Faculty of Natural Science and Technology
Department of Physics

NTNU
Innovation and Creativity

MASTER'S THESIS
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Thesis started:	19.01.2009
Thesis submitted:	22.06.2009

DISCIPLINE: POWER ENGINEERING

Norsk tittel:	*"Aldring av XLPE og PEEK under høytrykk ved påkjenning av gassutladninger"*
English title:	*"Degradation of XLPE and PEEK under high pressure by Partial Discharges"*

This work has been carried out at SINTEF Energiforskning AS, under the supervision of Gunnar Berg

Trondheim, 13.06.2009

Gunnar Berg

Responsible supervisor

Ph.D. Research Scientist at SINTEF Energy Research AS

Abstract

This project aims to investigate the effect of partial discharges on high voltage insulation in a high pressure environment. The tests can help to achieve greater understanding of partial discharges and their degradation effect on high voltage insulating materials. New and more resistant materials and insulating systems are needed in the future to increase the lifetime and safety of high voltage installations, in particular for subsea equipment. Experience is also needed in order to find defects and malfunctions at an early stage before serious errors can occur.

The materials tested are cross-linked Polyethylene(XLPE) and Polyetherehterketone(PEEK), prepared as 2mm thick circular discs.The experimental equipment supports testing in a high pressure environment. Nitrogen gas is used in the high pressure vessel as testing environment. The samples are exposed to partial discharges and allowed to age and deteriorate in a monitored cell where partial discharge levels may be viewed. The first tests were run to puncture the samples and find the time to breakdown, while some tests of the later tests were shut down before breakdown to see if any electric tree structures could be found in the exposed area of the discs.

A series of tests was also conducted to examine how the inception and extinction voltages varies with the spark gap and the pressure.

The results confirms that higher pressure increases the discharge inception voltage of the system, but at the same time, it speeds up the breakdown time of the system. PEEK was found to have a higher withstand strength to partial discharges compared to XLPE.

Sammendrag

Målet for denne oppgaven er å undersøke hvilke effekter delutladninger har på høyspentisolasjon under høytrykk, og forsøkene som er gjort kan gi en bedre forståelse av dette. Det er behov for nye og mer motstandsdyktige materialer og isolasjonssystemer for å øke levetiden og skkerheten til høyspentinstallasjoner i fremtiden, spesielt for utstyr benyttet i kraftforsyning under vann. Det er også bruk for erfaring for å finne defekter og funksjonsfeil tidlig, før alvorlige feil og ulykker kan oppstå.

Materialene som er brukt er krysslenket Polyetylen(XLPE) og Polyetereterketon(PEEK). Prøvene er 2mm tykke, sirkulære skiver, og testes i et høytrykksmiljø. Nitrogengass, N_2, blir brukt som testmiljø for forsøkene. Prøvene blir utsatt for delutladninger, og eldes i en overvåket celle der delutladningene kan måles. De første testene ble utført for å finne ut hvor lang tid det tok før prøvene fikk gjennomslag, mens senere forsøk ble avbrutt før gjennomslag for å undersøke om det hadde oppstått elektrisk trevekts i prøven.

Det ble også utført en serie forsøk for å finne ut hvordan tennspenning og slukkspenning blir påvirket når avstanden mellom elektrodene eller trykket i systemet varierer.

Resultatene viser at høyt trykk øker tennspenningen til systemet, og at tiden til gjennomslag går ned når trykket øker. Forsøken viser også at PEEK tilsynelatende har større motstandsdyktighet mot delutladninger enn det XLPE har.

Preface and Acknowledgments

This master's thesis is written in the spring of year 2009 as a part of my master degree in technical physics at the Norwegian University of Science and Technology. I have studied the effect of partial discharges on high voltage insulation in environments of different pressures, how the time to breakdown is affected by the pressure, and how the breakdown process develops when the material is exposed to partial discharges. The work was done for SINTEF Energy Research AS, and was carried out in the high voltage lab M1 in the electro building at NTNU Gløshaugen. The project was supervised by Gunnar Berg at SINTEF and Erik Wahlstrøm at the Department of Physics.

I would like to thank Gunnar Berg for guidance and help during the project, Oddgeir Kvien at SINTEF for help with equipment setup and experimental assistance, Sverre Hvidsted at SINTEF and Erik Wahlstrøm at the Department of Physics at NTNU.

Aleksander E. Aksnes

Trondheim, June 14. 2009

Contents

List of Figures

List of Tables

1 Introduction

This report presents the results of the work done in cooperation with SINTEF Energy Research AS. The aim for the work was to examine the effects of partial discharges on high voltage insulation materials. Included in the study was the effect of high pressure and how the breakdown process develops through the material. Study of these kinds of processes are important for the development of new and better insulating materials with higher withstand strength against partial discharges. Increased pressure is very important for high voltage subsea power supply, where many components are pressurized to the surrounding hydrostatic pressure. Partial discharges attacks the insulation and causes ageing and reduced lifetime, ultimately puncturing the insulation and shortcircuiting the equipment. It is therefore desirable to prevent or reduce these effects to the minimum in systems where they may cause damage. Subsea equipment at large depths is very difficult to monitor, repair and replace, thus high reliability is important.

The setup used is equipped with a pressure vessel, which enables the test cell to operate while pressurized. Various gases may also be used in this cell. In the tests presented within this report, nitrogen gas is used at pressures ranging from 1-7 bar. The materials used are cross-linked polyethylene(XLPE) and Polyetereterketon(PEEK). XLPE is a well knows standard material for partial discharge testing, and PEEK is a promising new high-performance polymer with good properties for use subsea.

The setup measures partial discharge impulse levels, phase angle plots and time to breakdown. The time to breakdown is an important result of the tests, but it is also interesting to study some of the samples before the breakdown occurs. This is because the breakdown melts the material in the exposed area and erases all traces of the breakdown process itself. The results presented shows that partial discharges in a high pressure environment needs shorter time to cause breakdown, but also that the amplitude of the discharge impulses and the impulse frequency are important parameters.

This report starts by describing the theory and background for partial discharges and their impact on insulation materials. Then a description of the equipment is given, before the experimental results are presented and discussed.

2 Theory

This section will explain some of the most important properties of partial discharges in high voltage systems, and how the system reacts when pressure is applied.

2.1 The Townsend Discharge

The Townsend Effect[9, page 56]is important because it is the initial stage of most breakdowns, and it describes how a current can bridge the air gap between two potentials and create a streamer in a homogeneous field. It also describes how high energetic electrons are created. To start this effect, free electrons are required. These can be created in different ways, e.g. field emission (requires very high field strengths), thermal emission or ionization, electron-ion pair creation by radiation or emission from a cathode, i.e. by UV radiation(photoelectron). The electrons are accelerated by the electric field and starts moving in the opposite direction of the field. When colliding with other particles, if the electron has gathered enough energy, the electron has a chance of ionizing that particle, releasing a new free electron and leaving a positive ion behind. The new electron then goes on colliding with yet another particle, and so the number of electrons starts growing exponentially. This is called an electron avalanche. These avalanches are moving against the direction of the field, until they reach the other potential. In order to sustain the discharge, there must be a constant flow of new free electrons. These can either come from the cathode or from effects in the gas, like meta-stable molecules, positive ions or photons from excited molecules in the avalanche.

2.2 Partial Discharges

Partial discharges(PD) [1, 9, 11] are electric discharges which only partly bridges the distance between two potentials. The PD will first start occurring at the inception voltage, which is when the applied electric field in a small region of the insulating material exceeds the electric strength at that point. Should the voltage be lowered below the extinction voltage, the discharges will stop. Each discharge really is a local breakdown of the insulation. Liquids and gases are often referred to as self healing materials because they regain their insulating ability after being affected by PD, or even after suffering a full breakdown. In the case of solid insulation however, the result is that the insulation is bombarded by the discharges, and they have the effect of ageing and degrading the material. The materials molecular structure in the bombarded area changes and weakens, resulting in a lowering of the breakdown voltage of the material. The breakdown voltage of a system is the voltage level at which a breakdown would occur immediately. If the process is allowed to continue, over time the discharges will eat through the insulation due to high temperature and radiation. Finally they will cause a massive breakdown of the system when the insulation is punctured and the two potentials are bridged completely by the discharges through a conducting channel.

The classical and most common way to describe partial discharges, is to use the magnitude of the discharge current pulse, the external voltage at the time of the discharge, and the phase angle of the external voltage at the time of the discharge[7, 12, 14]. Phase angle plots are a popular way to present the results, showing the frequency of occurence of each discharge magnitude across the phase angles of the applied external voltage. For an example, see figure 2.3. The points in the phase plot may look scattered and random, both in phase angle and pulse magnitude. If the discharges could be viewed in sequence[7], i.e. when they were measured compared to each other, then the measurements would seem much less random. This has to do with the generation of space charges[3, 17] related to the discharges in the system. These space charges reduces the electric field which triggered the discharge, making it harder to maintain the continuing partial discharges and therefore demanding an even stronger electric field to trigger the next discharge. For DC voltage, this often means that the discharges stop until the space charges has been transported away. For a varying AC field, the space charge which weakened the field one moment, will strengthen it when the field changes polarity, causing discharges at lower applied voltage than would be necessary without the space charge. In short, the discharges occur when the superposition of the local space charges and the applied electric field exceeds the local strength of the material.

There are several ways in which PD may arise, and the next sections will cover some of the most important ones:

2.2.1 Partial discharges in cavities and voids

This PD phenomenon takes place in voids and cavities in solid materials or liquids, and involve free electrons in an electric field. Due to this, the Townsend mechanism is the most important theory for describing this PD. The insulation material will start ageing and deteriorating from the high energetic electrons bombarding it, until the insulation is punctured and the gap is bridged by the current.

2.2.2 Surface discharges

Surface discharges occur on the interfaces of different insulating materials, e.g. gas/solid interface. This is the main type of PD which is studied in this project. The discharges erupts from the high voltage electrode, down to the surface of the insulation. It may move a distance along the surface while trying to reach ground. The area where the discharge hits will change on a molecular level and weaken over time. The deterioration is mainly due to heat, causing the material to melt and creates channels, holes and craters in the material surface, as can be seen in figure 2.1. This process continues until the breakdown voltage is lowered to the discharge levels and a breakdown occurs. The spark gap is also an important parameter here, because it greatly impacts the shape of the electric field between the electrodes. A very small spark gap will cause a "'squeeze"' effect of the field lines, and making the field very sensitive to changes in gap distance.

Small changes made to a bigger gap distance would not have the same effect. From this, it is expected a bigger change in inception voltage if we increase the gap distance from 0.5mm to 1.0mm than if it was changed from 4.5mm to 5mm. Figure 2.2 shows discharges from a Ø10mm hemisphere electrode with 1 mm air gap above the polymer disc. The discharge is most concentrated below the electrode, but surface discharges are spreading on the sample as well. The image is borrowed from the SINTEF KMB Subsea Materials project.

A simple estimate of the energy involved in the discharges can be made. Assuming an average discharge pulse of 20 nC and an applied voltage of 20 kV. The formula for electric energy gives $E = UQ$, where E is the energy, U the applied voltage and Q is the charge measured in Coulomb. This gives $E = 0.0004$J/pulse. Again, assuming 240 000 counts during a 600 second plot, gives 400 pulses/second. Multiplying the frequency by E gives a power of 0.16J/s. This energy will be spread out over an area of the sample, but with a certain focus at one point, see figure 2.2. This estimate is just to get an impression of how much energy goes into the samples, using reasonable average values for each parameter.

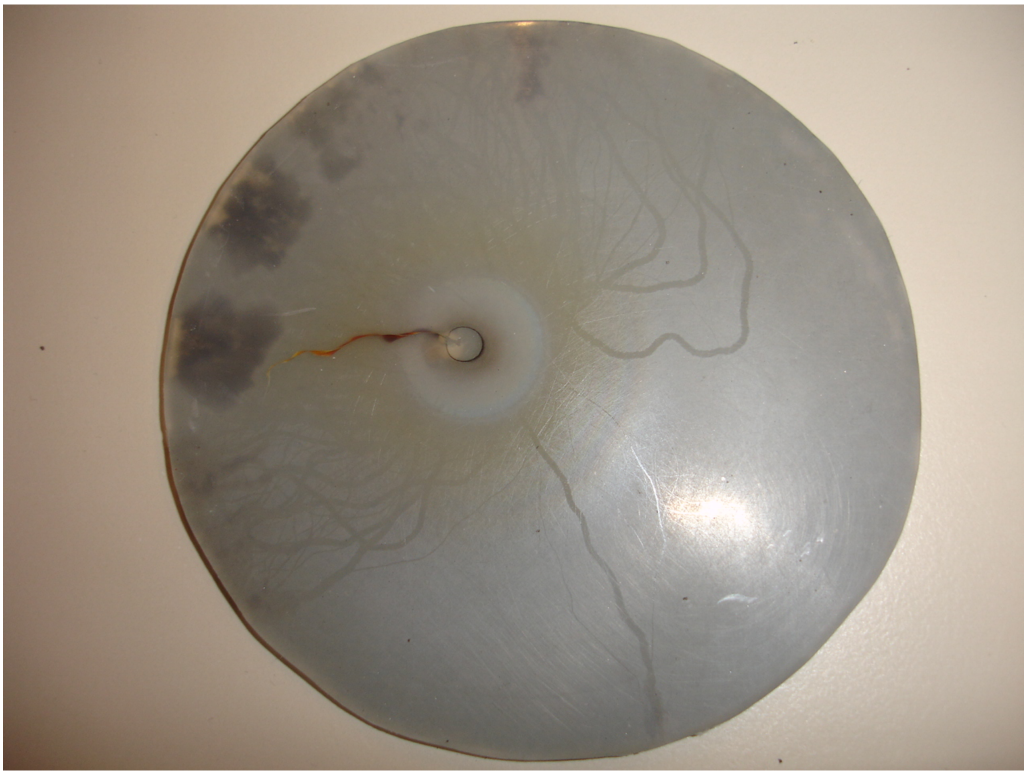


Figure 2.1: Traces of partial discharges on the surface of the second XLPE sample disc after breakthrough. These currents travels the surface to get around the edge of the sample to the ground electrode. Sample radius is 36.5mm

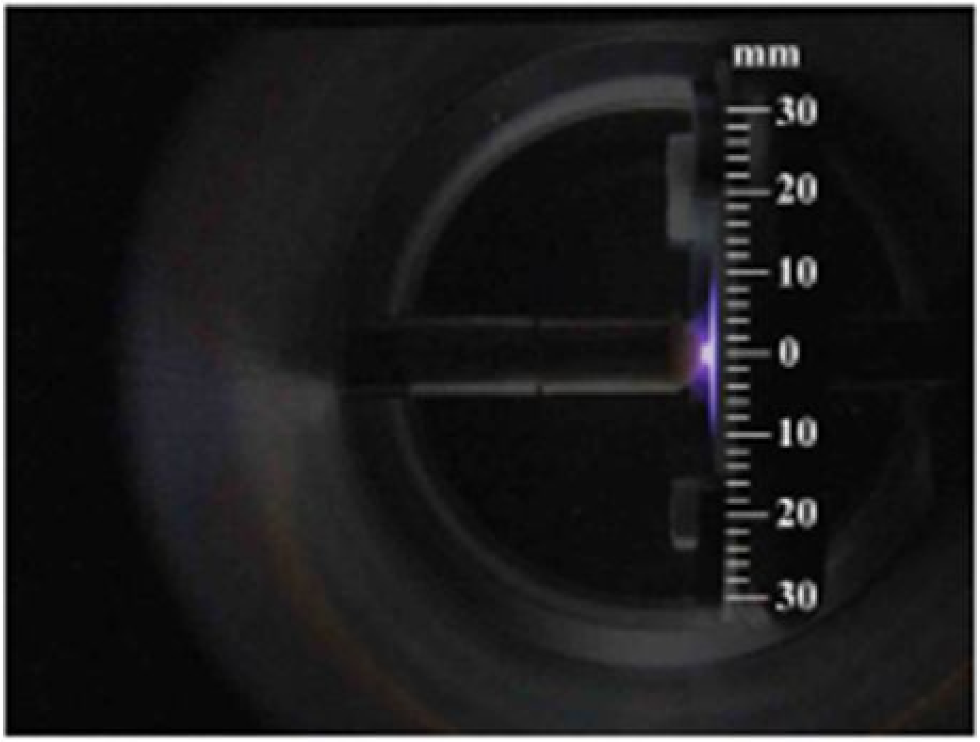


Figure 2.2: Visual appearance of discharges from a Ø10mm hemisphere electrode with 1 mm air gap above the polymer disc. Image borrowed from the SINTEF KMB Subsea Materials project.

2.2.3 Corona discharges

The last PD phenomenon which will be covered here is corona, or gas discharges. They occur at sharp edges or thin conductors where the electric field stress is particularly high. These are self-sustaining discharges extending only over that part of the gap where the stress is highest. If present in high voltage measuring systems such as is used in this project, corona may be the source of much noise and disturbance. It is therefore advisable to ensure a corona free setup by smoothing out any sharp edges which may otherwise cause discharges. Corona may be identified in the measuring data if there are a lot more readings on one half cycle of the phase than the other. Corona usually appear on the negative half cycle[9, page 72] because the inception voltage for the negative corona is lower than for positive corona. Figure 2.3 shows a plot measured on the ICM, which is the measuring system used in these tests. The plot is taken from an earlier test during a student project, on a XLPE sample which did not show any signs of ageing. Almost all of the discharges is located in the negative phase half, and the discharge count is quite high. These observations all indicate that the discharges in the plot has a high probability of being corona discharges, since the measurements then could originate from corona somewhere else in the setup. After that particular test, it was discovered that a part, used to smoothen the electric field above the high voltage electrode in the cell, was missing. When replaced, the experimental results returned to normal.

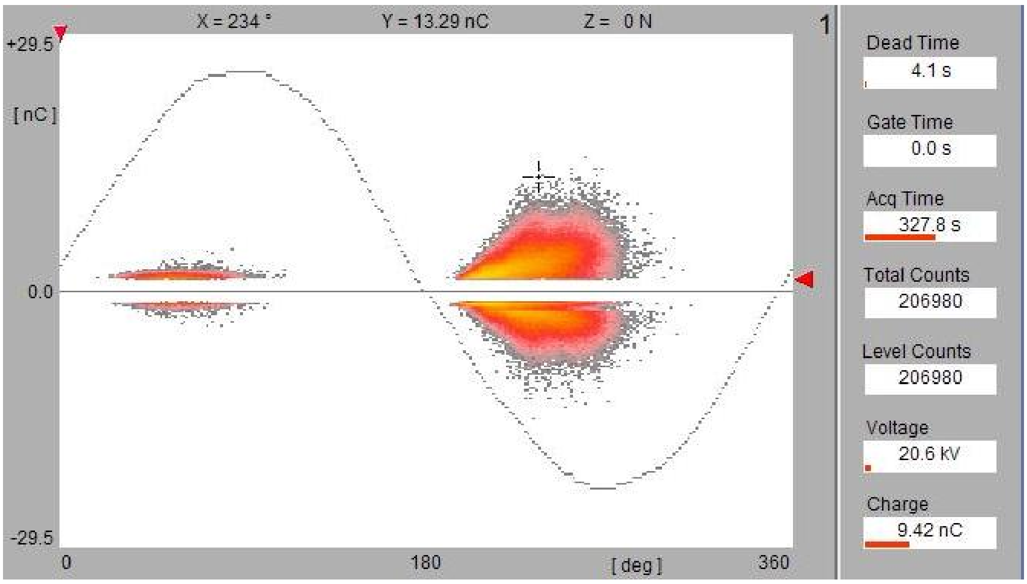


Figure 2.3: ICM phase plot of corona discharges. The plot is taken from an experiment on a XLPE disc during a student project prior to this master thesis.

2.3 Partial discharges and pressure

If the system is being kept under high or low pressure[6, 15], certain effects will start to affect the inception voltage. The equation 1 below is called the Pachen Law[9, page 62-63].

$$U = \Theta(pd) \tag{1}$$

Where U is the sparkover voltage, p is the pressure, and d is the distance between the electrodes. The law states that the sparkover voltage in a homogeneous field at a given temperature is a function, Θ, of the product $p \cdot d$ only. The Pachen curve is showed in figure 2.4. The sparkover voltage is the voltage needed to produce electrons with enough energy to start electron avalanches and produce a breakdown in an air gap.

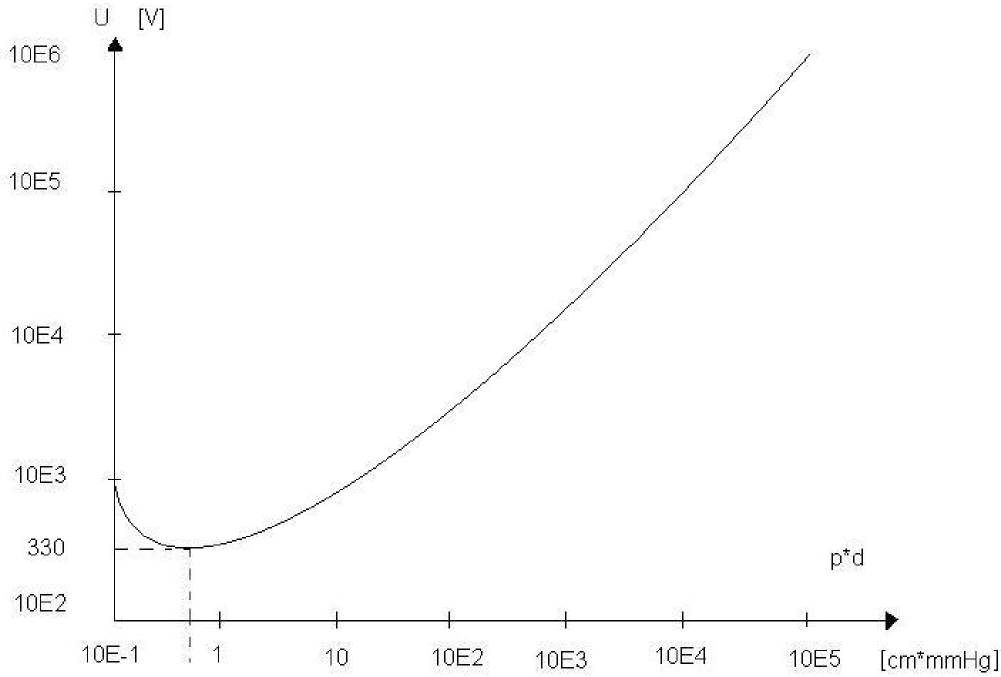


Figure 2.4: The Pachen Curve for air[9, page 62-63]

The physics causing the shape of the curve is easy enough to explain. When the pressure is increasing on the right hand side of the minimum, the density of the air also increases. This means that the free path for the electrons is decreasing, causing the energy which the electrons manages to build up between each collision to decrease. As a result, the voltage needed to get enough energy must increase. Time to breakthrough will often be shorter at high pressures because the energy levels of the discharges tends to be higher. On the left hand side the rise in voltage is explained by the lack of gas molecules for the electrons to collide with. PD is a stochastic process, and the chance of hitting molecules with ionizing effect decreases with the number of gas molecules. Therefore the voltage must increase to make sure that the few collisions actually taking place has a higher chance of having an ionizing effect. To change the gas in the test environment is also interesting because different gases has different electronegativity, and therefore different ability to intercept free electrons. Fewer free electrons increases the inception voltage in the air gap between the electrodes.

2.4 Electrical Treeing

When insulation is exposed to partial discharges, the material starts deteriorate and age. The discharges will often start working its way through the material in a certain way, called electrical treeing[4, 13, 16]. These tree-like structures most often originates from weak points or impurities on the surface, and extends into the material while branching off in different directions. After a while, the structure will come close to reaching the other side of the material, and this is when the system suffers a breakdown. Figure 2.5 shows an electrical tree growing from a 3 μm needle tip in a XLPE sample, both before and after the sample breaks down. The after picture shows a large carbonized breakdown channel. The picture is borrowed from a SINTEF research project. The study of such tree structures is well known[4, 13, 16], where a needle is molded into the material and the tree starts growing from the tip. One thing SINTEF would like to look into however, is whether trees will start growing during surface discharges, where the electrode is placed above the sample, or if the breakdown process instead is mainly due to heat and radiation degradation in such a case.

There are several effects taking place during tree growth. The lengthening of the tree channels is mainly a solid state phenomenon[16], while the widening of the channel diameter is caused by the partial discharges taking place in the structure. The tree growth involves a chemical change to the material, and some of the polymers are transformed to smaller byproducts and fragments. When these byproducts is located in the channels, they may shorten the free electron path. As a result the partial discharges may decrease in number or vanish completely. Figure 2.6 shows a series of plots from the XLPE1 experiment where this may have happened. The pressure in the tree channels is the commanding parameter in this situation. If the pressure is above a critical value, decided by the physical attributes of the channels, the discharges will stop until the byproducts has diffused into the surroundings. The diffusion of byproducts goes at a higher rate for higher temperatures[13], which is one of the reasons why tree growth progresses faster at higher temperatures.

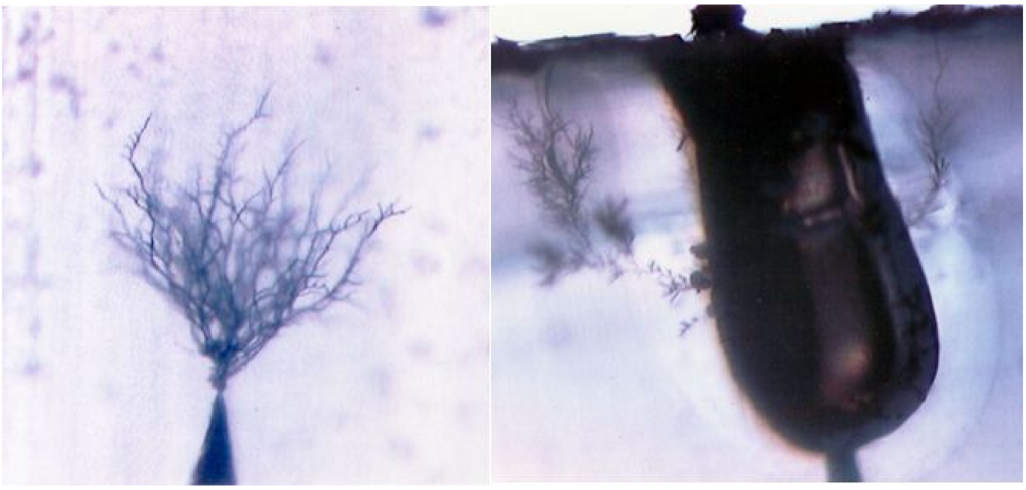


Figure 2.5: Left: Electrical tree growing from a 3 μm needle tip in a XLPE sample. Applied voltage = 5 kVrms AC. Right: Same sample after breakdown, showing large carbonized breakdown channel.

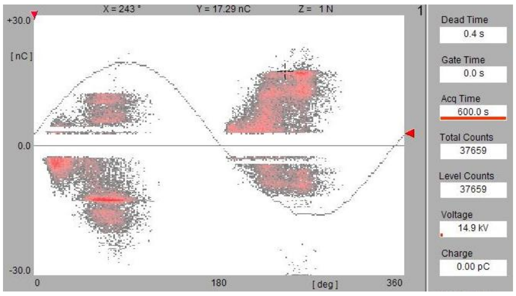
2.5 The test objects

2.5.1 Preparation of the test objects

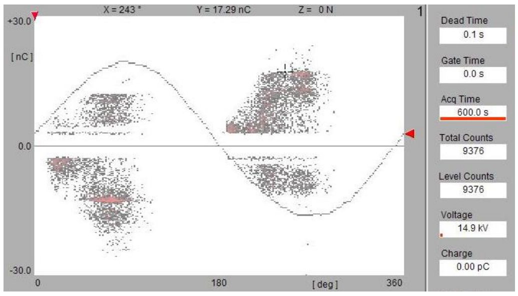
The test objects, examples of which can be seen in figure 2.7 and 2.8, is approximately 2mm thick discs with radius of approximately 36.5mm. Two different materials are used, XLPE and PEEK. All samples are washed in isopropanol and dried before testing. A field guiding varnish is applied to one side of the samples to better prevent local spots on the object surface suffering from significantly larger amounts of electrical field stress. The side with the varnish is faced away from the high voltage electrode, down onto the plane electrode.

2.5.2 Cross-linked Polyethylene

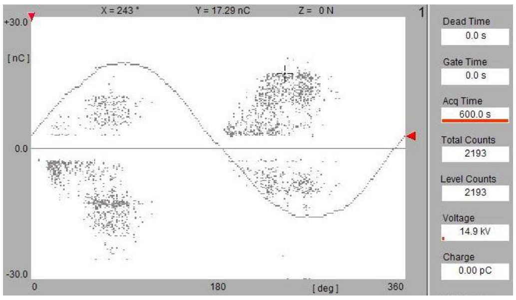
Cross-linked Polyethylene (XLPE)[9, page 169] is produced by processing polyethylene(PE) in such a way that the molecules gets linked together into a large interconnected grid with chemical bonds between the molecules. Such materials is called thermosetting polymers. It can operate in temperatures up to 125 $^\circ$ C, and manage fault temperatures of 250 $^\circ$ C for short periods of time. Its resistance to cold flow and abrasion is superior to that of regular PE, and its dielectric properties is comparable. Today, XLPE is the most commonly used material for high voltage cables. The great weakness of XLPE is partial discharges and the reduced life time because of them. This is why XLPE has become a reference material for PD measurements[3, 5].



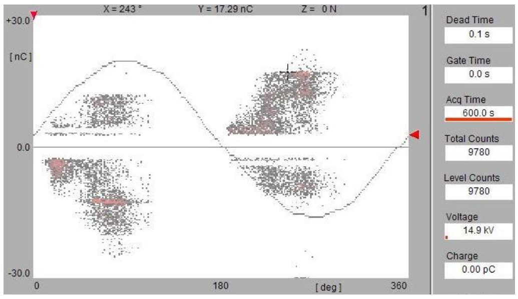
(a) Plot after 55 hours and 30 minutes.



(b) Plot after 55 hours and 40 minutes.

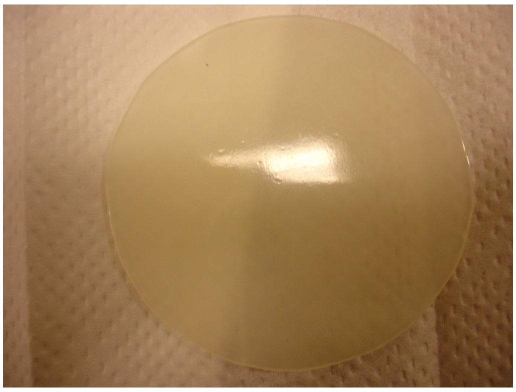


(c) Plot after 55 hours and 50 minutes.

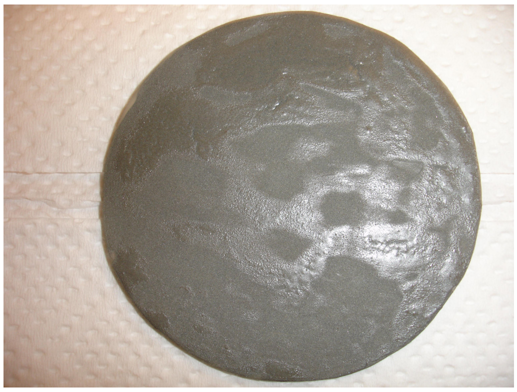


(d) Plot after 56 hours.

Figure 2.6: Series of plots where the discharges almost vanishes a little while, then comes back. The plots are 10 minutes apart. This is the effect byproducts from discharges in the tree channels might have on the discharge activity.

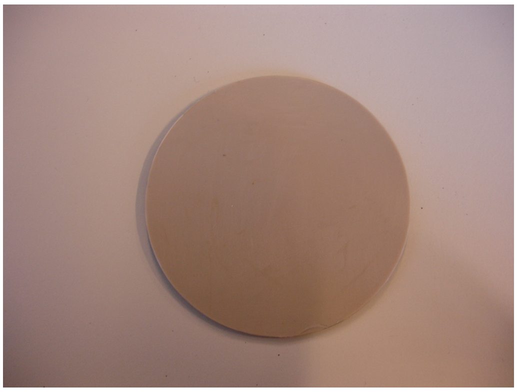


(a) XLPE sample.

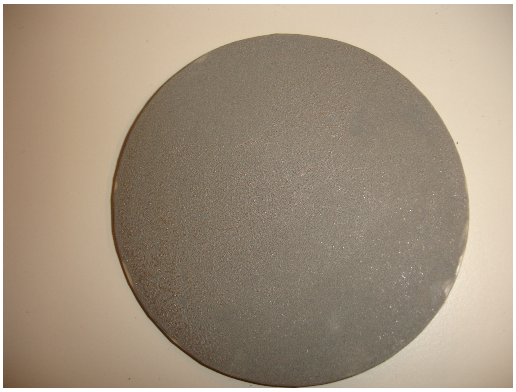


(b) XLPE sample with varnish.

Figure 2.7: XLPE sample before and after applied varnish. Radius of the sample is 36.5mm



(a) PEEK sample.



(b) PEEK sample with varnish.

Figure 2.8: PEEK sample before and after applied varnish. Radius is 36.5mm

2.5.3 Polyetherehterketone - PEEK

Polyetherehterketone [8, 10], or PEEK, is an organic polymer used in many demanding applications in recent years, like bearings, piston parts, pumps, compressor plate valves, and cable insulation. The use ranges from the aerospace, automotive, teletronic, and chemical process industries, to the medical implant industry. It is also used for electronic components like mobile phone secondary battery gaskets, speaker diaphragms, connectors and signal relays[10]. It is a thermoplastic, meaning it does melt when heated, and unlike thermosetting polymers it can be remelted and remoulded. Even so, it has a high temperature resistance compared to many other high-performance polymer materials. In addition it has a high tensile strength performance, low outgassing levels and good radiation resistance. Many see this material as promising for use in high voltage applications and lead-free soldering equipment components, and much research goes into how to make the best compound. Glass filled PEEK is one of the most commonly seen composites. Compared to XLPE, PEEK is a much harder and more rigid material. See table 1 for some detailed properties of PEEK.

Table 1: Properties of PEEK polymer material

Density	1320 kg/m^3
Tensile strength	92MPa
Glass temperature	143°C
Melting point	343°C
Thermal Conductivity	0.25W/(m·K)

3 Equipment and Setup

This section will cover all hardware and software used to perform the measurements in the setup, and explain how the circuit works.

3.1 Circuit for measurements

The circuit[9, page 204-215] used for the tests is a standard setup for measuring partial discharges. It consists of a measuring capasitance, a high voltage transformer, the test cell with the test sample placed in the spark gap between the two electrodes, and the ICM measuring system connected to a pc. The high voltage transformer has a ratio 45 kV/220 V between the low-voltage/high-voltage parts of the circuit. The schematics of the circuit can be seen in figure 3.1 and the components in figure 3.2. The gas cylinder in the background contains pressurized N_2 gas which keeps the pressure constant. In addition, toroids are used on joints between the units to suppress corona discharges.

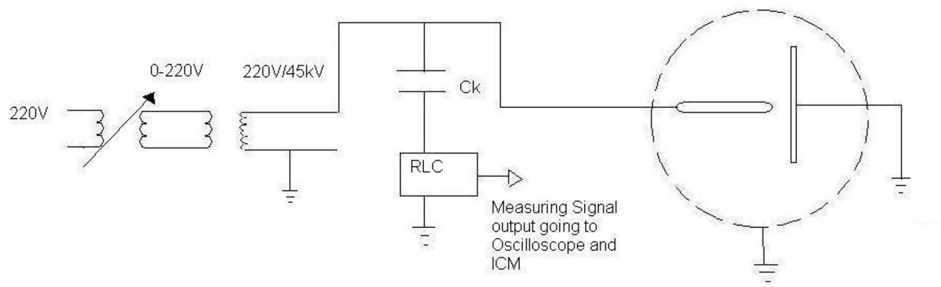


Figure 3.1: Diagram for the high pressure measuring system. The dotted circle is the test vessel. The capacitor C_K, connected to the measuring RLC unit, sends out a charge whenever a discharge causes the voltage over the test vessel to drops. The signal then proceeds to the ICM measuring system.

The working principle behind the circuit is as follows. The applied voltage creates an electric field from the high voltage electrode, down onto the plane electrode and the test sample. When the applied field exceeds the electric strength of its surroundings, a discharge will occur, and the discharge current is drawn from the measuring capacitance. The RLC unit is a passive wide band PD measuring shunt, transferring the PD current pulses to the ICM unit with a center frequency of 300 kHz and bandwidth 200 kHz. The ICM system measures the external current needed to restore the voltage across the test sample to the level it was prior to the partial discharge. From this the ICM can give plots showing the discharge pulse amplitude, the frequency distributions of the pulse heights of the discharges, and the phase angles of the external field when the discharges occurred. For reference, see the section on ICM and figure 6(b).

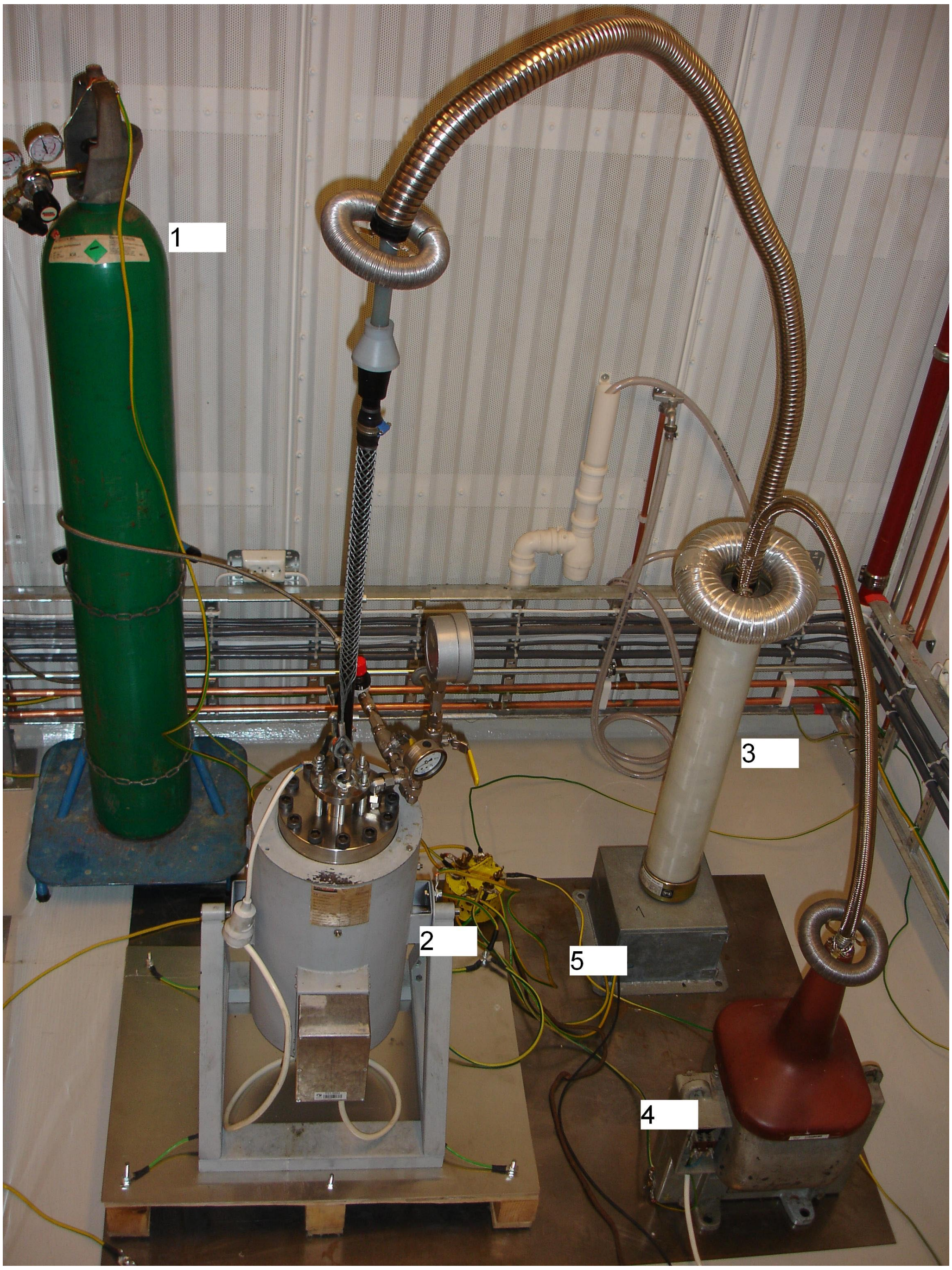


Figure 3.2: The equipment used in the high voltage setup: 1) Gas cylinder supplying nitrogen gas. 2) Pressure vessel containing the test chamber. 3) 800pF Measuring capacitance. 4) High voltage transformer. 5) RLC unit hidden under the measuring capacitance.

3.2 The test chamber

The test chamber in use, see figure 3.2 and 3.3, is equipped with a high voltage electrode and a ground electrode. There is also a test object holding device attached to the ground electrode. The high voltage electrode is fixed at 1mm distance from the test objects.

The test cell itself is contained in a pressure vessel to allow increased gas pressures, and it is possible to use different gases in the test environment. The chamber is built to withstand pressures up to 100 bar, and is also equipped with a heating element so that testing at different temperatures is possible. Preliminary testing uncovered a leak in the chamber, but even after all O-rings were replaced, the chamber was still leaking gas. This is why the gas cylinder must continuously replenish gas to the chamber, and the use is for the moment restricted to non hazardous gases such as nitrogen gas, N_2, which was used in this work. Another candidate gas might be methane, CH_4, which is relevant for subsea gas processing.

The high voltage cable goes down vertically on top of the lid, and is secured by a netting device, which works along the same lines as a Chinese finger trap, bolted down on the lid. This is necessary because the cable would otherwise get launched out of the chamber if the gas pressure by accident exceeds the maximum limit. The lid itself is secured by 12 large bolts on the top of the chamber. The high voltage electrode is located at the end of the cable going through the lid, and the ground electrode is supported under the lid by three nylon bars with threads. This makes it possible to adjust the gap between the electrodes. Under the ground electrode hangs seven lengths of copper wires which are in contact with the the cell to ensure grounding during testing. It is not possible to visually monitor the experiments during testing.

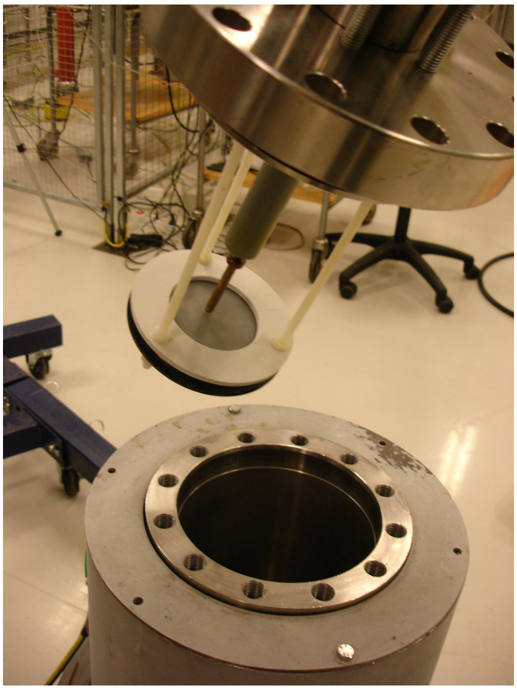
3.2.1 The electrodes

The electrode for the measuring systems can be seen in figure 4(a). It is made of brass and has a radius of 3mm. The radius refers to the curvature of the tip of the electrodes. The electrode is fitted in the chamber with 1 mm gap between the electrode and the test object surface, and the test object itself is placed directly on the ground plane electrode and secured by the holding device.

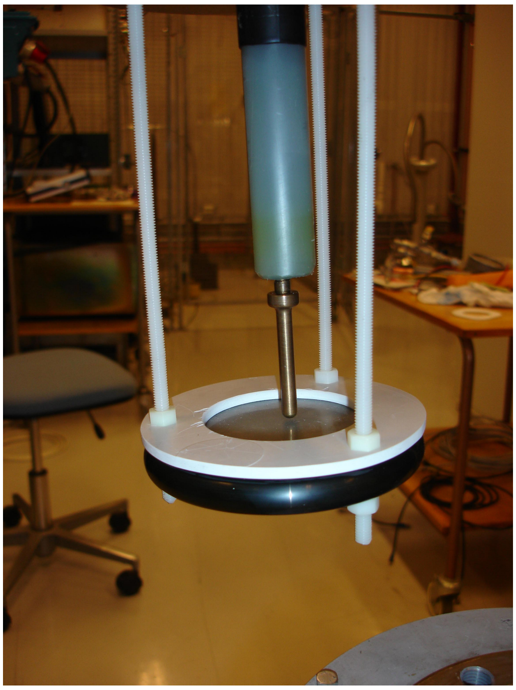
The ground electrode can be seen in figure 4(b). This plane electrode has a brass core with 25 mm radius, and insulating material in the outer area with a total diameter of 110 mm. This is done to make the creeping path of the discharges to ground longer to prevent discharges from creeping along the surface of the test object and reach ground potential at the edge. However, given enough voltage, this still happens

3.3 Instruments used in the setups

A variable transformer(variac), see figure 3.5, is used in the setup to provide the high voltage transformer with power to the low voltage input.



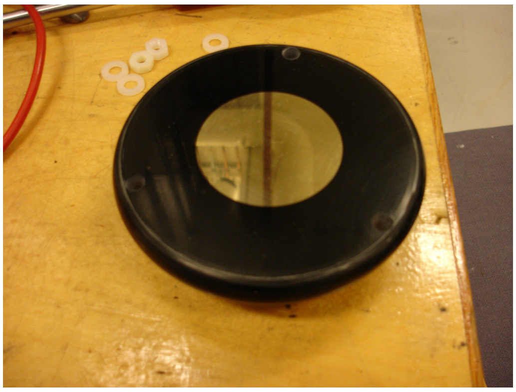
(a) Lid off



(b) Test object placement

Figure 3.3: The high voltage test chamber

(a) High voltage electrode, 3 mm radius



(b) Plane electrode

Figure 3.4: The high voltage electrodes.

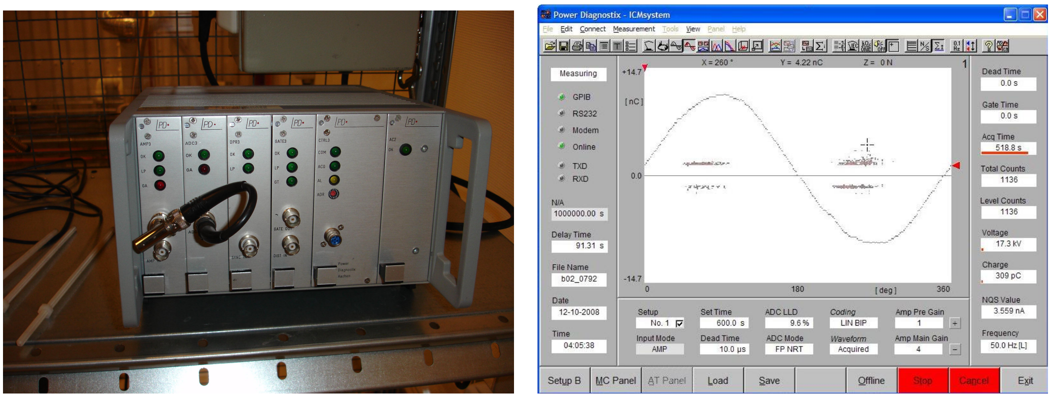
Figure 3.5: The variac used in the setup, supplying the low voltage input to the high voltage transformers.

The variac has two switches. Closing the first will supply the variac with power from the grid, but no output will be delivered to the circuit. The second switch will supply the high voltage transformer with power and the circuit will be active. The red light on top will shine continuously when the circuit is active. When the test objects suffers a breakdown, the variac will cut the output to the circuit and stop the testing. The red light will start to flash, indicating that switch 2 is open. The switch 1 is also used to shut down the system in case of emergency. The variac is connected to the main grid, so it supplies an AC signal with a frequency of 50Hz.

3.3.1 ICM

The ICM[2], see figure 6(a), is a fully computer controlled unit for measuring PD activity. The acquisition of partial discharge pulses is sorted with respect to the magnitude of the pulse and the phase angle of the externally applied voltage at the time. All this is done automatically, and is then presented in a three dimensional phase angle/ charge pulse amplitude plot. The color of the plot is the third dimension, where brighter color means higher frequency of occurrence. The plot also shows the sinusoidal of the signal, which gives a better phase reference. Example of such a plot is shown in figure 6(b).

The computer program is called ICM system, and is manufactured by Power Diagnostix. This program controls all displays and functions of the ICM unit through a graphical interface. The ICM used in this project is a single channel unit. It has 12 bit AD, which is compressed to either 8 bit unipolar or 7 bit bipolar.



(a) ICM unit.

(b) Phase/amplitude plot.

Figure 3.6: The ICM, an automated PD measuring system, and a typical ICM plot.

The system is simple to use because of all the automatic functions, but it also holds limited options for for tracking the signal between the circuit and the final output on the screen.

3.4 Microtome

A microtome is a mechanical instrument designed to slice samples for microscopic examination. The samples made are thin and transparent, making them easy to study. Microtomes come with different blades, steel, glass and diamond. In this work, a steel blade was used to slice thin samples from XLPE6 and XLPE7 to check if there were any tree structures present in them after being exposed to partial discharges. The samples shows the inside of the disc, and are 250μm thick. Figure 3.7 shows a sample from XLPE6 made with the microtome.

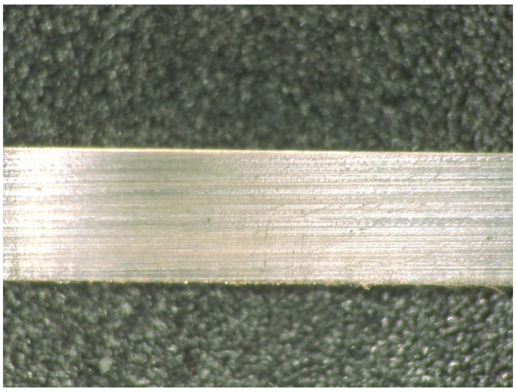


Figure 3.7: A 250μm thick XLPE sample made with a microtome from the XLPE6 disc. The picture is taken with a light microscope with x40 enlargement. The sample width is the same as the disc thickness, which is 2 mm.

4 Results and discussion

This section will present the results obtained during testing, and how they are interpreted. The results will mainly be presented in the form of pictures of the samples and some plots from the measurements, though most of the plots are presented in the appendix A in numerical order. The plots each covers 600 seconds of measurements, and there is a 10 second delay after one file is completed, giving time to saving the file before the next one is started. Each plot has values to the right showing the total number of discharges measured in that time period. During all the tests, the equipment measured discharges around 60-100 pC which were regarded as background noise. These were present even when there was no applied voltage to the system, and were filtered away by the ICM system so they do not appear in the presented plots. Also, even though discharges at 35nC were confirmed by the sensors, no measurements above 25nC appears in the plots due to saturation. The sensors may further have been saturated at 35nC, so higher discharge levels may have occurred during testing and never been registered. An important thing to notice in these plots are how the discharge levels often goes up right before breakthrough. This is the case both in figure A.1 and A.2.

Eleven sample discs were used in the partial discharge breakdown tests. Eight XLPE samples, referred to as XLPE1-8, and three PEEK samples, known as PEEK1-3. In addition, a series of tests were performed to gain a certain knowledge of the inception and extinction voltage levels at different electrode gaps and gas pressures. The result of these voltage level tests will be presented below, followed by the results and discussion of the individual sample tests in numerical order.

4.1 Inception and extinction voltage levels

These tests were all performed on test sample XLPE3. As the tests were brief at each parameter setting, and the pulse amplitude at relatively low levels, it was assumed that they would not greatly affect the later breakdown testing of the sample. The goal was to obtain graphical plots of inception voltage as a function of the electrode gap,$V(d)$, for each pressure level. The pressures used were 1, 2, 3 and 5 bar, and the gaps were fixed at $d=$0, 0.5, 1, 2, 3, 4 and 5mm.

The procedure was to set a certain spark gap between the high voltage electrode and the sample, and find the inception voltage at current pressure by slowly increasing the applied voltage until partial discharges well above the constant noise starts occurring. When the discharges had been allowed to continue for a few minutes, the voltage would be lowered until the extinction voltage, upon which the discharges would stop. Then the material was given about 15 minutes resting time before the pressure would be increased and a new test initiated, until all pressures had been applied to all spark gaps.

The results are presented in figure 4.1 and 4.2. The first plot shows the inception voltage as a function of spark gap for different pressures, and the second is a similar plot for the extinction voltage.

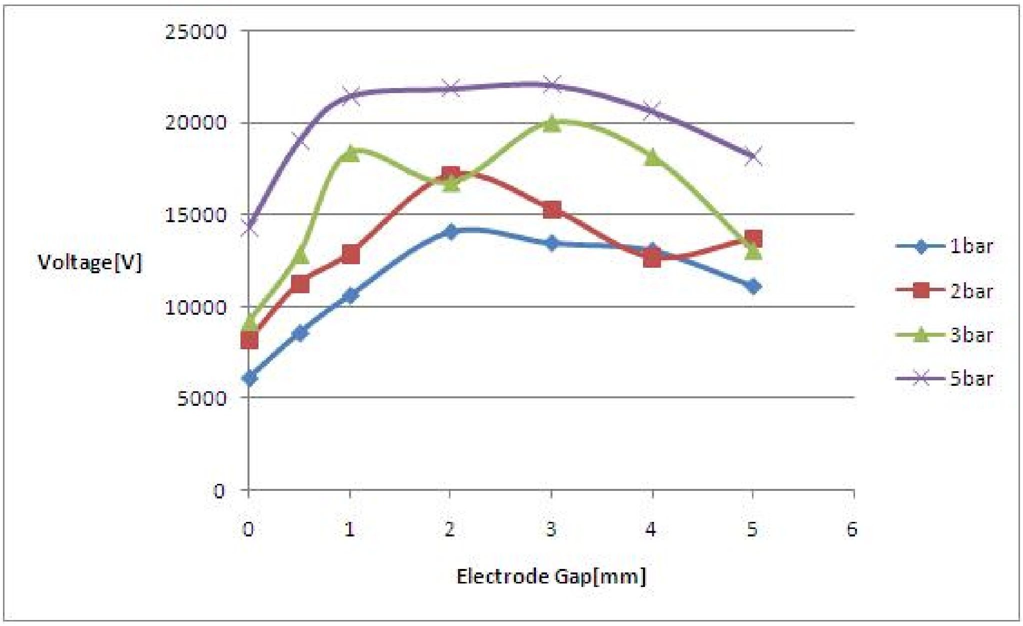


Figure 4.1: Plot showing the inception voltages with the spark gap as variable for pressures 1, 2, 3 and 5 bar.

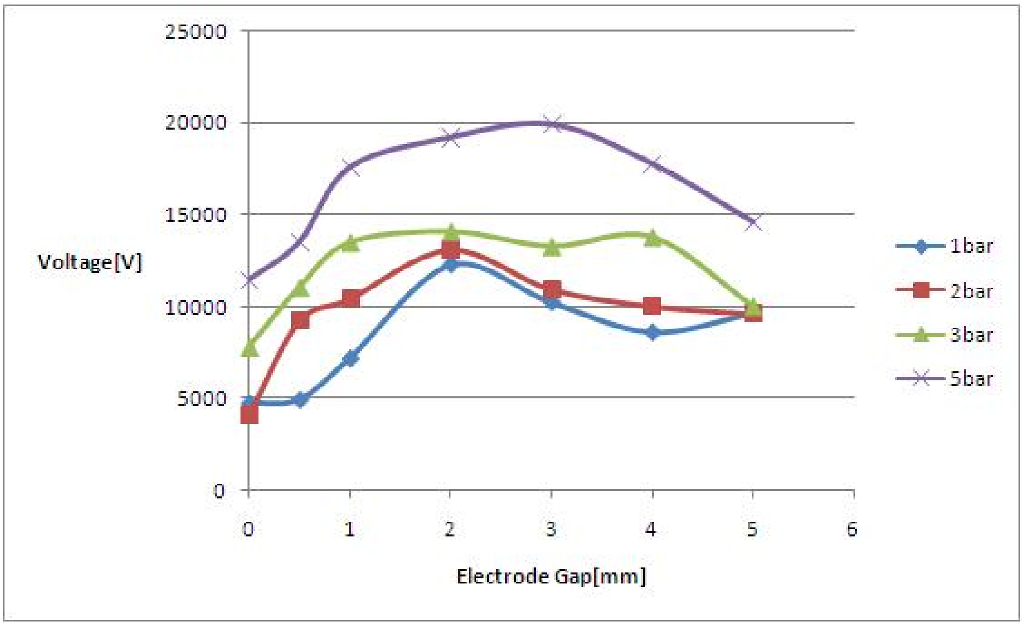
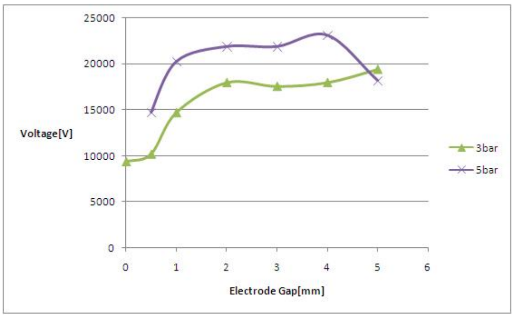


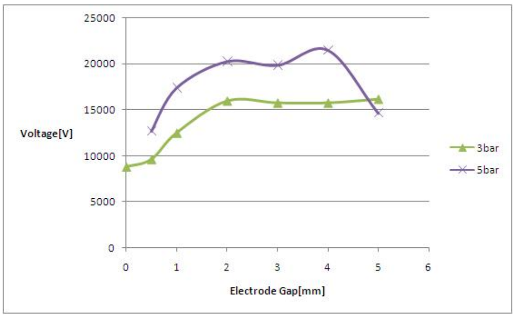
Figure 4.2: Plot showing the extinction voltages with the spark gap as variable for pressures 1, 2, 3 and 5 bar.

These plots did not turn out entirely as expected. The theory section 2.1.2. about surface discharges, explains that the changes in the electric field as the spark gap changes is greater for small spark gap values. This is also confirmed in the plots, as all pressures shows a steep climb from 0mm to 1mm. The 1 bar and 2 bar even continues climbing steadily to 2mm spark gap. As the spark gap increases, the changes made to the electric field are smaller, so the climbing of the graphs should diminish. What is observed however, is that the inception voltage reaches a maximum around 2-3mm gap, and starts decreasing towards 5mm gap.

As this result was somewhat surprising, a second set of tests was done for 3 and 5 bar only, to confirm the first results. These confirmation tests is shown in figure 4.3. This time the 3 bar graph shows a shape more in agreement of the anticipated results. The 5 bar is still reduced from 4mm to 5mm. It is possible that parameters like too little resting time in between tests or local conditions in the test setup causes the inception voltage to drop for the larger gaps.



(a) Inception voltages.



(b) Extinction voltages.

Figure 4.3: Plots showing the inception and extinction voltages with the spark gap as variable for pressures 3 and 5 bar. These tests were made as confirmation of the first set of tests.

4.2 Partial discharge tests on sample disks

These tests were about exposing material samples of either XLPE or PEEK, to partial discharges. The goal was to find how resistant the materials were to partial discharges under high pressure, and what effect the discharges would have on them. The first tests aimed to find out approximately how long it would take for a breakdown to occur. Later on it was attempted to shut down the test preliminary to the breakdown, to try and see how the tree structures, described in section 2.3, progresses through the material. Table 2 shows the most important parameters for the tests performed on each sample. All samples has a spark gap of 1mm and uses N_2 as gas environment.

Table 2: The parameters of each partial discharge test

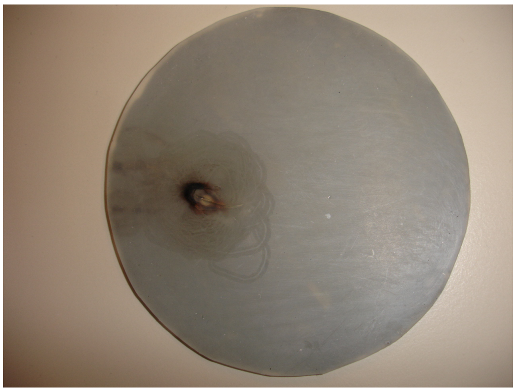
Sample	Material	Voltage	Pressure	gas	gap	time	breakdown
XLPE1	XLPE	15.5 kV	5 bar	N_2	1mm	83 h 55 min	yes
XLPE2	XLPE	21.5 kV	5 bar	N_2	1mm	64 h 15 min	yes
XLPE3	XLPE	28.6 kV	7 bar	N_2	1mm	7 h 52 min	yes
XLPE4	XLPE	28.6 kV	7 bar	N_2	1mm	10 h 54 min	yes
XLPE5	XLPE	25.3 kV	6 bar	N_2	1mm	13 h 09 min	yes
XLPE6	XLPE	24.5 kV	6 bar	N_2	1mm	11 h 13 min	no
XLPE7	XLPE	24.1 kV	6 bar	N_2	1mm	14 h 16 min	no
XLPE8	XLPE	25.2 kV	6 bar	N_2	1mm	8 h 11 min	yes
PEEK1	PEEK	21.5 kV	5 bar	N_2	1mm	70 h 20 min	yes
PEEK2	PEEK	20.2 kV	5 bar	N_2	1mm	0 h 20 min	yes
PEEK3	PEEK	21.8 kV	5 bar	N_2	1mm	47 h 25 min	no

4.2.1 Partial discharge test of XLPE1

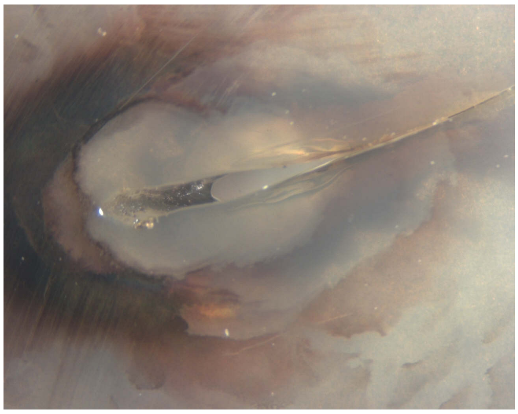
The first test was supposed to give some hint of what results could be expected from later experiments. It was also supposed to give an indication that the test equipment was in functioning order. A pressure of 5 bar was used. This sample had the lowest inception voltage of all the samples, only 15.5 kV. It had also the longest running time, although closer inspection revealed that 341 of the 496 recorded plots showed no discharges. The reason for this may be byproducts hindering the discharges due to the low voltage applied, as explained in section 2.3. Towards the end, the discharges occurs at a higher frequency, and the sample is finally punctured after almost 84 hours. Figure 4.4 has some pictures taken of XLPE1 with a camera and a light microscope. Figure 4(a) shows that the electrode was a little displaced inside the tank. This was corrected somewhat in later experiments, since it probably caused the actual spark gap to be less than 1mm. This is probably also the explanation to the low inception voltage. Figure 4.1 shows that the inception voltage drops fast towards 15 kv for 5 bar and spark gap less than 1mm. 4.4 also shows a 25mm wide area around the crater with traces of surface currents. These traces were seen more or less on all of the samples tested, and confirms that we have surface discharges, section 2.1.2, onto the sample during testing. Plots can be found in figure A.1 in appendix.

4.2.2 Partial discharge test of XLPE2

This was the last test of XLPE material at 5 bar. A voltage of 21.5 kV was used, and it took 64 hours to get a puncture. The discharge levels were fairly stable during the test, until they increased slightly right before the end. The plots can be seen in figure A.2 in appendix. Figure 4.5 shows four images taken of the sample after breakdown. They show that the crater from this sample is more circular and smaller than XLPE1. Still, the crack leading from the crater is longer, 19mm,



(a) Full picture showing a displaced puncture through the material. The edges around the hole are burnt, and the surface of the material around the hole shows clear signs of currents tracing along the surface.



(b) A light microscope image with a x6 enlargement. It shows the burnt edge and the crater at which the breakdown occurred. The material is melted around the sharp pointed hole, and there is a crack running inwards from the hole.

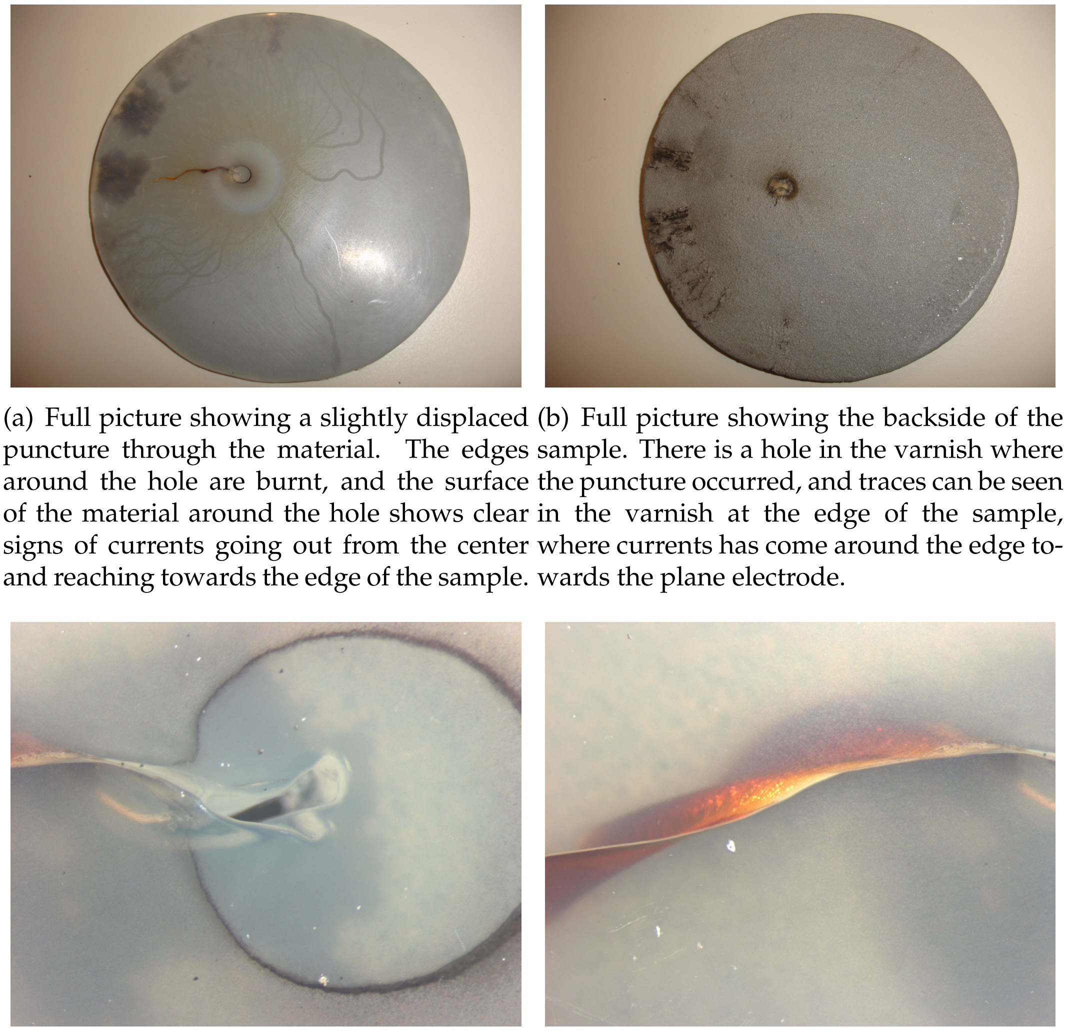
Figure 4.4: A picture and a light microscope image taken of XLPE1 after breakdown. Sample radius is 36.5mm.

compared to 10mm for XLPE1. Figure 5(d) also shows burning along the crack, which was not present for XLPE1. Figure 5(b) shows the marks in the varnish from currents at the edge nearest the crater. These are the currents tracing along the surface, getting around the edge of the sample and going towards the plane electrode. The marks stops suddenly where the conducting part of the plane electrode begins.

4.2.3 Partial discharge test of XLPE3

As mentioned, this was the sample used for the series of tests to determine inception and extinction voltage levels for different gaps and voltages in figure 4.1 and 4.2. A pressure of 7 bar was used for this test, and that gave a severe impact on the results. The sample had an inception voltage of 28.6 kV, and was punctured after only 7 hours and 52 minutes. As can be seen in figure 4.6, the sample suffered considerable damage when it broke down. It has a long crack going from one side to the other, and when it hits the edge of the conducting part of the plane electrode, it splits both ways and goes along the edge of the electrode. The backside, figure 6(b), also shows clear marks all around the edge from currents coming over the edge from the front, reaching for ground.

The plots for the test, see figure 4.7 and appendix, is also different from the two earlier tests. The discharge count is much higher, and there are distinct horizontal levels in the plot, indicating frequent impulse values. These kinds of patterns in the plot are an indication that the discharges originates from the electrode system, since there is a fixed voltage and a fixed distance between the electrodes. It should be mentioned that the nitrogen supply needed replacement after the



(a) Full picture showing a slightly displaced puncture through the material. The edges around the hole are burnt, and the surface of the material around the hole shows clear signs of currents going out from the center and reaching towards the edge of the sample.

(b) Full picture showing the backside of the sample. There is a hole in the varnish where the puncture occurred, and traces can be seen in the varnish at the edge of the sample, where currents has come around the edge towards the plane electrode.

(c) A light microscope image with a x12 enlargement. It shows the burnt edge and the procircular crater at which the breakdown occurred. The material is melted around the sharp pointed hole, and there is a crack running outwards from the hole.

(d) A light microscope image with a x25 enlargement. It shows part of the crack produced by the puncturing of the material. The picture shows that the crack is almost flowing in a wave-like movement, and the inside of the crack is discolored by the charge running through it.

Figure 4.5: Pictures of XLPE2 after the breakdown. Sample radius is 36.5mm.

previous tests, and the new supply proved difficult to control concerning gas replenishment to the cell, due to a low resolution on the valves. It is possible that the pressure dropped somewhat before the supply kicked in, and that this may have caused a somewhat premature breakdown. After this sample experiment, the valves on the gas supply was exchanged with the old ones, so the pressure remained constant in all the remaining experiments.

(a) Full picture showing the punctured sample and the large crack moving both to the right and to the left out from the center.

(b) Picture of the backside showing large traces in the varnish from charges tracing towards ground.

Figure 4.6: Pictures of XLPE3 front and back, showing severe damage to the sample.

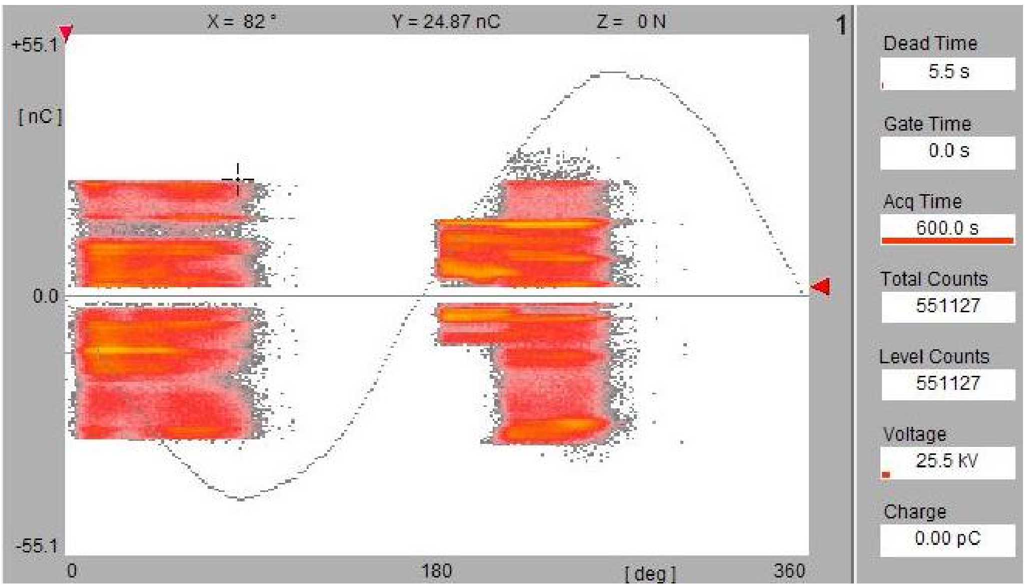
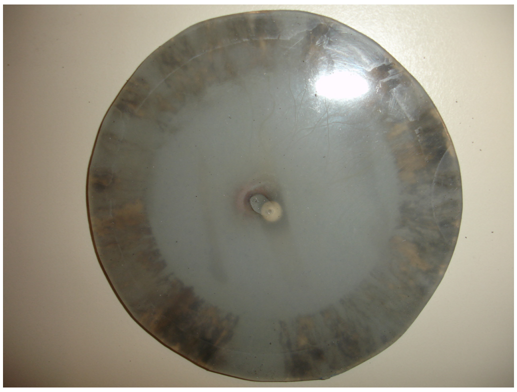


Figure 4.7: A phase angle plot of XLPE3 after 6 hours and 46 minutes. It shows heavy partial discharge activity. Sample radius is 36.5mm.

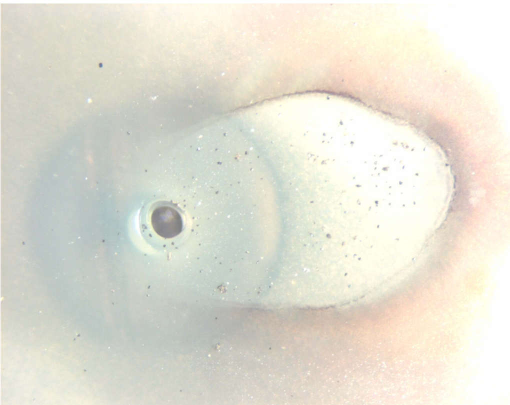
4.2.4 Partial discharge test of XLPE4

This sample is tested at 7 bar and 28.6 kV. As this is the same parameter values as XLPE3, it comes natural to compare the results of these two samples. In addition, the plots in figure A.4 shows much the same activity as XLPE3, seen in figure A.3. The outcome for the two is, however, completely different. Figure 4.8 shows four pictures taken of the sample after breakdown. The front does not show the same damage seen in XLPE3. Instead, there is a small crater, with a small hole going straight down to the plane electrode. There are no cracks or fractures to be seen around the crater. The backside, figure 8(b), does show proof that there has been a lot of discharges going around the edges to the plane electrode during the test. The blast from the breakdown has removed varnish around the hole in an almost perfect circle. The different results may have been caused by structural differences in the two samples, or some other unknown factor has taken effect. The experiment ran for 10 hours and 54 minutes before it broke down.

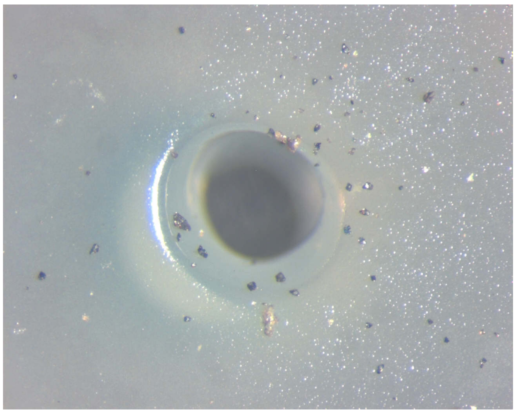


(a) Full picture showing the punctured disc. The crater and hole is almost circular, and there are no fractures or cracks extending from the hole.

(b) Picture of the backside showing large traces in the varnish from charges tracing towards ground.



(c) A x6 microscope picture showing the crater and hole through the sample.

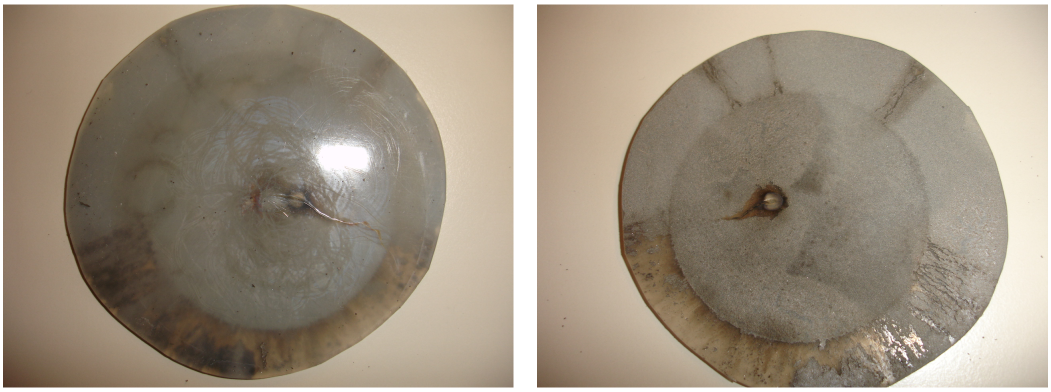


(d) A x25 microscope image of the hole.

Figure 4.8: Pictures of XLPE4, front and back, and a x6 and x25 enlarged picture of the puncture cite. Sample radius is 36.5mm.

4.2.5 Partial discharge test of XLPE5

The inception voltage for this sample at 7 bar seemed to be a little too high, so the pressure was lowered to 6 bar. Then the inception voltage was 25.3 kV, and it took 13 hours and 9 minutes before it broke down. These results are expected from theory for pressure, inception voltages and breakdown time. Compared to the tests done with 7 bar pressure, XLPE5 has lower inception voltage and longer breakdown time. The plots shows very stable discharge levels, and the last six are included in figure A.5 in appendix. Figure 4.9 shows some pictures taken of the sample after breakdown.



(a) Full picture showing the punctured disc. There is a small crater and a crack leading outwards from it. There are also a lot of traces from discharges on the surface of the sample.

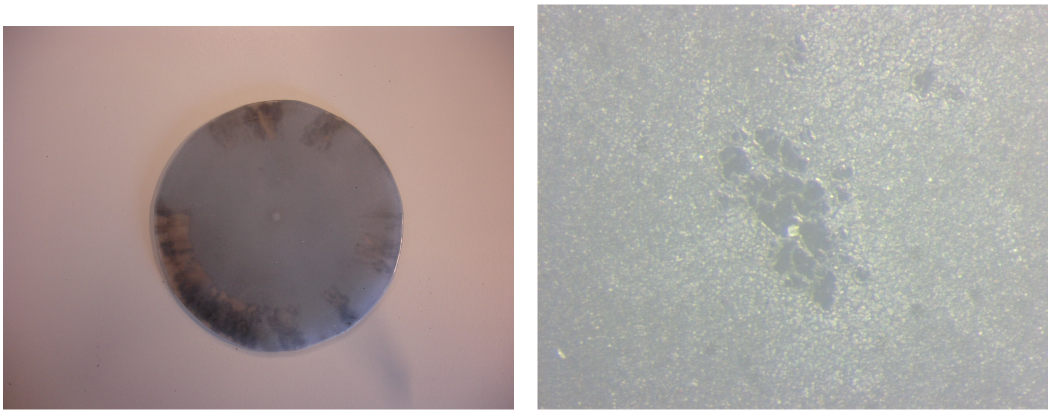
(b) Picture of the back side. The hole has burnt edges, and the the varnish the lower side is almost removed completely from discharges going around the edge from the front.

Figure 4.9: Pictures of XLPE5, front and back. Sample radius is 36.5mm.

4.2.6 Partial discharge test of XLPE6

This disc was also tested at 6 bar, and based on the breakdown times of previous results, the test was terminated after 11 hours and 13 minutes. The applied voltage was 24.5 kV. Even though the disc was not punctured, it was expected to show some damage from being exposed to partial discharges. Figure 4.10 shows some pictures taken of the sample. The first picture shows a discoloring of the area below where the high voltage electrode was, and figure 10(b) shows a x50 close-up image of the bleached spot. There is clear damage to the area, with a crater and some minor pits scattered around, although it is so small it is hard to see with the bare eye.

The microtome samples, one of which can be seen on figure 3.7, did not show any electric tree structures for XLPE6.



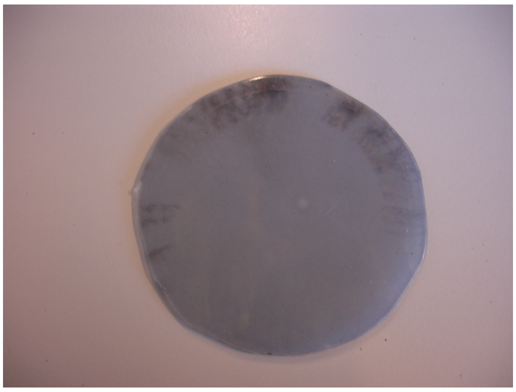
(a) Full picture showing the front of the disc. There is a bleached spot under where the high voltage electrode was, and the edges shows that currents has been moving towards the edge and ground on the other side.

(b) x50 enlargement of the bleached spot. There is a crater and smaller pits showing where the partial discharges has aged the sample.

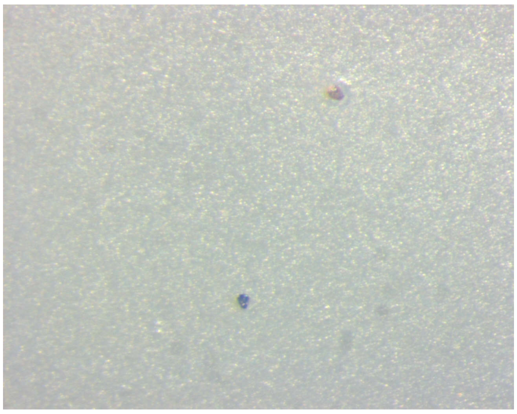
Figure 4.10: Pictures of XLPE6, a full picture and a x50 close-up of the bleached spot under the electrode. Sample radius is 36.5mm.

4.2.7 Partial discharge test of XLPE7

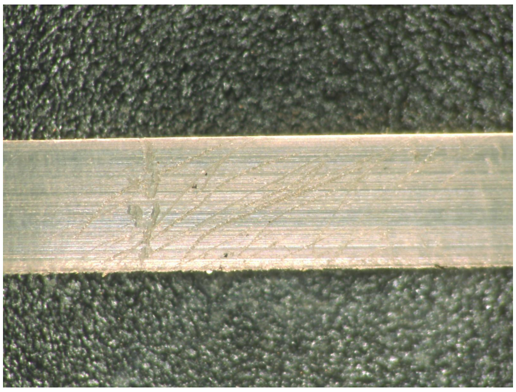
This was the second sample terminated before breakdown. It was exposed to 24.1 kV at 6 bar pressure for 14 hours 16 minutes, three hours longer than xlpe6. Figure 11(a) shows that, other than the bleached spot and the usual traces of charges going towards ground along the disc surface, there are not much damage to the disc. The bleached spot is not as clear as in XLPE6, and figure 11(b) shows what looks like a single tiny hole in the surface. The lower spot looks like some kind of foreign fragment. A study of the samples made with the microtrome does show a couple of interesting pictures. Both picture 11(c) and 11(d) shows some irregular channels and scratches, but it is not clear what might have made them. There are no indication of carbonization, which is present in most cases where electrical damage is involved, but that option can not be left out either. It should also be noted that the mark on figure 11(d) originates from the side facing the ground electrode, which is covered with varnish. One of the larger marks on figure 11(c) also originates from that side, though on that sample there are seemingly marks coming from both sides. A deeper structural analysis would have to be made of these samples in order to determine if the marks are tree structures or if something else made them.



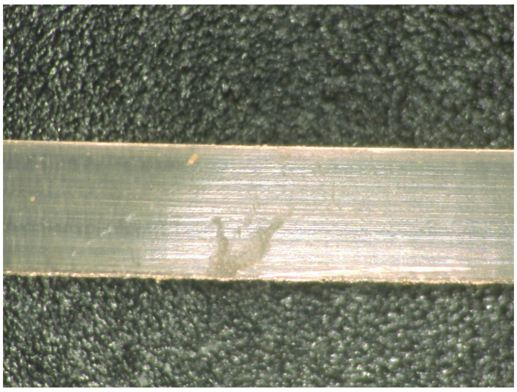
(a) Full picture showing the disc. There is a bleached spot near the center and the upper edges on back side is missing varnish from currents trying to reach ground potential.



(b) A x50 enlargement of the bleached spot on the surface of the sample. It shows two spots, where the upper one seems to be a hole and the lower one probably a foreign fragment on the surface.



(c) A x40 microscope picture showing the fourth microtome sample. It has several scratches moving in an arch, and two larger irregular channels moving towards each other from both sides of the sample. This might be tree growth. The sample has a width of 2 mm.



(d) A x40 microscope image of the the fifth microtome sample. It shows a clear irregular mark, which might be tree growth, coming from the varnish side. The sample has a width of 2 mm.

Figure 4.11: Pictures of XLPE7 and two microtome samples from it. Sample radius is 36.5mm.

4.2.8 Partial discharge test of XLPE8

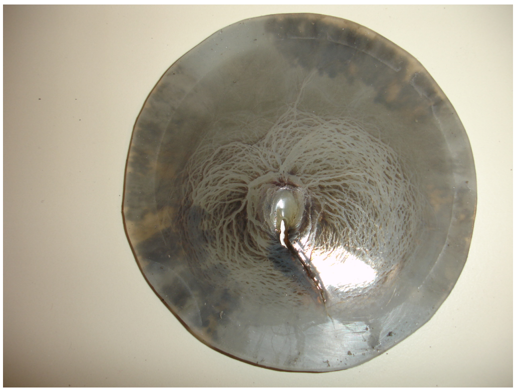
This was the last XLPE sample tested. A voltage of 25.2 kV was applied under 6 bar pressure. The intention was to terminate this sample after 16 hours, just a little longer than XLPE7, but the sample was punctured after only 8 hours and 11 minutes. The plots does show heavy partial discharge activity compared to XLPE6 and 7, see figure A.8, A.6 and A.7 in appendix, and especially the one showing the breakthrough has a high discharge count, over 1.2 million discharges. The sample showed signs of the activity by heavy scorch marks and the surface is darker than the other samples because large parts was covered by soot. The soot makes the traces from surface currents more clear to study. The results of the test may indicate that the sample had some sort of weakness, causing the electric field stress to be particularly high. Figure 4.12 shows pictures of the front and back of the sample after breakdown in addition to a microscopic image taken of the surface pattern made by currents.

4.2.9 Partial discharge test of PEEK1

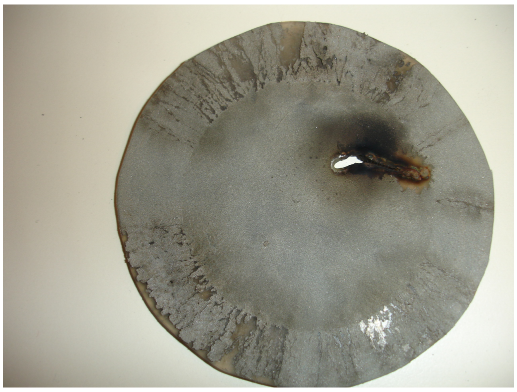
The pressure were lowered to 5 bar for the all the PEEK samples, which also caused the inception voltage to go down a little. PEEK1 was tested at 21.5 kV, and suffered a breakdown after 70 hours and 20 minutes. Although the voltage was a little less than for the XLPE samples, the partial discharge levels remained much the same as for the other material at higher voltages, and the plots look similar, see figure A.9 in appendix. Figure 4.13 shows some pictures taken of PEEK1 after breakthrough. One apparent thing is that the material seems to have reacted a little different from XLPE when punctured. The biggest difference from XLPE is seen right around where the disc was punctured. There is not a crater, like for XLPE, instead the area appears melted and transformed. Since PEEK is not a thermosetting material, it can be melted and remoulded. In comparison, the XLPE materials does not appear melted in the same way, just burnt and damaged. Figure 13(c) shows the punctured area enlarged x20. It has a clear symmetry, and the deep trench moving from the small hole is the symmetry axis. However, the material is so resistant that no crack appears through the disc.

4.2.10 Partial discharge test of PEEK2

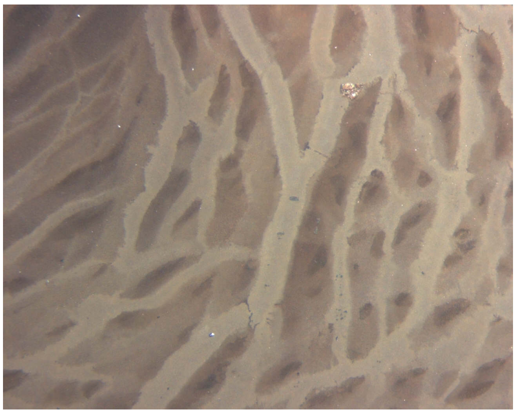
This sample was exposed to a voltage of 20.2 kV and 5 bar pressure. Even though this was even less than PEEK1, PEEK2 had a breakdown in less than 20 minutes of testing. The only reasonable explanation seems that the sample had some kind of defect or production error, causing the electrical field stress to be more than the material could handle even for a short period of time. This is an important result that shows the importance of good insulation materials when dealing with high voltage installations. A weak material may not give any warning before breaking down, causing mass failure. Figure 4.14 presents three pictures taken of the material after breakdown. Notice how far towards the edge the punctured hole is in figure 14(b), even though the electrode was placed at the opposite end



(a) Full picture showing the sample front. There is a large crack going from where it was punctured, and the crack itself is scorched with burning along the edges. The surface is covered in soot, enhancing the traces from the currents going over the edge towards ground.



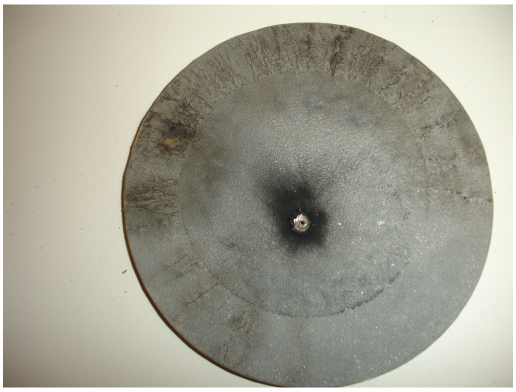
(b) The back of the sample also has a large scorch mark from the breakdown, and varnish has disappeared around the edges.



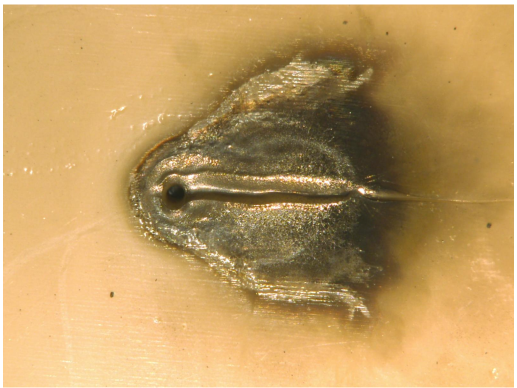
(c) A x12 microscope picture the pattern engraved by surface currents.

Figure 4.12: Pictures of XLPE8. The sample has sustained heavy damage from the breakdown. Sample radius is 36.5mm.

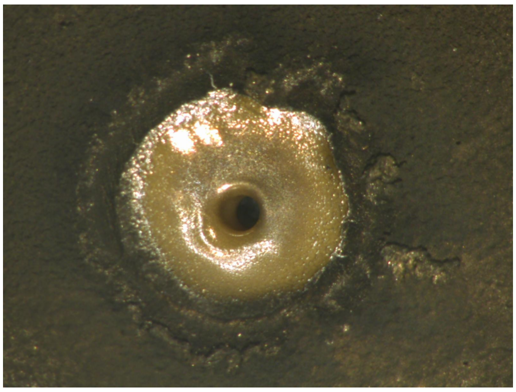
(a) Full picture showing the disc. There is a charred spot near the center, and there are lines going out from the center where surface charges has gone. There also is a flowing pattern in the surface near the edges of the disc.



(b) The backside shows much the same traces of surface charges towards ground as the XLPE samples. The punctured hole is in the center of a charred circle of varnish.



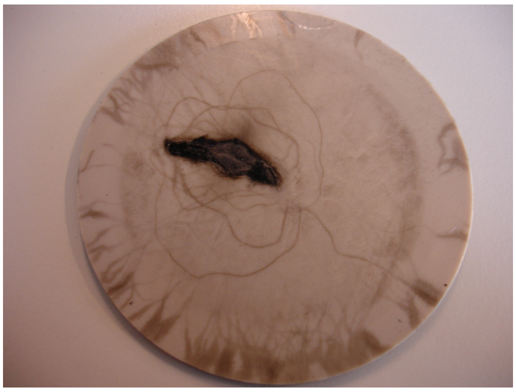
(c) A x20 microscope picture showing a close-up of the puncture in front of the sample. It has a clear symmetry, and a melted trench stretches from the hole and inwards.



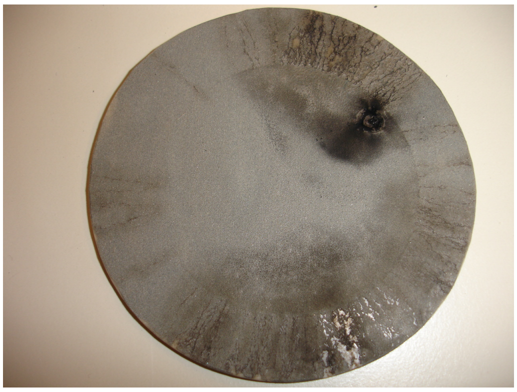
(d) A x40 microscope image of the the hole seen from the back. The varnish is blasted away at the spot, and the hole itself appears smooth around the edges.

Figure 4.13: Pictures of PEEK1 showing pictures of front and back after the breakdown. Sample radius is 36.5mm.

of the charred area almost in the center of the disc. There must have been a weak spot there to make it break down so fast.



(a) Full picture showing the sample. There is a long, charred area going from the center, and there are paths in the surface from currents tracing along it towards ground potential.



(b) The backside misses varnish at the edges, and there is a charred hole where the breakdown occurred.

(c) A x8 microscope picture showing a close-up of the puncture in front of the sample. The hole itself is to the far left of the charred area.

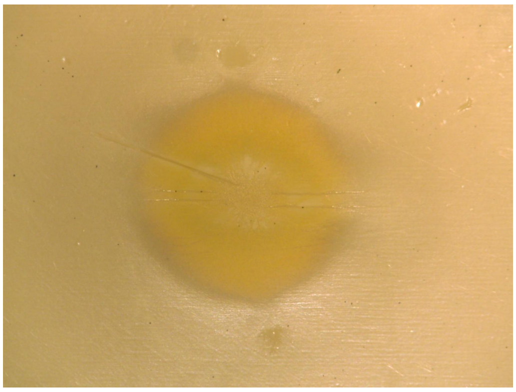
Figure 4.14: Pictures of PEEK2 showing pictures of front and back after the breakdown. Sample radius is 36.5mm.

4.2.11 Partial discharge test of PEEK3

PEEK3 was the last sample tested. The applied voltage was 21.8 kV, and the pressure was 5 bar. The experiment was terminated before breakdown after 47 hours and 25 minutes. During testing, the sample had been exposed to fairly high levels of discharges, see figure A.11 in appendix, and was expected to break down soon. This expectation was based on the resent increases in discharge levels for the latest plots. For the other samples, the discharges usually increased a little before they were punctured. The sample can be seen in figure 4.15. The figure 15(b) shows a close-up of the exposed area under the high voltage electrode. The center of it shows traces of the discharges digging into the material. Above and under the center are what seems to be two pits in the surface. There are also two parallel lines scratched into the material going through the center, and one more tilted line intersecting the parallel ones. These three lines are so straight and fine cut, it seems they could have been made by a knife or a sharp blade. This illustrates the damaging effect electricity and discharges can have on physical objects and materials. Unfortunately, PEEK is too rigid and hard to be cut in the microtrome the same way XLPE6 and 7 was, so a more deep examination of the material sample can not be made at this point.

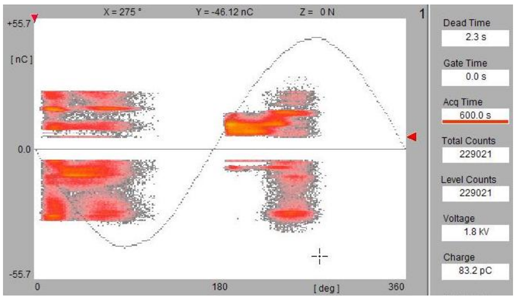
Some of the plots for PEEK3 shows some interesting activity in the early stages of the experiment. Figure 4.16 shows six plots measured in succession between 50-100 minutes into the experiment. In figure 16(d) the activity suddenly increases to over 1 100 000 counts in ten minutes, which is more than five times the activity shown for the sample the rest of the time during testing. One reason for this might be a sudden physical change in the sample causing the electric field stress to increase notably. After a little while, another change may have caused the field to diminish to normal levels again. If the sample had any weak points to start out with, such a drastic change in discharge activity might as well have led to a quick breakdown of the system.

(a) Full picture showing the front of the disc. There is a discolored spot under where the high voltage electrode was, and the edges shows that currents has been moving towards the edge and ground on the other side.

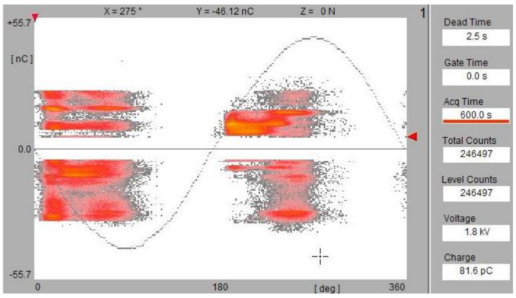


(b) x25 enlargement of the discolored spot.

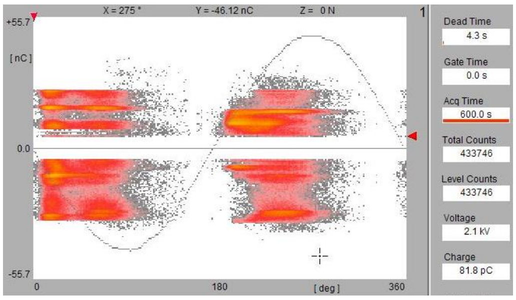
Figure 4.15: Pictures of PEEK3, a full picture and a x25 close-up of the discolored spot under the electrode. Sample radius is 36.5mm.



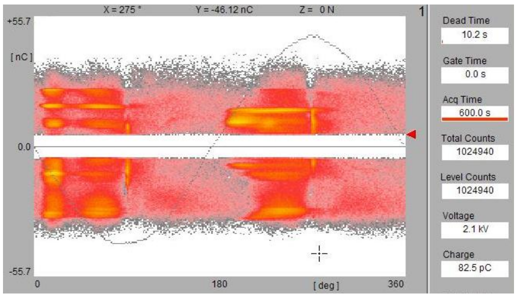
(a) Plot after 50 minutes.



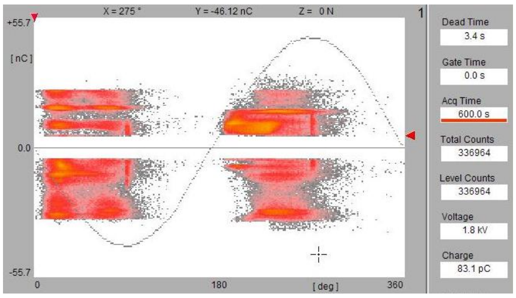
(b) Plot after 60 minutes.



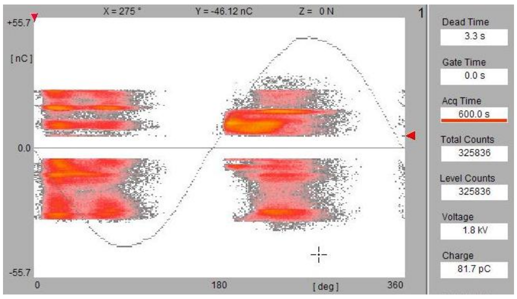
(c) Plot after 70 minutes.



(d) Plot after 80 minutes.



(e) Plot after 90 minutes.



(f) Plot after 100 minutes.

Figure 4.16: Series of plots from PEEK3. The plots are 10 minutes apart. After going normal for about 50 minutes, the activity suddenly increases drastically for a few minutes, before going back to normal levels.

4.3 Measurement and material observations

The measurements gave much interesting information about the impact of a high pressure environment and the differences between XLPE and PEEK when exposed to partial discharges.

The influence of the pressure shows clear trends throughout the results, and both inception voltage and time to breakthrough seems to be directly connected to it. The inception voltages of samples XLPE1-2 and PEEK1-3 were all tested at 5 bar. Table 2 shows that these all had inception voltages in the 20-22 kV range. Individual differences were to be expected, since the electrical field is affected by physical appearance. Figure 4.1 shows that the inception voltage for 5 bar and 1 mm gap is approximately 21-22 kV. Sample XLPE1 shows an inception voltage of

15.5 kV, but this sample had a displaced high voltage electrode causing the spark gap to decrease. Following the paschen law, see 2.3, this should cause a lower inception voltage, as the result shows. Samples XLPE5-8 were tested at 6 bar, and shows inception voltages in the 24-25 kV range, all higher than the samples tested at 5 bar. Samples XLPE3-4 were tested at 7 bar, and shows the highest inception voltages at 28.6 kV.

The time to breakthrough is a more complex parameter, and is impacted by pressure, discharge count, pulse magnitude of the discharges and the samples individual resistance and strength. Even so, the results shows that pressure is one of the most important parameter of these, see table 2. The samples XLPE1-2, PEEK1 and PEEK3, which were tested at 5 bar, has a much longer time to breakdown than the rest of the samples. PEEK2 is the exception, with a breakdown time of 20 minutes. This result was clearly due to a sample defect, causing almost instant puncture. PEEK3 is the second lowest time, and that sample was terminated deliberately before breakdown. At 6 bar, the samples XLPE5-8 shows a significantly lower breakdown time. XLPE6 and XLPE7 were stopped at 11 and 14 hours before breakdown, while XLPE5 and XLPE8 broke down at 13 and 8 hours. XLPE8 showed the highest discharge levels of these by far, hence the low breakdown time. See figure A.8. The sample might have had a structural weakness compared to the others, causing a local high electrical field stress. The two samples tested at 7 bar, XLPE3 and XLPE4, shows the shortest breakdown times, just below 8 and 11 hours. Overall, the impact of pressure to the breakdown times is significant. These results are in agreement with the expected behavior discussed in 2.3.

Whether electrical treeing, see 2.4, is a significant effect for surface discharges or not is hard say from these tests. Only two samples were successfully stopped before breakdown and sliced with a microtome, and only one of them showed anything that might be electrical tree growth, see figure 4.11. Further structural study of this sample would have to be done, and preferably more tests should be performed, before any conclusions can be taken. However, the results does not exclude the possibility that tree growth can form under these circumstances, and if present, they are one of the elements leading a sample toward breakdown. If the structures seen in figure 11(c) were tree growth, they were about to puncture the sample at any moment.

Moving on to the materials and their differences, there are some things to take notice of. As mentioned in 2.5, both samples seems to be vulnerable to partial discharges, but the nature of the breakdowns are a little different due to the molecular structures of the materials. The XLPE samples, being a thermosetting material, has a tendency to get craters around the point of puncture, and often there are cracks going in one or several directions from the hole. This was seen clear on sample XLPE3 in figure 6(a). The XLPE material does get deformed and damaged from the discharges, but does not get completely melted and remoulded from the breakdown as seen for the PEEK1 sample in figure 4.13. This difference comes from PEEK being a thermoplastic material, see 2.5.3, and it has high heat resistance. The breakdown times for the materials seems to be about the same for those tested at 5 bar, ranging between 64-84 hours, not including PEEK3, which were stopped at 47 hours. It is hard to say how long PEEK3 would last until breakdown if it had been allowed to continue testing. The inception voltages for the two materials at 5 bar is also about the same.

Which of the two materials to prefer comes down to other material qualities than PD resistance. In applications where flexibility is required, XLPE is the preferred, since PEEK is much too rigid. However, the robust and resistant qualities of PEEK makes it promising for use in high performance applications requiring high pressure and/or heat resistance.

5 Conclusion

This work has involved the influence of high pressure to the inception voltage and breakdown time of materials exposed to partial discharges. Individual properties and differences between the materials XLPE and PEEK, when exposed to partial discharges, was examined. In addition, a microtrome was used to look for electrical tree structures in samples exposed to surface discharges.

As anticipated, the inception voltage seems to be directly dependent of the pressure, the higher the pressure, the higher the inception voltage. This effect is apparent in all tests done. The most important result is the major reduction in breakdown times when the pressure is increased from 5 to 6 bar, and further to 7 bar. On average there is a drop from about 72 hours to about 12 hours breakdown time, which is a reduction to about one sixth of the breakdown times at 5 bar. If partial discharges should arise in pressurized high voltage equipment subsea, this result might prove to be of great significance, causing the equipment to break down up to 6 times faster than it would have at atmospheric pressure. Individual properties, defects and the discharge levels the material is exposed to also has a great impact on the breakdown time of the sample.

There are not enough test results to say whether electrical tree growth is a major factor for breakthrough in the case of surface discharges from an elevated high voltage electrode above the sample. XLPE7 shows some traces and structured on the microtrome samples which might be tree structures, but deeper structural analysis is required in order to state what the traces originates from.

XLPE and PEEK shows similar properties for partial discharge resistance. Both with about the same inception voltage and breakdown times for 5 bar pressure. Structural differences due to XLPE being a thermosetting, and PEEK being a thermoplastic polymer, causes them to react a bit different in the case of a breakdown. PEEK melts and is remolded from the heat and blast from the breakdown, while XLPE shows a smooth crater, often with cracks extending from the point of the puncture.

This method of testing materials is meant to help rank PD resistance for different insulation materials, and so far the results are promising. The hope for the future is to be able to predict the time to breakdown relatively accurate for different materials, gases and pressures.

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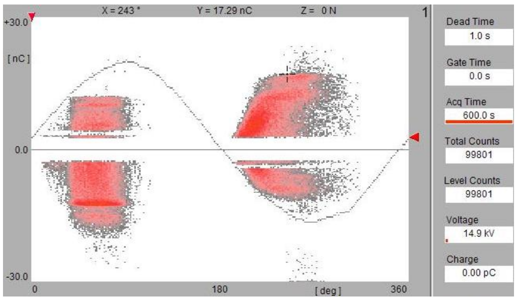
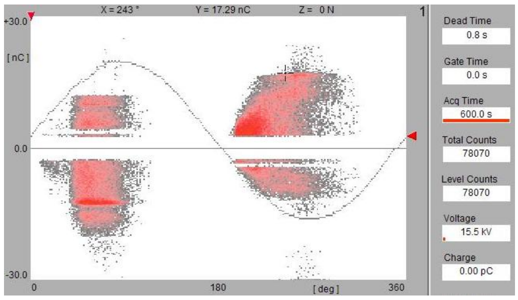
A Plots from the experiments

This appendix will present a selection of plots for each sample test done. Each plot, except the last one in each figure, covers 600 seconds of measurements, and there is a 10 second delay in between the plots. The reason that the last plot may cover less, is that the sample may have broken down at any time during the recording of that particular plot. The total discharge count in the plot is given on the right side of each plot. The voltage measurement given below the discharge count should not be given any significance, as it is not correct in most of the plots. The actual applied voltage was monitored by a voltmeter and is given in the caption of each figure, as well as in table 2. The plots are selected to give an idea of how the discharge levels developed for each experiment before they broke down or were shut down intentionally. They will be numbered by the numerical order in which they were recorded, and the last plot in each figure is always the last one recorded for that sample.

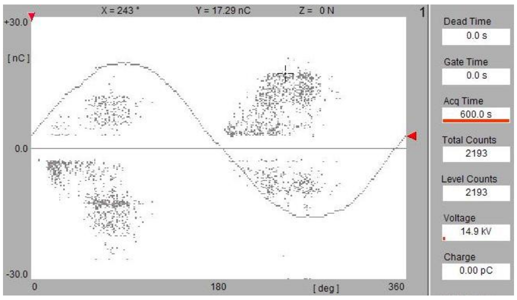
A.1 XLPE1



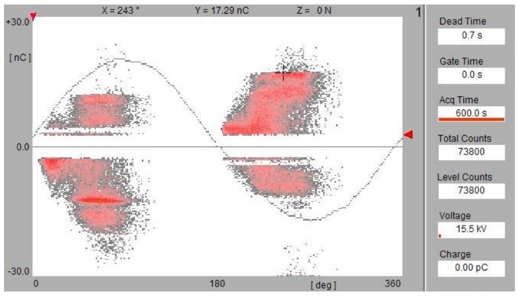
(a) Plot 5.



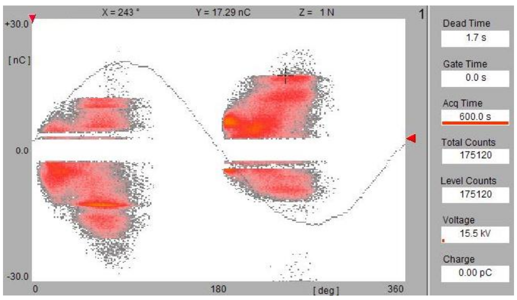
(b) Plot 20.



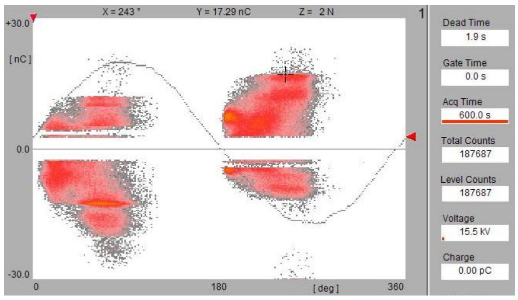
(c) Plot 330.



(d) Plot 460.



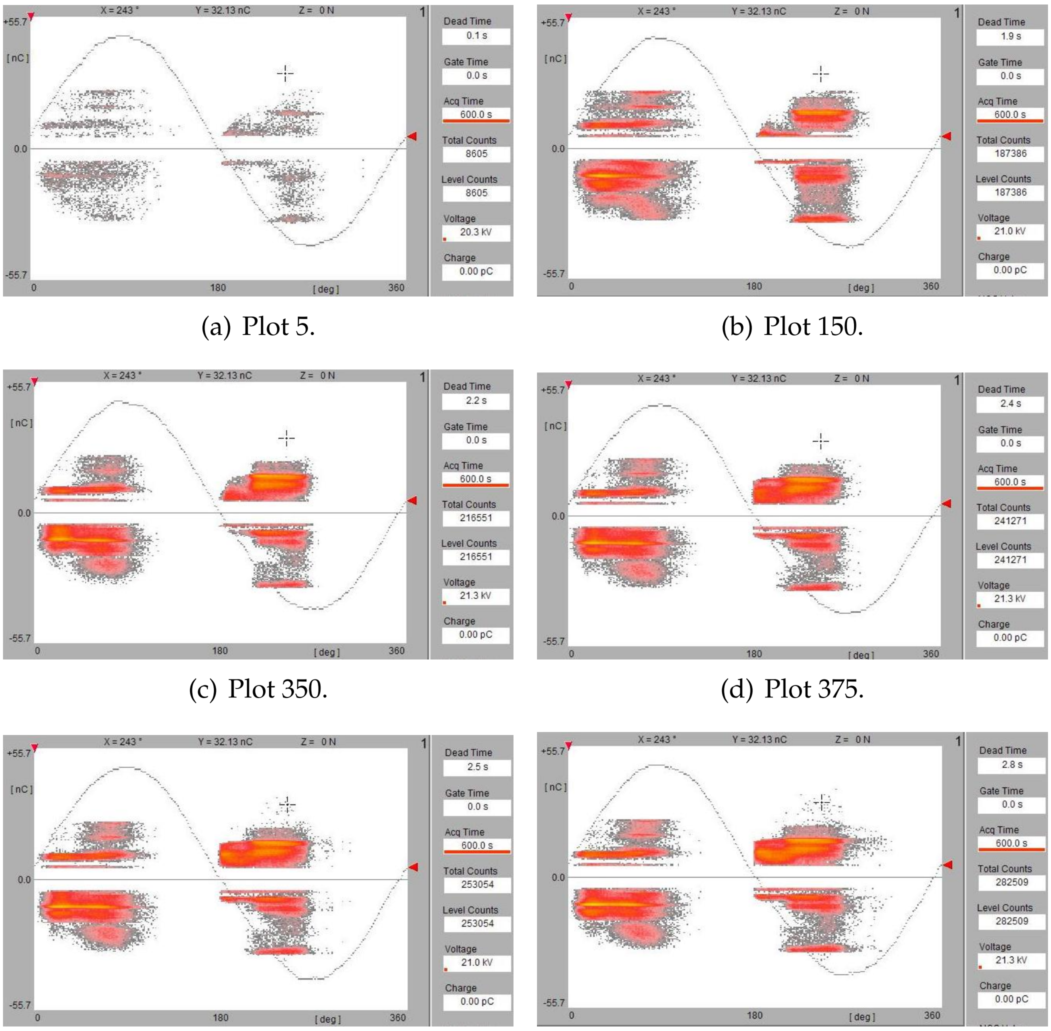
(e) Plot 494.



(f) Plot 496.

Figure A.1: Selected plots from XLPE1. Voltage 15.5 kV.

A.2 XLPE2



(a) Plot 5.

(b) Plot 150.

(c) Plot 350.

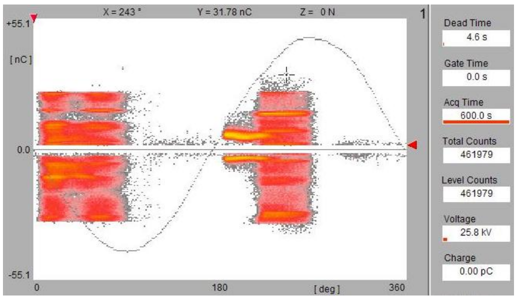
(d) Plot 375.

(e) Plot 377.

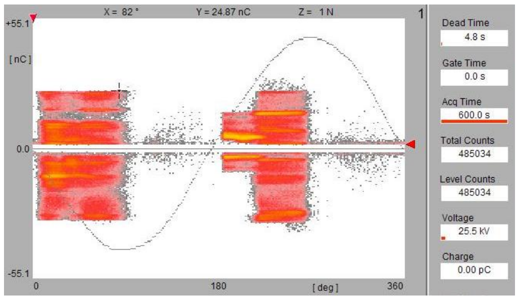
(f) Plot 380.

Figure A.2: Selected plots from XLPE2. Voltage 21.5 kV.

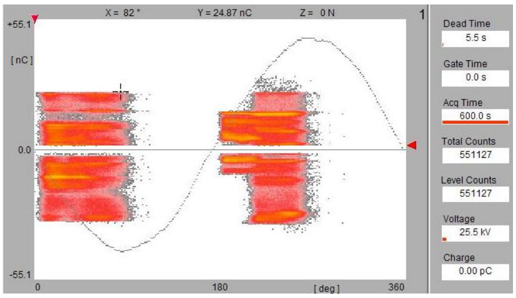
A.3 XLPE3



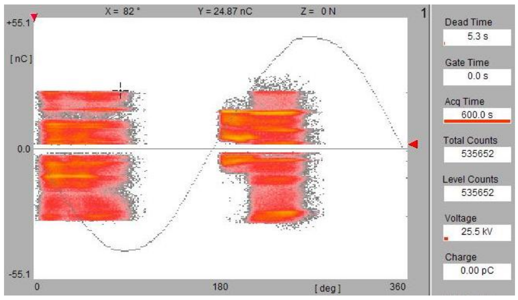
(a) Plot 10.



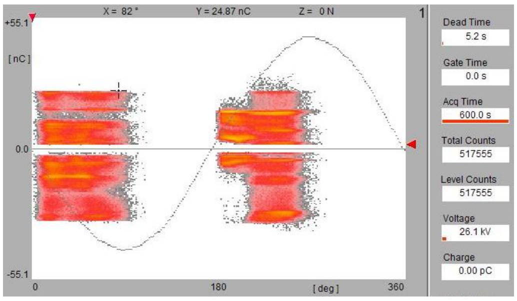
(b) Plot 25.



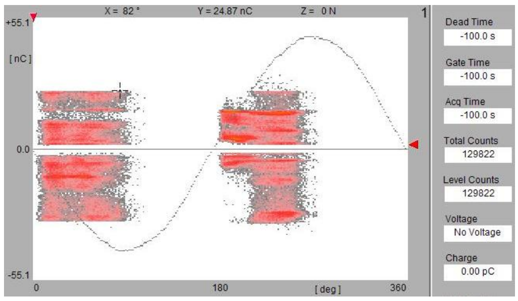
(c) Plot 40.



(d) Plot 46.



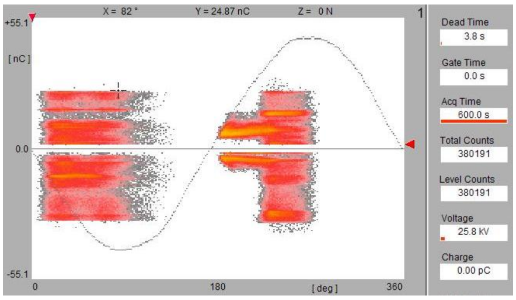
(e) Plot 47.



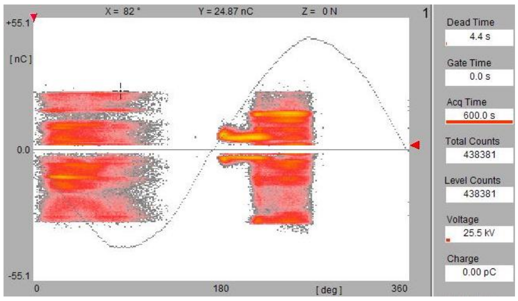
(f) Plot 48.

Figure A.3: Selected plots from XLPE3. Voltage 28.6 kV.

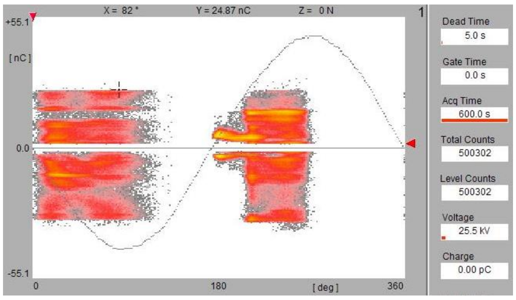
A.4 XLPE4



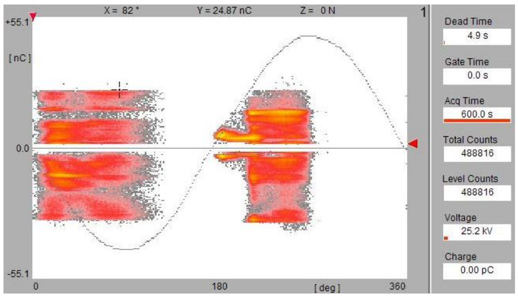
(a) Plot 10.



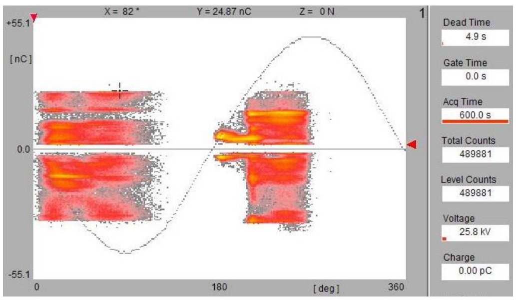
(b) Plot 50.



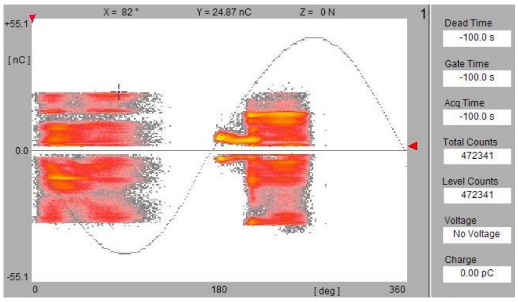
(c) Plot 61.



(d) Plot 64.



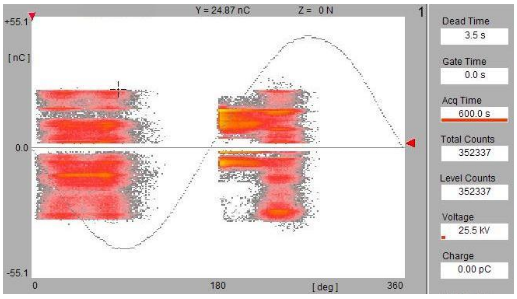
(e) Plot 65.



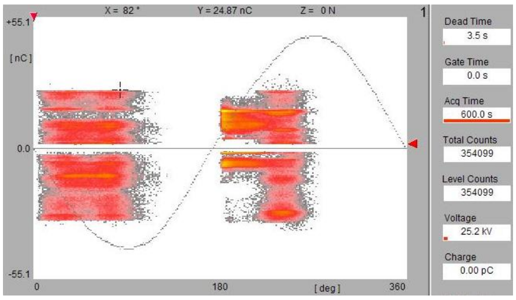
(f) Plot 66.

Figure A.4: Selected plots from XLPE4. Voltage 28.6 kV.

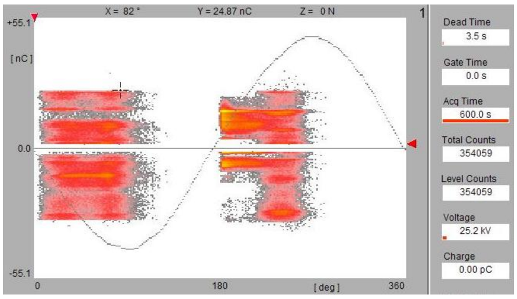
A.5 XLPE5



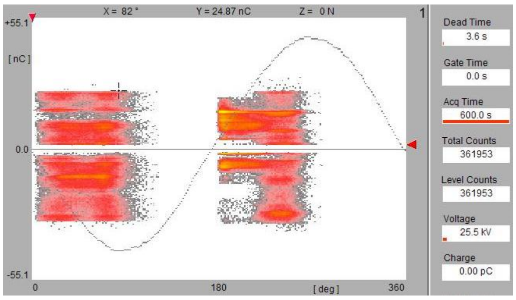
(a) Plot 77.



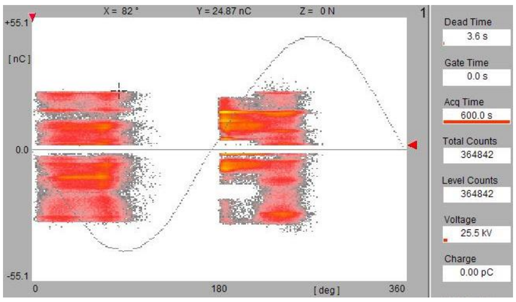
(b) Plot 78.



(c) Plot 79.



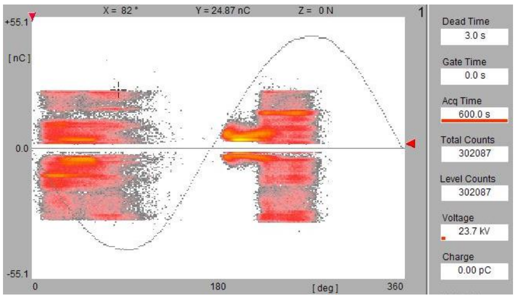
(d) Plot 80.



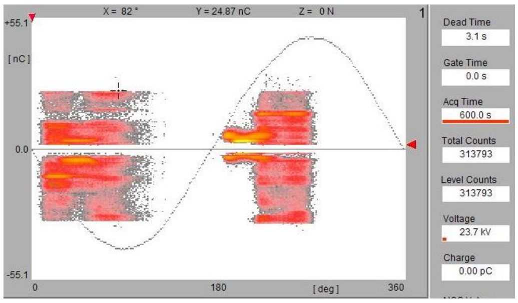
(e) Plot 82.

Figure A.5: Selected plots from XLPE5. Voltage 25.3 kV.

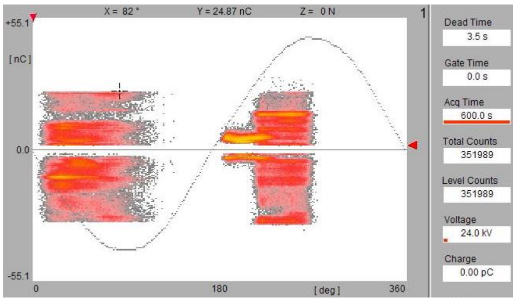
A.6 XLPE6



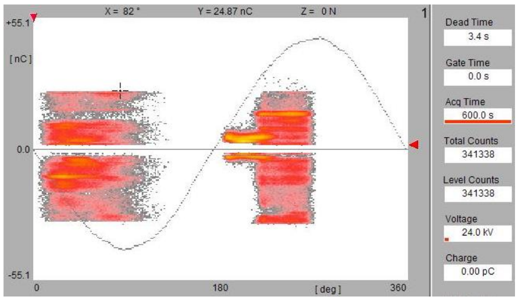
(a) Plot 10.



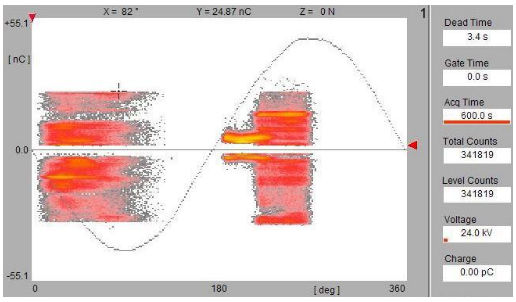
(b) Plot 40.



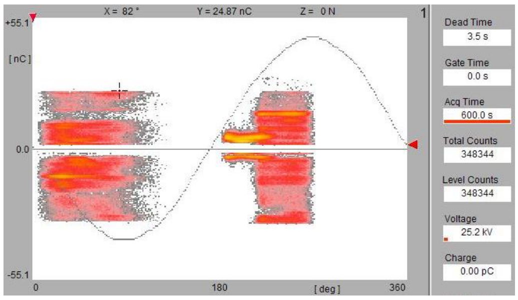
(c) Plot 60.



(d) Plot 69.



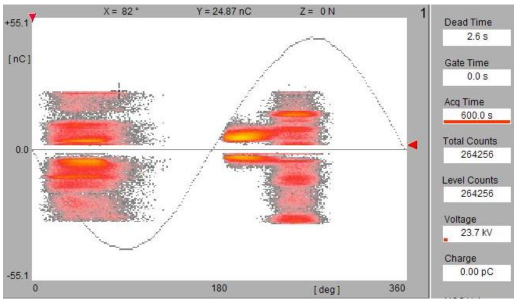
(e) Plot 70.



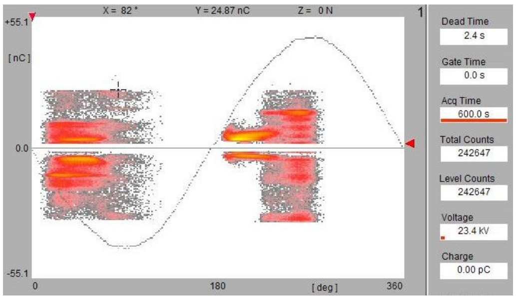
(f) Plot 71.

Figure A.6: Selected plots from XLPE6. Voltage 24.5 kV.

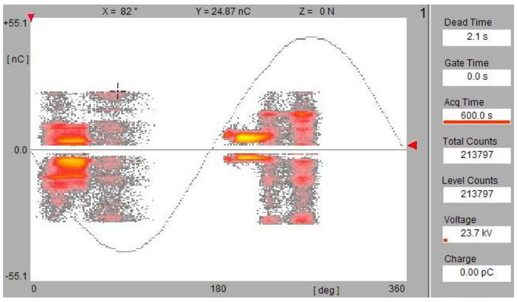
A.7 XLPE7



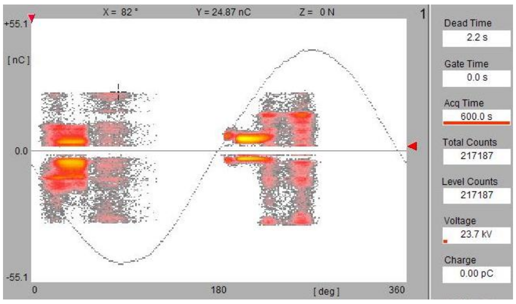
(a) Plot 10.



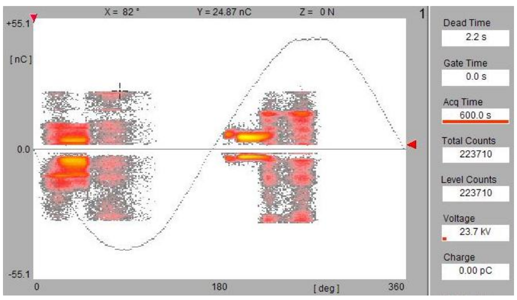
(b) Plot 40.



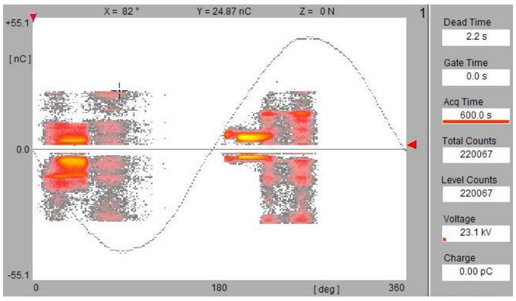
(c) Plot 70.



(d) Plot 88.



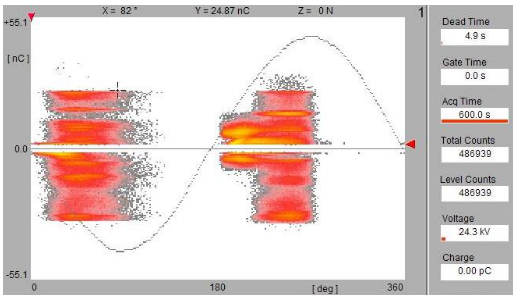
(e) Plot 89.



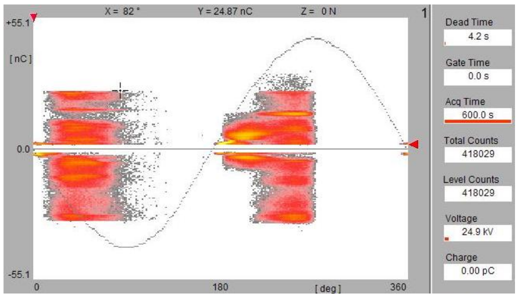
(f) Plot 90.

Figure A.7: Selected plots from XLPE7. Voltage 24.1 kV.

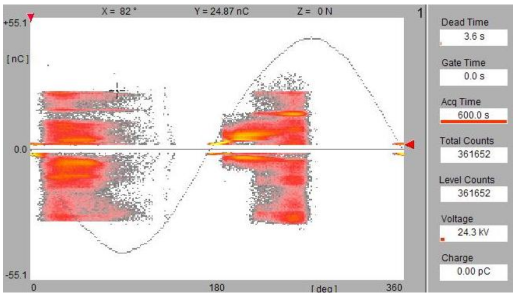
A.8 XLPE8



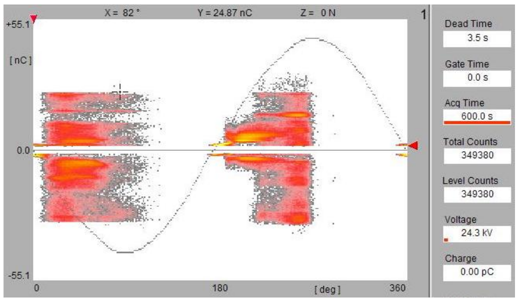
(a) Plot 10.



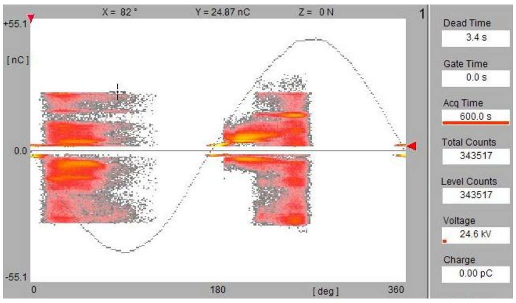
(b) Plot 30.



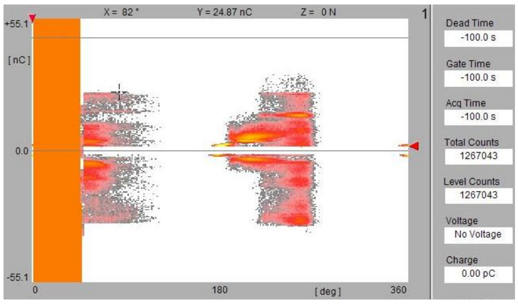
(c) Plot 45.



(d) Plot 48.



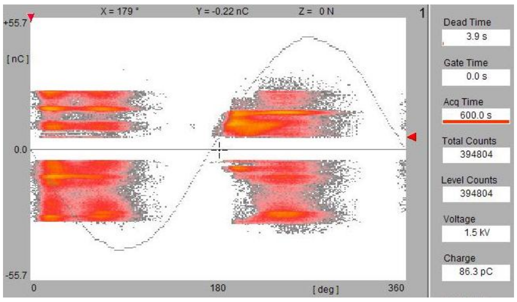
(e) Plot 49.



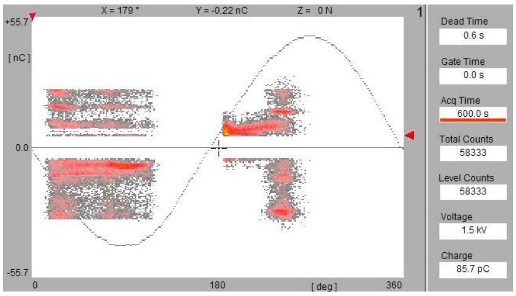
(f) Plot 50. The breakdown caused the plot recording to glitch.

Figure A.8: Selected plots from XLPE8. Voltage 25.2 kV.

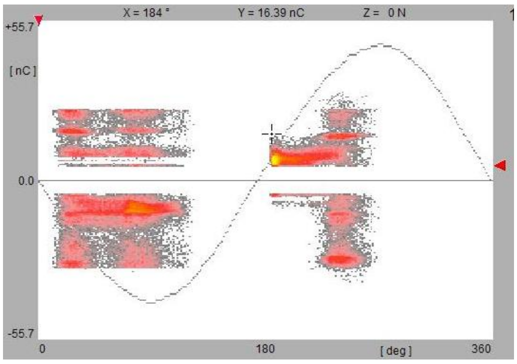
A.9 PEEK1



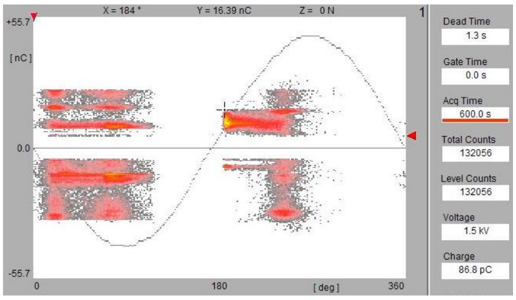
(a) Plot 5.



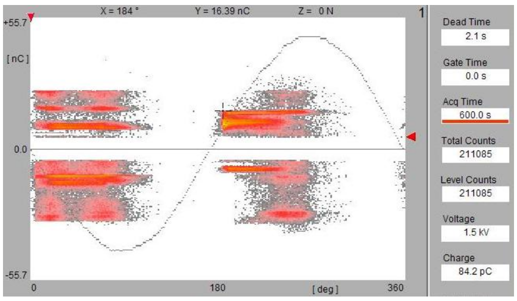
(b) Plot 200.



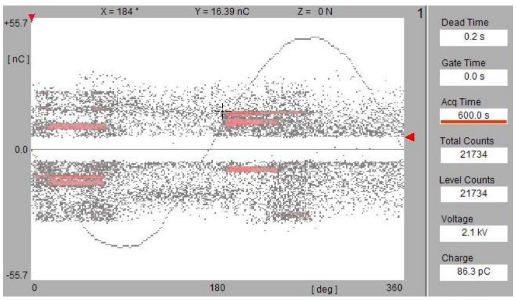
(c) Plot 350.



(d) Plot 416.



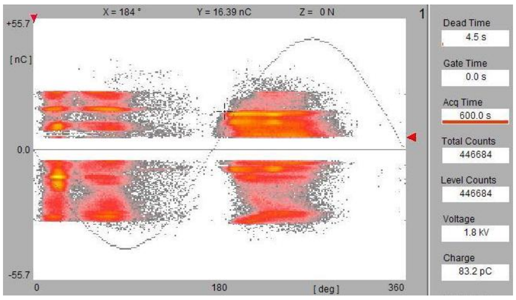
(e) Plot 417.



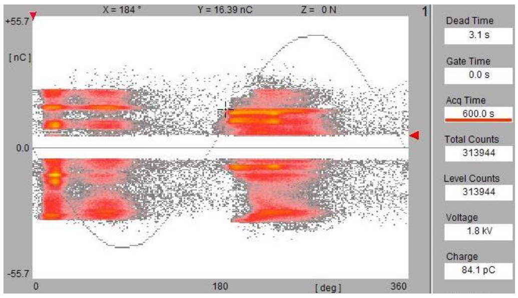
(f) Plot 418.

Figure A.9: Selected plots from PEEK1. Voltage 21.5 kV.

A.10 PEEK2



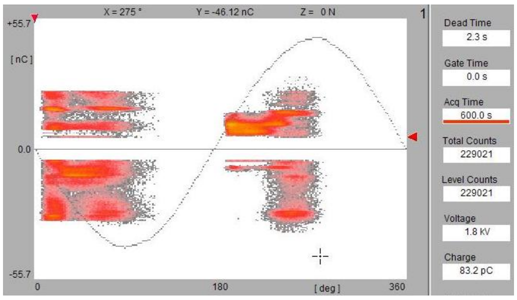
(a) Plot 1.



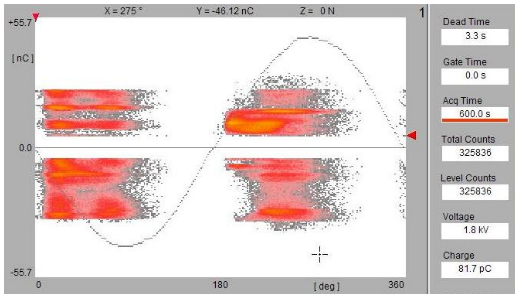
(b) Plot 2.

Figure A.10: Selected plots from PEEK2. Voltage 20.2 kV.

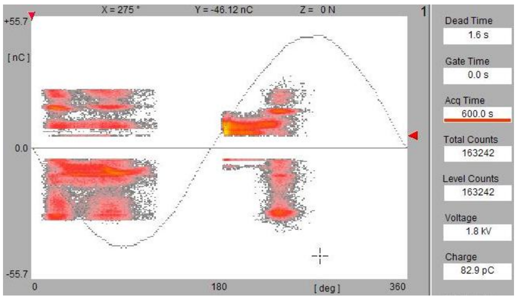
A.11 PEEK3



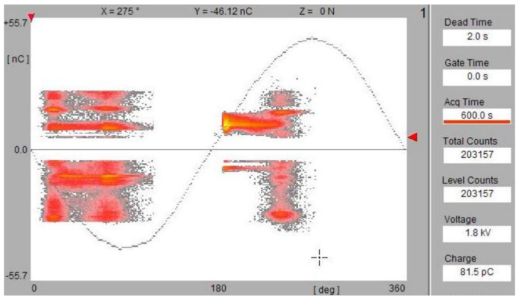
(a) Plot 5.



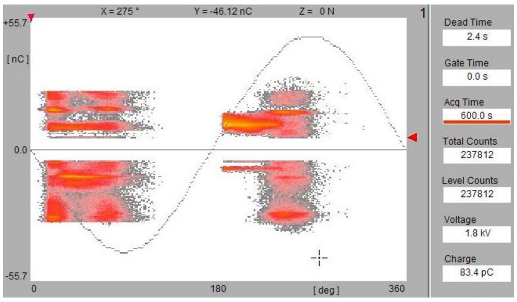
(b) Plot 10.



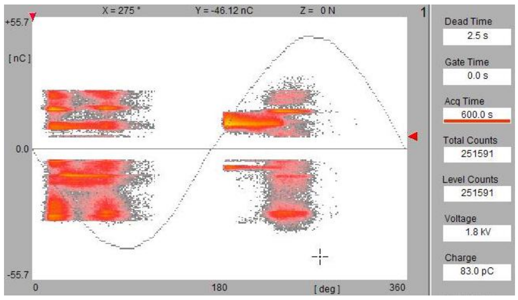
(c) Plot 150.



(d) Plot 260.



(e) Plot 270.



(f) Plot 280.

Figure A.11: Selected plots from PEEK3. Voltage 21.8 kV.