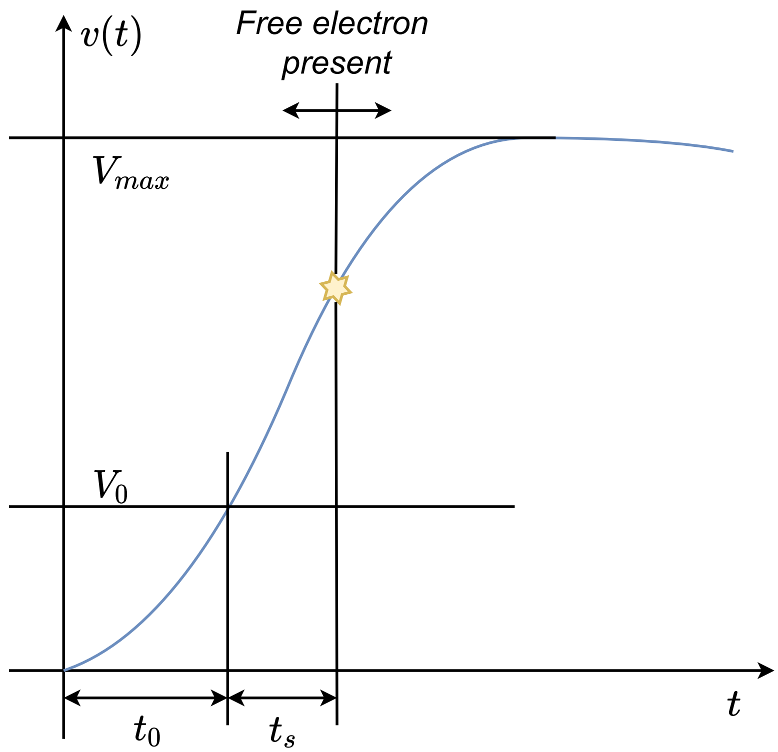


Figure 2.5: Statistical delay of inception, because inception cannot occur until a free electron is present to start the electron avalanche.

Chapter 3

Experimental methods

3.1 Setup

A 1.2 MV marx impulse generator was used in the laboratory setup to generate impulse voltages on a rod-plane gap inside a tank. High-speed cameras were used to capture images of the discharges, and a PMT was used to observe any light inside the pressure vessel and troubleshoot the timing of the camera trigger. Since the PMT and camera are light-sensitive, the tank, PMT, and camera were placed inside a tent. Additionally, the camera was placed inside a faraday cage to protect it from the electromagnetic fields. A schematic of the laboratory setup is shown in Figure 3.1. In the control room, an oscilloscope was used to record the impulse voltage, the trigger signal for the camera, and the voltage from the light observed by the PMT.

The gap between the electrode and ground was set to 53 mm, as this was the maximum possible inside the tank. In an attempt to reduce the capacitive currents, the electrode configuration was reversed so that the ground plane was placed on the side of the impulse generator, and the rod electrode was grounded. The plane was then subjected to the impulse voltage so that a negative impulse voltage from the generator resulted in positive streamers from the grounded rod-electrode. This way is equivalent to regular positive streamers.

Both positive and negative streamers were investigated. For synthetic air, the positive inception voltage is expected to be lower, while for AirPlus, the negative inception voltage may be lower. The polarity effects are therefore very interesting to look at, but it is expected to share some characteristics of SF_6.

The tank has two windows on opposite sides, one for the camera and one for the PMT. These windows are made of polycarbonate (PC Lexan pl klar Exell-D) and are not letting any UV light through [16]. This essentially affects the wait time for a start electron to start the positive electron avalanches as explained in section 2.5.

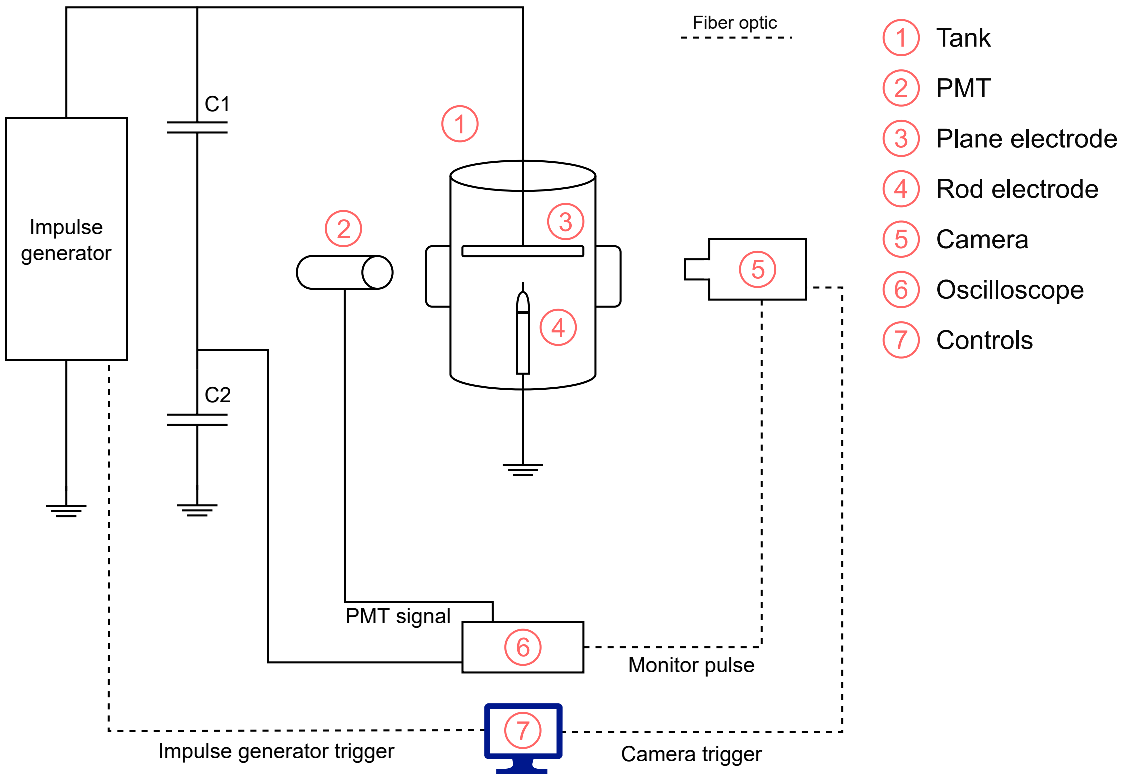


Figure 3.1: The schematic of the experimental rod-plane setup used in the high voltage lab at NTNU. The tent used is not shown, but is covering the camera, the PMT and the tank. The camera is also placed inside a separate Faraday cage.

3.1.1 Impulse Generator

For generating the lightning impulses, a 60 kJ 12 stage marx impulse generator was used. This impulse generator is capable of producing lightning and switching impulses up to 1.2 MV. It produces a non-standard lightning impulse with a front-time of around 200 ns when only one stage is used, which is the case for a majority of the experiments in this project. A standard lightning impulse has a front time of 1.2μs [17]. The generator is shown in Figure 3.2. Both one and two stages were used for this project, with a maximum of 150kV, limited by the connection to the test object.

Figure 3.2: The 12 stage marx impulse generator

3.1.2 Lambert HiCam

The camera used for capturing the streamer activity was a Lambert HiCam. This camera uses two powerful image intensifiers, giving it two essential properties. First, it makes the camera capable of capturing high-resolution images, even in very low lighting. This is done by using a photocathode to convert the photons into electrons. These electrons are then accelerated towards a micro-channel plate and depending on the voltage over the channel, several electrons are generated. These electrons are then accelerated further into an anode screen, converting the electrons back to photons using a phosphor layer. This is done twice to increase the light intensity further before the photons are finally transferred to the camera sensor. This makes it very applicable for capturing images of streamers. The second use of the image intensifiers is essentially using it as an ultra-high-speed shutter, reducing the effective exposure time.

One lens was used for this project, with a focal length of 180 mm, and an aperture of f/2.8. The camera was placed approximately 3 m away from the electrodes. Using the software "Intensifier Control" and "TimeViewer", the voltage and timing of the image intensifiers could be set manually. As it could only capture one image, the exposure times used were mostly around 500 μs, resulting in "long exposure" images. This was to capture the whole duration of the streamer activity.

To create an accurate understanding of what a typical streamer for the different configurations looks like, a total of 15 images were captured for each setup. Compared to capturing only one image, this eliminates the uncertainty in case one image is an anomaly. All the images in one series were captured at the same voltage, with a waiting time of 180 seconds between shots.

3.1.3 Photomultiplier tube (PMT)

To be certain that the photos taken by the camera are at the right time, a photomultiplier tube (PMT) was used. The PMT measures continuous light emission. It detects photons by multiplying their photo-electric current utilizing a series of dynodes [18]. The PMT used for this project was Philips 56AVP, which has a spectral response between 380-680 nm. The voltage from the PMT can then be compared with the monitor frame from the camera to find out whether the camera has captured the light from the streamers or not. There is some internal time delay in the PMT depending on the voltage applied, which is further explained in section 3.4.

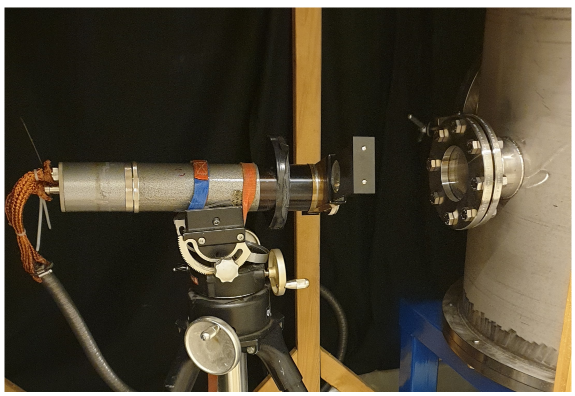


Figure 3.3: The PMT aimed at the electrodes inside the tank.

3.2 Electrode configurations

Some of the following are taken from the specialization project. Following the round-robin test performed by Cigre working group D1.67, a rod with a needle was used [3]. The needle was used to increase the factor of inhomogeneity, as in this setup, the rod without needle does not provide an electric field inhomogenous enough to propagate streamers without a following breakdown. The electrode configuration is shown in Figure 3.4 and Figure 3.5, and a picture of the electrode inside the tank is shown in Figure 3.6. The configurations were used at a gap distance of 53 mm from the tip of the needle to the plane. The needle was protruding 3 mm out from the rod, and the plane diameter is 250 mm, approximately five times the length of the gap.

The material used for the rod electrode was brass, while the plane was made of steel. There are several viable material options, the most common being copper, aluminum, or steel. Brass is not the optimal material to use, as it cannot resist wear as well as copper [19]. It also has a lower conductivity than copper, but the advantage being it is easier to machine. The conductivity and wear issues are not important, as the current and total energy from the impulse voltage is minimal.

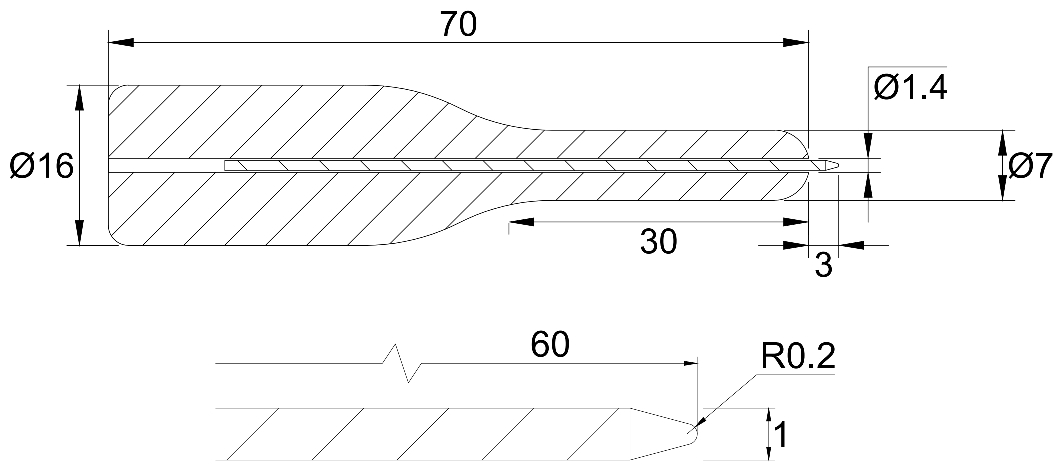


Figure 3.4: Rod configuration with Ogura needle. The rod electrode is inspired by the ones used in the Cigre report, while the same needle is used [3].

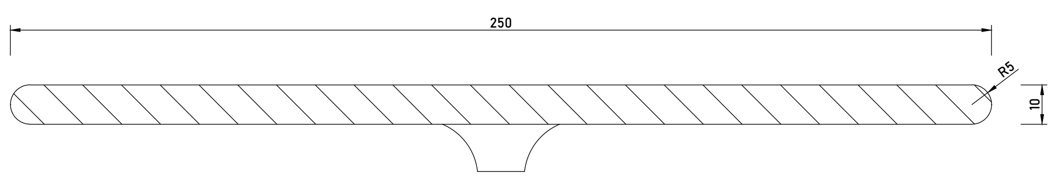


Figure 3.5: The plane used in the laboratory experiments, with a diameter of 250 mm, and 10 mm thick.

Figure 3.6: The rod-plane gap inside the tank. This configuration is 53 mm gap with needle.

To produce as inhomogeneous field as possible, special made steel treeing needles from Ogura were used [20]. The needle was protruding 3 mm out from the rod and is shown in Figure 3.4.

3.3 Up-and-down method

In this section, the up-and-down method is described for breakdowns but can also be used for finding the inception voltage. For a breakdown to take place in a gap, there must be a start-electron to initiate the first avalanche. This is a statistical phenomenon, and the breakdown voltage is hence also a statistical value. Higher voltage increases the field, which increases the chance of an electron starting the avalanche. The 50% breakdown voltage is then used experimentally to describe at what value there is a 50% chance of breakdown.

To estimate the 50% breakdown voltage $\hat{V}_{bd50}$ a procedure called the up-and-down method can be used [21]. This is a method to determine the impulse strength of a spark gap. The first step is to apply a voltage below the expected breakdown voltage and then increase the impulse voltage in steps of Δv. This is repeated until a breakdown occurs, and the voltage is then lowered by Δv. From here, if there is a breakdown, the voltage is decreased by Δv, and in the case of no breakdown, the voltage is increased by Δv. After a number of repetitions, the voltages will oscillate around the 50% breakdown voltage $\hat{V}_{bd50}$. An example of how an up-and-down test may look like is illustrated in Figure 3.7. In this example, Δv is set to 1 kV, and the number of repetition shots is 30. To get a reasonable estimation of $\hat{V}_{bd50}$, the number of shots should be at least 20. It's worth noting that the first shot to be counted should be in the vicinity of the 50% breakdown voltage.

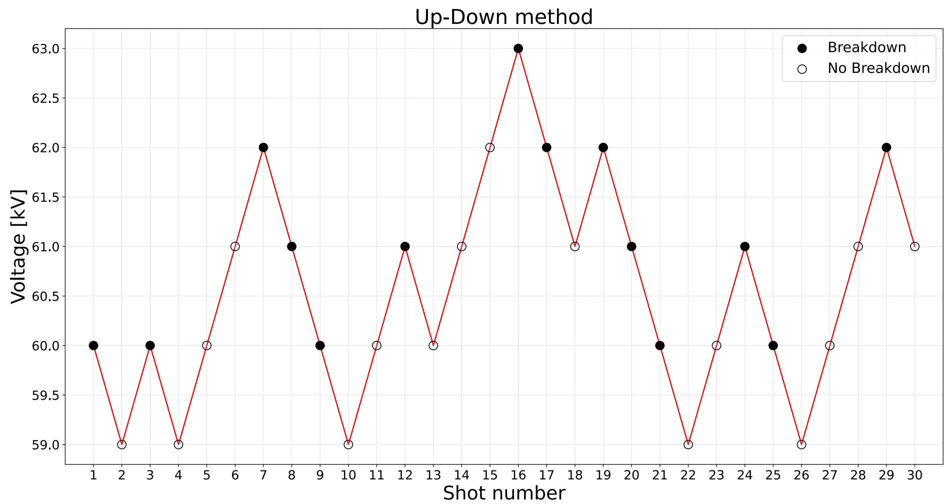


Figure 3.7: An example of how an up-down test may look like.

By doing an infinite number of up-and-down tests, it would be possible to determine the 50% breakdown voltage $\hat{V}_{bd50}$ with a 100% certainty, the certain withstand voltage (0% chance of breakdown) and the certain breakdown voltage (100% chance of breakdown), but as this is not possible, a test of 20-30 shots is seen as sufficient. An interval of 3 minutes between the shots was used, as this was thought to be enough to ensure the shots were independent. In practice, the withstand voltage is usually defined as the voltage where there is 2%, or less probability of breakdown [22].

To calculate the 50% breakdown voltage $\hat{V}_{bd50}$ from the results, the following equation is used [23]:

$$\hat{V}_{bd50} = u_0 + \Delta u \left(\frac{A}{k} \pm \frac{1}{2} \right) \tag{3.1}$$

where u_0 is the lowest voltage value where a breakdown occurs, k is the number of occurrences for the considered event, and Δu is the defined voltage step. For the ± 0.5, 0.5 has to be subtracted if the event is breakdown and added if the event is withstand. The parameter A can be calculated as follows:

$$A = \sum_{i=1}^{r} i \, k_i \tag{3.2}$$

where i is the number of steps from the voltage u_0, k_i is the number of breakdowns at that voltage level, which corresponds to $u_i = u_0 + i\Delta u$.

3.4 Time delays

As the streamer and discharge phenomenons are very fast, where almost every ns is of significance, the delay in the connections between the different components in the setup must be accounted for. Some of the cable lengths were already known, while some were unknown. The unknown cables were measured using a signal generator and the time delay for the reflected signal on an oscilloscope. A sketch of this setup is shown in Figure 3.8. Most of the connections were coaxial cables, with a known transfer speed of 5 ns/m or 200 000 km/s. Both to confirm this as well as to test the signal generator and reflected wave, it was tested on a 4 m long coaxial cable. The signal is shown in Figure 3.9, the left red line indicates when the signal was applied, and the right red line indicates when the reflected signal hit the oscilloscope again. The total time traveling to the end and back, a total of 8 m, was approximately 40 ns. This confirms the transfer speed of 5 ns/m.

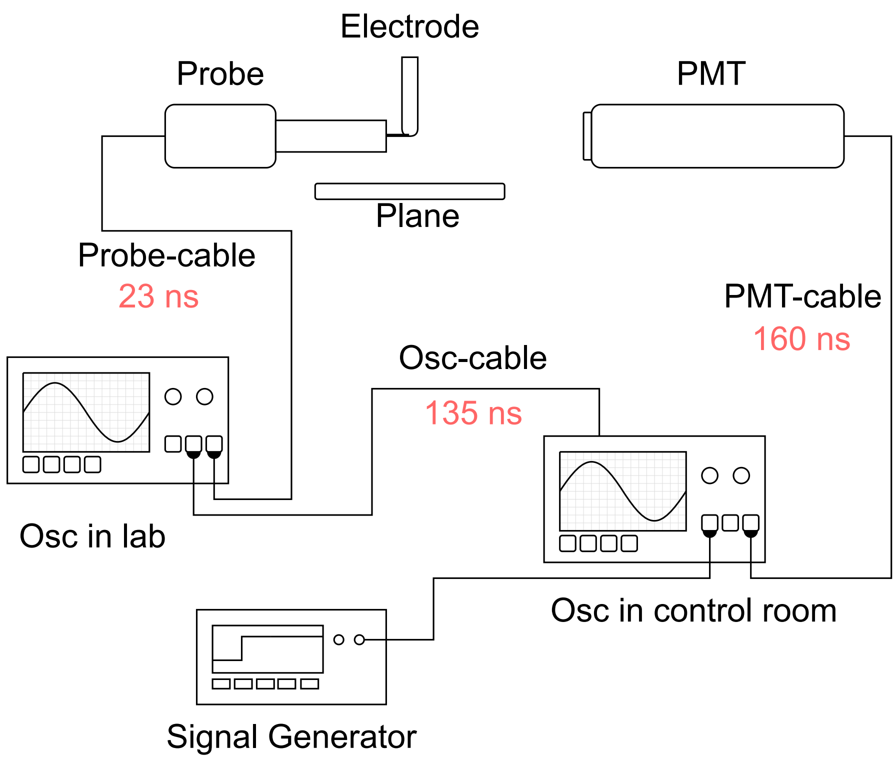


Figure 3.8: A sketch of the setup used to measure the time delays between the different equipment in the laboratory.

In Figure 3.8, the delay setup is shown. It works by applying a step voltage from the signal generator to the oscilloscope in the control room. This oscilloscope then acts as the reference, as all different signals end up back to this scope. The PMT is directly connected to this oscilloscope with a cable with a travel time of 160 ns one way. The step signal from the signal generator is forwarded through the oscilloscope in the lab, which is connected through the cable to the resistive divider. The travel time in the osc-cable is 135 ns. The length of the probe cable is 4.572 m, resulting in a travel time of approximately 23 ns.

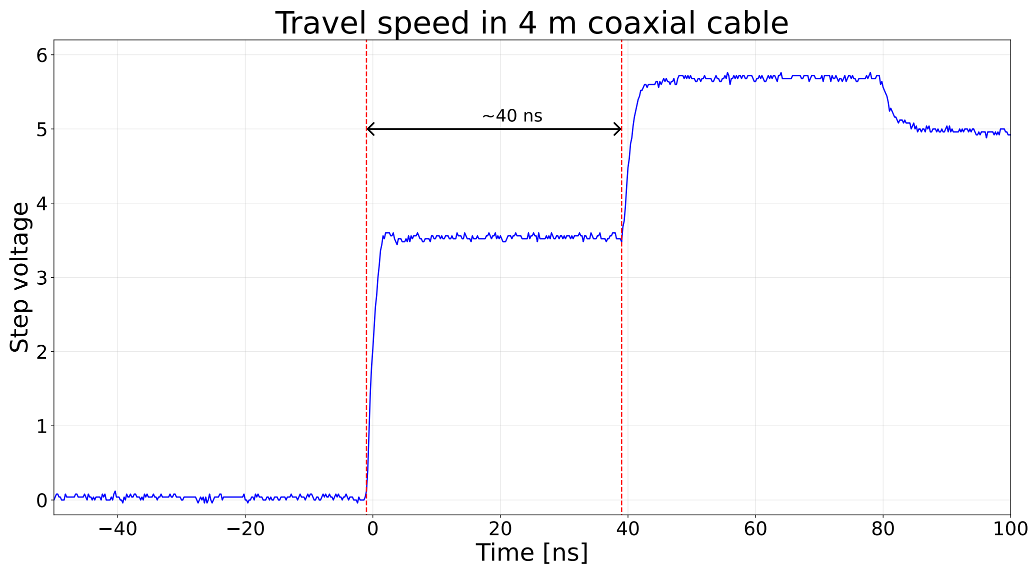


Figure 3.9: The signal from testing the travel speed in the coaxial cable.

There is also an internal delay in both the PMT and the probe. The probe is connected directly to the rod electrode, and the PMT is approximately 1 m away from the electrodes inside the tank. The travel time for the photons between the electrode and the PMT is assumed to be roughly the same as the internal travel time inside the probe. The internal delay in the PMT is dependent on the voltage applied to it. In most tests, this voltage is set to 2400 V. The internal delay was measured in 1969 by a research group in the physics department at NTNU, shown in Figure 3.10. From this, the delay can be read to be approximately 37.6 ns at 2400 V.

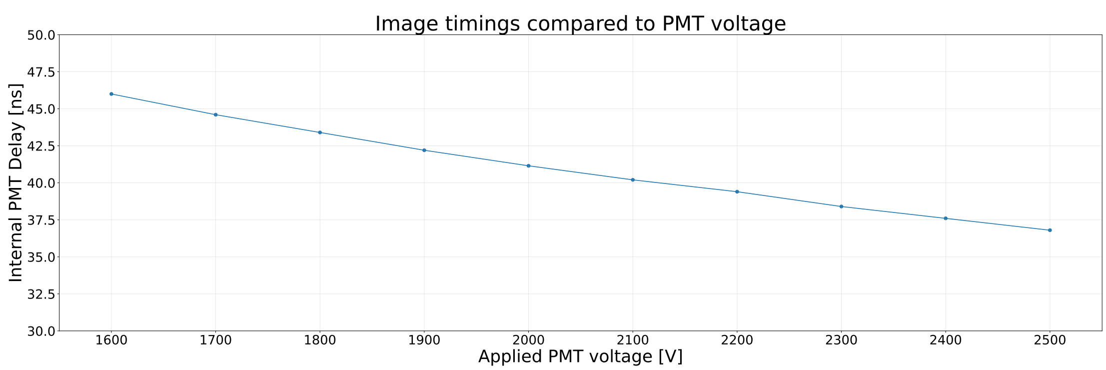
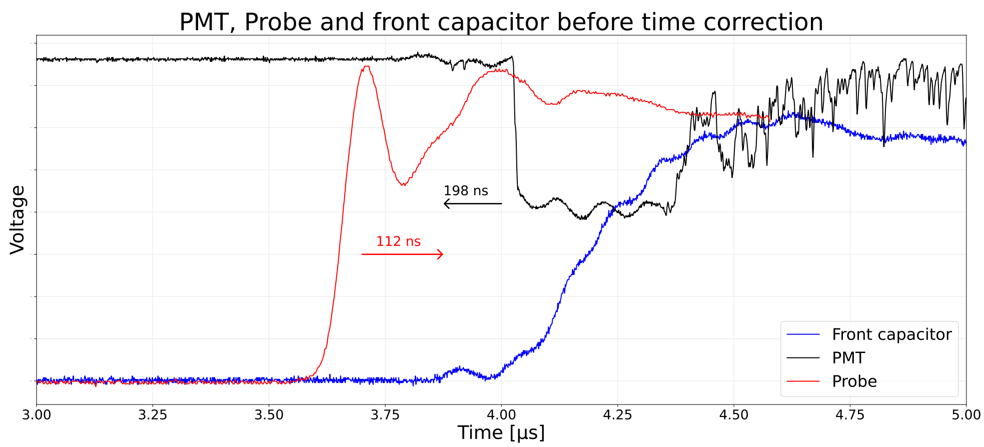


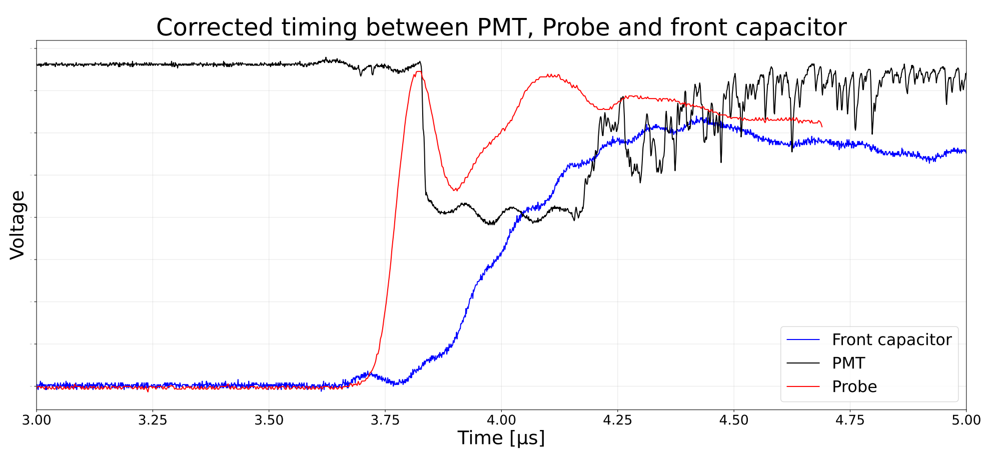
Figure 3.10: The measured delay internally in the PMT (56AVP) depending on the voltage applied.

In conclusion, the data from the experiments have to be shifted according to these travel times. When the PMT signal is discovered on the oscilloscope in the control room, the light was actually emitted 160 ns + 37.6 ns = 197.6 ns earlier (when ignoring the travel time for the photons). When the oscilloscope in the lab receives the signal from the probe, the probe sent the signal 23 ns prior. To synchronize the shifted probe signal to the PMT signal, the probe signal has to be moved 135 ns to the right. This is because the reference for the lab oscilloscope is 135 ns after the oscilloscope in the control room.

In Figure 3.11 an example is shown. in Figure 3.11a the original PMT signal occurs at the very start of the front of the voltage measured by the front capacitor. The corrected timings are shown in Figure 3.11b. Here, the probe voltage is moved 112 ns to the right, and the PMT and front capacitor voltages are moved 198 ns to the left. This is a more accurate representation of when the PMT observes light in relation to the actual voltage over the gap, shown by the probe voltage. It makes much more sense that the light is emitted close to the first peak of the voltage.



(a) How a typical test with PMT may look like before it is corrected according to the different time delays.



(b) Corrected plot of when the light from the PMT is actually occurring.

Figure 3.11: Difference between before and after time corrections.

When plotting and showing the voltage over the electrodes and the PMT voltage in the results chapter, these delays are taken into account. Since the probe measurements were done after all the experiments, a 'fake' curve will be implemented to better show when the light is occurring relative to the actual voltage over the electrodes. This is a better indication than the voltage measured at the front capacitor.

3.5 Gas and filling

The gases used were both technical air and AirPlus. To ensure the gas was as pure as possible, all the air inside had to be removed first. This was done using a B143R11 Dilo service cart to empty the tank down to below 1 mbar. Some small amount of ambient air will be mixed with the rest, but without a perfect vacuum, this is inevitable. As both synthetic air (SA) and AirPlus (AP) contain oxygen and nitrogen, this is assumed not to be a problem.

Synthetic air was already pre-mixed in containers with a pressure of 200-300 bar. SA is a mixture of 20% oxygen and 80% nitrogen. By connecting the container to the vacuumed tank, the filling was a relatively straightforward process, consisting of opening the valves slowly until desired pressure. Since SA is a completely green gas without toxins, it can be released straight from the tank into the surrounding air. This means filling the tank to 1.5 bar first, then decoupling the SA container, is the fastest and easiest as once the experiments on 1.5 bar are done, the valve between the tank and surrounding air is opened slowly until the tank contains 1.3 bars of pressure. The same goes between 1.3 bar to 1.0 bar. This is with the assumption that the gas quality is not decreased after an experiment, as the amount of breakdowns is kept to a minimum. After that, the tank door can be simply opened, but the same valve was opened completely first to ensure the inside of the tank contained atmospheric pressure.

To fill the tank with AirPlus, the C5-FK was filled on the vacuumed tank. The ratio for AP is 7.5% C5-FK and 92.5% synthetic air. The tank was then filled with C5-FK until the pressure reached 0.1125 bar. It was filled further with synthetic air until 1.5 bar of pressure was reached. When reducing the pressure to 1.3 bar, the AP was released into a separate container. Both positive and negative tests were done in 1.5, 1.3, and 1.0 bar pressure without changing the gas. This was done assuming the gases were well mixed, and the removed gas was approximately the same SA/AP ratio. Since there were only a few tests with complete breakdown, it was also assumed there was little to no gas decomposition, and the gas quality was the same in all tests. The experiments were also not conducted immediately after the filling, but waiting at least a few hours to ensure the gas was completely mixed. The gas was also filled from the bottom of the tank, which further helped mix the gas faster.

3.6 Impulse voltage correction

At a relatively late stage of the experiments, it was discovered that the voltage measurements from the front capacitor were not correct for the test object. Both the amplitude of the voltage as well as the shape and front time were different than the actual voltage over the gap. To find and document the correct measurement, a voltage probe of the type North Star PVM-100 was used. This probe has a limit of 150 kVpeak, 100 MHz. It was also used a resistive divider to measure the voltage, but when measuring with both the resistive divider and the probe, it turned out that the resistive divider was actually influencing the voltage measured by the probe. The voltage measured by the probe alone with the front capacitor is shown in Figure 3.12, and the measurement with both the probe and the resistive divider is shown in Figure 3.13.

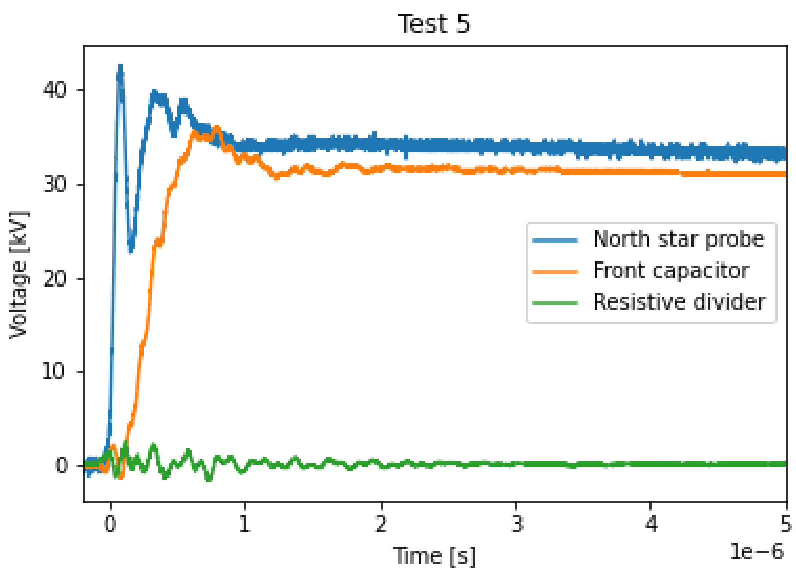


Figure 3.12: The voltage measured by the North star probe, with one stage of the impulse generator, compared to the front capacitor. The real voltage over the test object has a big overshoot, as well as much faster front-time.

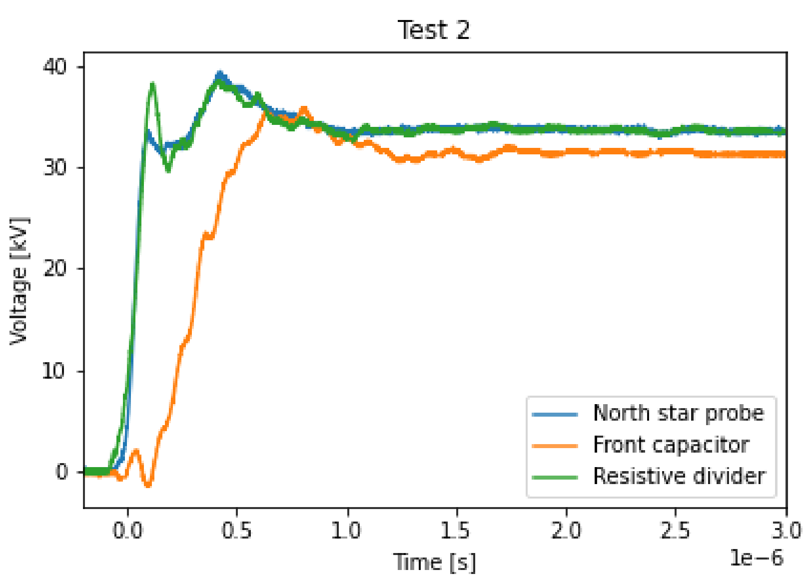


Figure 3.13: The voltage measured by the North star probe and the resistive divider compared to the front capacitor. The voltage measured by the probe is different from the measurement without the resistive divider, meaning the resistive divider is influencing the shape of the voltage.

It can be observed that the initial voltage peak is dampened, while the second peak is relatively similar. The most important thing to note is that even though the voltage is set to 35 kV, the actual voltage peak over the test object is around 42 kV with the probe alone and just below 40 kV with the resistive divider. Since all the experiments were done without the resistive divider, the measurements with the probe alone are viewed as the most correct measurements.

The impulse generator was used with both one and two stages connected, and the probe showed the front times and initial overshoot were quite different depending on the number of stages connected. The measurement from the probe with two stages is shown in Figure 3.14, and the overshoot is no longer the highest peak. The shape of the voltage is also closer to that of the front capacitor, but it still has the initial overshoot with a very fast front time. The peak is also closer to the applied voltage of 35 kV than the front capacitor is measuring.

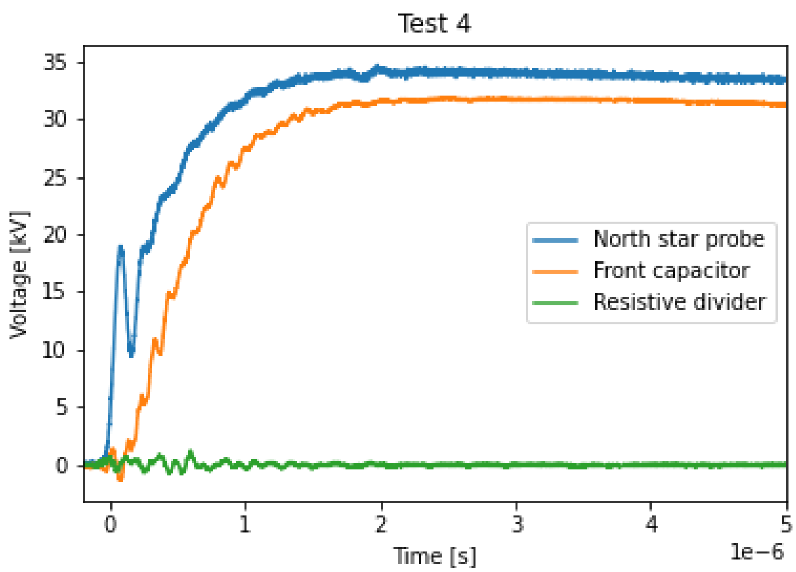


Figure 3.14: The voltage measured by the North star probe without the resistive divider compared to the front capacitor, using two stages of the impulse generator. With two stages, the waveform is more similar to that of the front capacitor, but it still has an initial overshoot. The peak voltage measured by the probe is also closer to the voltage applied, which is 35 kV in this case.

Tests were also done with more than two stages, and the initial overshoot was getting smaller and smaller the more stages connected.

As mentioned, most experiments were done before discovering the faulty measurements by the front capacitor. To correct this, a correction factor has to be used. This correction factor α_{corr} is shown in Equation 3.3. This factor is different for different numbers of stages used by the impulse generator and is not dependent on the voltage. This factor is used on the resulting 50% inception voltage for the up-down tests.

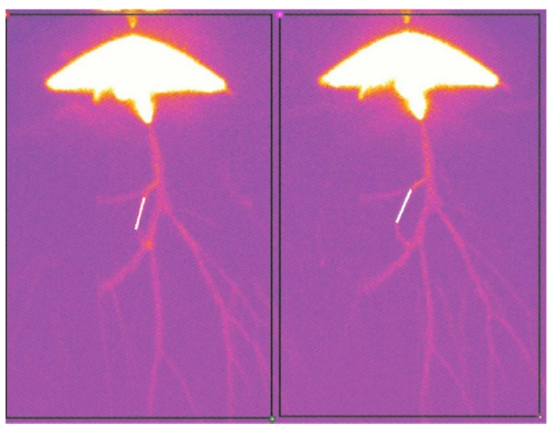
$$\alpha_{\text{corr}} = \frac{V_{\text{probe, peak}}}{V_{\text{cap, peak}}} \tag{3.3}$$

Using Equation 3.3, the correction factors are found to be $\alpha_{\text{corr, 1stage}} = 1.1556$ for a single stage and $\alpha_{\text{corr, 2stage}} = 1.03$ for two stages.

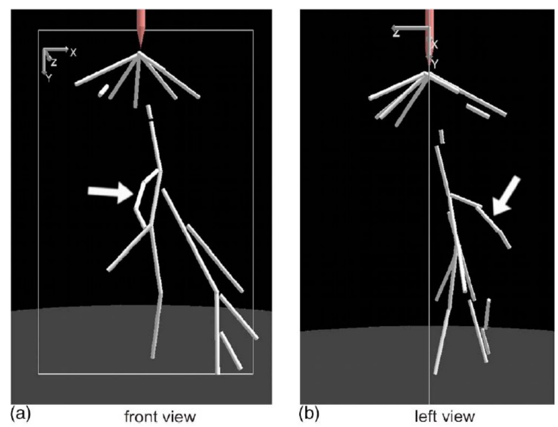
3.7 Stereoscopic 3D-photography

There is a wide array of information to take from regular 2D images of pre-breakdown phenomena. However, this is mostly information limited to a narrow plane perpendicular to the camera angle. Because streamers are low light intensity phenomena, gathering as much of the light as possible is desirable. This is done by opening the aperture as much as possible. The downside of this is a very narrow depth of field. Thus, much of the information is lost because many of the streamer branches move outside the narrow plane in focus. Also, it can be difficult to distinguish between the branches coming towards and those going away from the camera.

In some cases, this can potentially lead to false conclusions. An example is shown in Figure 3.15 from [24]. Here, in the 2D image, it looks like the streamer branch is forming a loop. When looking at the 3D recreation of the branches in Figure 3.15b, it can be seen that in reality, the branch is moving towards the camera and not forming a loop at all.



(a) The two 2D images used to create a 3D model. From these images alone, it looks like the streamer branch with the white line is forming a loop. By looking at this image alone, it would be almost impossible to know if this was actually the case or not.



(b) The 3D model created from the two 2D images. In the left image, the front view is shown, where it still looks like the marked branch is a loop. In the right image, which is the left view of the model, it is shown that the marked branch is not a loop, but pointing towards the camera.

Figure 3.15: The images captured by Nijdam et al, showing how 2D images can lead to false conclusions [24].

Most 3D photography is done using two cameras or lenses and automatically creating a 3D representation of those two inputs with integrated software. This was considered for use in this thesis, but there are a couple of problems. Firstly, two high-speed cameras would be needed with a sturdy setup. The cameras used for streamer photography are rather expensive, leading to a very high cost. Secondly, the windows of the pressurized tank are very narrow, and there would not be enough room for two cameras to look into the same window. The main opening of the tank would be large enough, but that would defeat the whole purpose of the tank as this door is closed when the tank is pressurized.

A method called stereoscopic photography avoids these problems while still producing a 3D image or model. This is done by using mirrors and/or prisms to split the image into two separate viewpoints. By using another set of mirrors, the angle between the viewpoints can be changed to whatever desired angle. A schematic of the mirror setup is shown in Figure 3.16. In this schematic, the mirrors are placed inside the tank, but they can also be placed outside, as long as the window is large enough. This method also has some downsides. The most important one is that the resolution is essentially halved, as the image is split into two separate images. Another downside is that it requires a very precise mirror setup in order to get accurate results. The mirrors also need to be high-quality optics to be able to reflect close to 100% of the light with as little distortion as possible.

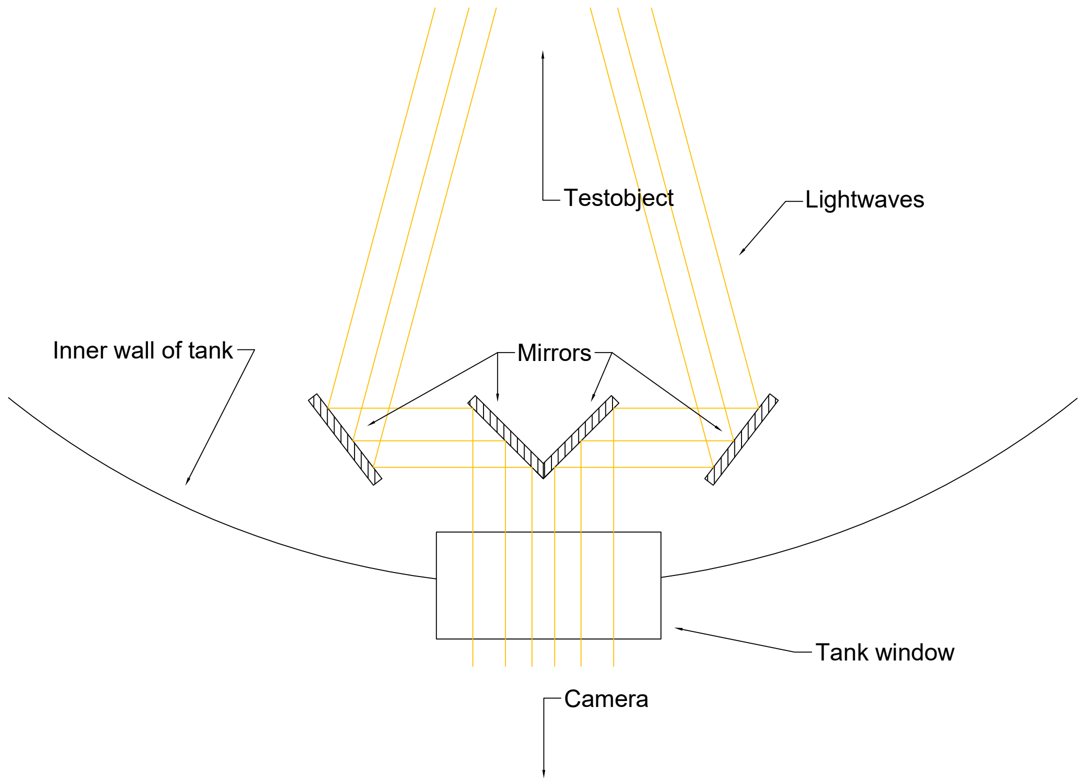


Figure 3.16: The sketch of how the mirror setup may look like. Here, the mirrors are placed inside the tank.

As the mirror setup is a relatively easy part as long as a good setup is used, the most challenging part of this side-project proved to be the software part. The goal was to create a 3D model of the streamers branches. This way, the positional information of all three dimensions could be gathered and analyzed.

A simple setup was made using cheap mirrors from a hardware store to try out the method. Testing was done using a phone camera and the simple steel wire model shown in Figure 3.17. Several pictures were taken of the model from different angles. The goal of this was to confirm that the 3D model was correct. The image used to create the 3D model is shown in Figure 3.18a. The left viewpoint can be seen in the left half of the image, and the right viewpoint in the right half. The angle between the viewpoints is measured to be 43°, and a top view of the mirror setup is shown in Figure 3.18b. From Figure 3.18a the model looks a little different in the two viewpoints, but it is still easy to see that it's the same object. This is due to the small angle between them. If the angle between them were close to 90°, there would be more information in the data, but it would be harder to compare them because the two viewpoints would look completely different.

This would be possible with a low amount of streamer branches (1-3 branches), but with at least 10+ branches, this becomes significantly harder.

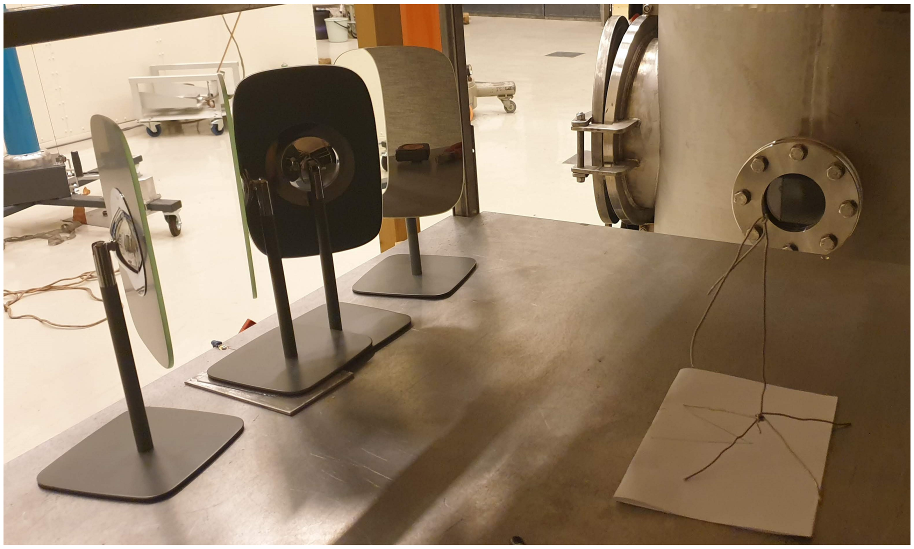


Figure 3.17: The crude setup used for testing. The mirrors on the left side of the image with the steel wire model on the right.

(a) The image used for creating the 3D model.

(b) The setup seen from a higher angle

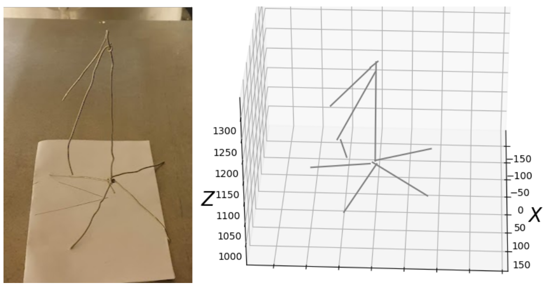
Figure 3.18

A script was made using Python, where each line segment had to be manually selected. Four points must be selected for each line segment, each with an x- and y-coordinate. First, the top and bottom points of the left view, then the top and bottom of the right view. Using equation Equation 3.4 with these coordinates and the angle between the viewpoints, the z-coordinate for the start and end of the line segment can be calculated. Then the line is plotted onto a 3D model. The order in which the points are selected is not really important, as long as the correct xy-coordinate pair is used to calculate the z-coordinate.

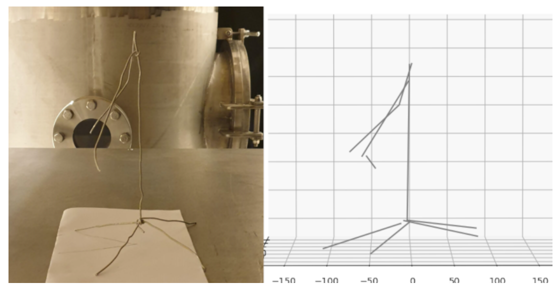
$$z = \frac{(x_r - x_l)}{2sin(\alpha/2)} \tag{3.4}$$

where α is the angle between the viewpoints, 43° in this case, x_r is the x-coordinate in the right view, and x_l is the x-coordinate in the left view.

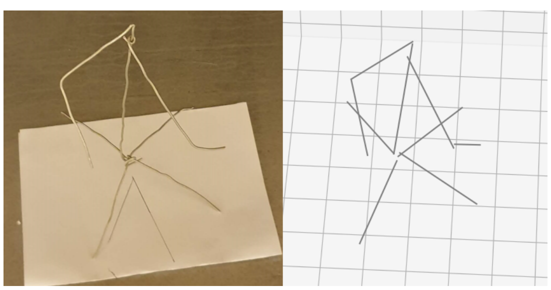
With multiple branches with several bends, this becomes a rather tedious process, but the outcome is a detailed 3D model of all the streamer branches. The comparison between the resulting 3D model and the actual model from different angles is shown in Figure 3.19.



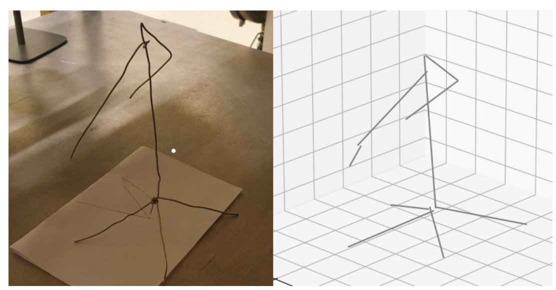
(a)



(b)



(c)



(d)

Figure 3.19: The comparisons between the 3D model and actual pictures of the model.

Some test images were captured of streamers, and one is shown in Figure 3.20. The views are split approximately at the dotted line in the middle. In the left view, only one streamer can be seen protruding from the rod, marked with (2), while in the right view, two streamers from the rod can be seen (1) and (2). (1) is most like obscured behind the rod in the left view, while (2) can be seen in both views. The streamers are quite blurry, and when there are so many small branches, it is hard to distinguish between them and identify a single streamer in both views. An example is (3), which looks like a single streamer branch in the left view, but in the right view, there are two main branches, (3.1) and (3.2). (3.1) is probably partly obscuring (3.2), and the light that can be seen in (3) is a combination of both (3.1) and (3.2).

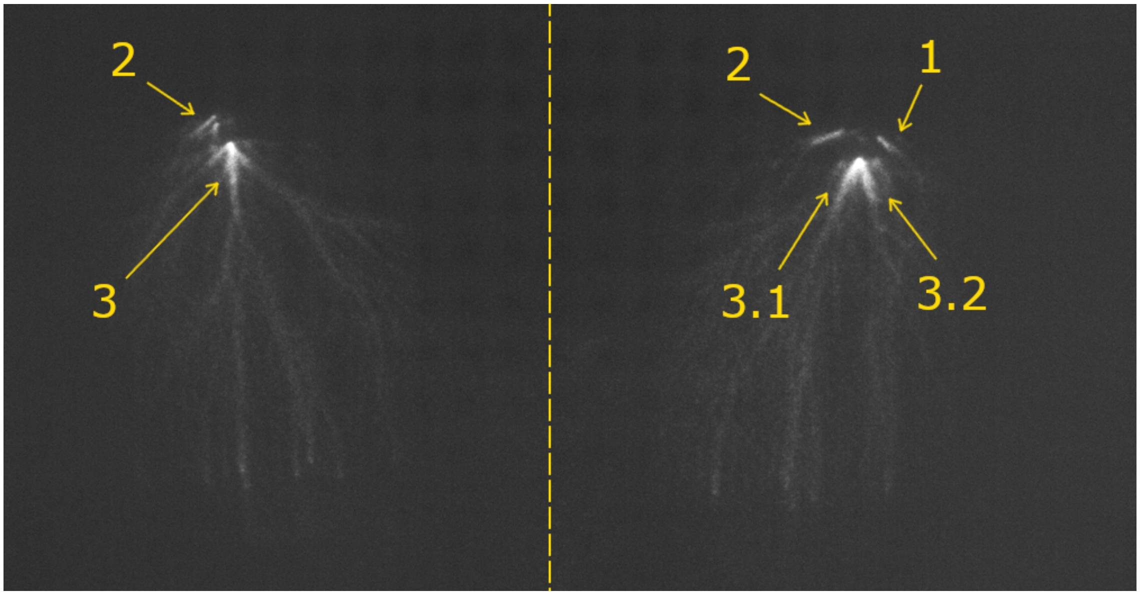


Figure 3.20: A stereo-photography of streamers. (1) is most likely hidden in the left view, behind the rod, while (2) is shown in both views. Streamer (3) in the left view is hard to identify in the right view.

Another example is shown in Figure 3.21. Here branch (1) is relatively wide and bright compared to the rest in the right view but not in the left view. (1) in the right view might be a combination of several branches obscuring each other, like (3) in Figure 3.20. A possible way to correctly identify each streamer is by the height it hits the plane, shown in the red circles. If the mirror setup is completely straight, unlike this setup, the height (y-value of the pixels in the image) should be the same in both views, and a streamer branch can then be traced from that point and upwards.

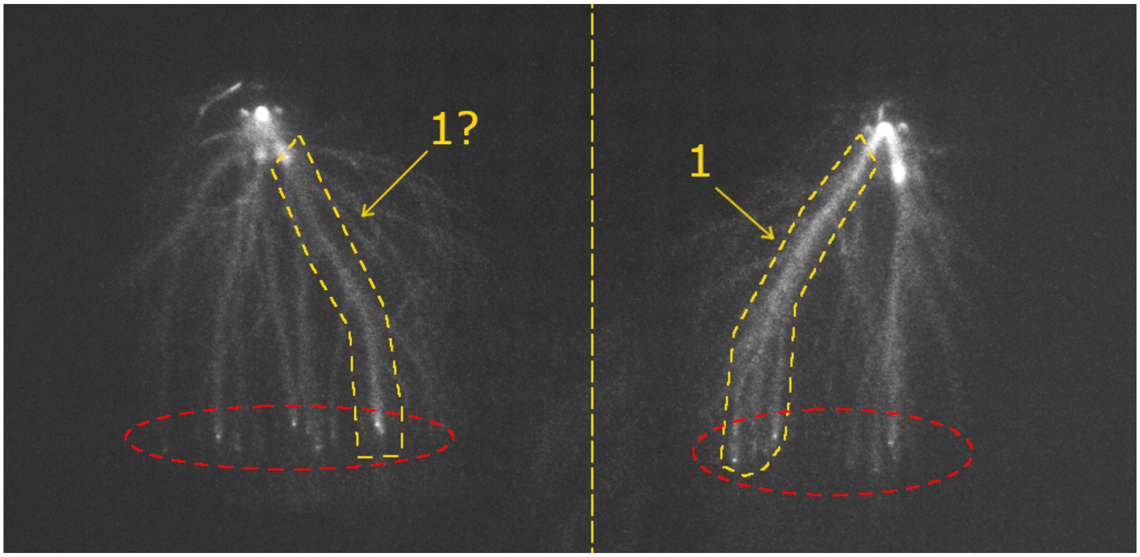


Figure 3.21: Another stereoscopic streamer image. Here it is difficult to determine what branch in the left view is corresponding to (1) in the right view. The red area marks the places where each branch hits the plane, and this could be used to identify the separate streamer branches, by using the y-value of this position.

Stereoscopic photography of streamers might be more applicable with high-speed cameras that capture several short exposure images instead of one long exposure image. That way, it would be easier to trace each streamer separately, as fewer branches would be visible at one time.

Chapter 4

Inception Voltage

Simulations of the inception voltages in the different gases and pressures were conducted to be best able to evaluate the results from the experiments. This was done by evaluating the streamer integral. COMSOL Multiphysics was used for this by simulating the electric field distribution. Then the result from this simulation was used in a Python script to further calculate inception and breakdown voltage. The script is developed by Hans Kristian Hygen Meyer, and is presented in Appendix B.

4.1 COMSOL Model

A detailed model of the electrodes was made in COMSOL to simulate the electric field distribution in the gap. With this simulation, the maximum electric field could also be determined in order to calculate the inhomogeneity of the gap. The electrode geometry was symmetrical, meaning the COMSOL-model could be made in 2D with axisymmetrical geometry. This also decreases the computational power needed.

In Figure 4.1 the geometry from the model is shown. This geometry is inverted, without any materials except for air in the gap. This simulation was also used for AirPlus, and synthetic air as the gas properties does not affect the electrical field distribution. The walls of the tank are not to scale since the important part of the model is the gap between the needle and the plane. Since the electrodes were reversed, meaning the voltage was applied to the plane, the ground potential was set to the rod, and the electric charge was set to the plane. Except for the voltage showing 0 kV on the rod, there was no difference. It was mainly done to ensure the simulational setup matched the real experiment. Both ways were tested with the python script, and both ways resulted in the same values. The edges of the model were set to zero charge.

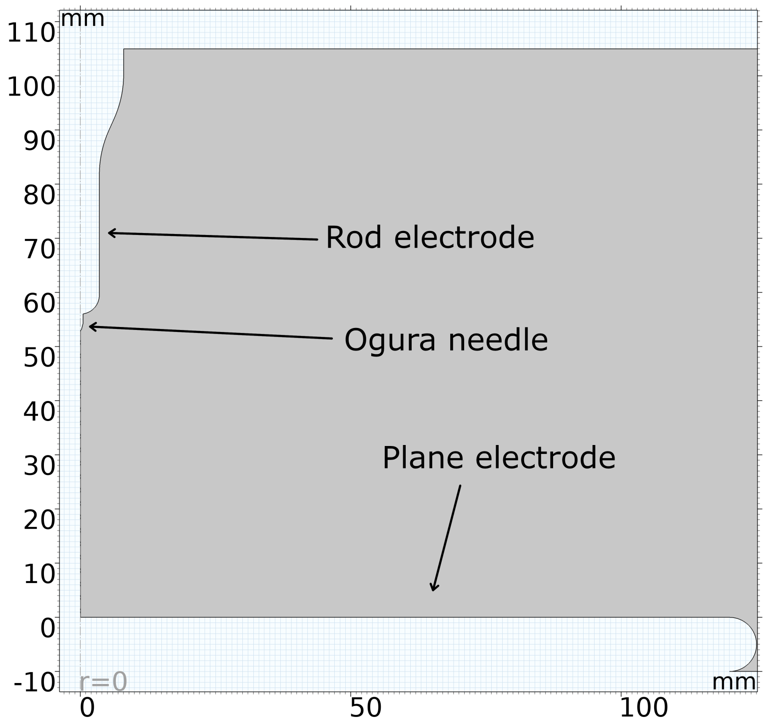


Figure 4.1: The geometry for the electrodes. The model is axisymmetrical, meaning it revolves 360° around the left edge in the figure.

The mesh of the geometry around the needle can be seen in Figure 4.2. The quality of the mesh was set to extremely fine to make sure the mesh around the needle was detailed, as the field distribution around the maximum field is the most important for the calculation of the inception voltage.

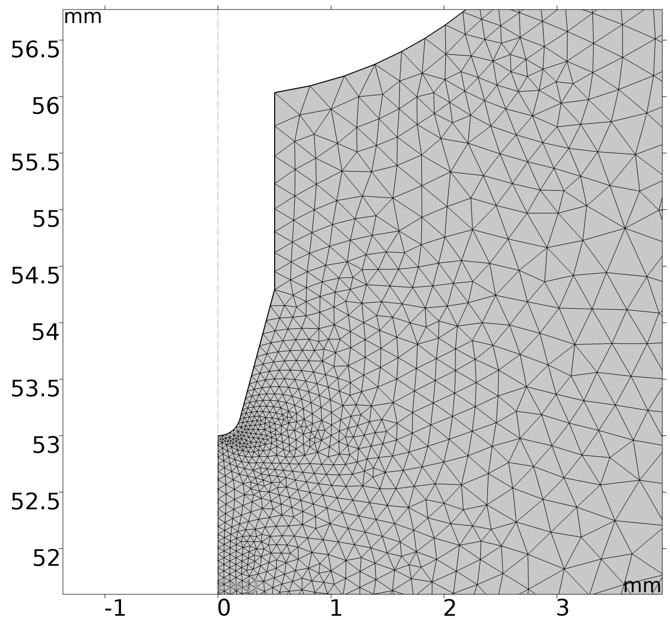
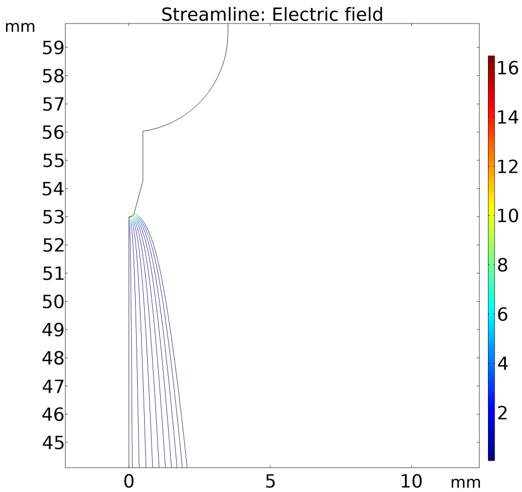
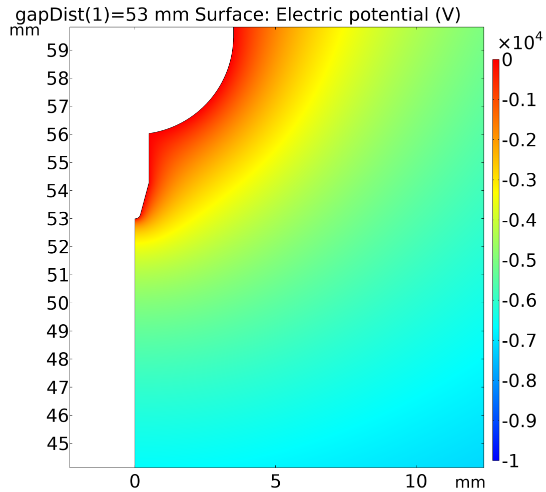


Figure 4.2: The mesh of the geometry surrounding the needle. This is the sharpest point, with the highest need for detail. It was set to 'extremely fine' in COMSOL.

The streamlines for the electric field is shown in Figure 4.3a and the electric potential is shown in Figure 4.3b. The field lines contain the data points used for calculating the inception voltage. Only the field lines from the tip of the needle are exported because the inception will almost always happen at the maximum field. It is worth noting that the scale in the electric potential plot in Figure 4.3b goes between 0 V and -10 kV. The negative voltage was applied to the plane in the real experiment, so this is also done in the simulation. The electric field is still the same, regardless of the reversed polarity or not. This further proves that a positive streamer from the needle can be achieved both with a positive voltage applied to the needle or a negative voltage applied to the plane.



(a) Streamlines for the electric field.



(b) The electric potential.

Figure 4.3: In the left figure, the streamlines for the electric field is shown. These lines are the datapoints used for calculating the inception voltage. In the right image, the electric potential is shown. It is worth noting that the electric potential is negative and is applied to the plane, and not the rod. This is reason for the scale on the right hand side, showing a range from 0 V on the needle to -10 kV on the plane. Both images are also cropped, to better show the needle.

The colored electric field lines shown in Figure 4.3a were exported to a csv file for use in the python script.

4.2 Inception voltage script

By using the streamer integral in Equation 2.1, the theoretical inception voltage can be estimated. The script imports the field lines for the background field and the voltage applied from the COMSOL model, as well as the wanted gas and pressure. It then evaluates the streamer integral and increases the field gradually until the integral is larger or equal to $\ln N_c$. The voltage when this condition is met is the resulting inception voltage and is the lowest possible voltage where inception can occur.

4.3 Simulation results

The following are the inception voltages calculated with the script described in section 4.2. It was conducted on the different test configurations presented in Table 5.1, meaning the different parameters for the simulation are pressure and gas but only positive voltage polarity. The results with positive polarity are shown in Table 4.1. The results are also plotted in Figure 4.4, with the x-axis being the different gases.

Table 4.1: The simulation results for the positive inception voltages, depending on the gas used and the pressure. Voltages are given in kV.

Simulated Positive Inception Voltage		
Gas / Pressure	Synthetic air	Air Plus
1.0 Bar	8.22 kV	10.53 kV
1.3 Bar	9.59 kV	12.33 kV
1.5 Bar	10.47 kV	13.48 kV

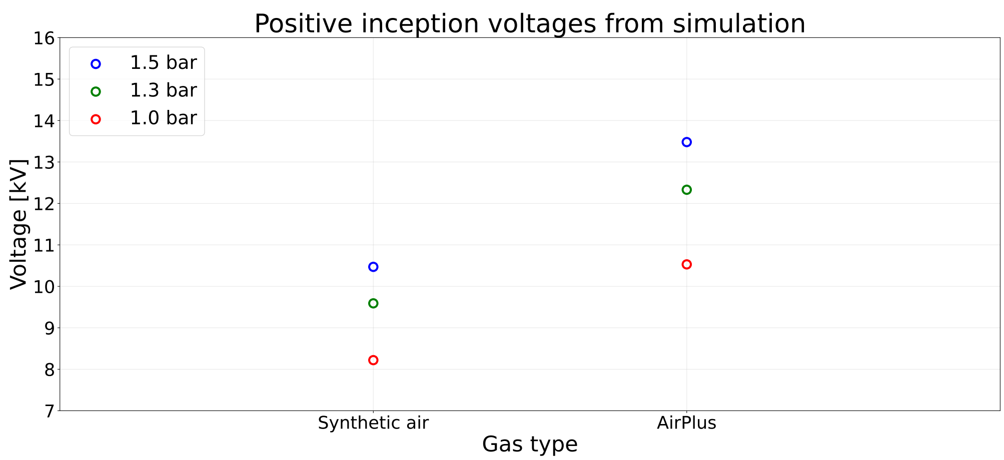


Figure 4.4: Plot of the simulated inception voltages, in absolute values, with the gas type on the x-axis.

The best way to compare the different tests is to look at the ratio between the inception voltage with the different pressures and gasses:

$$\theta_{(AP/SA)p} = \frac{V_{AirPlus,p}}{V_{SyntheticAir,p}} \tag{4.1}$$

with p being the pressure, and $\theta_{(AP/SA)p}$ describing how much higher the inception voltage is for AirPlus than of synthetic air at the given pressure. When applying this equation for positive voltages, the increase for 1.0, 1.3, and 1.5 bar pressure is 28.1%, 28.6%, and 28.7%, respectively. These results are also shown in Table 4.2 for a better overview.

This means that according to the simulations, there is always an increase in inception voltage of around 29% ±1% from synthetic air to AirPlus, regardless of the pressure.

Table 4.2: The voltage increase from synthetic air to AirPlus for the different pressures using the simulated inception voltages.

Pressure	$\theta_{AirPlus/SyntheticAir}$
1.0 Bar	28.1%
1.3 Bar	28.6%
1.5 Bar	28.7%

Chapter 5

Results and Discussion

Since there have been many different configurations, the results from each will be presented and discussed in this chapter. For the experimental up-and-down tests, plots of the complete tests with corrected voltages are shown in Appendix A.

The main research question for this thesis is:

- What are the differences in pre-breakdown mechanisms for a very inhomogeneous rod plane gap between synthetic air and AirPlus in different pressures for both positive and negative polarities?

To get a better overview of the different experiments, a test matrix is presented in Table 5.1. This includes all the various test parameters, resulting in 12 different configurations. The gas type, pressure, and streamer polarity are the three different parameters. All the experiments were conducted according to the methodology described in chapter 3.

Table 5.1: Test matrix for the different configurations.

Streamer Polarity	Pressure	Synthetic Air	Air+
Positive	1.0	SP1	AP1
	1.3	SP2	AP2
	1.5	SP3	AP3
Negative	1.0	SN1	AN1
	1.3	SN2	AN2
	1.5	SN3	AN3

5.1 Experimental results

Even though many of the tests had inclining or declining voltage trends, possibly voiding the results, the resulting plots from the up-and-down tests for inception voltage are presented in full in Appendix A. The resulting 50% inception voltages are shown in Table 5.2 and Table 5.3, and are also shown in a plot in Figure 5.1. The up-and-down test for AP3 was not conducted. This was because when doing the up-and-down test for AN3, the voltage kept increasing, which is generally a sign that the wait time is too short and would probably void the results. It can also be seen from Figure 5.1 that many of the resulting 50% inception voltages are not making any sense. In all instances, increasing the pressure should also increase the voltages. Alas, for both SP, SN, and AN, 1.5 bar of pressure does not yield the highest inception voltage. For AN, 1.0 bar is even the lowest-performing pressure. The experimental results were expected to give higher voltages than the simulations, but it was also expected that increasing the pressure would also increase the voltages somewhere in the vicinity of the simulations.

Table 5.2: The experimental results for the positive inception voltages, depending on the gas used and the pressure. Voltages are given in kV.

Positive Inception Voltage		
Gas / Pressure	Synthetic air	Air Plus
1.0 Bar	22.52	26.74
1.3 Bar	27.60	44.04
1.5 Bar	26.30	-

Table 5.3: The experimental results for the negative inception voltages, depending on the gas used and the pressure. Voltages are given in kV.

Negative Inception Voltage		
Gas / Pressure	Synthetic air	Air Plus
1.0 Bar	-54.64	-48.81
1.3 Bar	-61.32	-47.94
1.5 Bar	-36.61	-46.27

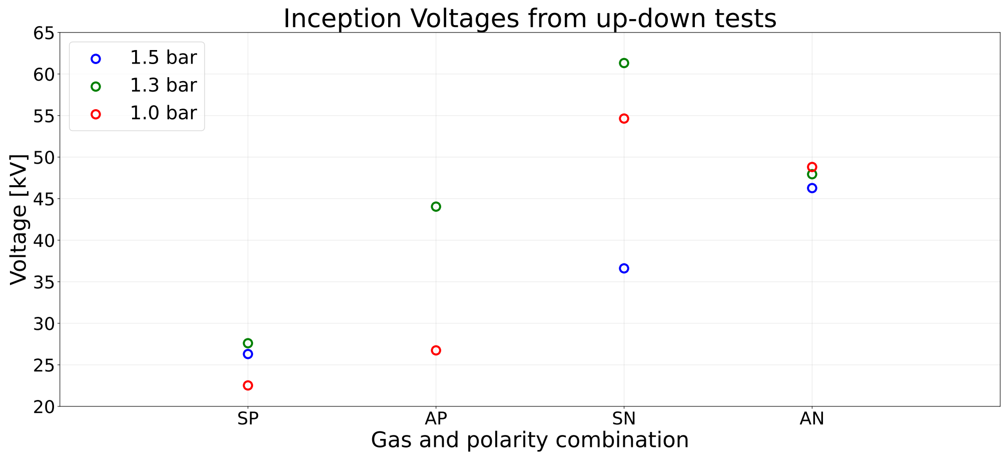


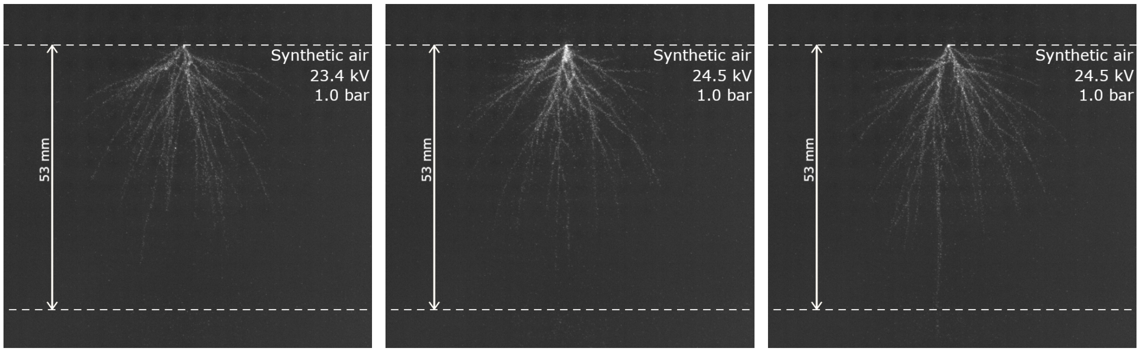
Figure 5.1: Plot of all the experimental inception voltages, in absolute values. The gas type and polarity combinations are presented on the x-axis with the abbreviations from Table 5.1.

In the following part, all the different configurations are presented with a few images from the image series, and some include images from the up-and-down tests. This is to get a better view of how the streamers look like close to the inception voltage as well as closer to the breakdown voltage. The images are not necessarily shown in consecutive order, but there was always a waiting time between images of 180 seconds. This part is rather extensive, so a shorter summary can be found in section 5.2. The info about each test is indicated in the image. The gap length is always 53 mm, which is to the tip of the needle and is shown on the side to get a better view of the length of the streamers. Also, the diameter of the plane electrode is 250 mm. Since the camera height is slightly above it, it may look like the bottom line is incorrectly placed, but this is due to the depth perception of the plane.

5.1.1 Synthetic air results

SP1 - Synthetic air, positive streamer, 1.0 bar

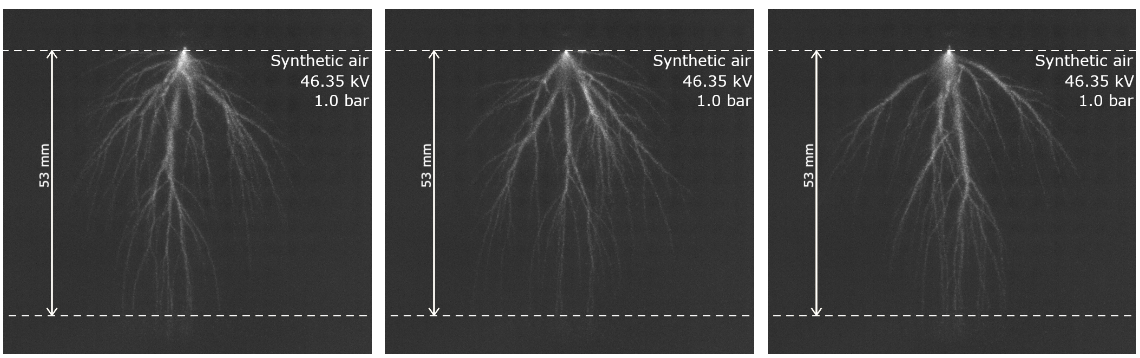
The resulting positive 50% inception voltage from the up-and-down test in synthetic air at 1.0 bar was found to be 22.52 kV. Some images captured during this test are shown in Figure 5.2. These images show the smallest possible streamers for this configuration, as all the images with any light emission at all are similar to these. Some of the branches are even propagating all the way to the plane.



(a) (b) (c)

Figure 5.2: Images captured during the up-and-down test for inception voltage for the SP1 configuration.

The following images, shown in Figure 5.3, are from the series of images captured at 46.35 kV. For these images, two stages of the impulse generator were used, meaning the initial voltage spike was significantly lower than that of only one stage. These streamers also look very similar to the images captured closer to the inception voltage. The difference is that at 46.35 kV, there are almost always a few streamer branches propagating all the way to the plane. The light intensity is also higher than at the inception voltage, even when the intensifier voltage is 800 V for the up-and-down test and 700 V for the image series.

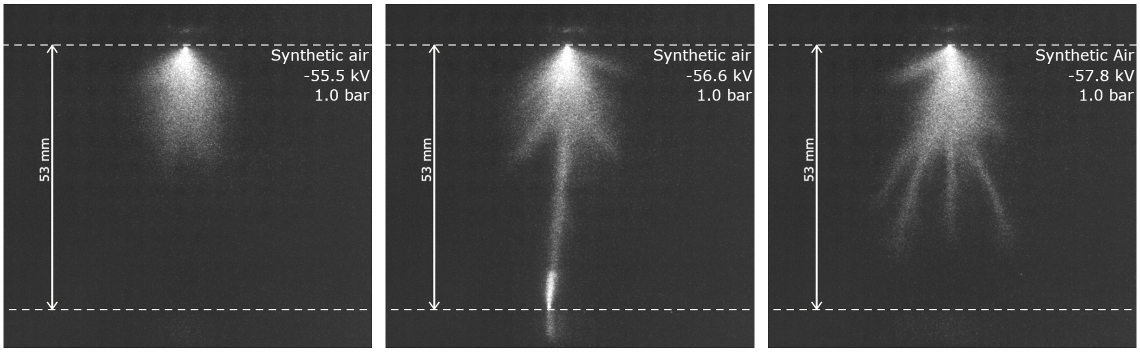


(a) (b) (c)

Figure 5.3: Images from the SP1 configuration. The voltage for all these images are 46.35 kV.

SN1 - Synthetic air, negative streamer, 1.0 bar

The negative 50% inception voltage was much higher than the positive, all the way at 54.64 kV. The lowest voltages yielding any light were around this voltage, and the discharges at this level are cloudy without any clear branches, as shown in Figure 5.4a. In Figure 5.4b and Figure 5.4c there is further branching from the cloud. These are captured at a slightly higher voltage, but it's probably just a stochastic phenomenon and not caused by the increased voltage. This is further observed in several of the negative streamers.



(a) (b) (c)

Figure 5.4: Images captured during the up-and-down test for inception voltage for the SP1 configuration.

The images shown in Figure 5.5 are captured at -80.9 kV. At this voltage, there were several different types of streamers to observe. In some instances, there were just low amounts of light, like the one in Figure 5.5d. Here, streamers are also propagating from the rod above the needle. In other cases, there was a combination of a cloud and branches, like Figure 5.5b and Figure 5.5f. The downside of capturing only one long exposure image was that it would be interesting to see the time span of these streamers. Especially noticeable in Figure 5.5a, Figure 5.5b and Figure 5.5f is that the streamers seem to be coming from both the needle and the plane. It is unknown whether this actually is the case, as the cloud from the needle could be appearing first, and then the second cloud from the plane sometime later. In Figure 5.6, the measured voltage and PMT voltage is compared. The PMT is saturated at around 5 V, but if the streamers from the plane occurred at a later time, it would most likely be possible to see this on the PMT signal, but this was not the case for any of them.

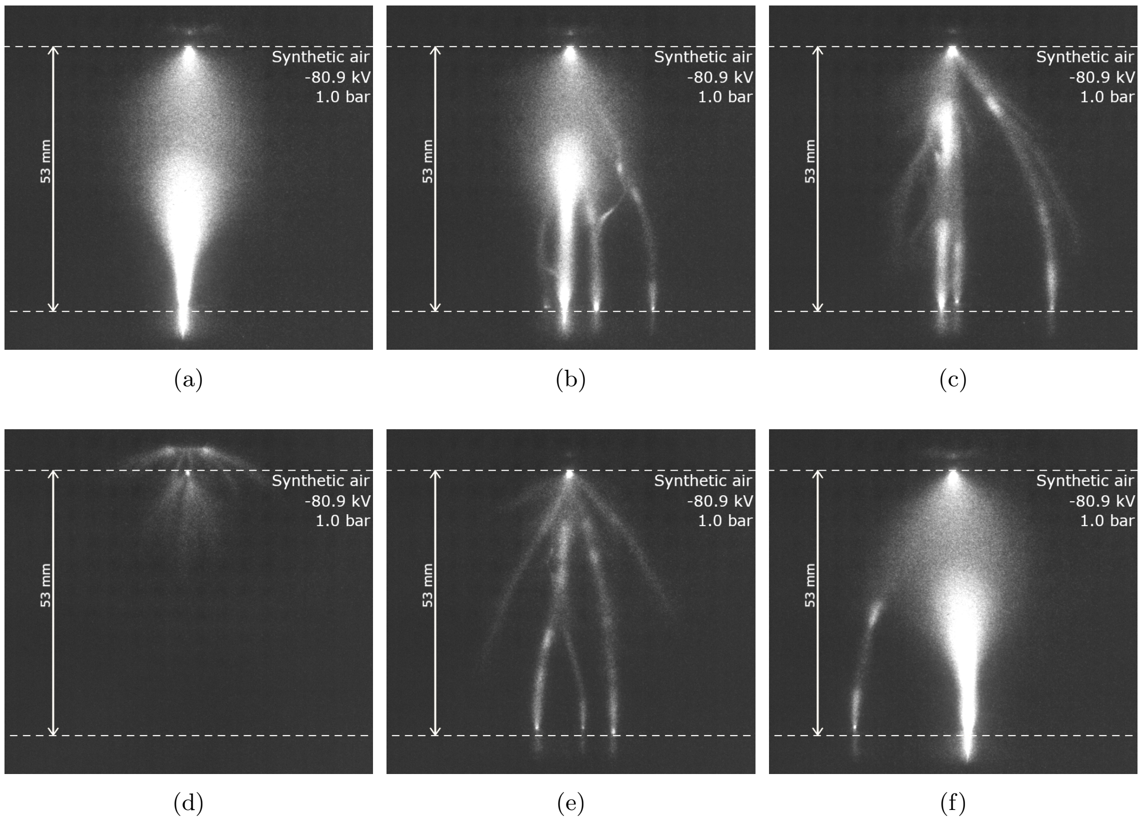


Figure 5.5: Images from the SP1 configuration. The voltage for all these images are -80.9 kV.

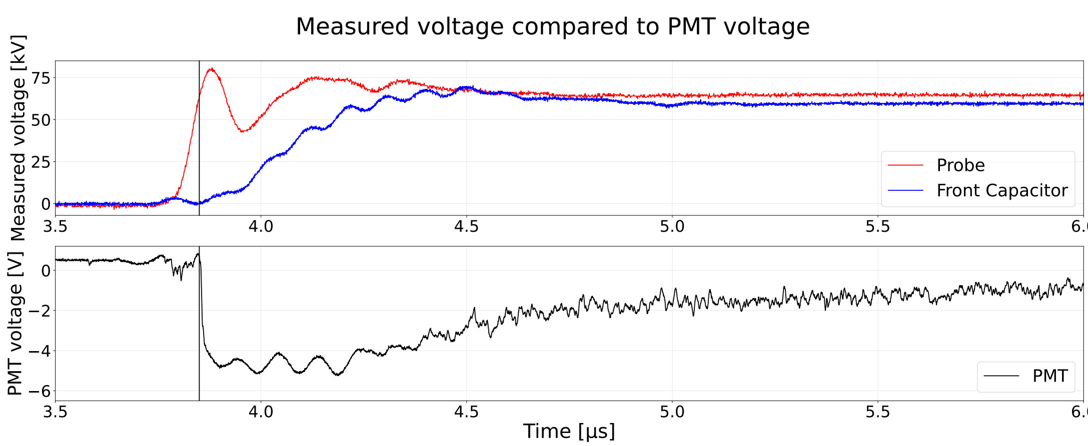
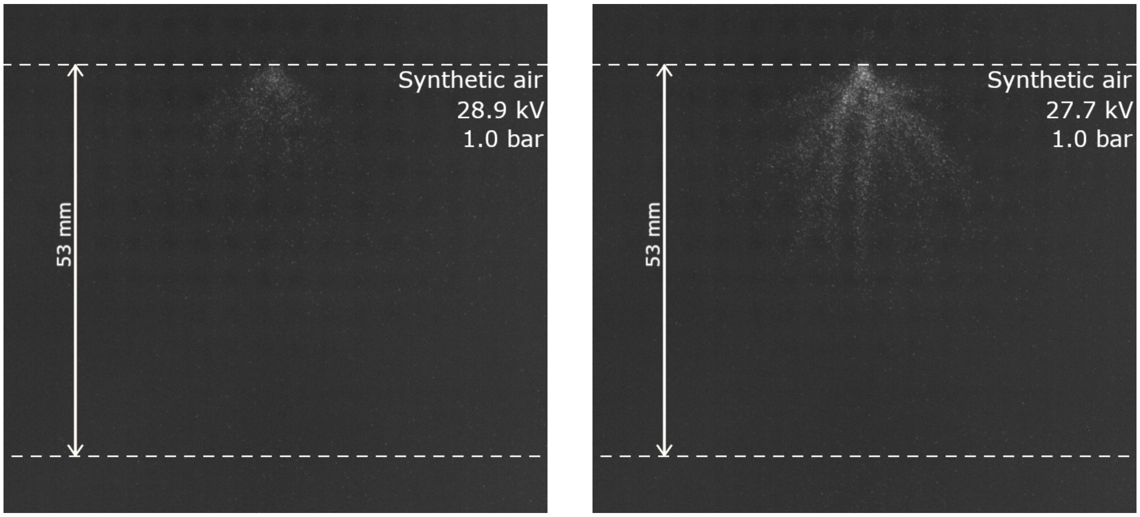


Figure 5.6: The measured voltage compared to the PMT voltage. There is no indication of any light later in the PMT signal.

SP2 - Synthetic air, positive streamer, 1.3 bar

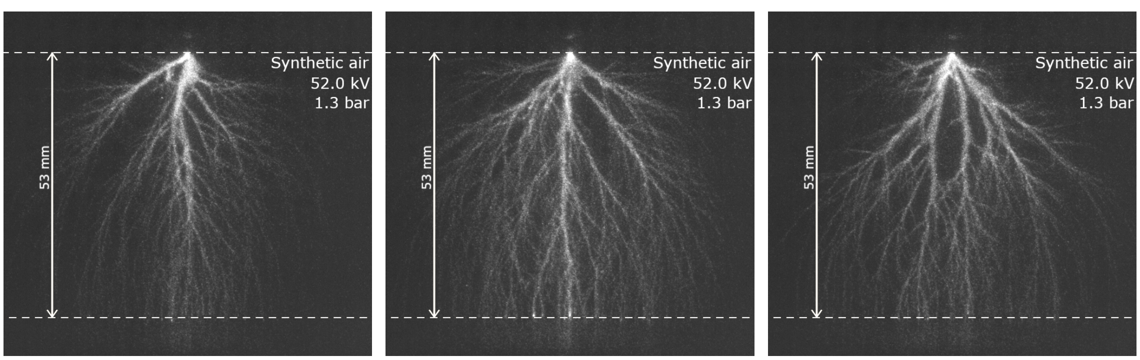
When increasing the pressure to 1.3 bar, the positive streamers close to the inception voltage are significantly less bright. This can be seen in Figure 5.7.



(a) (b)

Figure 5.7: Images captured during the up-and-down test for inception voltage for the SP2 configuration.

The images shown in Figure 5.8 are captured at 52.0 kV. The voltage is slightly higher than those captured in SP1, and more branches can be seen. The positive streamers for 1.3 bar at this voltage are also almost always propagating all the way to the plane. There are only one of the 15 images where this is not the case.



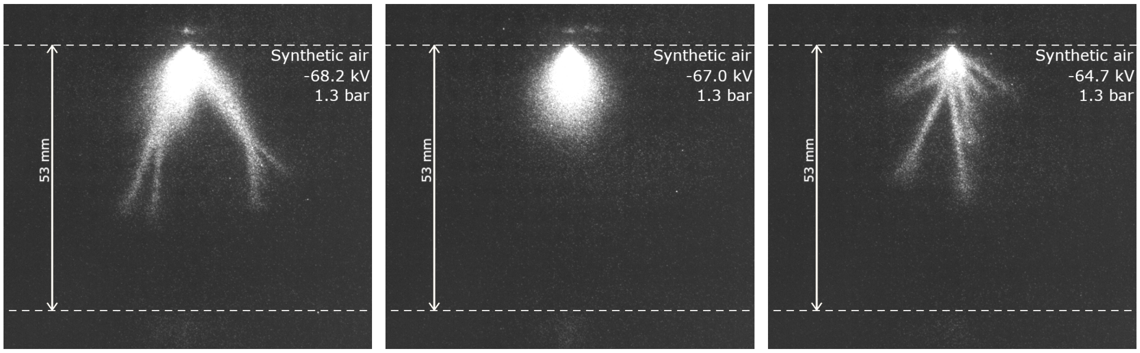
(a) (b) (c)

Figure 5.8: Images from the SP2 configuration. The voltage for all these images are 52.0 kV

SN2 - Synthetic air, negative streamer, 1.3 bar

The inception-images shown in Figure 5.9 are very similar to those for SN1 (Figure 5.4). The major difference is the voltage increase at about 10 kV. The inception voltage was found to be

-62.32 kV from the up-and-down tests.



(a) (b) (c)

Figure 5.9: Images captured during the up-and-down test for inception voltage for the SN2 configuration. These are very similar to the images in SN1.

Same as for SN1, the images in SN2, shown in Figure 5.10 are captured at the same voltage of -80.9 kV. Despite this, the increased pressure is showing no visual changes to the streamers. In Figure 5.10d, the streamer look like a cloud streamer, as explained in section 2.2.

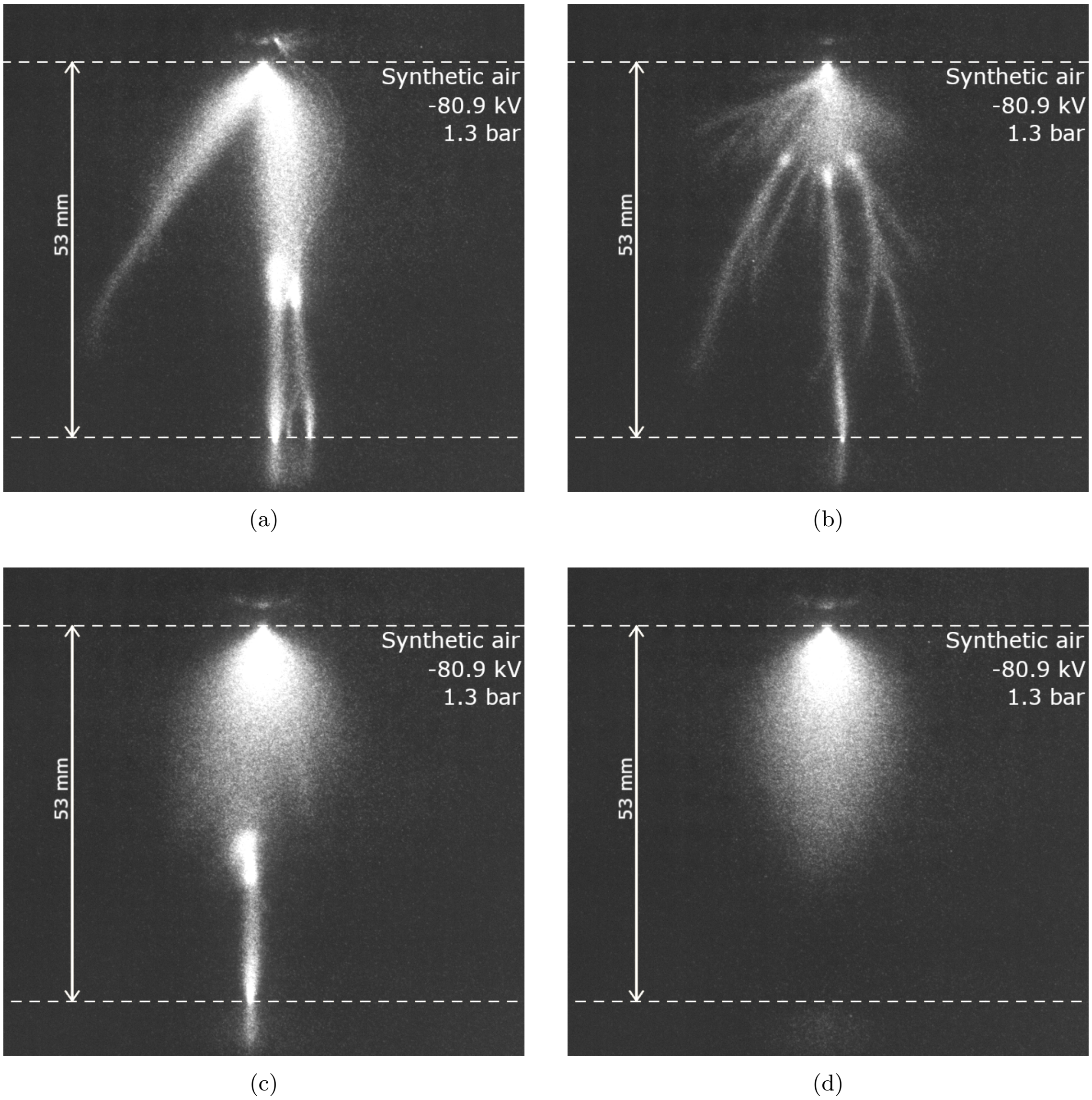
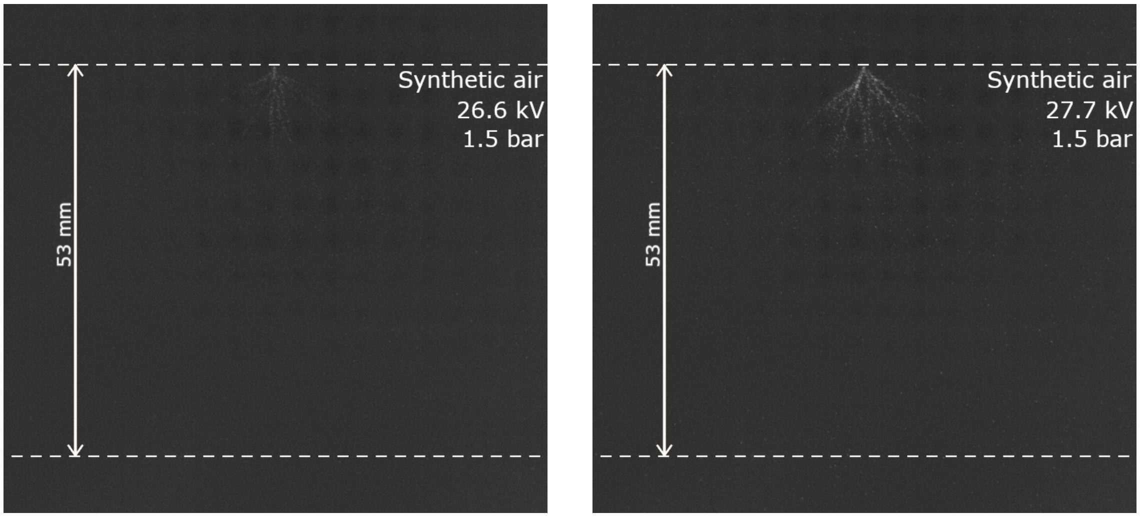


Figure 5.10: Images from the SN2 configuration. The voltage for all these images are -80.9 kV, and are visually very similar to SN1.

SP3 - Synthetic air, positive streamer, 1.5 bar

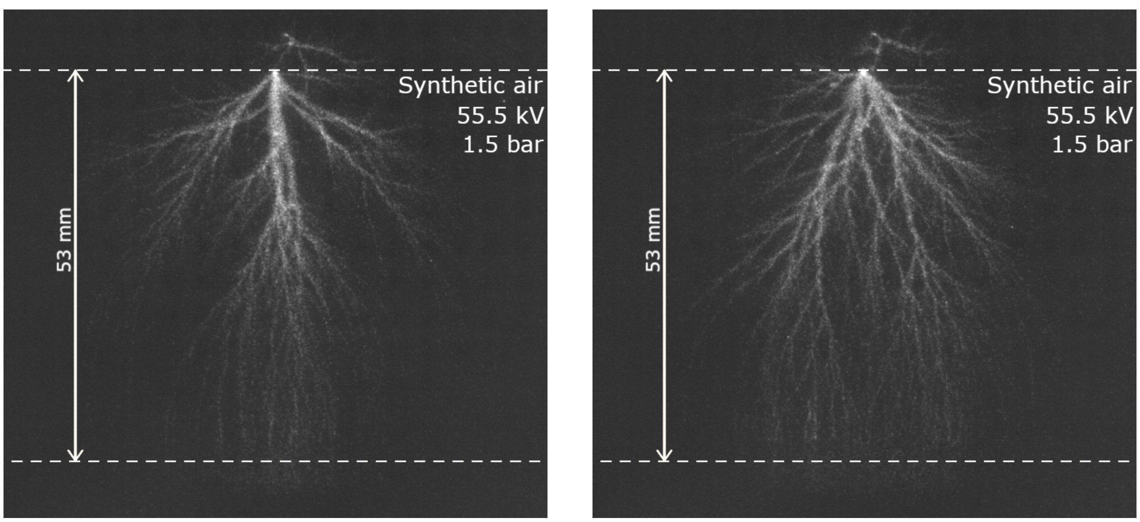
With a pressure of 1.5 bar, the positive streamers in synthetic air are very short and dark. Examples are shown in Figure 5.11.



(a) (b)

Figure 5.11: Images captured during the up-and-down test for inception voltage for the SP3 configuration.

The images in Figure 5.12 are captured at a voltage of 55.5 kV, which is slightly higher than the voltage in SP2. Same as for the negative streamers, increasing the pressure to 1.5 bar is not of great significance. The main difference is that the number of small side branches is decreased, and the streamers are lower in light intensity. They are also gradually decreasing the closer to the plane they get, and it looks like they are barely touching the plane.

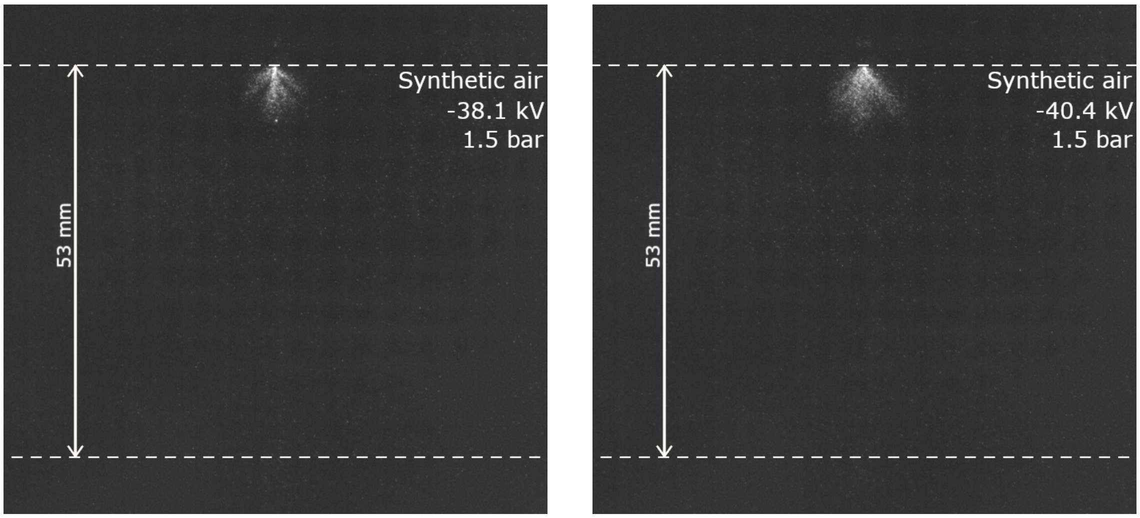


(a) (b)

Figure 5.12: Images captured for the SP3 configuration.

SN3 - Synthetic air, negative streamer, 1.5 bar

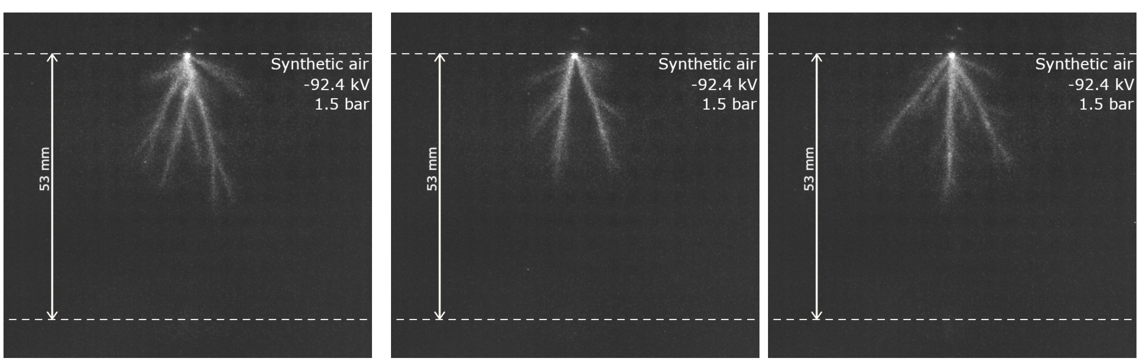
The negative inception voltage was found to be significantly lower for 1.5 bar than for 1.3 bar, which is most likely a fluke. In theory, the inception voltage should be higher with a higher voltage. The images in Figure 5.13 are captured at around -40 kV, which is almost 30 kV lower than for SN2. This, in turn, results in very small streamers.



(a) (b)

Figure 5.13: Images captured during the up-and-down test for inception voltage for the SN3 configuration.

For the image series shown in Figure 5.14, the voltage is increased to -92.4 kV. The increased pressure to 1.5 bar in SN3 is giving very different results compared to both SN1 and SN2. At 1.5 bar and -92.4 kV, the negative streamers are no longer cloudy, but they are clear branches. The number of branches is low compared to positive streamers, and the length is also much shorter. Almost all the streamers in SN3 are approximately the same length, around half the distance of the gap.



(a) (b) (c)

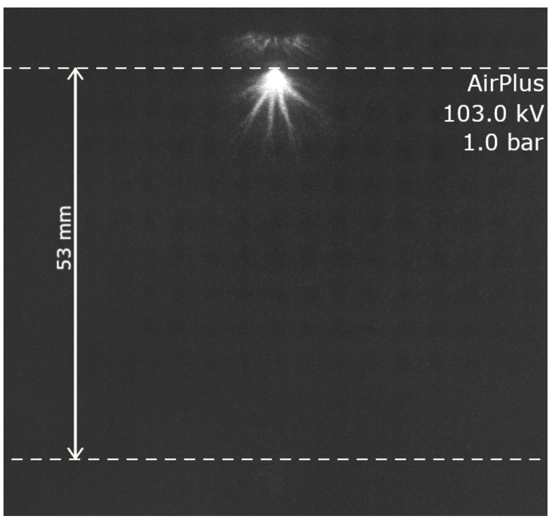
Figure 5.14: Images from the SN3 configuration. The voltage for all these images are -92.4 kV

5.1.2 AirPlus results

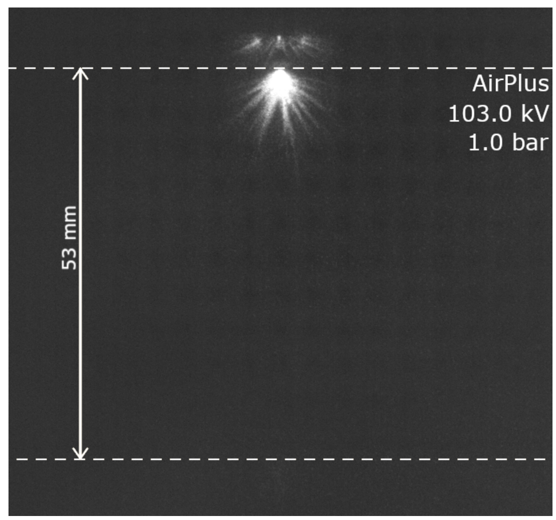
The following are the results from the AirPlus experiments. None of the images from the up-and-down tests will be shown, as these only show a small point of light at the tip of the needle.

AP1 - AirPlus, positive streamer, 1.0 bar

The positive streamers for AirPlus at 1.0 bar, shown in Figure 5.15, are relatively straight compared to those in synthetic air. Also, they are always the same length, around 10-12 mm long. In our setup, increasing the voltage does not increase the length; it only results in the following breakdown. AP1 is done using two stages of the impulse generator. It's also worth noting that the spiky streamer discharges can be seen protruding from the edges of the rod as well, and not just the needle. The spikes from the needle might be the third stage of a cloud streamer, as explained in section 2.2. With a frame-by-frame view of these streamers, it might've been possible to see the three different stages, where the shell forms and propagates before it breaks formation and forms separate streamers.



(a)

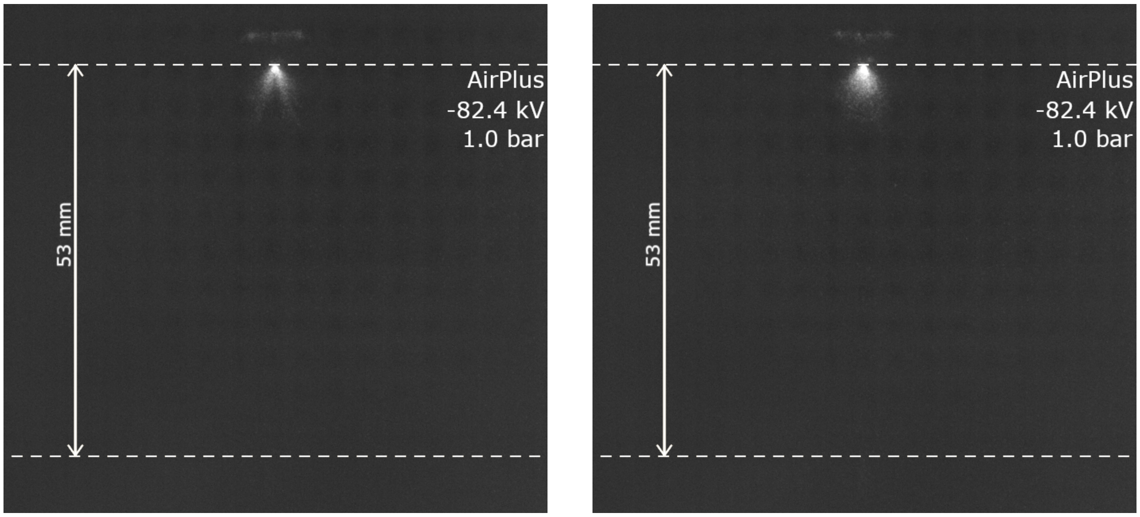


(b)

Figure 5.15: Images from the AP1 configuration. The voltage for all these images are 103.0 kV

AN1 - AirPlus, negative streamer, 1.0 bar

The negative streamers in AirPlus are cloudy, like some of those in synthetic air at 1.0 and 1.3 bar, although much smaller. The images shown in Figure 5.16 are captured at -82.4 kV using two stages on the impulse generator. In Figure 5.16a the streamers appear to form two wide streamers.

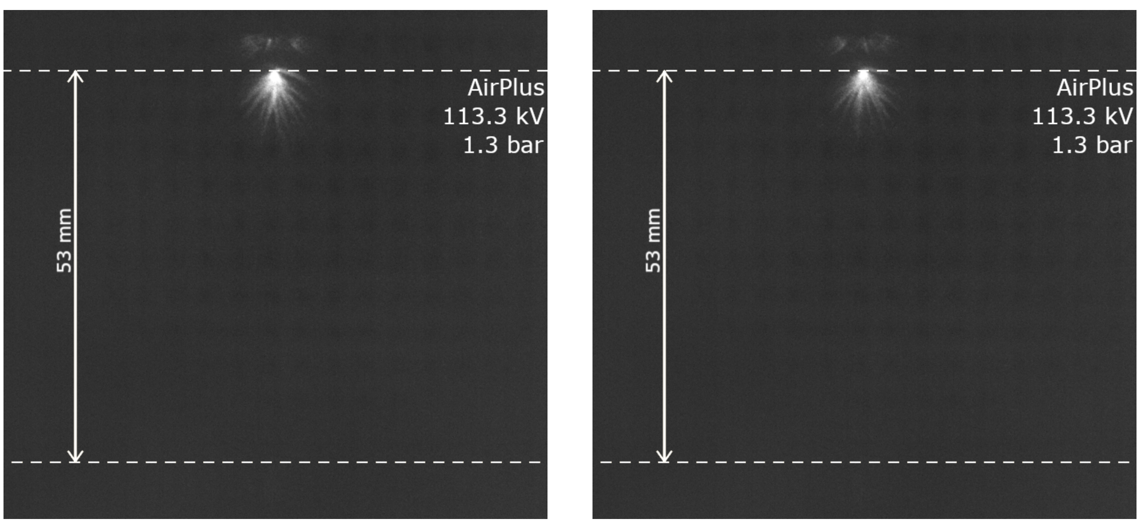


(a) (b)

Figure 5.16: Images from the AN1 configuration. The voltage for all these images are -82.4 kV

AP2 - AirPlus, positive streamer, 1.3 bar

The streamer discharges seen in Figure 5.17 are almost identical to those in AP1, with the difference being slightly shorter branches and fewer discharges from the rod. This clearly indicates that AirPlus is quenching the streamers with increased pressure, as these images are captured at 113.3 kV, 10 kV more than AP1. Also, same as in AP1, this might be a cloud streamer, where the third stage is most prominent in the image. This is explained in section 2.2.

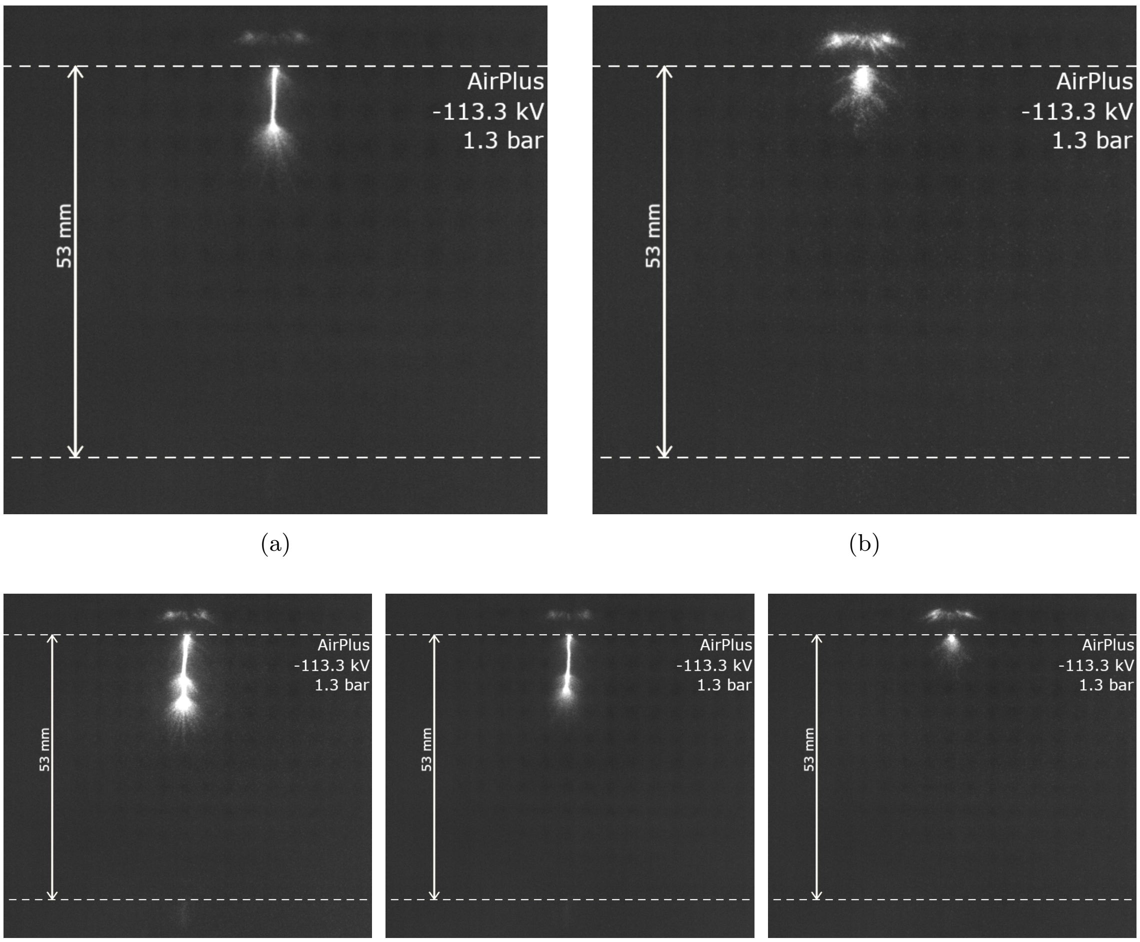


(a) (b)

Figure 5.17: Images from the AP2 configuration. The voltage for all these images are 113.3 kV

AN2 - AirPlus, negative streamer, 1.3 bar

When increasing the pressure of AirPlus to 1.3 bar and increasing the voltage to -113.3 kV, the streamers look like one of two ways. The first, shown in Figure 5.18b and Figure 5.18e, look very similar to those of AP2, with the spiky streamers with streamers also propagating from the rod. The other type, shown in Figure 5.18a, Figure 5.18c and Figure 5.18d, are looking more like a short leader, where the tip is further propagating short streamers. When this is the case, there are much less discharges from the rod.



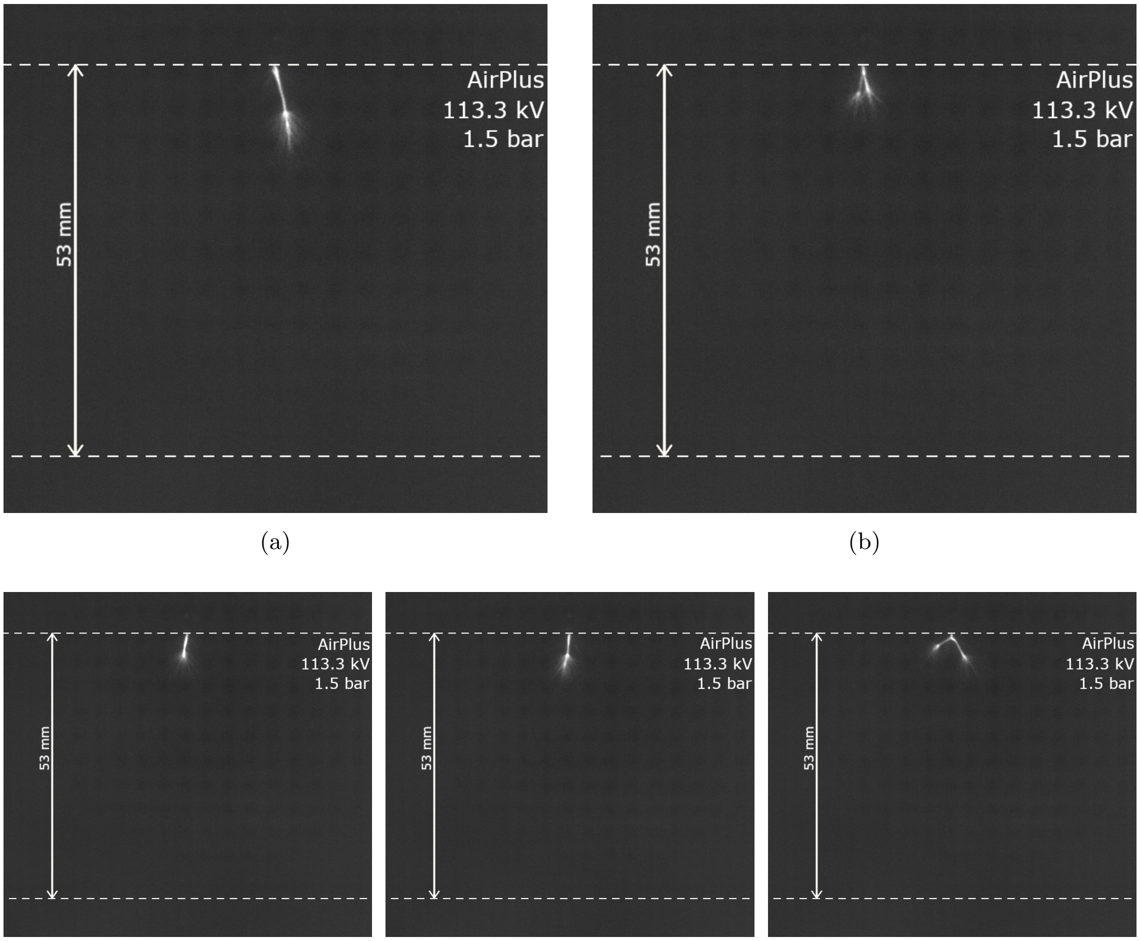
(a) (b)

(c) (d) (e)

Figure 5.18: Images from the AN2 configuration. The voltage for all these images are -113 kV

AP3 - AirPlus, positive streamer, 1.5 bar

The same leader phenomena from AN2 also occurs for the positive streamers in 1.5 bar. These are shown in Figure 5.19. These are taken at the same voltage with positive polarity, and the difference is they are both shorter in length and thinner than in AN2. There are also no visible discharges from the rod, which may be an indication that at 1.5 bar, AirPlus is quenching the streamers from areas of weaker electric field.

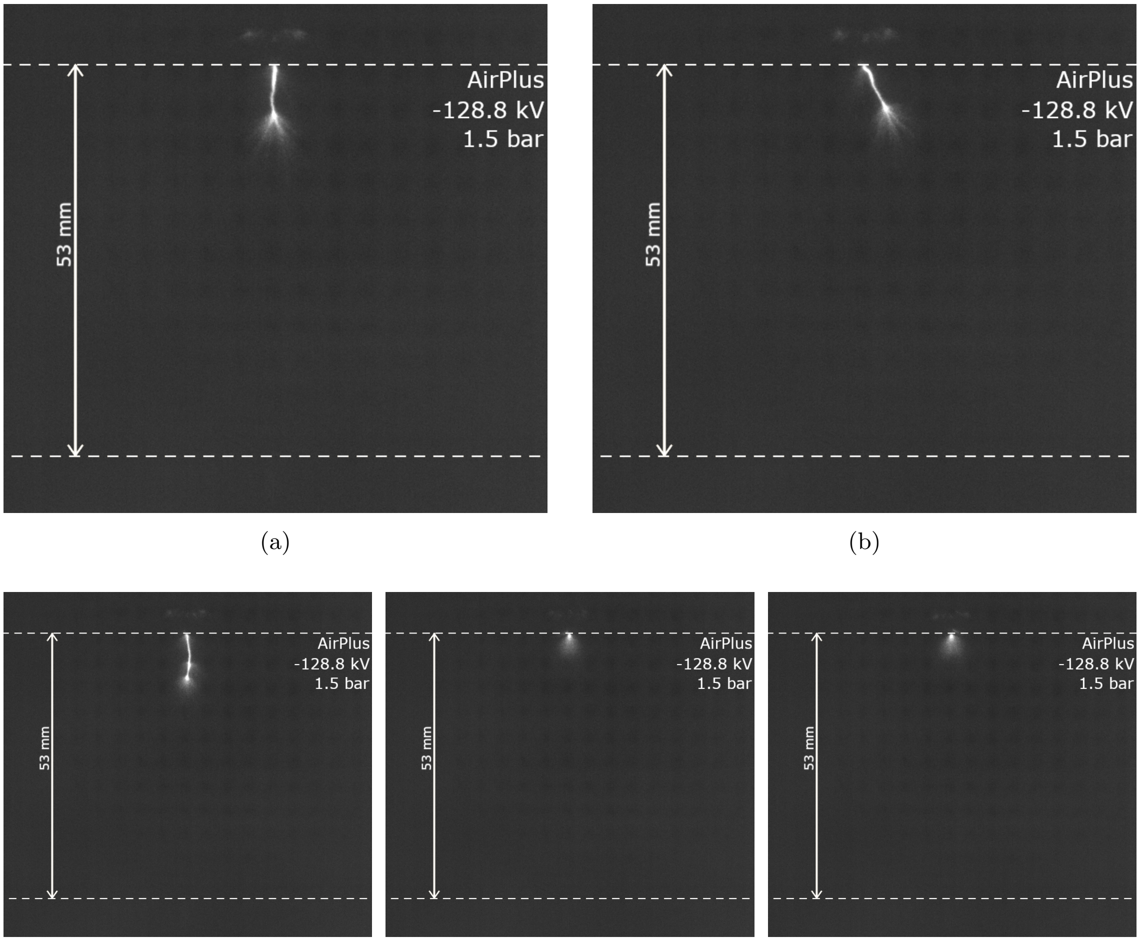


(a) (b) (c) (d) (e)

Figure 5.19: Images from the AP3 configuration. The voltage for all these images are 113.3 kV

AN3 - AirPlus, negative streamer, 1.5 bar

For negative polarity in AirPlus at 1.5 bar, the voltage is further increased to -128.8 kV. The images are shown in Figure 5.20. Again, there is not much difference from the images from AN2. AN3 and AP3 are very alike, almost indistinguishable. The difference is that there is also some visible discharge from the rod, as well as the occasional cloud-streamer, like those in Figure 5.20d and Figure 5.20e. This cloud-like streamer occurred in five of the 15 images captured.



(a) (b) (c) (d) (e)

Figure 5.20: Images from the AN3 configuration. The voltage for all these images are -128.8 kV

5.2 Summary of the experimental results

When looking at all the positive polarity tests in synthetic air, they all seem to act primarily the same. With the increased voltage for 1.5 bar, the main streamers seem to be smaller, thinner, and of less light intensity, but small streamers are also starting to propagate from the rod, an area of less field strength. This can be seen at the top right image in Figure 5.21. There seems to be little difference between 1.0 to 1.3 bar, as for 1.3 bar, there are more branches and more light, but the voltage is also higher for this image.

The negative streamers in synthetic air at 1.0 and 1.3 bar look to be mostly alike, as there are several different types of streamers for both pressures, and they are also captured at the same voltage. For both of them, it looks like streamers are propagating from both the rod and the plane. A thought was that the streamers from the rod propagate to the plane first, with following secondary streamers from the plane. The PMT signal showed no indication of this, however, as it only shows emitted light at the front of the voltage impulse. This is inconclusive, as the PMT is saturated within a very short time, but within 500 ns, it is down to half the saturation voltage again. If the secondary streamers happen within this timeframe, it would be impossible to know.

The negative streamers in 1.5 bar appear to look more like the positive streamers, as it has clear branches and is not cloudy like the negative streamers in 1.0 and 1.3 bar. Even though the voltage is increased, this is the only configuration with synthetic air during the tests where the streamers never propagate all the way and makes contact with the plane. This is most likely because of the shorter available path for the electrons to accelerate in due to the increased amount of gas molecules.

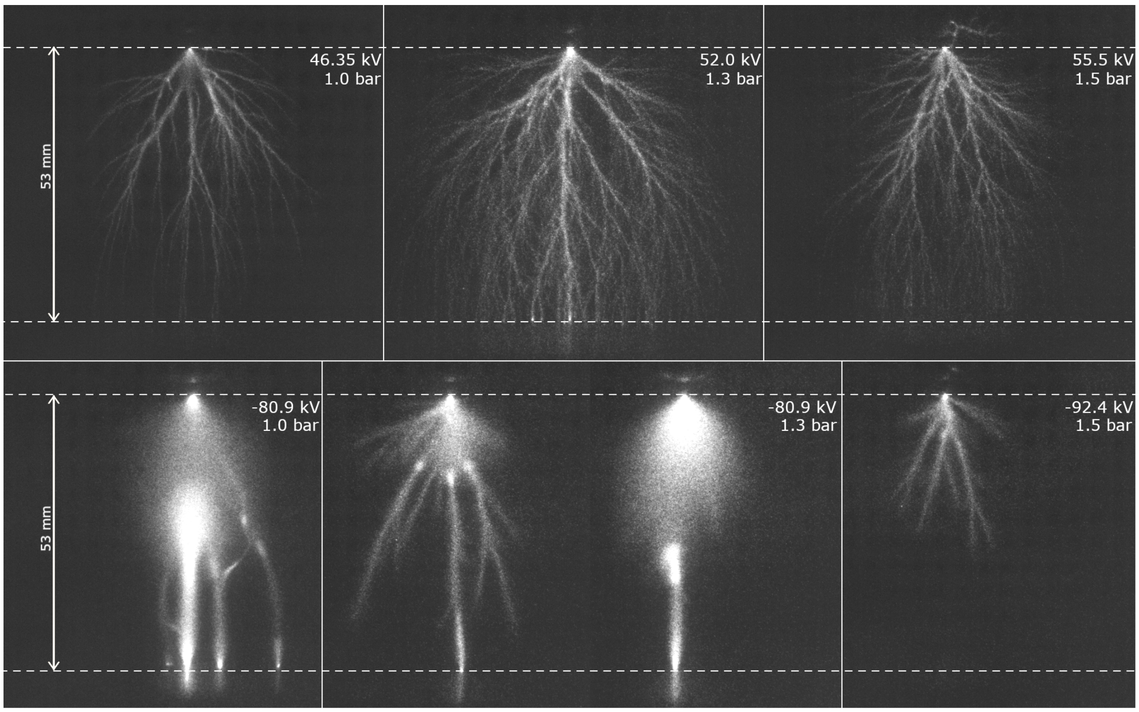


Figure 5.21: A collective image of the streamers in different pressures and polarities in synthetic air. The top images are the positive polarities, and the bottom ones are the negative.

A comparison of the different AirPlus images is shown in Figure 5.22. Compared to synthetic air, the streamers in AirPlus never seem to propagate to the plane. In fact, it's never even close, even for any polarity or pressure. For positive polarity, the voltage is more than doubled from the synthetic air under any pressure.

Same as synthetic air, the positive streamers in AirPlus at 1.0 and 1.3 bar are very similar. In both pressures, the streamers are short and straight, with additional streamers propagating from the rod. In 1.5 bar, however, it's almost always only one or two thin branches, looking like leaders. From the tip of these leaders, there is further propagation of streamers. These tip-streamers look like a miniature of the short and straight streamers in 1.0 and 1.5 bar.

For negative streamers in 1.0 bar AirPlus, there was only this cloudy, diffuse streamer. There were no captured images at a higher voltage at this pressure. At 1.3 bar, the voltage was increased to -113.3 kV, and it switched between the thin leader with tip-streamers, very similar to those in 1.5 bar with positive polarity, and cloudy, diffuse streamers like those in 1.0 bar with negative polarity. The negative leaders in 1.3 bar were longer, wider, and brighter than the positive ones in 1.5 bar.

When increasing the pressure to 1.5 bar and the voltage to -128.8 kV, it was the same as for 1.3 bar. It switches between a leader with tip-streamers and cloudy streamers. For 1.5 bar, however, the leader is very thin and is almost identical to those in 1.5 bar with positive polarity, except for the extra discharges from the rod.

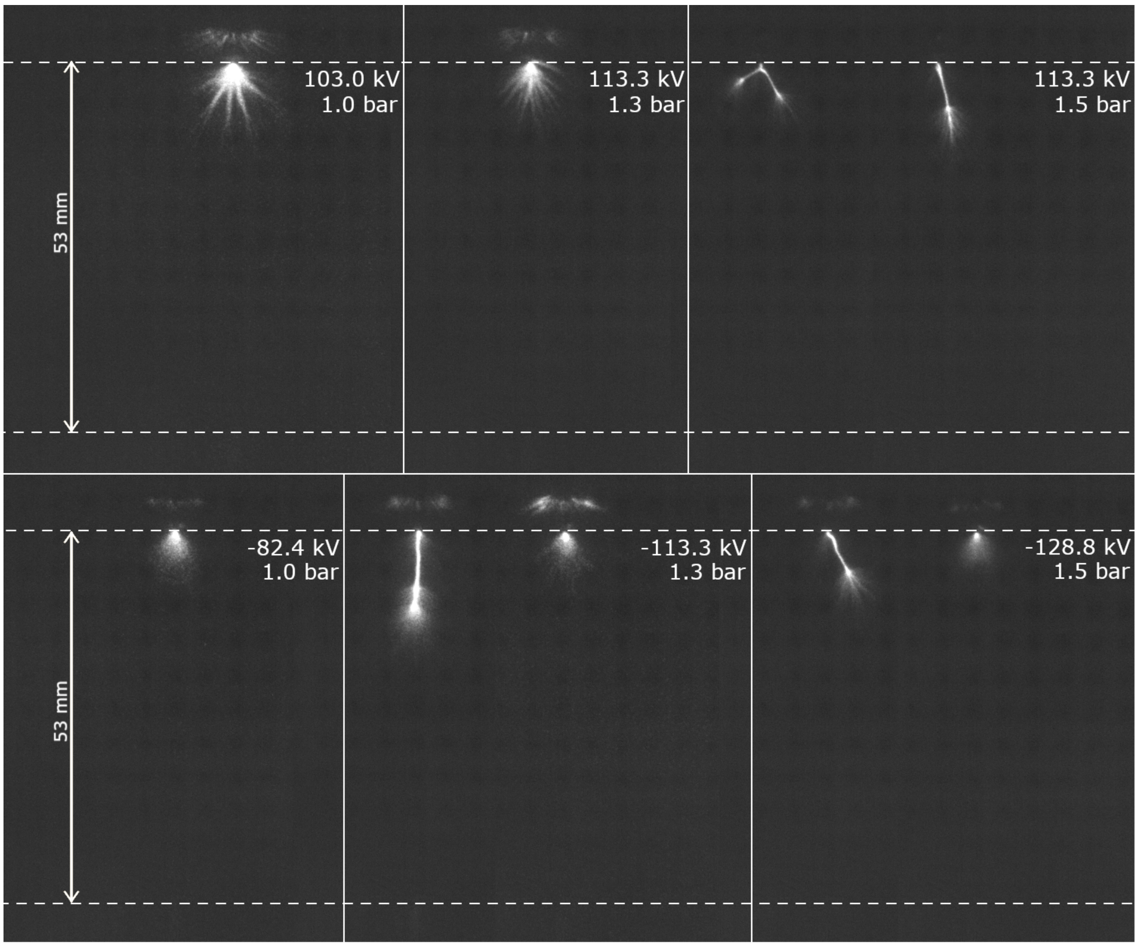


Figure 5.22: A collective image of the streamers in different pressures and polarities in AirPlus. The top images are the positive polarities, and the bottom ones are the negative.

5.3 Sources of error

5.3.1 PMT Saturation

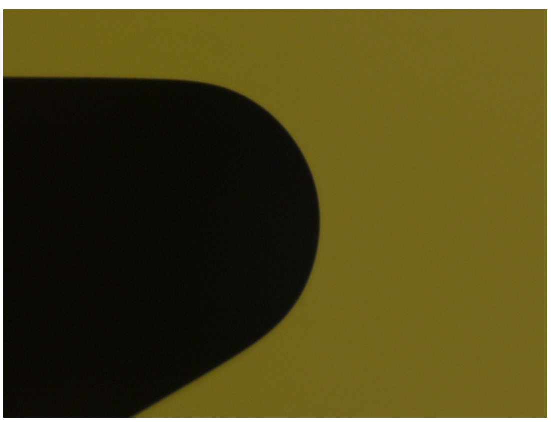
The voltage applied to the PMT was set to 2400 V in most of the experiments. This was because initially, the PMT was just used as a simple light detector, and applying a voltage close to maximum made sure if there were any light at all, it would be detected. The downside of this was that the PMT was almost always saturated when any light was present. The amount of light can hence not be measured effectively, and the only time-based information available is the time when the signal is detected. This means, as mentioned in section 5.1.1 that the PMT signal cannot be used to determine if some of the light appears later.

5.3.2 Gap distance

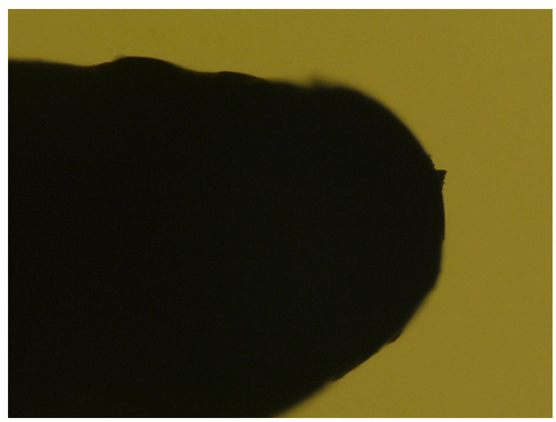
A crank underneath the tank is used manually to adjust the gap distance in the tank. This was set to the maximum distance, and then the gap was measured by hand. Since it's a small space, an accurate reading can be difficult. It is the same gap for all experiments (53 mm), but this may not be exact. The error in gap distance is estimated to be around ±0.5 mm. The protrusion of the needle is also measured manually and is protruding 3 mm from the rod. This was done more exact, but there is always some error present. The needle is estimated to protrude 3 mm ±0.1 mm.

5.3.3 Wear on the electrodes and needle

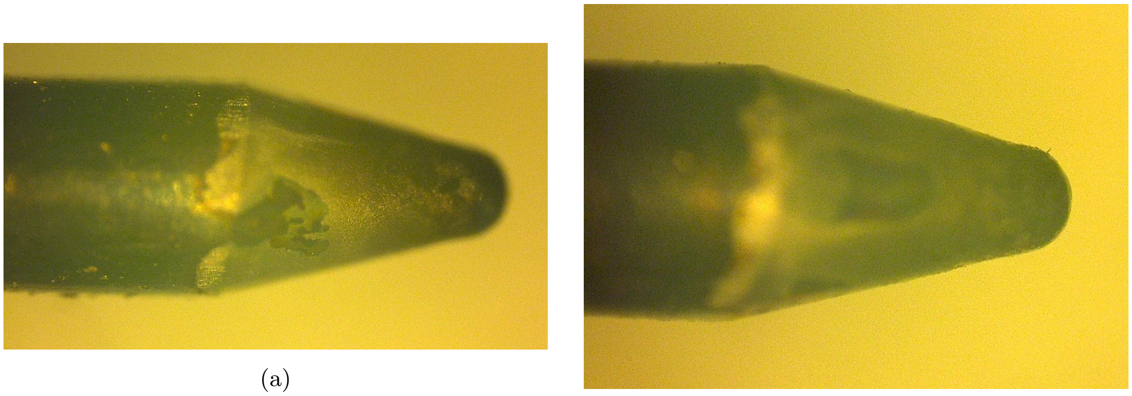
When looking at both the plane and rod electrode, some wear from the experiments can be seen. The most prominent marks are most likely from some of the breakdowns that were tested. From some of the experiments, it was also noticed streamers protruded from a specific spot on the rod and not the needle. The needle was looked at in a microscope to investigate any wear further, and several imperfections were found. A new needle is shown in Figure 5.23a and the old needle, used for breakdown tests in the specialization project, is shown in Figure 5.23b. For this project, only a few breakdown tests were performed, resulting in less wear. A new needle was used, and the needle was examined with a microscope after all the tests. This needle is shown in Figure 5.24b and shows some imperfections but no severe damage.



(a) A brand new needle, never used in any experiments.



(b) The needle after many breakdowns during the specialization course.



(a) (b)

Figure 5.24: The needle used for the experiments during this project. Some imperfections found.

Chapter 6

Conclusions

- The goal of this project was to better understand how pre-breakdown mechanisms, specifically streamers, act in different pressures and polarities in AirPlus compared to synthetic air. This was done by applying a lightning impulse to a very inhomogeneous plane-rod gap and capturing images of it using high-speed cameras. The motivation for the project was to get a broader understanding of how AirPlus acts as an insulation gas and if it is suited for replacing SF_6 in MV and HV applications in the near future.
- The results from the up-and-down tests are not to be trusted, as most likely 180 seconds is not enough waiting time between shots to be completely independent of each other. From the images captured, it can be seen that in all cases, the streamers are shorter in AirPlus than in synthetic air, even though the images from AirPlus are captured at higher voltages. None of the streamers or leaders in this setup reached the plane without a following breakdown, contrary to the tests in synthetic air, where almost all configurations propagated streamers over the whole gap. Negative streamers in 1.5 bar were the only exception to this. The images also show that increasing the pressure of synthetic air doesn't significantly change the visual appearance of the positive streamers, except for an increase in the number of smaller branches, and discharges from the rod and the needle. For negative streamers in synthetic air, the increased pressure to 1.5 bar resulted in shorter branches, where none of the streamers reached the plane.
- Increasing the pressure of AirPlus resulted in discharges more similar to leaders than streamers, for both polarities on 1.5 bar and the negative discharges in 1.3 bar. Visually, it's hard to differentiate between the positive and negative streamers/leaders in 1.5 bar, and the negative discharges were captured at a higher voltage than the positive. For 1.0 and 1.3 bar AirPlus, the positive streamer branches are short and straight. The negative streamers in 1.0 bar are cloudy and diffuse, but these images were also shot at a lower voltage than the positive streamers. When comparing synthetic air and AirPlus, all images show that AirPlus performs better when it comes to restraining streamer discharges.

Chapter 7

Further Work

A list of possible further work:

- As the up-and-down tests for the inception voltage was unsuccessful in finding trustworthy 50% inception voltages, a better way of finding these would be useful. For the tests in this project, the inception delay was too much of a statistical parameter. To remove the stochastic part of finding the inception voltage, there are at least a few things that can be done. One thing that could be done is to install a UV light inside the tank. This will provide the free electrons needed to start the first electron avalanche. It will lower the perceived inception voltage, but it will also show the lowest possible voltage where inception could occur, should a free electron be at the right place at the right time. Another thing is to install a fan inside the tank, both to better mix the gas both after filling as well as to remove space charge between the shots. This could probably reduce the waiting time significantly. Applying a DC voltage with opposite polarity of the impulse voltage to the electrodes in between shots could also help remove the space charge in the gap. Another way to find the inception voltage could be to use the PMT signal more actively. If using a UV-lamp provides the free electron needed to start the electron avalanche, this would happen at the earliest time and lowest voltage possible, meaning it would be possible to read the voltage level at the exact time the PMT detects light. By looking at (FIG 5.7), if the UV-lamp had been present, the voltage could theoretically be read from the plot, and the up-and-down tests would've been unnecessary, as this could be read from the tests at higher voltages, for example, when capturing the images.
- Because of the capacitive currents in the system, the current flowing in the gap during the discharges was hard to measure. The discharge current is many orders lower than these currents, and it proved hard to filter it out. The streamer current could potentially be used to characterize the streamer and identify whether it was a streamer or leader. In examples like the negative streamers in 1.0 bar of synthetic air Figure 5.5, the current could potentially provide information about whether the streamers from the plane occurred simultaneously as the streamers from the rod or if it happened at a later time.
- This project has largely been around capturing images of both positive and negative streamer discharges in different pressures of both AirPlus and synthetic air. An even more extensive study would be helpful in understanding the characteristics of AirPlus, where different electrodes and gaps are tested with different inhomogeneities, as well as testing and comparing with SF_6. Also, it would be helpful to do this using both HiCam with long exposure images as well as another camera capable of capturing several short-exposure images, such as

SIMX16. A large study like this would most likely be too much for a master thesis but would help obtain large quantities of data.

- The tank used in this project had windows that blocked UV light. By installing windows on the tank capable of letting UV light through, such as quartz-glass, as well as UV-compatible camera equipment, there is possibly much more data to acquire. In this project, it has been limited to light with wavelength within visible light, but many of the photons excited during the streamer discharge probably have wavelengths in the UV range.
- As mentioned, it was discovered quite late in the project that the impulse voltage was not a standard lightning impulse. It could be advantageous to do the same experiments with more stages of the impulse generator connected, as this proved to remove the initial voltage spike. For the images, it probably didn't make that much of a difference, but it is possible this would produce more reliable inception voltage measurements, at least if using the method described above.
- The mirror setup used in this project, unfortunately, didn't produce any viable results. It was a side-project during this thesis and proved that the software part was rather difficult. For someone with software experience, this would probably be relatively simple, and there might be easier ways to complete the task of producing the 3D model from the images. Regarding the hardware part, Newport and Edmund Optics provide high-quality mirrors and prisms to be used in a better setup. The setup used in this project was only a proof of concept and never got out of this phase. Nijdam et al. are already using stereoscopic 3D imaging actively to get more data out of streamer images and can be used for inspiration [24]. Using a camera like SIMX16 with stereo-imaging could also be beneficial, as tracing the streamer branches frame by frame would probably be easier than the long exposure images.

References

[1] D Koch. "SF6 properties, and use in MV and HV switchgear". In: *Cahier technique* 188 (2003).

[2] United States Environmental Protection Agency. *High GWP Gases and Climate Change*. 2021. URL: `https://web.archive.org/web/20121018211612/http://www.epa.gov/highghwp/scientific.html`.

[3] Christian M. Franck et al. *Electric performance of new non- SF6 gases and gas mixtures for gas-insulated systems*. Tech. rep. Cigre, 2021.

[4] Maik Hyrenbach et al. "Alternative gas insulation in medium-voltage switchgear". In: *Proceedings of the 23rd International Conference on Electricity Distribution, Lyon, France*. 2015, pp. 15–18.

[5] T. M. P. Briels, E. M. van Veldhuizen, and U. Ebert. "Time Resolved Measurements of Streamer Inception in Air". In: *IEEE Transactions on Plasma Science* 36.4 (2008), pp. 908–909. DOI: `10.1109/TPS.2008.920223`.

[6] TMP Briels, EM Van Veldhuizen, and Ute Ebert. "Positive streamers in air and nitrogen of varying density: experiments on similarity laws". In: *Journal of Physics D: Applied Physics* 41.23 (2008), p. 234008.

[7] S Nijdam et al. "A peculiar streamer morphology created by a complex voltage pulse". In: *IEEE Transactions on Plasma Science* 39.11 (2011), pp. 2216–2217.

[8] She Chen et al. "Nanosecond repetitively pulsed discharges in N2–O2 mixtures: inception cloud and streamer emergence". In: *Journal of Physics D: Applied Physics* 48.17 (2015), p. 175201.

[9] AG Rep'ev and PB Repin. "Dynamics of the optical emission from a high-voltage diffuse discharge in a rod-plane electrode system in atmospheric-pressure air". In: *Plasma Physics Reports* 32.1 (2006), pp. 72–78.

[10] P Tardiveau et al. "Diffuse mode and diffuse-to-filamentary transition in a high pressure nanosecond scale corona discharge under high voltage". In: *Journal of Physics D: Applied Physics* 42.17 (2009), p. 175202.

[11] Victor Tarasenko. "Runaway electrons in diffuse gas discharges". In: *Plasma Sources Science and Technology* 29.3 (2020), p. 034001.

[12] George V Naidis et al. "Subnanosecond breakdown in high-pressure gases". In: *Plasma Sources Science and Technology* 27.1 (2018), p. 013001.

[13] VF Tarasenko et al. "Formation of wide streamers during a subnanosecond discharge in atmospheric-pressure air". In: *Plasma Physics Reports* 44.8 (2018), pp. 746–753.

[14] Tomáš Hoder et al. "Emerging and expanding streamer head in low-pressure air". In: *Plasma Sources Science and Technology* 29.3 (2020), 03LT01.

[15] Sander Nijdam, Jannis Teunissen, and Ute Ebert. "The physics of streamer discharge phenomena". In: *Plasma Sources Science and Technology* 29.10 (2020), p. 103001.

[16] Astrup. *Glass material.* URL: https://kundeportal.astrup.no/plast/pc/plater-exell-klar-ekstrudert-uv-bestandig.

[17] Tao Wen et al. "Discussion on lightning impulse test waveform according to breakdown characteristics of SF6 gas gaps". In: *IEEE Transactions on Dielectrics and Electrical Insulation* 24.4 (2017), pp. 2306–2313. DOI: 10.1109/TDEI.2017.006605.

[18] M.J. Pelletier and C.C. Pelletier. *Photomultiplier Tubes.* 2005. URL: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/photomultiplier-tubes.

[19] Engineering360. *Electrodes and Electrode Materials Information.* https://www.globalspec.com/learnmore/materials_chemicals_adhesives/electrical_optical_specialty_materials/electrical_contact_electrode_materials/electrical_contact_electrode_materials. 2021.

[20] Ogura. http://www.ogura-indus.co.jp/en/product/section17.php.

[21] Andreas Küchler. *High Voltage Engineering.* first. https://link.springer.com/book/10.1007/978-3-642-11993-4. Springer Vieweg, Berlin, Heidelberg, 2018.

[22] Hans Kristian Hygen Meyer. "Dielectric barriers under lightning impulse stress Breakdown and discharge-dielectric interaction in short non-uniform air gaps". PhD thesis. NTNU Trondheim.

[23] Arthur Francisco Andrade et al. *Evaluation of statistical methods used in the estimation of breakdown voltage distribution.* Tech. rep. The Institution of Engineering and Technology, 2019.

[24] S Nijdam et al. "Stereo-photography of streamers in air". In: *Applied Physics Letters* 92.10 (2008), p. 101502.

Appendices

Appendix A

Up-and-down experiments

In this appendix, the data for the up-and-down tests are shown. The black line represents the 50% inception voltage for the test, and the blue line indicated the corrected 50% inception voltage according to how many stages of the generator was connected for the test. The factor between the corrected and original inception voltage is explained in section 3.6.

SP1 - Synthetic air, positive streamer, 1.0 bar

The SP1 configuration is the test with positive streamers in synthetic air at 1.0 bar pressure. The up-down test is shown in Figure A.1. The corrected 50% inception is shown to be 22.52 kV.

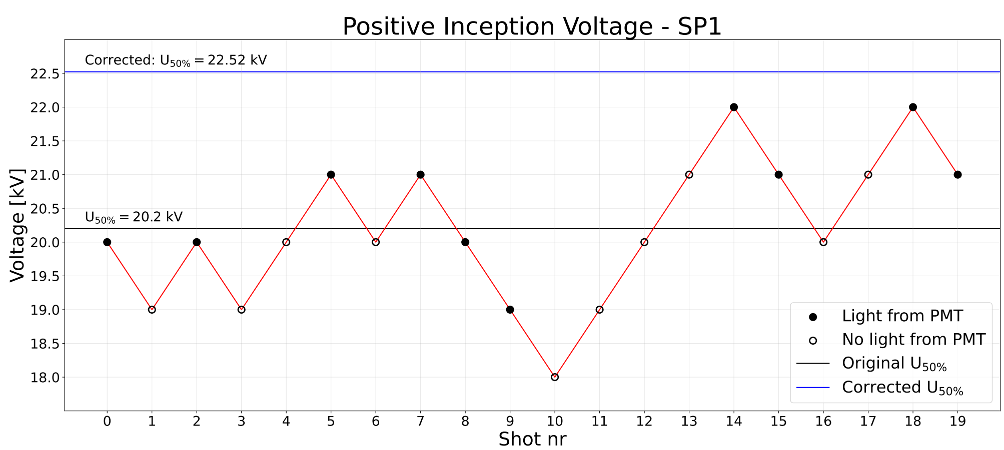


Figure A.1: The up-and-down test for SP1, the positive inception voltage for synthetic air under 1.0 bar pressure. The blue line shows the corrected 50% inception voltage to be 22.52 kV.

SP2 - Synthetic air, positive streamer, 1.3 bar

The SP2 configuration is the test with positive streamers in synthetic air at 1.3 bar pressure.

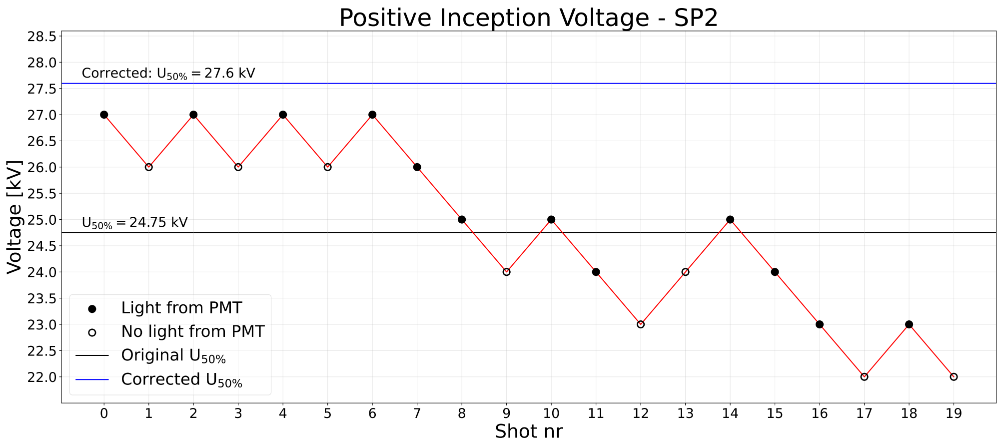


Figure A.2: The up-and-down test for SP2, the positive inception voltage for synthetic air under 1.3 bar pressure. The blue line shows the corrected 50% inception voltage to be 22.52 kV.

SP3 - Synthetic air, positive streamer, 1.5 bar

The SP3 configuration is the test with positive streamers in synthetic air at 1.5 bar pressure.

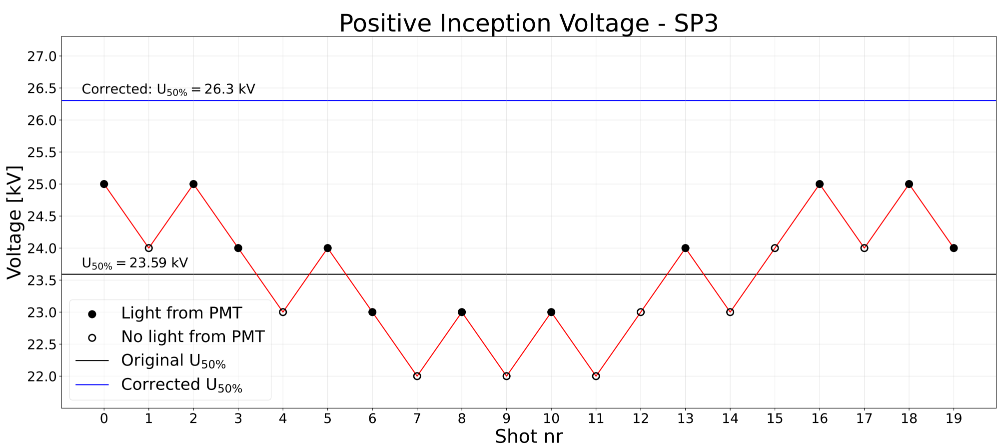


Figure A.3: The up-and-down test for SP3, the positive inception voltage for synthetic air under 1.5 bar pressure. The blue line shows the corrected 50% inception voltage to be 26.3 kV.

AP1 - AirPlus, positive streamer, 1.0 bar

The AP1 configuration is the test with positive streamers in AirPlus at 1.0 bar pressure.

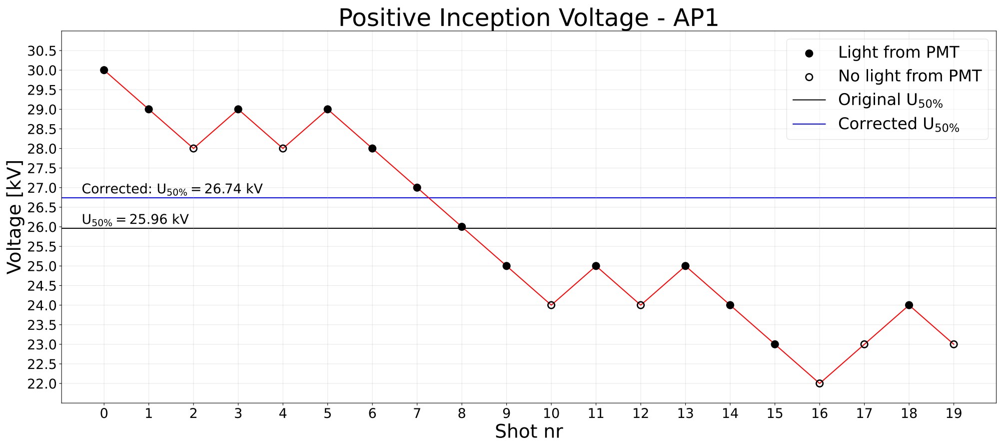


Figure A.4: The up-and-down test for AP1, the positive inception voltage for synthetic air under 1.0 bar pressure. The blue line shows the corrected 50% inception voltage to be 26.74 kV.

AP2 - AirPlus, positive streamer, 1.3 bar

The AP2 configuration is the test with positive streamers in AirPlus at 1.3 bar pressure.

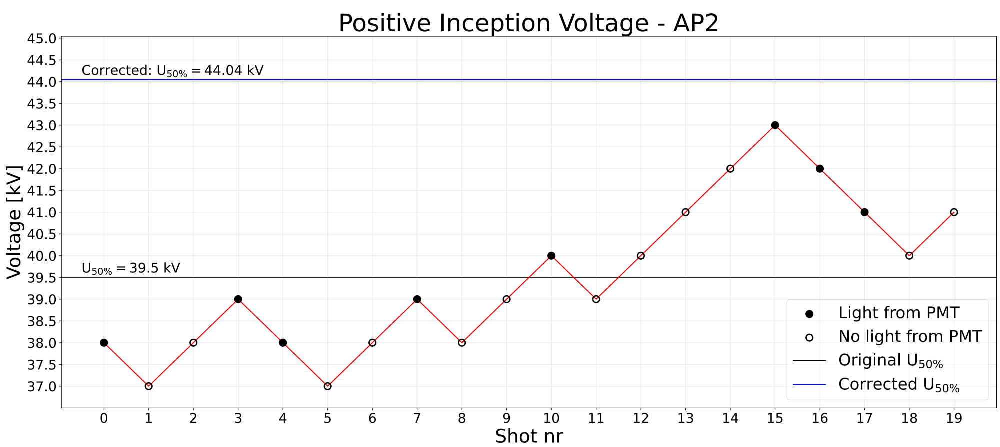


Figure A.5: The up-and-down test for AP2, the positive inception voltage for AirPlus under 1.3 bar pressure. The blue line shows the calculated 50% inception voltage to be 44.04 kV.

SN1 - Synthetic air, negative streamer, 1.0 bar

The SN1 configuration is the test with negative streamers in synthetic air at 1.0 bar pressure.

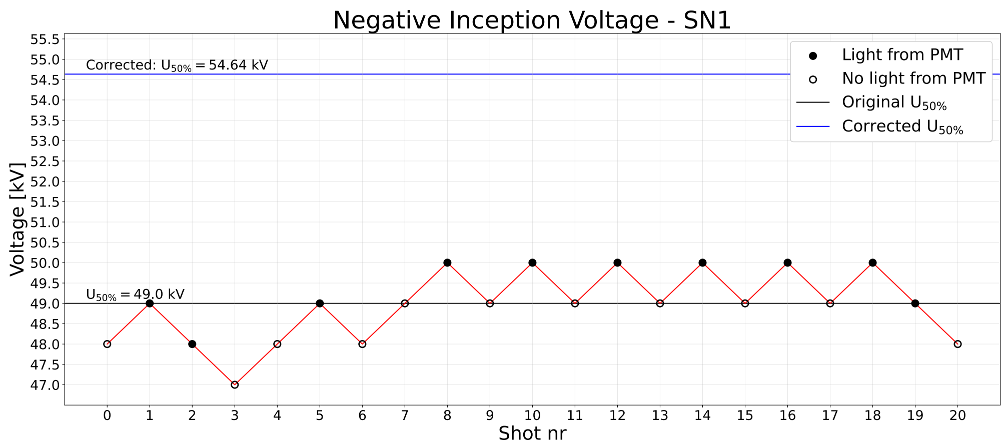


Figure A.6: The up-and-down test for SN1, the negative inception voltage for synthetic air under 1.0 bar pressure. The blue line shows the calculated 50% inception voltage to be 54.64 kV.

SN2 - Synthetic air, negative streamer, 1.3 bar

The SN2 configuration is the test with negative streamers in synthetic air at 1.3 bar pressure.

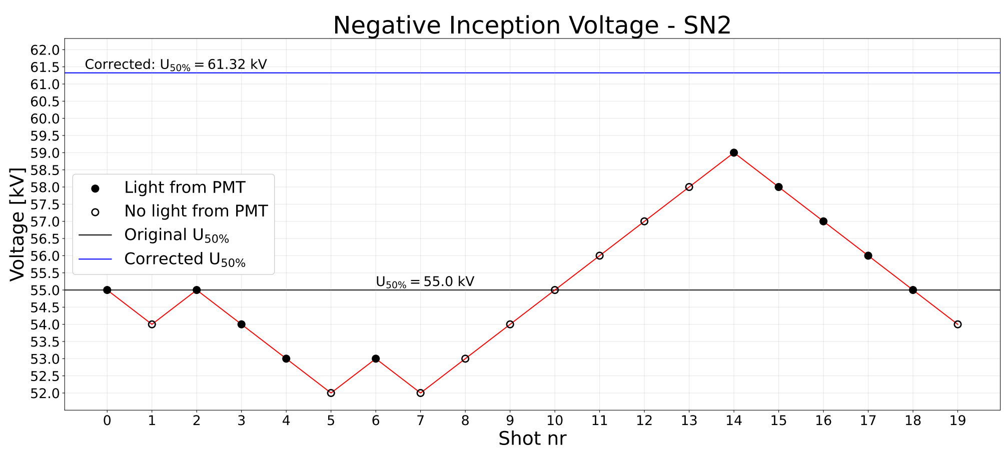


Figure A.7: The up-and-down test for SN2, the negative inception voltage for synthetic air under 1.3 bar pressure. The blue line shows the calculated 50% inception voltage to be 61.32 kV.

SN3 - Synthetic air, negative streamer, 1.5 bar

The SN3 configuration is the test with negative streamers in synthetic air at 1.5 bar pressure.

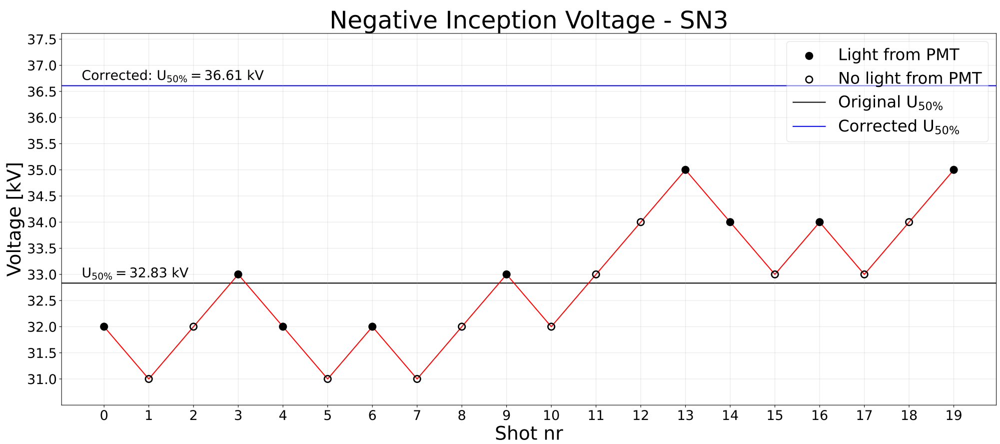


Figure A.8: The up-and-down test for SN3, the negative inception voltage for synthetic air under 1.5 bar pressure. The blue line shows the calculated 50% inception voltage to be 36.61 kV.

AN1 - AirPlus, negative streamer, 1.0 bar

The AN1 configuration is the test with negative streamers in AirPlus at 1.0 bar pressure.

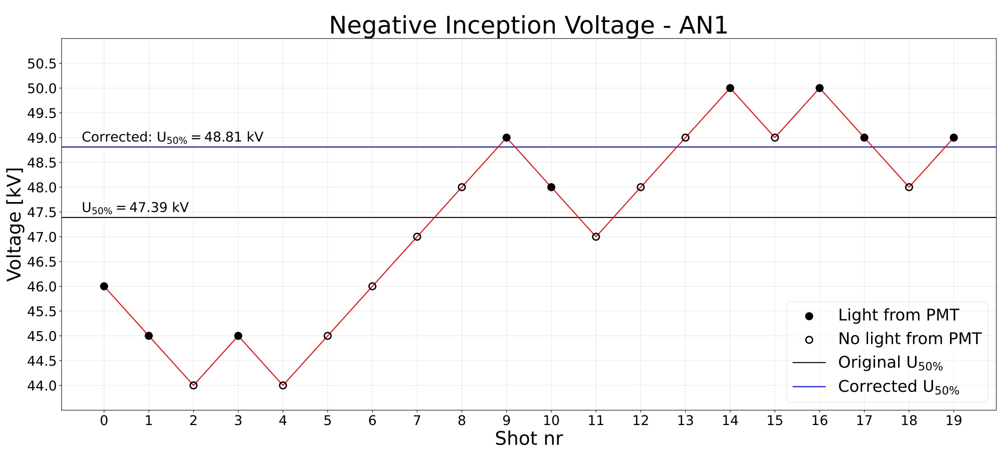


Figure A.9: The up-and-down test for AN1, the negative inception voltage for AirPlus under 1.0 bar pressure. The blue line shows the calculated 50% inception voltage to be 48.81 kV.

AN2 - AirPlus, negative streamer, 1.3 bar

The AN2 configuration is the test with negative streamers in AirPlus at 1.3 bar pressure.

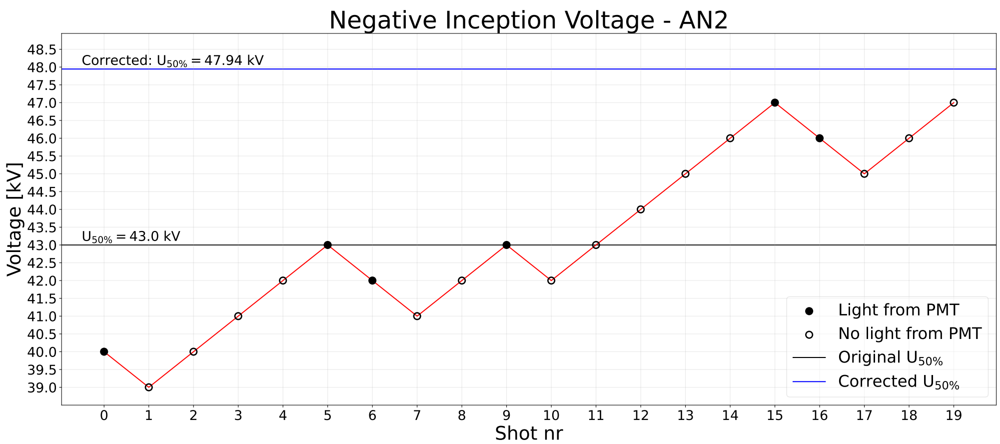


Figure A.10: The up-and-down test for AN2, the negative inception voltage for AirPlus under 1.3 bar pressure. The blue line shows the calculated 50% inception voltage to be 47.94 kV.

AN3 - AirPlus, negative streamer, 1.5 bar

The AN3 configuration is the test with negative streamers in AirPlus at 1.5 bar pressure.

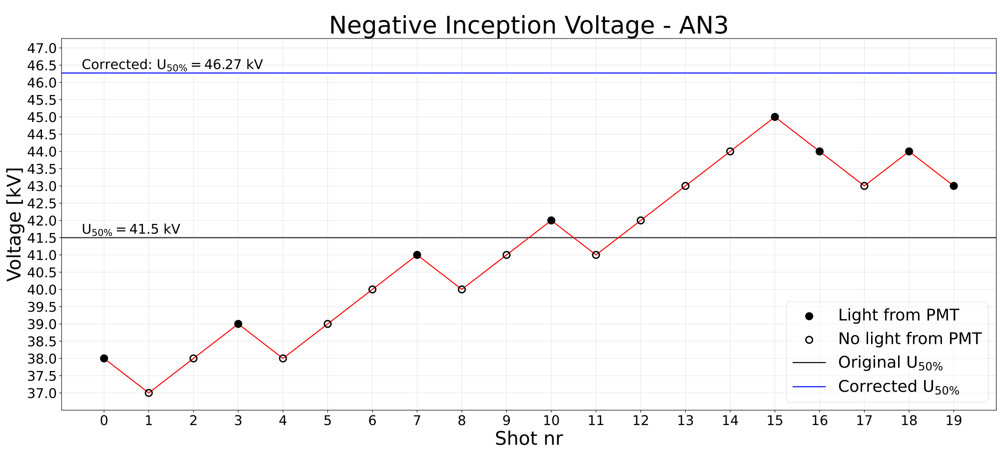


Figure A.11: The up-and-down test for AN3, the negative inception voltage for AirPlus under 1.5 bar pressure. The blue line shows the calculated 50% inception voltage to be 46.27 kV.

Appendix B

Python Code - Inception Voltage

The following is the code developed and provided by Hans Kristian Hygen Meyer. It is a python script that uses the field line calculations from a COMSOL model, as explained in chapter 4.

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-


"""
Created on Fri Jan  5 17:00:44 2018

@author: hans.meyer@sintef.no

Written by Hans Kristian Meyer and Julia Glaus.
This script calculates streamer inception voltages along field lines in air,
air+ or sf6, using fit functions mainly from Petcharaks PhD thesis, 1995.

Field lines are generated from COMSOL simulations.
The input is either a field line with electric field strength in kV/mm and distance
in x and y directions in mm from a 2D or 3D simulation. Also,
the applied voltage and pressure must be given. 10 kV and 1 bar is default.

Place the CSV field lines you want to calculate in the chosen folder and run
python inception.py.

For help run python inception.py --help

The default output file is inception.txt.

Currently only the standard COMSOL export formats is accepted.
```

```
Also, the script estimates breakdown voltage based on propagation distance
U = E_st*d + U_0, where E_st = 0.54 kV / mm, U_0 = 23.7 kV


"""

import pytest  # for testing
import numpy as np
from abc import ABC, abstractmethod
import glob
import os
import pandas as pd
import argparse
parser = argparse.ArgumentParser()
parser.add_argument('-m', '--medium', type=str, default='air',
                    help="air, air+, or sf6. Default air")
parser.add_argument('-p', '--pressure', type=int, default=1,
                    help="in bar. Default 1")
parser.add_argument('-v', '--voltage', type=int, default=10,
                    help="applied voltage in kV. Default 10")
parser.add_argument('-f', '--file', type=str, default='inception.txt',
                    help="filename for outfile. Default inception.txt ")
parser.add_argument('-fo', '--folder', type=str, default='./',
                    help="folder with fieldlines. Default ./ ")
args = parser.parse_args()


class Line(ABC):
    """
    Generic abstract class for electric field lines.
    The output format of the calculated field lines may differ, so this class
    is only meant as a template for a field line.
    """

    @abstractmethod
    def get_values(self, line):
        return

    def __init__(self, file, delim, voltage):
        return

    def get_inception(self, line):
        """
        This function calculates inception voltage.
        Integrates the ionization coefficient for the given gas and pressure.
        If the resulting integration does not exceed the given streamer
        constant, the field is scaled up.
        """
        if self.medium == 'air':
            STREAMER_CONSTANT = 9.15  # for ionization integral (log(N) where
```

```
    # N is the critical number of electrons required to initiate a
    # streamer in air)
elif self.medium == 'air+':
    STREAMER_CONSTANT = 12.9
elif self.medium == 'sf6':
    STREAMER_CONSTANT = 10.15

U = self.voltage  # applied voltage in kV
P = self.pressure  # pressure in bar
k = 0.01  # voltage scaling factor
STEP_SIZE = 0.001  # Increase voltage scaling factor if inception is
# not achieved
C = 0  # counter
u_i = 0  # Inception voltage
iteration_counter = 0
while C < STREAMER_CONSTANT:
    #  Scale field
    field = self.E*k

    # Start at high field end of field line
    if field[-1] > field[0]:
        field = np.flip(field)
    #  FIND ALPHA
    alpha = np.zeros(len(field))
    for i in range(len(field)):
        if self.medium == 'air':
            # (from Julia Glaus?)
            if field[i]/P > 14:
                alpha[i] = (1175*np.exp(-28.38*field[i] / P)) * P
            # From Petcharaks
            if field[i]/P > 7.943 and field[i] / P <= 14:
                alpha[i] = (16.7766*(field[i]/P)-80.006)*P
            if field[i]/P >= 2.588 and field[i]/P <= 7.943:
                alpha[i] = (1.6053*(field[i]/P-2.165)**2-0.2873)*P
            if field[i]/P < 2.588:
                break

        elif self.medium == 'air+':
            # From ABB?
            if field[i] / P > 10 and field[i]:  # Valid to 19.2
                alpha[i] = (19.452 * field[i] / P - 118.48)*P
            if field[i] / P >= 5.53 and field[i] / P <= 10:
                alpha[i] = (17.418 * field[i] / P - 97.46) * P
            if field[i]/P < 5.53:
                break

        elif self.medium == 'sf6':
            # From Petcharaks
            if field[i] / P >= 12.36:  # kV/mm Valid to 21 kV/mm
                alpha[i] = (22.359 * field[i] / P - 180.171) * P
```

```
                if field[i] / P >= 8.9246 and field[i] / P < 12.36:
                    alpha[i] = (27.9 * (field[i] / P - 8.9246)) * P
                if field[i]/P < 8.9246:
                    break

            else:
                print('Please choose a medium. air, air+ or sf6')

        # INTEGRATE ALPHA
        C = np.trapz(alpha, self.dist)

        # SCALE UP VOLTAGE
        u_i = U*k

        # INCREMENT SCALING FACTOR
        k = k+STEP_SIZE
        iteration_counter += 1

    return u_i

def get_propagation(self):
    """
    This function calculates breakdown voltage in air based on the streamer
    propagation (stability) criterion.
    """
    return 0.54*self.length + 23.7


class FieldLine(Line):
    """
    This class takes  field line in the format (x coordinate, y coordinate,
    (optional) z coordinate, field line number, field strength, dimension),
    which is the standard output format of COMSOL Multiphysics.
    This class inherits the Line() class
    """

    def __init__(self, line, applied_voltage, pressure, medium, dim):
        self.dimension = dim  # dimension
        self.voltage = applied_voltage
        self.pressure = pressure
        self.medium = medium
        self.get_values(line)
        self.u_i = self.get_inception(line)
        self.Uprop = self.get_propagation()

        return

    def get_values(self, line):
        # line = np.stack(line)
        self.x = np.asarray(line['x'])
```

```
        self.y = np.asarray(line['y'])
        self.E = np.asarray(line['E'])
        if self.dimension == 3:
            self.z = np.asarray(line['z'])
        self.get_distance()

    def get_distance(self):
        self.dist = np.zeros(len(self.x))
        dl = np.zeros(len(self.x))
        if self.dimension == 2:
            for i in range(0, len(self.x)-1):
                dl[i] = np.sqrt((self.x[i+1] - self.x[i])**2 +
                                (self.y[i+1] - self.y[i])**2)
                self.dist[i+1] = self.dist[i]+dl[i]
            self.length = self.dist[len(self.dist)-1]
        elif self.dimension == 3:
            for i in range(0, len(self.x)-1):
                dl[i] = np.sqrt((self.x[i+1] - self.x[i])**2 +
                                (self.y[i+1] - self.y[i])**2 +
                                (self.z[i+1] - self.z[i])**2)
                self.dist[i+1] = self.dist[i]+dl[i]
            self.length = self.dist[len(self.dist)-1]


class ComsolReader:
    """
    This class reads .csv files from COMSOL. If the file contains several field
    lines, the reader will split them up. Check out template files in this
    repo.
    """

    def __init__(self, file, delim):
        self.f_lines = []
        df_meta = pd.read_csv(file, sep=r',', nrows=7, index_col=0,
                              header=None).T  # metadata
        self.dim = int(df_meta['% Dimension'].values[0])
        print(self.dim)
        self.comsol_model = df_meta['% Model'].values[0]
        print('{2}\n The file {0} comes from COMSOL simulation {1} \n{2}\n\n\n'
              ''.format(file, self.comsol_model, '='*50))
        self.comsol_type = df_meta['% Description'].values[0]
        df = pd.read_csv(file, skiprows=7)  # read data to pandas dataframe
        if self.dim == 2:  # 2D file
            df = df.rename(columns={'% x': 'x', '% r': 'x', 'z': 'y',
                                    'Color': 'E'})
            # name columns according to COMSOL Multiphysics export format
        if self.dim == 3:   # 3D file
            df = df.rename(columns={'% x': 'x', 'Color': 'E'})

        if self.comsol_type == 'Streamline':
```

```
            for j in range(max(df['Streamline']) + 1):
                self.f_lines.append(df[df['Streamline'] == j])  # split the
                # bundle in new dataframe for each fieldline
        if self.comsol_type == 'Line':
            self.f_lines.append(df)


class InceptionCalculation():
    """
    This class performs calculation of inception voltages on a list of field
    lines
    """

    def __init__(self, in_files_list, out_file, applied_voltage, pressure,
                 medium):
        self.in_files_list = in_files_list
        self.df = pd.DataFrame()
        print(in_files_list)
        if os.path.isfile(out_file):
            os.remove(out_file)
        else:
            pass
        self.out_file = out_file
        self.voltage = applied_voltage
        self.pressure = pressure
        self.medium = medium
        self.get_inception()
        self.write_to_file()

    def get_inception(self):
        for file in self.in_files_list:
            self.calculate_file(file)

    def calculate_file(self, file):
        incs = []  # list of inception values for each field line
        bundle = ComsolReader(file, ',')  # Read the bundled file from COMSOL
        [field_lines, dim, comsol_model] = [bundle.f_lines,
                                            bundle.dim,
                                            bundle.comsol_model]
        count = 1
        for line in field_lines:
            if dim == 2:  # 2D file
                inc = FieldLine(line, self.voltage, self.pressure,
                                self.medium, dim).u_i
                print('For {}D field line {} the inception voltage in {:.2f} '
                      'bar {} is: {:.2f} kV'.format(dim, count, self.pressure,
                                                    self.medium, inc),
                      end="\r")
                incs.append(inc)
                count += 1
```

```
            if dim == 3:  # 3D file
                inc = FieldLine(line, self.voltage, self.pressure, self.medium,
                                dim).u_i
                print('For {}D field line {} the inception voltage in {:.2f}'
                      'bar {} is: {:.2f} kV'.format(dim, count, self.pressure,
                                                    self.medium, inc),
                      end="\r")
                incs.append(inc)
                count += 1

        data = {'Filename': file,
                'Origin': comsol_model,
                'Dimension': dim,
                'Pressure [bar]': self.pressure,
                'Applied voltage [kV]': self.voltage,
                'Medium': self.medium,
                'No. of lines': len(field_lines),
                # 'Inc. voltages': incs,
                'Min. inception voltage [kV]': min(incs)}

        self.df = self.df.append(data, ignore_index=True)
        self.df = self.df[data.keys()]
        print(self.df)

    def write_to_file(self):
        self.df.to_csv(self.out_file, mode='a', index=False)


if __name__ == '__main__':
    # Find all files *.csv in folder (except the example files for the testing)
    list_of_files = glob.glob('{}/[!example]*.csv'.format(args.folder))

    out_file = args.file
    #applied_voltage = args.voltage  # kV in COMSOL
    applied_voltage = 10
    #pressure = args.pressure  # bar
    pressure = 1.5 # bar
    #medium = args.medium
    medium = 'air'
    calc = InceptionCalculation(list_of_files, out_file, applied_voltage,
                                pressure, medium)
```

NTNU

Norwegian University of
Science and Technology