Doctoral Thesis

Pulsed X-ray induced partial discharge measurements

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Pulsed X-ray Induced Partial Discharge Measurements

A thesis submitted to attain the degree of

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(Dr. sc. ETH Zurich)

presented by

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2013
Abstract

The partial discharge (PD) measurement technique is a non destructive diagnostic method for high voltage insulation apparatus. Partial discharges are breakdown phenomena in gas inclusions of insulation which may eventually lead to a total breakdown of the dielectric.

The detection of PDs during post-production quality check of an insulation is difficult mainly because of the statistical time lag, which results from a lack of a start electron. The use of short X-ray pulses (duration 50 ns) has shown to eliminate the statistical time lag by providing start electrons for the partial discharge (PD) development, which makes it possible to detect very small voids at low electric field levels.

This work shows PD measurements on self-produced epoxy samples containing single spherical voids of defined size. The main aim of the experiments was to show how reliable pulsed X-ray induced PD (PRXPD) measurements are on detecting all relevant voids in insulation. Further, the effect of the X-ray dose on the phase resolved PD pattern (PRPD) characteristics through comparing it to natural PD inceptions was investigated. The minimum X-ray dose for PD inception was determined experimentally and general guidelines were given how to implement a PRXPD setup on any HV - equipment.

The principal purpose of the pulsed X-ray induced partial discharge (PXIPD) measurements project is to provide a more comprehensive analysis of the interactions between the X-ray pulse with the gas in the void and the bulk material in order to understand the influence of X-ray pulses on the partial discharge mechanism and its development.
To study the PD mechanism by analyzing the shape of the discharge pulse a time-resolved PD detection circuit was developed (TRXPD). TRXPD measurements with an ultra-wideband detection circuit and a photomultiplier tube allow the comparison of individual PD current pulses from naturally incepted and X-ray incepted voids at different doses and different field strengths.

It is concluded that the method of using ultra-short X-ray pulses to trigger PD is generally applicable and only those voids are triggered that would have incepted naturally with longer waiting times. No particular overvoltage stress is needed to test the insulation system.

Furthermore, the minimum PD inception field for a spherical cavity in transparent epoxy is determined very precisely by applying a single X-ray pulse at different phase angles of the applied ac voltage. It is also shown how this measurement procedure can be used for a deterministic approach of modeling PD activity in spherical voids and determining parameters like effective work function, surface charge decay time, residual field after PD inception and other material characteristics.
Zusammenfassung

Die Teilentladungsmesstechnik ist eine zerstörungsfreie Diagnosemethode für Hochspannungsbetriebsmittel. Teilentladungen (TE) sind Entladungsprozesse in Gaseinschlüssen der Isolation die letztendlich auch zum totalen Durchschlag des Dielektrikums führen können.


Die vorliegende Arbeit zeigt TE-Messungen an selbstproduzierten Epoxidharzproben mit einem einzigen sphärischen Lunker definierter Grösse. Das Ziel der Experimente war zu zeigen wie verlässlich röntgengepulsgetriggerte TE-Messungen (engl. PXIPD) für die Detektion aller relevanten Fehlstellen in einen Dielektrikum verwendet werden können.

Ferner wurde der Einfluss verschiedener Röntgendosen auf die phasenaufgelösten TE Muster durch Vergleiche mit natürlichen (konventionellen, ohne Röntgenstrahlen) TE Mustern untersucht. Die minimale Röntgendosis für den TE-Einsatz wurde experimentell bestimmt und Leitlinien für die Implementierung röntgenpulsgetriggter TE-Messungen an einem beliebigen Hochspannungsbetriebsmittel gegeben.

Um den TE-Mechanismus zu untersuchen wurde ein zeitaufgelöster TE-Messkreis (eng. TRXPD) entworfen, der die breitbandige Detektion und Aufnahme der TE-Pulse als schnelle Stromimpulse möglich

Es wurde gezeigt, dass die Anwendung sehr kurzer Röntgenpul- se bei der TE-Messung generell nutzbar ist und es werden nur die Fehlstellen durch den Röntgenpuls gezündet, die nach genügender Wartezeit auch natürlich zünden würden. Die elektrische Überbelastung des Isolationssystems während einer TE-Messung wird dadurch vermieden, dass keine hohen Feldstärken mehr benötigt werden um den statistischen Zeitverzug zu verkürzen.

Darüber hinaus wurde gezeigt, wie die minimale Einsatzfeldstärke für einen Lunker in Epoxidharz durch die Applikation eines einzelnen Röntgenpulses bei verschiedenen Winkeln der anliegenden AC Spannung experimentell und sehr genau bestimmt werden kann.

Zudem wurde gezeigt, wie die präzise Röntgenpulstriggerung für ein deterministisches TE-Model in sphärischen Lunkern verwendet werden kann und Parameter wie die effektive Austrittsarbeit, die Abklingzeitkonstante der Oberflächenladung, das verbleibende elektrische Feld nach einer TE und andere Materialparameter bestimmt werden können.
Acknowledgments

I am very grateful to my supervisor Prof. Christian Franck for his continuous effort, ideas and encouragement during the whole project duration.

I gratefully acknowledge that I was given the possibility to cast my samples and perform some of the first PD measurements at the ABB Corporate Research. Special thanks to Henning Fuhrmann for helping me through the first steps into the theory of partial discharges and the valuable discussions especially during the minimum X-ray dose measurements. Thanks to Lorenz Herrmann for coordinating the project results between the High Voltage Laboratory and ABB Research Center, the continuous discussions and his contribution in studying the impact of X-ray irradiation on the epoxy bulk characteristics.

To Andrej Krivda I am very grateful for helping me to start the first experiments, for introducing me to the epoxy casting processes and his valuable advice and ideas about improving the PD measurement setup. Thanks to Leopold Ritzer for helping me develop the sample casting method and for the interesting discussions.

I feel very lucky and honored to have had the opportunity to work in a very friendly and professional environment like the High Voltage Laboratory. Special thanks to Karin Sonderegger, Hans J. Weber and Henry Kienast for their continuous support from the very first day I arrived at the HVL.

The project was financially supported by ABB Switzerland (Corporate Research).
List of own publications

Several journal and conference contribution resulted as an outcome of the research in this thesis. The content of selected publications has been integrated in the text of this work. Publication [4] was the basis of section 5. Publication [5] is used in section 6; publication [1] in section 7; [2] and [3] for section 8 and section 9, respectively.


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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CONV. PD</td>
<td>conventional PD measurements, without X-ray</td>
</tr>
<tr>
<td>DSO</td>
<td>digital storage oscilloscope</td>
</tr>
<tr>
<td>NIST</td>
<td>national institute of standards and technology</td>
</tr>
<tr>
<td>PMT</td>
<td>photomultiplier tube</td>
</tr>
<tr>
<td>PRPD</td>
<td>phase resolved partial discharge</td>
</tr>
<tr>
<td>PRXPD</td>
<td>phase resolved X-ray induced partial discharge</td>
</tr>
<tr>
<td>PXIPD</td>
<td>pulsed X-ray induced partial discharge</td>
</tr>
<tr>
<td>TRXPD</td>
<td>time-resolved X-ray induced partial discharge</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>semi-axis length parallel to the electric field in a spheroidal void</td>
</tr>
<tr>
<td>$A$</td>
<td>electrode area</td>
</tr>
<tr>
<td>$b$</td>
<td>semi-axis length perpendicular to the electric field in a spheroidal void</td>
</tr>
<tr>
<td>$B$</td>
<td>parameter in the streamer criterion</td>
</tr>
<tr>
<td>$C_0$</td>
<td>sample capacitance</td>
</tr>
<tr>
<td>$C_d$</td>
<td>capacitance in series with the void</td>
</tr>
<tr>
<td>$C_K$</td>
<td>coupling capacitance</td>
</tr>
<tr>
<td>$C_s$</td>
<td>stray capacitance</td>
</tr>
<tr>
<td>$C_t$</td>
<td>total sample capacitance</td>
</tr>
<tr>
<td>$C_{rad}$</td>
<td>parameter for the interaction of irradiation with gas</td>
</tr>
<tr>
<td>$C_{void}$</td>
<td>capacitance of the void</td>
</tr>
</tbody>
</table>
diameter of a spherical void

distance between sample electrodes

diameter of the measuring electrode

X-ray dose in Sv

$E_{\text{inc}}/U_{\text{inc}}$ PD inception field/voltage

$E_0$ background electric field

$E_{\text{str}}$ streamer inception field

$E_{\text{theor}} = E_{\text{inc}}$ calculated by the streamer criterion,

$E_0$ electric field

residual field in the void when a discharge has ended

field collapse in the void

electric field caused by the X-ray pulse in the bulk dielectric

pressure reduced critical field for streamer development in a gas

electric field enhancement factor

electric field in the void

charge magnitude distribution of PD rate

ac phase distribution of PD rate

ambient dose equivalent

measured X-ray dose

apparent discharge current

X-ray intensity

 capacitive current between the sample electrodes as a results of X-ray pulse
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>proportionality constant for the dosimeter</td>
</tr>
<tr>
<td>$K_c$</td>
<td>correction factor for the dosimeter</td>
</tr>
<tr>
<td>$K_{\text{crit}}$</td>
<td>natural logarithm of $N_{\text{crit}}$</td>
</tr>
<tr>
<td>$K_R$</td>
<td>proportionality constant for calculating $N_e$ given by the definition of Röntgen</td>
</tr>
<tr>
<td>$l_{\text{min}}$</td>
<td>minimum length within a void for an avalanche to develop into a self sustained discharge</td>
</tr>
<tr>
<td>$n$</td>
<td>parameter in the streamer criterion</td>
</tr>
<tr>
<td>$N_{\text{crit}}$</td>
<td>critical number of electrons for a streamer to develop</td>
</tr>
<tr>
<td>$N_e$</td>
<td>number of start electrons</td>
</tr>
<tr>
<td>$\dot{N}_{\text{e rad}}$</td>
<td>rate of first electron production by irradiation</td>
</tr>
<tr>
<td>$p$</td>
<td>gas pressure in a void</td>
</tr>
<tr>
<td>$q$</td>
<td>PD charge magnitude in picoCoulomb</td>
</tr>
<tr>
<td>$q_{\text{induced}}$</td>
<td>induced discharge magnitude on the sample electrodes</td>
</tr>
<tr>
<td>$q_{\text{real}}$</td>
<td>real discharge magnitude in the void</td>
</tr>
<tr>
<td>$q_s$</td>
<td>surface charge magnitude</td>
</tr>
<tr>
<td>$\Delta Q$</td>
<td>total induced charge on sample electrodes due to the X-ray pulse</td>
</tr>
<tr>
<td>$r$</td>
<td>radius of the void</td>
</tr>
<tr>
<td>$R_D$</td>
<td>damping resistance</td>
</tr>
<tr>
<td>$R_m$</td>
<td>measuring resistance</td>
</tr>
<tr>
<td>$s$</td>
<td>distance between X-ray source and the void in the sample</td>
</tr>
<tr>
<td>$V$</td>
<td>ionization chamber Volume of the dosimeter</td>
</tr>
</tbody>
</table>
**$V_{\text{eff}}$**  
effective void volume, within which a start electron may develop into a discharge

**$x_{\text{crit}}$**  
critical path length for a streamer to develop

**$x_i$**  
thickness of the attenuation material

**$Z_m$**  
measuring impedance

**$\alpha$**  
opening angle relative to main direction of the X-ray beam

**$\bar{\alpha}$**  
effective gas ionization coefficient

**$\epsilon_0$**  
permittivity of vacuum

**$\epsilon_r$**  
relative permittivity of the dielectric

**$\eta$**  
gas attachment coefficient

**$\gamma$**  
factor to calculate $E_{\text{res}}$ for pos. und neg. streamers

**$\kappa_s$**  
surface conductivity of the bulk dielectric

**$\mu$**  
linear attenuation coefficient for X-rays

**$\nu$**  
overvoltage factor, ratio of the applied voltage to inception voltage

**$\Phi_{\text{rad}}$**  
quantum flux density of ionization by irradiation

**$\rho$**  
density of the gas

**$\sigma$**  
photoconductivity of the bulk dielectric

**$\tau_{\text{st}}$**  
statistical time delay for the first-PD

**$\tau_{\text{tr}}$**  
effective lifetime of an electron in a trap
1 Introduction

Partial discharge (PD) diagnostic is an important quality check for the insulation of high voltage equipment. The sources of PD are mostly imperfections and cavities in the insulation material resulting from the manufacturing process or due to mechanical or electrical stresses during operation. PDs are gas discharge events in a cavity which may lead to material degradation and eventually to a total breakdown of the insulation.

Their initiation occurs only if two conditions are met, namely if the electric field in the cavity exceeds a minimum inception value $E_{\text{inc}}$ and a start electron is available.

The conventional PD measurement technique according to IEC-60270 [IEC00] is a well-established method, but encounters problems like correct PD data representation and detection sensitivity. Although substantial progress has been made on the detection sensitivity during the past decades, one fundamental problem remaining is the statistical time lag.

The statistical time lag results from a missing start electron and is a time dependent probability function which depends strongly on the void size. Natural irradiation may directly provide first electrons by volume ionization (gas ionization in the void) or by the surface photo effect, which releases electrons from the void surface [Nie95, GN95, Bog90, Hei98, CCMM05]. Experiments have shown that the statistical time delay is in the order of 30 minutes for $d = 1\, \text{mm}$ and around 3 days for $d = 200\, \mu\text{m}$ [Nie95]. This is especially problematic for factory outgoing or commissioning tests, where measurement time is limited. Another first electron supply mechanism is the field assisted electron detrapping from the void surface, but this is negligible in voids with no previous PD activity. Conventional
PD measurements make use of high ac overvoltage to increase the probability of start electron production and to initiate PD in voids, but overstressing of the insulation may result in irreversible damage of the healthy parts of the insulation.

In order to eliminate an inception delay and avoid applying an overvoltage to the test equipment, in the last decades it was tried to artificially provide start electrons in a void during a PD measurement, e.g. by using the ionizing radiation of X-rays [FN92, FRB92, SSFR06, FRT10]. However, in [FRB92] a strong influence of continuous X-ray irradiation on the partial discharge mechanism and pattern was observed. High continuous X-ray doses even inhibited PD in voids.

The pulsed X-ray induced partial discharge (PD) measurement (PXIPD) technique uses very short X-ray pulses (50 ns) to supply start electrons for PD initiation and thus eliminating the statistical time-lag. The gas in a cavity is ionized, while the ac voltage is applied and the PD activity is detected immediately after the decay of the X-ray pulse [SSFR06, FRT10, AFF10]. In this way the unwanted interaction of a continuous X-ray beam with the PD is avoided. These first PXIPD experiments have been successfully used to detect PD both on laboratory samples and real GIS insulators.

A more detailed and advanced study of the applicability of PXIPD to HV-insulation is presented in [AFSH11, AF12, AHF13, AF13]. These later publications have emerged from the work presented here.

This work shows PRXPD (phase-resoed X-ray induced PD) and TRXPD (time-resolved X-ray induced PD) measurements on self-produced epoxy samples containing single spherical voids of defined size. The main aim of the experiments is to show how reliable PRXPD is on detecting all relevant voids in insulation. Further, the effect of the X-ray dose on the PD characteristics through comparing it to natural PD inception is investigated. The minimum X-ray dose for PD inception is determined experimentally and general guidelines are given how to implement a PRXPD setup on any
HV - equipment.

TRXPD measurements with a triggerable X-ray source offer the possibility to apply start electrons (X-ray pulse) at different phase angles of the ac voltage. By doing so one can determine the minimum inception field of a spherical void very precisely and the effect of the electric field in the void at the moment of inception for different field levels \((E < E_{inc} \text{ and } E \geq E_{inc})\) can be studied.

After presenting a theoretical background about PDs and the interaction of X-rays with solid materials and gas molecules in section 2, the used different experimental setups and equipment are described in section 4.

In section 5 the first PXIPD measurements with laboratory samples in insufficiently degassed filled epoxy are shown. They contain spheroidal shaped voids with one-sided contact to the electrode. These first measurement proved the usability of the pulsed X-ray source and were not analyzed further. As the main focus of this work, later self produced samples of transparent epoxy with spherical voids of defined size were produced and a special measurement procedure was defined to perform PRXPD measurements. The results are given in section 6.

In section 7 it is shown how a pulsed X-ray source can be reliably integrated into a conventional PD measurement system. The minimum X-ray dose for PD inception in spherical voids is experimentally determined and verified theoretically. To do so, both the interaction of X-rays with gas molecules and the attenuation phenomena of X-rays by solid matter was taken into consideration.

In section 8 the effect of the X-ray dose on the triggering and the discharge mechanism is investigated by TRXPD current measurements with an ultra-wideband detection circuit and a photomultiplier tube. A comparison of PD pulses incepted by X-ray in different doses to PD pulses incepted naturally was made according to defined criteria like rise-time, pulse-width and peak current.

Section 9 is an extension of the investigations in section 8 where the influence of the overvoltage on the PD mechanism at the time
instant of X-ray pulse application is investigated. Furthermore, the advantages of this measurement technique on establishing a generally valid PD model are presented. It allows the semi-deterministic approach of PD modeling which enables a better estimation of important PD parameters necessary for the validation of PD models. Parameters like the time delay between subsequent PDs, the residual electric field after PD occurrence and other parameters can be determined more precisely. This is possible because of the controlled inception of the first-PD by X-ray and the definition of the minimum inception voltage very precisely.
2 Theoretical Background

2.1 Partial discharges

For a PD to develop in a void the following two conditions must be fulfilled simultaneously:

- the electric field in the void must exceed the minimum inception field strength $E_{inc}$
- a free electron has to be available.

Once a first free electron is available and the electric field is sufficiently high, it is accelerated and by ionization processes produces an avalanche. When this avalanche reaches a certain electron density, it becomes self-sustained which leads to a total breakdown of the electric field strength in the cavity. This discharge deploys charges (electrons and ions) on the cavity surface which may serve later as initiatory electrons for the next discharge. This is especially the case for ac voltages which is the topic of the present study.

The breakdown mechanism in gases has been the subject of study of several authors [GMTrd,MC78,Rae64,CKP70,PMCV84,KZK00]. They investigated the breakdown mechanism in short gaps with metallic boundaries for different gases and developed a threshold criterion, usually called streamer criterion:

$$\int_{0}^{x_{\text{crit}}} \bar{\alpha} \left[E(x)\right] \, dx \geq \ln N_{\text{crit}} \geq K_{\text{crit}},$$

(2.1)

where $\bar{\alpha}$ is the effective ionization coefficient (first Townsend coefficient), $E(x)$ is the electric field along the streamer path and $K_{\text{crit}}$
is the logarithm of the critical number of electrons $N_{\text{crit}}$ that an avalanche has to reach to develop into a self-sustained discharge. The integration is within $x_{\text{crit}}$, that is the distance within which $\bar{\alpha}$ exceeds zero.

In a spherical void inside a homogeneous background field, the electric field is homogeneous and $\bar{\alpha}$ can be assumed as constant. Equation (2.1) is thus simplified to:

$$\bar{\alpha}x_{\text{crit}} \geq \ln N_{\text{crit}} \geq K_{\text{crit}}.$$  \hfill (2.2)

The value of $K_{\text{crit}}$ depends very much on the type of the gas. The obtained $K_{\text{crit}}$ are empirical values from discharge experiments in gas gaps with metallic boundaries and vary between $\approx 19.8$ [MC78] and around 15 in [KZK00].

These studies were extended later and measurements were performed on gas gaps between dielectric surfaces [Dev84, HBW93, Bar08, Mor93].

In [CKP89] the same criterion is applied to dielectric bounded voids of spherical and spheroidal shape and a value of $K_{\text{crit}} = 9$ is obtained. The streamer criterion is then simplified to the following relation by taking $x_{\text{crit}} = d$ ($d$ is the diameter of the spherical void) the minimum inception field $E_{\text{inc}} = E_{\text{str}}$ can be determined and will be considered in this work as the streamer criterion [CKP89]:

$$fE_0 > E_{\text{str}} = (E/p)_{\text{crit}} p [1 + \frac{B}{(pd)^n}],$$ \hfill (2.3)

where $E_0$ is the applied background field (see figure 2.1). For air $(E/p)_{\text{crit}} = 25 \text{ V/(Pa m)}$, $B = 8.6 \text{ m}^{1/2}\text{Pa}^{1/2}$ and $n = 0.5$. $f$ is a factor that quantifies the field enhancement in the void and depends on the void shape and the permittivity $\epsilon_r$ of the surrounding bulk material [CKP89,Nie95]. For a spherical void within a homogeneous background field, the field in the void is enhanced by the factor:
\[ f = \frac{3 \epsilon_r}{1 + 2 \epsilon_r}. \] (2.4)

For epoxy (\(\epsilon_r \approx 4\)) \(f \approx 1.33\). \(p\) is the pressure in the void and is typically assumed to be in the range of \(p = 50 - 100\) kPa [GN95, BG89]. For spheroidal shaped voids the field parallel axis of the void is to be considered (see section 4.1).

Once the minimum inception field is reached in the void (\(fE_0 \geq E_{\text{inc}}\)) the second criterion necessary for a discharge to develop is the production of a start electron.

For voids in a solid insulation there are two first electron generation mechanisms, namely radiative ionization and surface emission from the cathodic void surface.

Natural irradiation (high energetic quanta of background and cosmic irradiation) may release a free electron by photoionizing the gas in the void (volume ionization) or by photoionization in the bulk material of the void and the subsequent escape of the photoelectrons into the gas volume.

Figure 2.1 a) depicts the main first electron production processes. The application of X-rays like the natural irradiation may ionize the gas volume and produce first electrons or it may ionize the surface of the void.

In [CP86] it is stated that the escape depth of photoelectrons generated in the material is small (\(\leq 10\) nm) so it is the volume ionization which is the dominant effect.

The surface emission mechanism includes also the field emission of electrons by high electric field strengths and in regions where where the effective work function of the bulk material is low. This is, however, considered to be negligible for epoxy surfaces because of the very high work function of smooth surfaces [ZBC$^+$87]. Once a first PD has developed in a void, additional surface emission effects become active, like detrapping of electrons from the insulator surface and electron release by ion impact [Nie95].
Theoretical Background

\[ f \cdot E_0 \]

\[ V_{\text{eff}} \]

\[ \text{gas molecules} \]

\[ \text{trapped electrons} \]

\[ \text{X-ray} \]

\[ \text{nat. irrad.} \]

\[ f \cdot E_0 \]

\[ E_0 \]

\[ \text{epoxy} \]

\[ \text{volume ionization} \]

\[ l_{\text{min}} \]

\[ d \]

\[ E_0 \]

\[ \text{surface emission} \]

\[ \text{epoxy} \]

\textbf{Figure 2.1:} X-ray application and first electron production processes in a void in solid insulation. \( E_0 \) is the background field, \( fE_0 \) the field inside the void and \( V_{\text{eff}} \) is the effective volume for first electron production.

Both photoionization of the gas volume and surface emission are stochastical processes and the rate at which electrons are produced in a cavity depends very much on the size of the void in the insulation and the strength of natural irradiation.

However, experiments made with epoxy have shown that the inception delay (statistical time lag) corresponds to the electron production rate by volume photo ionization \([\text{ZBC}^+87]\). Considering the small surface-to-volume ratio in small spherical voids, volume ionization is more plausible to happen. For voids which a direct contact to a metallic electrode, field emission may be more relevant at high electric fields.

For a void in a newly produced insulator which has not been subject to electrical stress and PDs, it is most likely that the first
2.1 Partial discharges

electron will be provided by natural irradiation [Nie95, CCMM05], i.e photoionization of the gas in the void.

In [WNP+88, NFG91] the average rate is given by which photoelectrons in a gas volume are produced by natural irradiation:

\[
\dot{N}_{e \text{ rad}} = C_{\text{rad}} \Phi_{\text{rad}} \rho \pi r^2 (d - l_{\text{min}}) ,
\]  

(2.5)

\[
(C_{\text{rad}} \Phi_{\text{rad}})_{\text{nat}} \approx 2 \times 10^6 \text{ kg}^{-1} \text{s}^{-1} ,
\]  

(2.6)

where \(C_{\text{rad}}\) characterizes the interaction between radiation and the gas in the void, \(\Phi_{\text{rad}}\) is the quantum flux density of the radiation, and \(\rho\) is the density of the gas. The rate at which electrons are produced in the gas volume depends on other parameters too, like the gas ionization coefficient \(\alpha\) and recombination and attachment coefficient \(\eta\).

The last part of the equation (2.5) represents the part of the gas volume within which electrons become effective in triggering a PD, since the avalanche started by a first electron needs the minimum path length \(l_{\text{min}}\) (the critical path length) in order to fulfill the streamer criterion. This is also shown in figure 2.1 b).

In [GN95] \(l_{\text{min}}\) is obtained from the streamer criterion:

\[
l_{\text{min}} = \left[ \frac{B}{\left( \frac{E}{E_{\text{crit}}} - 1 \right)} \right]^{\frac{1}{\pi}} / p ,
\]  

(2.7)

from which the “effective volume” can be calculated [Nie95]:

\[
V_{\text{eff}} \approx \frac{4}{3} \pi (d/2)^3 (1 - \nu^{-\beta}) ,
\]  

(2.8)
where $d$ is again the void diameter and $\nu = U_0/U_{\text{inc}}$ the ratio between the applied voltage and inception voltage, which later will be referred to as “overvoltage ratio”. The exponent $\beta$ is a relevant parameter in the streamer criterion and for the case of gas epoxy interface is taken to be $\approx 2$ [Nie95].

For the reasons mentioned above, the first electron is a statistical process and always connected to a statistical time lag [GN95, Nie95, Bog90, CCMM05]. Experiments have shown that it is in the order of 30 minutes for $d = 1$ mm and around 3 days for $d = 200 \mu$m [Nie95]. The measurement procedure for factory outgoing test and online PD measurements according to IEC 60270 [IEC00] gives a test time of 1 minute. Thus even voids of diameter $\geq 1$ mm may remain undetected during PD tests and develop PD during operation.

### 2.2 PD measurement and detection

A void in an insulation was modeled as a spark gap in a capacitive network by Gemant and Philippoff in 1932 [GP32]. The void represents a capacitor which in case of a breakdown causes a voltage drop on the electrodes of the test object. This voltage drop is very small compared to the applied voltage on the sample and is difficult to measure. It is accompanied by a displacement current which can be measured with the setup shown in figure 2.2. The conventional PD measurement technique is based on the classical capacitive network model and on the setup of figure 2.2, i.e. on measuring the displacement current $i_{\text{app}}$ [IEC00, Kre89, BBMZ86, CKP89, Bog90].

The test object is connected parallel to a coupling capacitor and the displacement current is recorded as a voltage pulse on the measuring impedance $Z_m$ (coupling device according to [IEC00]). The measuring impedance can be installed either in series to the coupling capacitor or the test object. The coupling capacitor, the sample and the measuring impedance provide a low impedance path with high frequency characteristics because PDs are high-frequency currents. The damping resistor $R_D$ serves as a current limiter in case of a total
breakdown of the test sample and also as a high impedance path for the PD current. In this way the fast PD current flows between $C_k$ and $C_t$.

There are two main methods of PD detection based on the setup in figure 2.2 which have been of practical and scientific interest:

- conventional PD measurement setup for routine tests and monitoring of electrical equipment (mostly phase resolved PD representation - PRPD)

- time resolved PD measurement setup for fundamental studies of PD physical characteristics (use of digitizing oscilloscopes)

The difference between the systems is the acquisition bandwidth and registration of PDs. The conventional PD measurement setup
uses a system of some hundreds of kHz bandwidth. Here the PDs are mostly “quasi integrated” by a low-pass and the amplitude of the voltage (peak level indicator) is taken as proportional to the PD charge, called the apparent charge [Küc09].

The time-resolved measurement uses detectors with bandwidth of some MHz and the temporal development of the PD current pulses is displayed. By integration of the current pulses the PD charge magnitude may be calculated. The time constant of the system has to be very small, which is very much influenced by the stray capacitance ($C_s$, see figure 2.2) in a conventional PD measurement system. For the conventional PD setup this is not important but it has to be decreased/avoided for the time-resolved setup (details in section 4.6).

The induced charge on the electrodes of the test sample is called the “apparent charge” and is much smaller than the real charge in the void [Küc09, Kre89, BBMZ86]. What is detected on the electrodes of the test sample is not the moved charge in the void but only its effect on the electrodes.

The Gemant and Philippoff capacitive network model of the void does not represent the electrodynamic effects of the discharge correctly, because a void cannot be represented as a capacitor. Later, field-theoretical analysis of the relation between the physical charge process and the induced PD signal on the electrodes was done in [CKP89, PCM91, PCM95]. Spherical and spheroidal voids in a homogeneous background field were analysed and the relation between the dipole moment of the charges moving in the void and the induced charge were given. A recent comparison of the Gemant and Philippoff model with the dipole model was done by Lemke [Lem12]. It is concluded that the “apparent charge” detectable at the terminals of the test object is well correlated with the dipole moment established at the partial discharge site and thus the PD severity.

Nevertheless, the capacitive network model is well accepted and makes it easier to calculate the charge transfer [Kre89, BBMZ86, Küc09, Kre91]. It is also accepted as the indicator of the PD intensity
2.2 PD measurement and detection

because it reflects the energy dissipated during the discharge related to the size of the void [Küc09, Kre91]. The author refers to the mentioned literature for more detailed discussion.

The role of the coupling capacitor is also important for the sensitivity of the system, and the relation $C_K \gg C_t$ has to be valid. Additionally, calibration of the whole setup together with the measurement system has to be done [IEC00, Kre89, BBMZ86].

The conventional measurement technique has been constantly improved in terms of PD data recording and interpretation. In the so-called “phase resolved PD pattern”, short PRPD, the PD pulses are displayed as $(q, \phi)$, i.e. the individual discharge magnitude as “apparent charge” $q$ relative to the phase angle $\phi$ of the ac voltage and their frequency of occurrence.

For the PRPD measurements in this work the conventional system is used as described in section 4.5. The time-resolved measurement setup is shown in section 4.6.

Partial discharges are gas ionization phenomena which emit light. If there is optical access to the PD source (transparent epoxy resin, gas gap with metallic boundaries etc.) the light emitted can be captured by a photomultiplier tube or a sensitive camera [LM81, CDS94, Dev84, Mor93]. The time-resolved PD measurements performed in this work include also the optical detection of PDs as shown in section 4.6.

2.2.1 PD charge

A PD in a spherical void with a diameter $d$ causes a voltage breakdown in the void and deploys the charge $\pm q$ on its walls (cf. figure 2.3). During this process it also produces acoustic waves, light, heat and chemical products.

The electric field in the void $E_{\text{void}}$ (cf. figure 2.3) at any time consists of two contributions, namely the field $fE_0$ due to the background field ($E_0 = U_{\text{applied}}/D$, $D$ is the sample gap distance) inside the void and the field $E_q$ due to the surface charges which remained from the previous PD.
Theoretical Background

Field strength inside the void after a PD

\[ E_{\text{void}} = f E_0 - E_q, \quad E_{\text{res}} = 0 \]

Figure 2.3: Charge deployment on the void surface after a PD and associated electrical fields. \( E_{\text{void}} \) is the resulting electric field inside the void, i.e. the sum of the field \( fE_0 \) caused by the applied background field \( E_0 \) and the field \( E_q \) caused by the dipolar charges on the void resulting from the PD.

When a PD occurs, \( E_{\text{void}} \) collapses down to a residual field \( E_{\text{res}} \) below which the discharge extinguishes. This gives the field collapse \( \Delta E \) and it can generally be expressed as follows:

\[ \Delta E = f E_0 + E_q - E_{\text{res}}, \quad (2.9) \]

where also the polarity of \( E_q \) has to be considered.

\( E_{\text{res}} \) is a characteristic of the streamer-like discharge mechanism [CKP89] and is proportional to the critical field of the gas:

\[ E_{\text{res}} = \gamma (E/p)_{\text{crit}} p. \quad (2.10) \]

It gives the residual electric field in the void immediately after the total breakdown of the void gap. \( \gamma \) is a dimensionless factor and for air it has the value \( \gamma_+ \approx 0.2 \) for positive streamers and \( \gamma_- \approx 0.5 \) for negative polarity streamers [Nie95]. (\( \gamma \) in this case does not refer to the Townsend secondary ionization coefficient as mostly used in the studies of the discharge mechanism).
2.2 PD measurement and detection

![Figure 2.4: Electric fields in the void and individual PDs distribution as phase resolved PD (PRPD) pattern shown for the first 3 ac half-waves. The first-PD may be initiated by an X-ray pulse, natural irradiation or surface emission. Important void parameters like statistical time delay $\tau_{st}$, $E_{res}$ and overvoltage factor $\nu$ are shown.](image)

We have found a better agreement of the experimental results and the PD model using $\gamma_{\pm} \approx 0.2$ (see section 9.5).

The magnitude of this discharge is directly related to the field collapse in the void [Nie95]:

$$q_{\text{real}} = \epsilon_0 \pi b^2 \left[ 1 + \epsilon_r (K - 1) \right] \Delta E ,$$  \hspace{1cm} (2.11)

Where $K = 3$ for spherical voids and is a dimensionless factor [CKP89]. The induced or apparent charge is

$$q_{\text{induced}} = -4/3 \epsilon_0 \epsilon_r \pi a b^2 K \Delta E \nabla \lambda_0 .$$  \hspace{1cm} (2.12)

For spherical voids $a = b = d/2$. The factor $\nabla \lambda_0$ is in case of plan...
parallel electrodes with gap distance D (see used sample geometry in section 4.1) simplified to $\lambda_0 = 1/D$. It is a dimensionless scalar field that describes the coupling of the void to the electrode at which the PD signal is measured [CKP89].

The surface charge field is directly proportional to the charge deployed by the discharge [Nie95]:

$$E_q \propto q_s.$$  \hfill (2.13)

The magnitude of the surface charge is directly proportional to the field collapse at the time of PD occurrence and can be written for spherical voids [GN95]:

$$q_s = \varepsilon_0 \pi (d/2)^2 \left[1 + 2\varepsilon_r\right] \Delta E,$$  \hfill (2.14)

where $\varepsilon_0$ is the vacuum permittivity and $\varepsilon_r$ is the relative permittivity of the bulk epoxy.

Figure 2.4 gives an insight into the changes of the electric field in the void when PDs occur and their phase distribution. The statistical time-lag is shown and the definition of the “overvoltage factor” is made graphically. The first 4 PDs are shown, where the first-PD is in this case incepted at the positive voltage peak. The subsequent PDs incept as soon as $E_{\text{void}}$ reaches the minimum inception field $E_{\text{inc}}$, at some cases with slight time-delay.

### 2.2.2 Charge deployment and charge decay

After a first PD has occurred, discharge electrons are injected in the anodic void surface and are available for a next discharge at field reversal. However, some of these trapped charges may diffuse into energetically deeper traps [GN95] or in the depth of the insulating material so that they cannot be detrapped at field reversal. This loss of electrons is roughly accounted for by an exponential decay
2.2 PD measurement and detection

The term \( \exp\left(-\frac{t}{\tau_{tr}}\right) \), where \( \tau_{tr} \) is a time constant giving the effective lifetime of an electron in a detrappable trap.

Another phenomenon occurring is that the deployed charges by a PD which are not detrapped have a limited lifetime mainly because of conduction along the insulator surface but also ion drift [Nie95]. This depends on the conductivity of the void surface and studies [Mor93, Mor05, HBW90] have shown that the surface conductivity increases with time and during the PD event. This surface charge decay is dependent not only on the surface conductivity \( \kappa_s \), but also on the geometric dimensions of the void [Nie95].

Niemeyer [NFG91] describes also the rate at which dipolar charge decay in a spherical void in dependence of surface conductivity and the voltage drop across the void:

\[
-\frac{dq}{dt} = \left(\frac{\pi}{2}\right) \kappa_s E d,
\]

\( E \cdot d \) is the instantaneous potential drop along the void, and \( \pi/2 \) a geometry factor.

Surface conductivity measurements of epoxy specimen subjected to PD were made at [HBW90]. For non-aged virgin samples the characteristic surface conductivity was found to be smaller than \( 10^{-16} \, (\Omega \, \text{cm})^{-1} \). Surface conductivities in the range of \( 10^{-12} \, (\Omega \, \text{cm})^{-1} \) and \( 10^{-11} \, (\Omega \, \text{cm})^{-1} \) were measured not long after the PD activity had started, in the range of minutes. It was also found that with time the average discharge magnitude decreased to a limiting value, indicating in the number of small amplitude discharges.

In [GN95, FG58] it was observed that in dielectric voids after some hours of PD exposure the PD rate decreased. Indications about the same effect can also be found at [Mor93, Mor05, HBW90]. In [Mor93] the samples used were flat cylindrical cavities in polyethylene with a high ratio of \( D/h \). However, in spherical voids where the \( D/h \) ratio is \( \approx 1 \) there may be additional effects that lead to charge decay.

According to [Nie95] charge decay along the void walls would have
various effects on the statistical PD characteristics by reducing the number of PD events per half cycle, change the PD charge magnitude and phase correlation of the pulses with the ac voltage.

Using the above equation the critical value of surface conductivity $\kappa_s$ can be derived above which the charge deployed by a PD decays before the next AC half period. In [Nie95] this was calculated for spherical voids in the mm range and estimated to be in the order of

$$\kappa_s \approx 5 \times 10^{-13} \text{ (}\Omega\text{cm})^{-1},$$

(2.16)

The charge deployed by a first PD in a virgin void is available for many ac half periods and causes a higher pulse rate of PD than in voids that have had PD activity for a certain time.

In this work mainly the initial stage of PD activity is investigated. The development of PD patterns in time are of only minor interest. Nevertheless, as will be shown in section 6, even after short PD activity of a void the above mentioned effects can be partly observed.

### 2.3 Review of X-ray use in PD measurements

First reports on X-ray application to PD detection were published in the 60’s [Mol67], but here X-rays were used to suppress PD activity and by this to locate the region of defect. An attempt to initiate PD with X-ray was made towards the end of the 80’s at Ontario Hydro [RFS88, BRFF91, FRB92]. Here, continuous X-ray irradiation was used and the measurements were performed on real GIS insulators with defined artificial defects. PD patterns were registered by conventional PD measurement equipment, and also wide-band measurements (400 MHz) of the PD pulses were performed by direct PD current measurements. The statistical time lag was eliminated and PDs were detected at low voltages. However the applied X-ray beam directly affected the height/phase distributions and patterns. They were narrowed and at overrated X-ray doses PDs were sup-
pressed completely [BRFF91, FRB92]. It was concluded that the X-ray beam ionized the gas in the cavity to the point of conductivity, thus shielding the electric field.

Niemeyer et al [FN92] used continuous X-rays for PD inception at artificially produced spherical voids ($d \approx 0.2 \text{ mm}$) in transparent epoxy. Small spherical voids showed PD only during X-ray application, thus no sustainable PD development was possible without X-ray for voids of this size. The same effects were observed for a spherical void of 0.6 mm diameter in [SSFR06].

2.4 PD mechanism - discharge types

For many decades the physical nature of PDs in cavities surrounded by a dielectric has been subject of study. This is important not only because of fundamental scientific interest but also due to the fact that the characteristics of the PD detection system have to be adjusted to the physical nature of PDs in order to be able to detect them [BN93].

An overview of the experience and the related phenomena to partial discharge mechanism is given in [Dev84, BN93, Mor93, Her94, HBW93, BN95, Bar05, Bar08, HBFS91, BLT89, CKP89].

Generally, two types of discharges have been observed: Townsend-like discharges and streamer-like discharges. Streamer-like discharges are considered to be the dominant PD mechanism as they have higher charge pulses and are easier to detect with conventional measurement systems. This is also valid for our measurements shown here. The streamer-model given in [CKP89, Bog90, GN95, Nie95, MK90] has shown to describe well the initial stage of PD in spherical or spheroidal voids.

Morshuis [Mor93] has shown by time resolved measurements that there are three stages of charge development in a flat cavity. These observations were also supported by microscopic images of the discharge surfaces, showing surface degradation and oxidation products after a time of PD activity.
At virgin voids the detected PD pulse shape is a streamer like discharge with characteristic steep front of some hundreds of picoseconds up to a few nanoseconds and amplitude of some tens of mA. After 10 to 60 minutes of discharge activity a change in the discharge mechanism was observed. The new discharge “Townsend like” was a slower discharge with a longer pulse rise time of several tens of nanoseconds. The discharge current has a broad pulse width proportional to the height of the void. Optical images also showed that the Townsend like discharge covers a greater part of the void surface and is a diffuse process. Since this discharge type has a lower amplitude, only hundreds of µA, they may remain sometimes undetected by conventional PD equipment [HBW90].

The chemical degradation of the void surface is not the topic of the present experiments but it is important to mention since these chemical degradation is believed to be the cause for the discharge mechanism change. This change makes it difficult to detect PD at every stage of aging PD measurements. Niemeyer [GN95] also observed a change in the PD rate after some hours of PD activity.

However, the measurements with spherical voids shown in section 6 seem to confirm this, especially for smaller voids in the range of ≤ 1 mm, here the PD seem to show a much lower PD rate and sometimes fully extinguish at the 2\textsuperscript{nd} or 3\textsuperscript{rd} session.

The temporal and spatial resolution of individual PD pulses in epoxy voids was measured in [HBFS91] by both electrical and optical means. It was observed that the optical images had duration times around 10 ns for streamer-like discharges, which had an electrical pulse of pulse-width < 1 ns. This was observed in the measurements shown in section 8 and 9, too.

The electroluminescence processes taking place in a discharge have been mostly studied with respect to their spectral characteristics [TB85, PSS00, TCL\textsuperscript{+}98, ATL\textsuperscript{+}09], but precise data about the duration of these individual processes is missing. It is generally known during ionization events in a gas, processes like photoluminescence and radiative recombination take place [TCL\textsuperscript{+}98]. The
2.5 X-ray attenuation

Electroluminescence is very much related to the gas type and other parameters like temperature and electric field. The precise study of the temporal character of these processes would require a focused research and would be a topic of advanced gas physics.

2.5 X-ray attenuation

An X-ray generator is usually a point source radiating radially outwards and forming a cone with an opening angle $\alpha$. The intensity decreases with the inverse-square of the distance to the source. At the same time the intensity decreases as it interacts with matter due to scattering and photoelectric effect.

The attenuation of a narrow X-ray beam with mono-energetic photons can be described by the Lambert-Beer law with the attenuation coefficient $\mu$, or the mass attenuation coefficient $\mu/\rho$ in units of cm$^2$/g (see figure 2.5). The mass attenuation coefficient for metals that are commonly used in electric power equipment is shown in figure 2.6. It decreases strongly with increasing X-ray photon energy and is around three orders of magnitude smaller for 100 keV photons.

**Figure 2.5:** X-ray beam cone and attenuation phenomena; $I_{1,2,3,4}$ is the X-ray intensity at different points; $\mu$ is the linear attenuation coefficient.
compared to 10 keV photons. In case the X-ray beam penetrates a layer of multiple different materials (index $i$), the transmitted intensity is calculated by considering the individual absorption of each material and its thickness.

For normal X-ray sources with a non mono-energetic energy spectrum, the attenuation has to be calculated by integrating over the energy spectrum. For simplification purposes, or if the full energy spectrum of the X-ray source is not known, only a few discrete energy bands (index $k$) can be treated. If $I_0$ is the initial X-ray intensity, then the intensity $I$ after penetrating a certain number of different materials (index $i$) with thickness $x_i$ is calculated by:

$$I = \sum_{k} I_{0k} \exp \left( - \sum_{i} (\mu_{ki} x_i) \right).$$  \hspace{1cm} (2.17)
Figure 2.7: Schematic (simplified) representation of a solid insulated cable with two defects.

An X-ray source typically shows a strong angular emission characteristic which has to be taken into account (see figure 4.4). In the example of figure 2.7, void $B$ may see a lower X-ray dose than void $A$ though there is less absorption along the line of sight.
3 Aim of this Work

The principal purpose of the pulsed X-ray induced partial discharge (PXIPD) measurements project is to provide a more comprehensive analysis of the interactions between the ultra short X-ray pulse with the gas in the void and with the bulk material.

The main practical goal of the project is to investigate how a pulsed X-ray source can be used to reliably trigger partial discharges in insulation voids of sub-millimeter size in a way that a PD signal is detectable and the void can be identified. Moreover, only those PD shall be detected that would have incepted naturally at any time during the service life of the insulation in the field.

Thus, the following parameters have to be varied systematically and their influence on PD inception and activity has to be investigated:

a) Radiation dose
b) Void size
c) Insulator material
d) Test voltage (rms value of the voltage applied to the sample)
e) Inception voltage (current value of the voltage on the test sample at instant of X-ray pulse) and corresponding phase angle

The mentioned studies are to be achieved by the following steps:

- Production of test samples with known void shape and size in clearly defined homogeneous field configuration. The production process should be as close as possible to the production process of real solid insulators.
• Phase and Time-Resolved PD measurements with the self produced samples

• Statistical modeling of the PD inception behavior
4 Experimental Setup

4.1 Samples

Two types of samples with the same geometry but different kind of voids were produced for the PXIPD measurements. Sample type A is shown in figure 4.1. They were used or the first PXIPD measurements shown in section 5. They contain spheroidal shaped voids with one-sided contact to the electrode. There was a total of 36 samples of type A. Two rod shaped electrodes were casted in filled epoxy resin, with an electrode distance of 2 mm. By insufficient degassing before the gelation process naturally created delaminatin-like voids occured. The other dimensions are given in figure 4.1.

![Figure 4.1: Sample type A. Left: sample of filled epoxy, 60% Si O$_2$, with shield electrodes; Middle: X-ray image of the sample with the spheroidal shaped void attached on the upper electrode, representation of the void geometry with minor radius $a$ and major radius $b$; Right: dimensions of the sample in mm (in axial symmetry, axis is left), with shield electrodes.](image)

After the first PXIPD measurements with samples of type A, two
X-ray images of each sample were made. It could be easily seen that the voids had an ellipsoidal shape and the major and minor radii of the voids were determined. Some of the samples had voids of major radius up to 0.7 mm because of insufficient degassing during curing. The analysis of the X-ray images showed that all of the voids are attached to one of the electrodes or have a thin layer of epoxy between the electrode and the upper wall of the void.

These samples have the advantage that the original material properties could be used as in real operating insulators but have the drawback that the void shapes are very irregular, the position of the voids between the electrodes can not be controlled and it is difficult to precisely determine the void size for very small voids. They were thus unsuitable for the further use within the scope of this thesis and samples of type B were made as shown in figure 4.2.

Figure 4.2: Sample type B. Left: sample with shield electrodes; Right: design of the transparent epoxy samples with rod-rod geometry electrodes and the single spherical (1 mm) void between.

As the main object of this work, self produced samples of transparent epoxy with spherical voids of defined size were produced and a special measurement procedure was defined to perform the first PRXPD measurements. The results are given in section 6. The gap distance between the rod electrodes was 3 mm and 4 mm depending on the void size. The voids were produced in the same way as
they occur during insulator production in a factory, i.e. by gelation of epoxy resin containing gas bubbles. An epoxy resin with a polyamine hardener at room temperature was used. Prior to gelation the gas bubbles were created in the mixture by either mixing without degassing or by pouring of the mixture from one bin to another. This way voids of different sizes and with almost the same surface conditions as in technical reality are obtained. In a next step small blocks of the cured epoxy containing a single void were cut, they were inserted between two rod shaped electrodes and casted with another epoxy (hot curing cycloaliphatic epoxy resin with a cycloaliphatic anhydride hardener). The diameter of the voids covered the range between 0.1 mm and 2.5 mm.

4.2 X-ray source

Two portable pulsed X-ray sources from the same manufacturer were used in the PXIPD measurements. For the PRXPD measurements of section 5 and section 6 the XR200 X-ray source from Golden Engineering was used, which emits short pulses of 50 ns duration. The maximum photon energy is 150 kV and the repetition rate of the pulses is 15 Hz. This X-ray source cannot be triggered at the ms scale, but still it has to be ensured that an X-ray pulse is given close to the voltage maximum. As the voltage frequency (50 Hz) and the X-ray pulse repetition rate (15 Hz) differ, one can estimate that with 5 repetitive X-ray pulses the maximum distance to the voltage maximum is 1.66 ms, which is only 13 % below the voltage peak value.

For the TRXPD measurements shown in section 8 and section 9 a prototype of the existing XRS-300 (300 kV tube) from Golden Engineering was built. This new source called XRS-3T could be triggered with a time delay of 2.5 µs upon receiving the trigger signal.

Figure 4.3 shows the measured temporal evolution of the X-ray pulse intensity, measured with a photomultiplier (PM) tube.

Most of the intensity of an X-ray beam is created by Bremsstrahlung.
Electrons are decelerated upon hitting the anode. The resulting energy spectrum is continuous with a decreasing intensity towards increasing photon energies.

For the XRS-3T no measured energy spectrum was available. The energy spectrum for a discrete number of energy bands was indirectly determined from attenuation measurements with materials of known absorption coefficients. A series of dose measurements were completed using Al, Fe and Pb as attenuation material. With each metal, measurements at 2 different distances and 10 different thicknesses were performed. The relative intensity of the three energy bands and the center of the energy bands themselves were then determined by a fitting procedure using the attenuation measurements together with the absorption coefficients taken from the National Institute of Standards and Technology (NIST) database. The results are shown in Table 4.1.

Additionally, the validity of the inverse square relation to the distance (see section 2.5) was experimentally confirmed by dose measurements at different distances. The results showed a good agreement within the accuracy of the measurement device (see section 4.3.1) and the scattering of the source itself.
4.2 X-ray source

**Table 4.1:** Energy spectrum of XRS-3T discretized in 3 energy bands.

<table>
<thead>
<tr>
<th>photon energy (keV)</th>
<th>relative intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>band 1</td>
<td>55</td>
</tr>
<tr>
<td>band 2</td>
<td>178</td>
</tr>
<tr>
<td>band 3</td>
<td>294</td>
</tr>
</tbody>
</table>

The intensity of the X-ray beam depends also on the angle of emission. The highest dose is irradiated at the direct line of sight ($\alpha = 0^\circ$) and decreases as the opening angle increases.

Figure 4.4 shows the measured angular emission characteristics of XRS-3T. These measurements were performed by measuring the dose at 10 different angles at each side of the source. For each angle the mean value of 10 pulses was taken.

![Figure 4.4: Angular emission characteristic of XRS-3T](image)


4.3 Dosimeter

A dosimeter of the type Melit RGD 27091 (X-ray and Gamma-Dosimeter) was used to measure the X-ray dose. It is designed to measure the ambient dose equivalent $H^*(10)$ within the energy range from 6 keV to 3.0 MeV. Internally, however, it measures a current $I_K$ in an air equivalent ionization chamber volume of $V = 600\, \text{cm}^3$ which is proportional to the number of charge carriers generated:

\[ I_K = K \rho V H^*(10). \tag{4.1} \]

The proportionality factor $K = 2.58 \times 10^{-2} \, \text{C/(kgSv)}$ is used to convert the internally measured current into the ambient dose equivalent $H^*(10)$ in $\mu\text{Sv}$. Hereby, the definition of Röntgen (R) is considered and $1\, \text{Sv} = 100\, \text{R}$ applies. The unit of Röntgen gives the amount of ionization (in Coulombs) in a unit mass of dry air and it is $1\, \text{R} = 2.58 \times 10^{-4} \, \text{C/kg}$. It is only valid for gamma and X-rays.

The relative response of the dosimeter for incident photons of energy $\approx 50 - 100\, \text{keV}$ is $\approx 30\%$ higher than for photons of energy $> 100\, \text{keV}$. An additional correction factor of $K_c = 1.3$ is thus used to convert the read-out signal $H_x$ to the ambient dose equivalent, i.e. $H^*(10) = H_x/1.3 \, H^*(10)$ is used for the calculation of charge carrier pairs (electrons) produced in the void volume. The manufacturer indicates an intrinsic error of $\pm 15\%$ and an additional error of $\pm 10\%$ in the energy range of 15 keV to 2 MeV.

4.3.1 Measurement accuracy of X-ray dose

To make a statement about the minimum dose with the measurements shown in section 7.3, the accuracy of the whole measurement chain needs to be known. As we cannot assess the accuracy and reproducibility of the source and the dosimeter individually, both devices are analyzed together. The dosimeter was placed in front
of the pulsed X-ray source with a distance of \( s = 200 \, \text{mm} \) and ten pulses were triggered. The measured dose per pulse was in the range of \( 76 \, \mu \text{Sv} \) to \( 97 \, \mu \text{Sv} \) with an average value of \( 88.3 \, \mu \text{Sv} \) at \( 8.3 \, \mu \text{Sv} \) standard deviation (9.4\%).

The reproducibility was also estimated in the lower measurement range. The dosimeter was placed 400 mm away from the X-ray source with 32 mm thick copper plates placed in between. Out of a series of 10 pulses, the measured dose per pulse was in the range of \( 0.07 \, \mu \text{Sv} \) to \( 0.16 \, \mu \text{Sv} \) with an average value of \( 0.11 \, \mu \text{Sv} \) and \( 0.031 \, \mu \text{Sv} \) standard deviation (29\%). As this lower range is of interest for us, we assume a measurement accuracy of 30\%.

### 4.4 Experimental setup for the determination of minimum X-ray dose

![Figure 4.5: PXIPD setup for the minimum dose measurement experiments, shown without the PD detection circuit.](image)

Figure 4.5 shows the experimental setup for the minimum X-ray dose measurements shown in section 7.3. For these measurements 4 samples of type B containing single spherical void with diameter 1 mm were used.
First, the inception voltage $U_{\text{inc}}$ of each sample was determined experimentally by using PXIPD without any additional attenuating material. It was found to be between $U_{\text{inc}} = (6...7) \text{ kV}_{\text{rms}}$. In a next step, an attenuation material (Al, Fe, Cu, or Pb) was placed between the X-ray source and the sample. Only one type of material was inserted at a time. Then, only the total thickness of the inserted material determines the attenuation of the X-ray beam. The desired absorber thickness was achieved by stacking several prepared plates of 0.5, 1 and 2 mm thickness. For the measurements, the ac voltage was first brought to 1 kV above the predetermined inception voltage $U_{\text{inc}}$. This corresponds to an overvoltage of about 20% and is comparable to the low overvoltages we use at PXIPD testing. In our used samples with this overvoltage, the $V_{\text{eff}}$ is roughly half of the total void volume.

Up to 3 X-ray pulses were then shot at the instant of voltage peak, each with a time delay of $\approx 5\text{ seconds}$. If no simultaneous PD inception occurred after the $3^{rd}$ pulse, the voltage was turned down to zero and one layer (0.5 or 1 mm) of the metallic attenuation material was removed. The voltage was then again brought to the same level and the procedure was repeated. Slices of material were removed until inception occurred. At this moment the voltage was immediately turned down without recording the phase resolved PD (PRPD) pattern. The absorber thickness was noted and the X-ray dose was measured with an ionization chamber. For this, the sample was removed and a dosimeter was placed at its position. To compensate for the scatter in the source intensity and the measurement accuracy of the dosimeter, the dose was determined as an average value of 5 X-ray pulses. This average value is taken as the minimum X-ray dose necessary for PD inception of the void under these conditions.

Generally, at inception, the voltage was turned down immediately to avoid long PD activity and associated inner void surface degradation such that each sample can be used more than once. As, at each measurement with the same sample, no PD inception without
X-ray application and with very thick layers of attenuation material was observed, this proved to be plausible.

4.5 PRXPD: Phase resolved X-ray induced partial discharge measurement setup

For the PXIPD measurements in section 5 and section 6, an LDS-6 System by Lemke Diagnostics was used, having a bandwidth of 100–400 kHz. The capacitance of the coupling capacitor was 1000 pF. With this setup, PD amplitudes down to 0.3 pC can be measured. The pulsed X-ray source (XR200) was integrated into a conventional PD measuring circuit as shown in figure 4.6. To do so $R_m$ is shortened and $Z_m$ is used as the PD measuring impedance.

The X-ray beam irradiates only the sample containing a single void while simultaneously the ac voltage is applied. The sensitivity of the PD detection system for the used test setup was below 0.5 pC, in compliance with IEC 60270 [IEC00] (see section 2.2), and the interference level around 0.3 pC.

![Figure 4.6: Principle diagram of the PXIPD circuit. By shortening of either $Z_m$ or $R_m$ it can be used as PRXPD or TRXPD setup. For TRXPD measurements the $C_K$ is replaced by the self-built $C_K$ shown in figure 4.7](image-url)

For the later TRXPD measurements of section 8 and section 9 data acquisition was done by DSO (see section 4.6) and in parallel
further PRXPD measurements were performed with a new PRPD system Omicron MPD600.

4.6 TRXPD: Time-resolved X-ray induced partial discharge measurement setup

The classical PD detection system makes use of a relatively small bandwidth and records the apparent discharge magnitude and its phase position, giving the so called phase resolve PD pattern - PRPD.

Figure 4.7: Diagram of the TRXPD measurement circuit and the PMT: Cross section of the “short discharge path ring coupling capacitor” $C_K$ with the sample in the middle. The epoxy ring with the high voltage electrode and ground electrode builds the coupling capacitor.

To be able to study the discharge mechanism of a PD, its apparent current pulse shape has to be recorded. Considering the time constant of a few ns for a typical PD (streamer-like), the time constant of the measuring circuit has to be small, i.e. a high bandwidth is needed. In the basic setup in figure 4.6 this is achieved by shortening $Z_m$ and using $R_m$ as the measuring impedance. Additionally, because of the large geometric dimensions of the conventional coupling capacitor $C_K$ which causes stray capacitances and inductances
(factors influencing the time constant), a new compact ring coupling capacitor $C_K$ was built. This is depicted in figure 4.7.

The grounded electrode together with the high voltage (HV) electrode forms the coupling capacitor. The capacity of the ring coupling capacitor has to be high enough to maintain a high sensitivity of detection [VvdL82, BS82]. A ring epoxy block with $\varepsilon_r \approx 4$ (at AC 50 Hz) was casted to get a higher capacity, but it was observed that even without the epoxy ring, the sensitivity of the system was sufficient.

The ground electrode of the sample is the measuring electrode with a diameter $D_m = 20\,\text{mm}$. In order to maintain a small stray capacitance, the diameter of the measuring electrode has to be small. On the other hand, a small diameter would induce currents in the coaxial guard electrode. The Ramo-Schockley theorem gives the optimal relation between the diameter of the measuring electrode $D_m$, the separation between the high voltage electrode and measuring electrode of the sample $D$ and the void diameter $d$ [WvdL89]:

$$D \leq 0.25(D_m - d) .$$  \hspace{1cm} (4.2)

For the sample used in these measurements $D = 3\,\text{mm}$ for voids with $d \leq 1.2\,\text{mm}$ and $D = 4\,\text{mm}$ for voids with $d \geq 1.3\,\text{mm}$, hence condition (4.2) is fulfilled. The resistor $R_D$ is 10 M$\Omega$ (should be high) and is needed to decouple the discharge signal from the high voltage source. This way, the discharge path is restricted to the compact capacitor system.

Using the equivalent circuit, as in [Mor93], a time constant of about 230 ps was calculated (cf. figure 4.8). This is well acceptable, since the PD pulses measured show a time constant of several hundreds of picoseconds, mostly around 1 ns.

A LeCroy digitizing oscilloscope with a bandwidth of 1 GHz with 10 GS/s was used. The PD current through the 50 $\Omega$ resistor $R_m$ is transmitted as a voltage signal by the 50 $\Omega$ transmission cable. The terminal connection to the oscilloscope is done over 50 $\Omega$, so that
Figure 4.8: Equivalent circuit of the TRXPD setup according to [Mor93], $C_K = 61 \text{ pF}$ with $\varepsilon_r = 1$ (when the ring epoxy is used with $\varepsilon_r = 4$ then $C_K = 130 \text{ pF}$).

reflections are avoided. The resulting resistance for the detected discharge current in this way is $25 \Omega$ (cf. figure 4.7).

PDs reveal themselves also in other forms like emitting radiation by excited particles, photons, ultrasonic sound, heat from particle impact and chemical reactions [Mor95]. The TRXPD measurements detect the individual PDs as an electrical pulse and at the same time the light emitted by the PDs was detected by a photomultiplier tube (Hamamatsu PMT Module H10721-110 with spectral response from 230 nm to 700 nm), a module consisting of a photomultiplier tube with a build in high voltage power supply. To bundle the light emitted from the void, a bi-convex lens was placed between the light source and the PMT. One part of the light is absorbed by the epoxy of the sample, but still a good sensitivity was possible. At least for the sample measured, the PMT pulse was in the order of some tens of mA.

The PMT signal was used as the trigger signal for the oscilloscope which then acquired both the electrical signal and the PMT signal. For our measurements the PMT pulses are a factor of redundancy of PD detection. They were used as the trigger signal for the oscilloscope which then acquired both the electrical signal and the PMT signal. In this way it is avoided that noise and other electromagnetic effects are misinterpreted as PDs. For these reasons the PMT
pulses are not used as PD pulse qualification data and will not be analyzed further in this work.

An important effect to consider is the superposition of the electrical noise of the X-ray source and the X-ray beam itself to the transmission coaxial cable and the setup. The oscillating current before the rise of the first PD pulse and after its decay corresponds to the current waveform and width obtained when there was no voltage applied and an X-ray pulse was shot (see section 8.3). This is more evident for the electrical signal; the PMT signal is much less influenced. Through appropriate shielding of both X-ray source and the coaxial cables, this effect was minimized as much as possible.
5 Phase Resolved PD Measurements on Spheroidal Voids

5.1 Introduction

This section shows PXIPD measurements performed with the 36 samples of type A depicted in section 4.1. They contain spheroidal shaped voids with one-sided contact to the electrode. The aim of the measurements was to show the applicability of PXIPD and to develop measurement procedures which later would be used for the self-produced samples of type B with spherical voids of defined size.

The results are compared with the theory presented in section 2. Although the PD behavior of these defects cannot be explained with the theoretical background given for spherical and spheroidal voids surrounded by epoxy, because of their contact to an electrode, the results still partly reflect a similar behavior.

5.2 Results

The 36 samples of filled epoxy were tested conventionally without X-rays before the PXIPD measurements. The PD magnitude and PD inception field for each sample that showed PD was recorded and the inception field classified as “apparent PD inception field”.

During PXIPD measurements each of the 36 samples was tested according to the following procedure: Starting at 2 kV$_{rms}$ the voltage was increased in steps of 1 kV$_{rms}$. At each voltage level first
Figure 5.1: Measured conventional (apparent PD inception) and PXIPD PD charge at minimum inception field. ($a$ is the void minor radius)

Figure 5.2: Measured conventional (apparent PD inception field) and PXIPD inception field (rms value) vs. void minor radius $a$
a PD measurement was carried out for 60 s without irradiation. If no PD was detected, the sample was irradiated with 5 X-ray pulses and a new measurement was started immediately. If PD was incepted the pattern was then recorded for 60 s and the sample was classified as “simultaneous X-ray triggered PD inception”. If no PD inception occurred even after irradiation the voltage was increased to the next level and the procedure continued until an inception occurred or the voltage of $22 \text{kV}_{\text{rms}}$ ($11 \text{kV}_{\text{rms}}$/mm) was reached. In case of PD inception without irradiation at a certain voltage level, but after having irradiated at the previous voltage level without any detectable PD activity, the sample was classified as “delayed X-ray induced PD inception”.

The radiation dose at the center of the sample was calculated to be $35 \mu\text{Sv}$ for 1 X-ray pulse.

During the PXIPD measurements 17 of the 36 samples showed detectable PD activity (see figure 5.1). The rest of the samples were PD free after both measurements. These samples had no voids that are visible in the X-ray images. For 6 of the samples PD inception was possible only after X-ray irradiation. Even though they had voids with a minor radius $a$ (void axis parallel to the electric field, see figure 4.1) up to $250 \mu\text{m}$ no PD inception was achieved with the conventional PD measurement up to $22 \text{kV}_{\text{rms}}$.

Figure 5.1 shows that the magnitudes of PD charge using PXIPD are lower than the PD magnitude of the conventional PD measurements and the PD magnitude increases for larger voids for all types of inception.

Figure 5.2 shows the PD inception field with and without pulsed X-ray application. One can observe that the PD inception level after using pulsed X-rays is much lower than after the conventional PD measurements. This is in agreement to the findings in [FRB92, FK09] and at the same time explains the difference in the PD magnitudes between the conventional PD and PXIPD measurement. Figure 5.2 compares the measured PD inception fields with the theoretically expected values using the streamer inception
criterion (equation (2.3)) presented in [GN95, CKP89]. For the majority of the voids the gas pressure is between 50 kPa and 80 kPa. This fits well with the expected values and the estimations made at [FK09, GN95].

5.3 Summary

Using pulsed X-ray irradiation in a PD measurement makes the statistical time delay disappear and the PD inception field is considerably lower than in the conventional PD measurement. This makes it possible to detect PD and test electrical insulation under a much lower electrical stress.

The detection of the spheroidal shaped voids with one-sided contact to the electrode and a diameter less than 0.5 mm was successful only with the PXIPD measurements and all the voids that could be seen on X-ray images showed PD activity after X-ray irradiation.
6 Phase Resolved PD Measurements on Spherical Voids

6.1 Introduction

In this section, PXIPD and conventional (CONV.) PD measurements on self produced single spherical void containing transparent epoxy samples of type B are shown.

The measurements were performed according to a pre-defined measurement procedure (see section 6.2).

The aim of these measurements was mainly to see (i) how reliable X-ray pulses can be used for PD detection, (ii) what the smallest void size is that can be detected and (iii) if there is a difference between an X-ray induced and naturally induced PD pattern. Further, it should show if and how a first X-ray PD inception of a void has an effect on a later natural PD inception of the same void and vice versa.

6.2 Measurement procedure

There were 2 groups of samples each containing 15 test samples with voids of diameter range from 0.1 to 2.4 mm, i.e. each void diameter was produced twice. Three measurement sessions were made with a waiting time of 2 weeks in between, during which the samples were short circuited and kept in a dark dry place.

The MP allows us to see if the PD inception levels and PRPD
patterns are reproducible at different sessions.

Figure 6.1: The measurement procedure (MP)

For the PXIPD measurements (cf. figure 6.1 X1, X2 and X3) the AC voltage was brought to 3 kV and then increased by 1 kV steps. At each voltage level 5 X-ray pulses were applied. If there was a PD inception within 10 seconds at the current voltage level the PRPD pattern was recorded for 60 seconds and the inception voltage was registered as the “PXIPD inception voltage”. After recording the PRPD pattern the voltage was decreased slowly and the PD extinction voltage was registered. In case of no PD inception the voltage was increased in steps of 1 kV (up to 33 kV) and the procedure was repeated. At the CONV. PD measurement (cf. figure 6.1 C1, C2 and C3) the main difference to the PXIPD sessions is that there was no X-ray pulse applied and at every voltage level the waiting time was 60 seconds before the voltage was increased by 1 kV. Here, if there was a natural PD inception at a certain level the PRPD pattern was recorded for 60 seconds and the inception voltage registered as the “apparent PD inception voltage”. After recording the PRPD pattern the voltage was decreased slowly and the PD
extinction voltage was registered.

6.3 Results

Figure 6.2 shows Session 1 of group 1 (X1). It can be clearly seen that PD are detected at electric field strengths close to the streamer inception field calculated with equation (2.3). \( E_{\text{inc}} \) (in the next plots always the rms value of the background field \( E_0 \) is plotted) increases with increasing void diameter. In the diameter range \( \approx 0.5 \text{ mm} \) the X-ray inception fields are much higher than the theoretically expected ones but the PD extinction fields (\( E_{\text{ext}} \)) of these 0.5 mm voids are close to the theoretical inception curve.

![Figure 6.2: Measurement procedure of group 1, session 1 (X1)](image-url)

Voids < 0.5 mm showed PD activity at the time instant of X-ray pulse application but PDs were not stable thereafter. For this reason these voids are not plotted in figure 6.2 since no stable PXIPD inception occurred.

Figure 6.3 shows X1, C2 and X3, i.e. all three sessions of group 1. 6 of 10 voids showed natural inception at session C2 but at very high
Figure 6.3: Measurement procedure of group 1, all sessions (X1, C2, X3)

Figure 6.4: Measurement procedure of group 2, all sessions (C1, X2, C3)
electric fields. The third measurement, with X-ray (X3), incepted PD in every void \((\geq 0.5\, \text{mm})\) at fields very close to the theoretical level.

Figure 6.4 shows C1, X2 and C3, i.e. all three sessions of group 2. At C1, the CONV. PD, only 2 of 8 voids showed natural inception at very high electric fields, which corresponds also to long statistical time lags. The second measurement, with X-ray (X2), incepted PD in every void \((\geq 0.5\, \text{mm})\) at fields very close to the theoretical level. At C3 most of the voids incepted naturally but at very high electric fields, i.e. the statistical time lag is also high.

\[ \text{Figure 6.5: PRPD pattern of a 2.4 mm void at } E_{0\text{rms}} = 4.6\, \text{kV/mm showing the typical bar structure for } q_{\text{min}} \text{ in } pC \text{ (PXIPD inception at } E_{0\text{rms}} = 2\, \text{kV/mm}). \]

Figure 6.5 shows the typical \(H_n(\phi)\) distribution of a large diameter void (2.4 mm). For voids of this size start electrons for consecutive PDs are abundant each time the electric field in the void exceeds \(E_{\text{inc}}\) i.e. the theoretically expected horizontal pattern at \(q_{\text{min}}\) can be seen (PRPD pattern characteristics described in [FN92]). Figure 6.6 shows the PRPD pattern of a 0.5 mm void and here additionally the typical arc structure can be seen showing both \(q_{\text{min}}\) and \(q_{\text{max}}\). For voids of this size start electrons for consecutive PDs are scarce i.e. there is not always immediately a PD when the field in the void exceeds \(E_{\text{inc}}\). PDs occur randomly at any field between \(E_{\text{inc}}\) and
Phase Resolved PD Measurements on Spherical Voids

Figure 6.6: PRPD pattern of a 0.5 mm void at $E_{0\text{rms}} = 6.3 \text{kV/mm}$ showing both the bar structure with $q_{\text{min}}$ and the bow like structure with $q_{\text{max}}$ (PXIPD inception at $E_{0\text{rms}} = 6.3 \text{kV/mm}$).

$E_{\text{max}}$. Since the PD magnitude (here in pC) is directly proportional to the electric field in the void at the time instant of the PD event, the PRPD pattern follows the electric field curve in the void.

6.4 Discussion

These measurements clearly proved that X-ray application eliminates the statistical time delay and incepts PD at low electric fields corresponding to the theoretical inception field. For voids with diameter $\geq 0.5 \text{ mm}$ PDs incept with an X-ray pulse without any time delay and PDs run stable. Voids with diameter $\leq 0.5 \text{ mm}$ showed no stable PD activity at the time instant of X-ray pulse application. These may be due to the relatively small effective void surface area which after the first PD initiated by the X-ray pulse supplies the consequent PDs with start electrons.

A previous PD inception (PXIPD or CONV. PD) has deployed charges on the walls of the void that later can be detrapped by the electric field and so start a naturally incepted PD (C2 in figure 6.3 and C3 in figure 6.4). These charges seem to be trapped at the void
walls and be available for detrapping even after 2 weeks of waiting time.

A PXIPD at X1 seems to have changed the PD inception conditions in the virgin void. At X3 the same voids have a lower PXIPD inception field $E_{\text{inc}}$ and also slightly lower PD extinction field $E_{\text{ext}}$. In [Mor93, Dev84, GN95] the effect of aging (continuous PD activity) on the gas and void bulk was explained as gas pressure reduction in the void due to oxygen consumption and oxidation of the void surface. These observations could also explain our observations, although the total PD activity was in the range of 10 min for each void.

The $H_n(q)$ and $H_n(\phi)$ distributions of PD allow the comparison of important physical and statistical parameters like the PD phase angle $\phi$, the PD magnitude $q$ and the PD rate. Changes in the PD rate were observed for all samples especially at the third session (X3 and C3). Again it may be suggested that the change of these characteristic parameters of a PD pattern is due to the time effect of the PD activity and not because of X-ray irradiation.

These measurements seem to prove the assumption that pulsed X-ray inception supplies only initial electrons by ionizing the gas volume and the further PD development shows no difference to a natural PD inception without X-ray application.

### 6.5 Summary

The PXIPD measurements of the self-made samples with single spherical voids confirmed that short pulsed X-ray application reliably incepts sustainable PD at low electric fields and without any statistical time delay. These measurements showed:

- X-ray application incepts PD at voids $\bar{\Omega} \geq 0.5$ mm
- for $\bar{\Omega} < 0.5$ mm no stable PD development was possible
• a previous PD inception favors a later CONV. PD inception but $E_{\text{inc}}$ are still very high

• no pattern difference between PXIPD and CONV. PD was observed; X-ray pulse supplies only initial electrons
7 Experimental Determination of Minimum X-ray Dose

7.1 Introduction

In this chapter it is shown how an X-ray source can be reliably integrated into a conventional PD measurement system. The minimum X-ray dose for PD inception is determined experimentally and verified theoretically. To do so, there is a need to understand both the interaction of X-rays with gas molecules and the attenuation phenomena of X-rays by solid matter.

For the measurements, 4 samples of type B each containing a spherical void of 1 mm diameter were used. The measurement setup and procedure was presented in section 4.4.

The main scope of this chapter is to answer the more general question regarding how PXIPD detection can be used for more complex insulation systems such as power cables, bushings, instrument transformers and other high voltage equipment. Here, the voids or other insulation defects (delaminations, etc.) may be “shielded” by metallic parts or other materials that attenuate the X-ray beam (figure 2.7).

7.2 Theory

The key question for the present investigation is which minimum dose is necessary to reliably trigger PD.

As an avalanche needs a certain minimum length to reach the critical number of electrons to develop into a streamer, not all elec-
trons produced in the void gas volume contribute to the streamer development. It is necessary to create at least one electron in the critical volume $V_{eff}$ of the void (see figure 2.1). The effective void volume $V_{eff}$ is a function of the applied field and for a spherical void is given in equation (2.8).

The number of electrons produced by a certain dose $D_x$ can be calculated using the definition of Röntgen, assuming the void gas is primarily air. This is justified because of the method of sample production and the reasonable approximation that most of the gaseous reaction and decomposition products (e.g. CH$_4$, CO$_2$, and NO$_x$) are not much different in respect to the ionization characteristics of dry air [Gal88].

For an effective void volume $V_{eff}$, irradiated by a dose $D_x$ (in Röntgen), the number of electrons, $N_e$, produced in the gas of density $\rho$ can be calculated by using the following relation:

$$N_e = K_R \ D_x \ \rho \ V_{eff} \ . \quad (7.1)$$

The proportionality constant is $K_R = 1.61 \times 10^{15}$ 1/(kg R).

7.3 Results

Table 7.1 shows the results of the measurements done with the 4 samples according to the procedure described in section 4.4. The measurements were done chronologically in the sequence as listed in the table. Columns 2 to 4 show the material, its maximum thickness, and the distance of the sample to the source at inception. As it was stated in section 4.4, the material thickness was increased in steps of 0.5 to 1 mm.

Column 5 shows the measured absolute dose (in $\mu$Sv/pulse as average of 5 pulses) for the case of PD inception. This value is the minimum X-ray dose that was necessary to incept PD in this void, neglecting the 25 mm of epoxy of the test sample. Column 6 shows
Table 7.1: Measurement and calculation results of the tests with attenuation materials (without considering the 25 mm of epoxy from the sample).

<table>
<thead>
<tr>
<th>No.</th>
<th>sample</th>
<th>material</th>
<th>distance</th>
<th>thickness</th>
<th>inception at</th>
<th>exp.</th>
<th>calc.</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>(µSv/pulse)</td>
<td>(µSv/pulse)</td>
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<tr>
<td>1</td>
<td>Fe</td>
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<td>0.16</td>
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<td>45</td>
<td>0.09</td>
<td>0.09</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Cu</td>
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<td>32</td>
<td>0.16</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>32</td>
<td>0.16</td>
<td>0.19</td>
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<td>48</td>
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</tr>
</tbody>
</table>

The calculated dose for the very same situation using the attenuation calculation with the 3 energy bands model described in section 4.2. As an example: the first sample was placed at 400 mm distance to the X-ray source. When decreasing the number of iron sheets thickness from shot to shot, PD inception occurred when the total thickness was \( \leq 32 \) mm. The dose measured under these conditions was 0.16 µSv/pulse (an average of 5 pulses). Calculation of the dose with the 3 energy bands model results in 0.21 µSv.

The experiments were repeated in different combinations: the same sample was used with different absorption materials and at different distances; different samples with voids of the same size have been tested with the same absorbing materials and with differ-
ent distances. Across all measurements, the minimum dose needed for inception was in the range of 0.05 to 0.16 $\mu$Sv/pulse. The calculated dose deviates not more than 25% from the measured values. With respect to the measurement accuracy of 30%, this can be interpreted as an agreement.

7.4 Discussion

First of all we want to relate the minimum required doses that were measured ($H_x$, from 0.05 to 0.16 $\mu$Sv) to the average number of additional electrons that were produced inside the voids by the X-ray pulse. The measured dose is attenuated by $\approx 30\%$ which compensates for the 25mm of epoxy from the sample. The number of electrons is thus calculated by inserting $D_x = H^*(10)$ into equation (7.1). $H^*(10)$ is estimated like in section 4.3. $V_{eff}$ is calculated using equation (2.8) where $d$ is the void diameter, $p$ the pressure inside the void, and $\rho$ the density of the gas inside the void (taken as dry air) at pressure determined by $U_{inc}$. The pressure of the gas inside the voids was determined by $U_{inc}$ and was taken to be 75 kPa, which is also in accordance to the measurements shown in [GN95].

A dose of $H_x = 0.16 \mu$Sv read at the dosimeter thus corresponds to $N_e = 2...3$ electrons produced by the X-ray source in a void of 1 mm diameter at an overvoltage of about 20%. The minimum measured dose of 0.05 $\mu$Sv still corresponds to $\approx 1$ created electron on average. For doses below these values we have not observed partial discharge initiation. Although it is statistically not meaningful to discuss about one electron or less, the numbers of electrons estimated by this simple equation are in the right order of magnitude and thus sensible.

From this estimation, we conclude that an arrangement should be chosen that enables a calculated average electron creation of at least 1. Of course, a certain safety margin should be included, since more than one X-ray pulse was occasionally required to trigger the discharge. The X-ray pulses were shot in time steps of about 5
If the device under test, together with the X-ray source and its placement allow, one could aim for a minimum dose that would suffice to create on average 5 to 10 electrons.

To be able to predict the dose at different defect locations in real power equipment, one has to rely on calculating the dose. The agreement between the measured and calculated dose in our experiments is within the range of our measuring accuracy. We thus conclude that it is possible to calculate the dose at every potential defect location given the equations above. The key defining parameter is the overvoltage factor $\nu$, since it defines the effective volume. The
higher the overvoltage factor the lower will be the minimum dose required to produce a certain amount of first electrons.

Based on this fundamental study with clear defined X-ray path and attenuation, we derive and propose a method to prepare and dimension the measurement setup for any piece of equipment using X-ray triggered partial discharge inception. Given the equipment geometry and the angular emission and energy spectrum of the X-ray source a PXIPD setup can be designed as plotted in the flow-chart in figure 7.1.

A fundamental step is the decision by the user about the minimum interesting void dimension $d_{\text{min}}$. The next defining factor is the used test voltage $U_{\text{test}}$ which defines the overvoltage factor and has a great effect on the minimum required dose. If the equipment is designed with a CAD program the electric field distribution $E$ can also be calculated numerically. The X-ray source can be virtually placed at the most suitable position. The dose is calculated for every insulator position where $E > E_{\text{inc}}$ by attenuating the beam along the lines of sight. From the local electric field value, an effective volume can be calculated for a potential defect at this location with the smallest diameter $d_{\text{min}}$. If within this effective volume, with the calculated dose $D_x$, the minimum number of electrons $N_e$ is achieved, it is likely to trigger all relevant voids in this setup and the PXIPD is considered to be ready. If not, as a first option, a closer location or another orientation angle of the X-ray source must be tried. In case the distance between the source and the insulator cannot be further decreased or its position not changed, the next options to try are increasing $U_{\text{test}}$ or the minimum void diameter to be detected. If the user does not change these main testing criteria ($U_{\text{test}}$ and $d_{\text{min}}$) an X-ray source with higher tube voltage should be tried. To illustrate the general flow diagram of figure 7.1 we give an example following figure 2.7. Instead of checking all points in the XLPE insulation we only look at void locations $A$ and $B$. Setting the test voltage to $U_n$ may lead to $E_A = 14 \text{kV/mm}$ and $E_B = 8 \text{kV/mm}$. We define the minimum relevant void size to $d_{\text{min}} = 50 \mu\text{m}$ which
leads to $E_{\text{inc}} \approx 5.8 \text{kV/mm}$, i.e. both our points $A$ and $B$ have to be considered. (The minimum detectable void size is not only defined by the background electric field but also the sensitivity of the detection system, here $d_{\text{min}} = 50 \mu \text{m}$ is taken as one plausible example).

The location of the X-ray source is fixed and its emission spectrum and intensity is known (including the angular characteristics of the beam). We follow the line of sight of the X-ray beam from source to void $A$ and $B$ and attenuate the intensity considering the energy dependent attenuation coefficients and the different materials. For the position of the X-ray source as given in figure 2.7 the resulting dose at the voids is $D_{xA} = 100 \mu \text{Sv}$ and $D_{xB} = 1 \text{mSv}$. Void $B$ is irradiated by a much higher dose than void $A$, even if it is located an angle of about $30^\circ$ from the direct line of sight (cf. figure 4.4). This is because void $A$ is located behind the massive cable conductor which strongly attenuates the X-ray beam. At the corresponding field levels $14 \text{kV/mm}$ and $8 \text{kV/mm}$, these calculated doses give a number of electrons which is higher than 5 only in void $B$. Thus, in order to achieve the minimum defined number of electrons $N_e$ in void $A$, something has to be changed in the setup. Figure 7.1 shows the recommended and numbered order of the rearrangements to be made.

### 7.5 Summary

The use of short X-ray pulses has proven to be very successful in eliminating the statistical time lag during PD measurements. The minimum dose measurements seem to justify the assumption that an X-ray beam mainly interacts with the void gas and even with a small number of electrons produced, can successfully lead to a PD development. The statistical variations of the minimum dose were within the measurement accuracy.

On the basis of minimum dose measurements it could be also shown how any X-ray source can be successfully used for a PXIPD
setup. The energy spectrum of the X-ray beam can be estimated by simple attenuation measurements and the dose at every insulation location can be estimated.

The provided measurement and calculation steps can be considered as guidelines and fundamental steps necessary for the design of a PXIPD setup.
8 Investigating the PD-Mechanism

8.1 Introduction

The TRXPD measurements provide a more comprehensive analysis of the interactions between the X-ray pulse and the void. This would help to understand the influence of X-ray pulses on individual partial discharges and their development.

In this chapter, the effect of the X-ray dose on the PD mechanism is studied by TRXPD measurements with the setup shown in section 4.6. Measurements are performed on a 1.2 mm spherical void of sample type B (see section 4.1).

Firstly, the X-ray impact on the epoxy bulk characteristics (bond breaking, etc...) and the possible influence of the X-ray dose on the electric field is investigated.

The procedure is repeated for 2 different X-ray doses at minimum inception voltage and at different overvoltages. Also comparison of X-ray induced PD pulses to naturally induced PD pulses is done.

8.2 X-ray impact on epoxy bulk properties

For reliable use of the PXIPD technique as a testing method, it is a prerequisite that X-ray radiation neither damages the insulation nor modifies the electric field by inducing mobile charge carriers in the insulation bulk. Damage caused by X-ray radiation in epoxy is studied extensively in nuclear applications [DBAV05, GFKV10, GW92, LH90] and is also a problem within large particle accelera-
tors [BMS82]. The typical aging mechanism is bond-breaking and subsequent oxidation leading to mechanical and dielectric deterioration of the material. In these studies, X-ray doses vary from 0 to several MGy and are applied in a wide range of dose rates, ranging from several Gy/h for $^{60}$Co sources up to some kGy/s for reactors or target areas of particle accelerators. The reported result is that the dielectric constant, chemical composition and mechanical strength do not underlie significant changes up to doses of $\approx 10^5$ Gy. A typical PXIPD test deposits dose at a very high dose rate in the range of some kGy/s, however leads to a very low total dose which does not exceed several mGy. Hence we can exclude any material damage due to the PXIPD testing technique. Another question is if the interaction between X-rays and epoxy has an influence on the electric field distribution in the volume between the electrodes in our test sample. We distinguish two cases with respect to the two different timescales of our experiment: First we consider the first-PD pulse. The pulse length of the first-PD pulse is only about 2 ns and is therefore superimposed by the 50 ns long X-ray pulse. Second, we look at subsequent PD pulses which occur within the next $10-20$ ms. X-ray radiation has enough energy to excite charge carriers of the valence states to the mobility edge. Due to the applied electric field $E_0$, positive and negative carriers are spatially separated and create an additional contribution $E'$ to the total electric field which is pointing to opposite direction than the original field $E_0$. In order to obtain an estimate for $E'$, we refer to X-ray induced photoconductivity measurements done in epoxy at high dose rates up to $108$ Gy/s [WBLH72]. From this reference we can estimate an average photoconductivity of $\sigma = 3 \times 10^{-11}$ S/m for dose rates on the order of $104$ Gy/s as deposited in our case during the X-ray pulse. Moreover the authors observe that the conductivity drops rapidly to 5 per cent of the maximum value at the end of the pulse. The reason for this might be re-trapping and recombination of the carriers. Hence we assume a conductivity of $\sigma_{\text{first}} = 3 \times 10^{-11}$ S/m in the case of first PD pulses and analogously $\sigma_{\text{sub}} = 0.05 \sigma_{\text{first}}$ for subsequent
PD pulses. With this information we can calculate the field change $E'$ from the capacitive current $j$ due to the total induced charge $\Delta Q$ flowing to the electrodes by:

$$E' = -\frac{\Delta Q}{CD} = -\frac{\Delta Q}{A\varepsilon_0\varepsilon_r} = -\frac{j\tau}{\varepsilon_0\varepsilon_r} = -\frac{\sigma E_0\tau}{\varepsilon_0\varepsilon_r}, \quad (8.1)$$

where $C$ is the sample capacitance, $D$ is the electrode distance and $A$ is the electrode area. With the PD pulse time of the first PD pulse being $\tau = 2$ ns, $\varepsilon_0 = 8.85 \times 10^{-12} \text{C}^2/\text{Jm}$ and $\varepsilon_r = 4$, the total contribution of the induced charge to the electric field is estimated to be $E'/E_0 = 2 \times 10^{-9}$. In the case of subsequent PD pulses we obtain $E'/E_0 = 4 \times 10^{-4}$. In reality this value is probably even smaller, as the conductivity is likely to drop further during the 10 ms till the subsequent pulse occurs and does not stay constant at 5 per cent of the peak value. As a result we find that the effect of the X-ray pulse on the electric field is negligible for both first and subsequent PD pulses.

### 8.3 Effect of X-ray dose on PD mechanism

The results shown in this section are for a spherical void of 1.2 mm diameter. Four other void sizes were tested according to the same measurement procedure and showed very similar behavior with respect to PD pulse mechanism, the used X-ray dose and test voltage. For this reason the void shown in this section can be taken as a representative of all, allowing at the same time a better and easily traceable illustration of the results. The inception voltage for the 1.2 mm void was calculated (using equation (2.3)) to be $U_{\text{inc}} = 5.5 \text{kV}_{\text{rms}}$, it the X-ray pulse is applied at phase angle of 90° which gives an absolute background field value of $E_{\text{inc}} = 2.6 \text{kV/mm}$ if $p = 75 \text{kPa}$ is taken as void gas pressure. The experimentally reproducible inception voltage for this sample was always $4 \text{kV}_{\text{rms}}$ at phase angle of 90° (absolute background field value of $E_{\text{inc}} = 1.9 \text{kV/mm}$). This
gives a void pressure of about 50 kPa, which is comparable with the pressure range estimated for spherical voids [GN95]. The minimum X-ray dose of 2 $\mu$Sv at 2.6 kV/mm gives $N_e \approx 5$ start electrons and the maximum X-ray dose of 70 $\mu$Sv provides $N_e \approx 150$. At 1.9 kV/mm (4 kV$_{\text{rms}}$ at 90°), the minimum X-ray dose still gives $N_e \approx 3$ and the maximum dose $N_e \approx 130$.

In the text below, a PD inception refers to a new PD test after a previous measurement with any X-ray dose is made and the voltage is shut down to stop the PD activity. The waiting time between the measurements with the same dose was in the range of a few minutes. The waiting time between the test with minimum and maximum X-ray dose was 1 day, and natural inceptions occurred mostly sporadically between individual PD measurements with X-ray. For each measurement, the X-ray pulses are shot at the positive peak of the applied voltage. In case of a natural inception, the first
pulse may occur at any phase angle of the ac voltage. The ac phase angle of the natural inceptions was not measured, only the rms value of the applied voltage is known.

The pulses are classified according to the following most important parameters: pulse height (in [mA]), rise-time (between 10% and the 90% level) and pulse-width between the 50% levels. In the caption of each diagram, the dose of the applied X-ray, background electric field (absolute value at inception instant) and the PD pulse rise-time and pulse-width are given. Another important classification of the PD pulses is the first-PD and the subsequent-PD. The first-PD refers to the first PD that is detected at an inception. For X-ray induced PD sequences, this is the discharge that was incepted directly by the X-ray pulse. The subsequent-PDs are the ones following the first-PD, meaning PD pulse number 2 to PD number 100.

Figure 8.1 (left) shows the first-PD pulse that incepted with a minimum dose of X-ray at a background inception field of 1.9 kV/mm. It has a peak value of about 40 mA and rise-time of 1.3 ns, the pulse-width is 1.4 ns. The corresponding PMT pulse is shown as a dashed line and is always broadened, this one having a rise-time of 2.9 ns and pulse-width of 10.8 ns. The general observation of longer PMT signals was made throughout all measurements. The first five subsequent-PDs following the first-PD pulse are depicted on the right side of figure 8.1. These subsequent-PD pulses are all similar but differ from the first-PD. They have a smaller amplitude of $\approx$ 10 mA, slower rise-time and longer pulse-width than the first pulse. Their peak values are all nearly constant.

It is important to mention the weak but still visible second current peak seen at the first-PD and subsequent-PDs in figure 8.1. It appears approximately 1 ns after the first current peak. This is a reflection due to a small impedance discontinuity, which is difficult to avoid (cf. figure 4.7).

Figure 8.2 shows the peak current of each PD and the time-delay between PDs for the sequence of figure 8.1. The time delay be-
between subsequent pulses is between 7 ms and 22 ms with most of the pulses having a time delay of 10 ms. A PD pulse repetition rate of \( \approx 1 \) pulse/halfwave is evident. It can be seen that not only the first five subsequent PDs have similar amplitude, but all 19 PDs shown in figure 8.2. In fact, all 99 recorded PDs at each new PD inception were similar.

![Figure 8.2](image.png)

**Figure 8.2:** Current peak values and time delay between subsequent PDs for the first 20 PDs at inception with minimum X-ray dose.

Figure 8.4 shows the current peak of the first-PD and the mean value of the corresponding set of 99 subsequent PDs in dependence of the electric field at the moment of first-PD inception. The PD sequence of figure 8.1 is depicted with the absolute value of applied background electric field \( E_0 = 1.9 \) kV/mm (cf. figure 2.1) on the horizontal axis. This plot indicates that the higher the electric field the higher the peak current of the first-PD. The subsequent PDs are not affected by the height of the field. They show an almost constant current peak at each applied background electric field.

While the current peak of first-PDs increases with increasing electric field, the rise-time is decreasing. This is shown in figure 8.3.

However, there is a certain scatter in the values of the current peak
8.3 Effect of X-ray dose on PD mechanism

Figure 8.3: PD inceptions with minimum X-ray dose. Dependence of first-PD rise-time on the electric field at inception instant.

Figure 8.4: PD inceptions with minimum X-ray dose. Dependence of the first-PD and subsequent PD current peak (mean value over 99 PDs) on the electric field at the moment of inception of first-PD.
and rise-time for a given value of the electric field. At 1.9 kV/mm the current peak of the first-PD varies between 20 and 60 mA, the rise-time between 0.8 – 2 ns. The subsequent-PDs show identical pulse shape characteristics after each inception with the values given in figure 8.2.

![Figure 8.5: Example of first PD Pulses at inception at 1.9 kV/mm. Left: with maximum X-ray dose. Right: at natural inception.](image)

It was also observed that for the first PD with increasing electric field the pulse-width tends to decrease.

In figure 8.4 a single measurement at inception field of $E_{\text{inc}} = 1.7$ kV/mm is shown (3.5 kV$_{\text{rms}}$ at phase angle of 90°). This is slightly lower than the always reproducible minimum inception field $E_{\text{inc}} = 1.9$ kV/mm. It was recorded after all the series of measurements for $> 1.9$ kV/mm of figure 8.4 was completed and was only a non-reproducible one time occurrence. For this reason it is not considered here as the minimum $E_{\text{inc}}$ for the void.

In figure 8.5, the first-PD pulses at two inception conditions are given, namely with maximum X-ray dose (left) and at natural inception (right) without any X-ray application. The maximum X-ray dose pulse has a peak value of about 25 mA and rise-time of 1.3 ns.
This pulse also shows a strong interference/noise, which is a result of
the closer distance of the X-ray source to the sample and measure-
ment setup (see Section section 4.6). Inceptions with a maximum
X-ray dose at inception minimum 1.9 kV/mm have shown that the
peak current of the first-PD can change between 20 and 30 mA, the
rise-time between 0.8 – 1.3 ns (4 measurements performed). This
is again in the range of the peak-currents shown for minimum X-
ray dose in figure 8.4. The time delay between subsequent pulses is
between 7 ms and 35 ms with most of the pulses having a time de-
lay between 7 and 10 ms. Natural inceptions occurred sporadically
between the PXIPD measurements. Since the exact phase angle of
the natural inception was not recorded, it cannot be stated at which
electric field level the first-PD occurred, only the applied rms value
of the electric field is known. At inception minimum, 1.9 kV/mm,
the natural inception has a peak current of 55 mA and rise-time of
1.2 ns. This is in the range of current peaks shown for minimum
X-ray dose inception depicted in figure 8.4. Natural inceptions at
higher electric fields (overvoltages) showed again that the recorded
first-PD current peaks are in the range of currents peaks recorded at
minimum (cf. figure 8.4) and maximum X-ray dose inceptions. The
subsequent PDs of a natural inception showed the same character-
istics as the ones at minimum and maximum X-ray dose inception
at every field level.

An example of the first-PD shape at overvoltage is given in fig-
ure 8.6. It shows the first-PD pulses at an overvoltage factor of 1.2
(2.3 kV/mm) for both minimum dose inception (left) and maximum
dose inception (right). The minimum dose pulse has a peak value
of about 70 mA, rise-time of 0.8 ns and pulse-width of 1 ns. The
maximum dose pulse has a peak value of about 80 mA and rise-time
of 0.7 ns and pulse-width of 1 ns. From figure 8.4 it can be revealed
that at higher overvoltages, the first-PD pulses can reach very high
peak currents (up to 230 mA at 5.6 kV/mm) and short rise-times of
< 0.5 ns. The subsequent pulses show identical pulse shape charac-
teristics like the subsequent pulses at inception at every other field
level. This is valid also for inceptions with a maximum X-ray dose and natural inceptions.

### 8.4 Discussion

The very first PD inception for this void was done by applying a minimum X-ray dose. The first-PD pulse may reach current peaks from 2-25 times higher than the subsequent-PD pulses and a rise-time below 1 ns with a pulse-width of about 1 ns. The subsequent-PDs are more diffuse and show rise-times between 1 ns and 2 ns with pulse-widths of about 3 ns. The first-PD pulse showed a steeper current rise and fall at every inception field, even when its current peak was very close to the one of the subsequent discharges due to low overvoltage. The first-PD pulse deploys charges on the void surface, which on polarity reversal provides start electrons for the subsequent-PDs. This is a confirmation of the results and PD model presented in [GN95].
The difference between the first-PD and subsequent-PDs was also observed at a natural inception and with a maximum X-ray dose, i.e. at every inception regardless of the inception conditions.

The time-delay between subsequent-PD pulses can vary, meaning that there is not always a PD at each voltage alternation. This implies that electron de-trapping from the bulk surface has a time delay behavior. This is especially seen after a number of re-inceptions of the void, but can vary at each measurement.

Since during the TRXPD measurements shown in this work the inception instant of the first-PD and the time delay between subsequent PDs is known, a deterministic modeling of dynamic processes occurring in a void is possible. Such a model would lead to more information about charge decay and statistical time delay between subsequent PDs.

The first-PD pulse at natural inception has the same pulse characteristics as the pulses incepted with a minimum and maximum X-ray dose. We observed natural PD inceptions mostly between individual X-ray PD inceptions, where the waiting time was few minutes. However, natural inceptions occurred also at voltage re-application after a longer waiting time at zero voltage (at least one day). For this reason we cannot determine the source of the start electrons for the natural inception. The electrons trapped in the void surface after a previous discharge may serve as the start electrons for the natural inception or the background irradiation provides the start electrons.

The first-PD pulses at inception with a maximum X-ray dose (cf. figure 8.5 left) seem to be quite similar to the minimum X-ray dose first-PD and naturally incepted first-PD with respect to rise-time and pulse-width. The current peaks are in the range of the current peaks for minimum X-ray dose shown in figure 8.4. The results allow us to conclude that that the number of start electrons of \( \approx 5 \) at minimum dose and \( \approx 150 \) at high dose has no significant impact on the discharge mechanism. The X-ray pulse itself has a width of 50 ns, having its highest intensity in the first 10 ns. This means that
most of the electrons generated by the X-ray will be there in the first 10 ns. But even with a large number of start electrons generated, it is reasonable to assume that only the first electron leads to a streamer discharge. All the following electrons are generated in a field that is strongly reduced by the charges deployed from the first streamer. It is thus plausible that no substantial difference in PD pulse shapes between minimum and maximum X-ray dose inception is seen.

Also at overvoltage, the first-PD pulses show the same behaviour. The measurement has clearly shown that the higher the voltage at inception instant, the faster and higher are the first PD pulses, no matter of the applied dose. The electric field (overvoltage factor) defines the first pulse shape/height. The subsequent pulses are similar at every applied sample voltage, which implies that the overvoltage factor has no effect on the PD mechanism of subsequent pulses. This is because the subsequent PDs incept as soon as the electric field in the void has reached the minimum inception field $E_{\text{inc}}$. This field is the result of the superposition of the electric field of the charges deployed on the void walls from the previous streamer and the applied background field.

These results are comparable with the measurements in [Her94, Kur93], where spherical cavities with a diameter between 0.8 and 2.0 mm were tested without X-ray. They measured discharges with a rise-time < 800 ps, pulse-width of 1 to 2 ns and amplitude ranging from 60 to 600 mA. In [HBFS91] measurements were performed on spherical cavities in transparent epoxy with diameters between 1 and 5 mm. They observed the parallel occurrence of streamer-like discharges (rise-time < 500 ps, width 700 ps) forming a bright channel either across the void or close to the surface and more diffuse discharges (rise-time > 1 ns, width 2 – 10 ns) covering the void with significantly less intensity.
8.5 Summary

The built TRXPD setup makes it possible to detect the PD current and its light emission simultaneously. The time constant of the setup is small so that sub-ns PD pulses can be detected successfully.

Individual PD pulses that incepted at different conditions were compared according to defined criteria like rise-time, pulse-width and peak current. The measurements confirmed that pulsed X-ray inception supplies only initial electrons and the further PD development shows no difference to a natural PD inception without X-ray application.

The very first pulse in a void with no previous PD activity is different from the subsequent pulses. This is an indication of the charge memory effect of the void for subsequent PD inceptions.

Further, the ultra-short X-ray pulse has no destructive impact on the mechanical and chemical characteristics of the solid insulation under test. The contribution of the accumulated X-ray dose to the background electric field is negligible, because of its short duration.

We conclude that using pulsed X-rays to incept PD is generally applicable and only those voids are triggered that would have incepted naturally with longer waiting times. No particular overvoltage stress is needed to test the insulation system and the statistical time-lag is eliminated.

To study the effect of overvoltage on the pulse shape, further experiments are to be performed. By applying start electrons (X-ray pulse) at different phase angels of the ac voltage one can study the effect of the electric field in the void at the moment of inception for different field levels, $E \leq E_{\text{inc}}$ and $E \geq E_{\text{inc}}$. 
9 Characterization of PD Behavior

9.1 Introduction

TRXPD measurements offer the possibility to apply start electrons (X-ray pulse) at different phase angles of the ac voltage. By doing so one can determine the minimum inception field of a spherical void very precisely and the effect of the electric field in the void at the moment of inception for different field levels ($E \leq E_{\text{inc}}$ and $E \geq E_{\text{inc}}$) can be studied.

In this chapter advanced TRXPD measurements are shown, where the influence of the overvoltage on the PD mechanism at the time instant of X-ray pulse application is investigated. Further, the advantages of this measurement technique on establishing a generally valid PD model are presented. It allows the semi-deterministic approach of PD modeling which enables a better estimation of important PD parameters necessary for the validation of PD models. Parameters like the time delay between subsequent PDs, the residual electric field after PD occurrence and other parameters can be determined more precisely. This is partly shown in section 9.5, whereby the investigation is restricted to the initial stage of PD activity.

9.2 PD model

9.2.1 Stochastic PD Model

Several PD models exist [GN95, FN92, MCM+99, CCC+03, ICL11, NFG91, GW96, Kur93, Hei99, FG98] which use a stochastic approach
to simulate PD behavior in a cavity. They are based on the streamer-like type of PD mechanism as described in section 2.1 and [CKP89, Nie95]. These models reproduce the statistical behavior of PD patterns in a cavity by comparing experimentally gained PRPD patterns with the simulations. The parameters of the models are adjusted by using the Monte Carlo simulation method, which generates the frequency of occurrence, pulse charge and ac phase angle \((q, \phi_i)\) of PDs.

When modeling the statistical behavior of partial discharges in cavities the most challenging and influencing part is the generation of PD inception time instant. The exact knowledge of individual PD occurrence times allows the discharge amplitude calculation and the availability of start electrons for the next PD after a time \(t\), when the electric field in the void has reached the minimum inception field again, so \(E_{\text{void}}(t) \geq E_{\text{inc}}\). Because this information is missing in the existing PD models, a certain rate of electron production \(N_e(t_0)\) is taken to start the simulation and a probability function is then implemented to calculate the probability of PD occurrence at any time \(t\). The electron generation rate \(\dot{N}_e(t)\) is a function of charge deployed on the void surface by a previous discharge and various parameters like the electric field in the void at time \(t\), the effective work function and temperature. The minimum inception field \(E_{\text{inc}} = E_{\text{str}}\) for the used cavity is in most of the cases estimated theoretically and is an important parameter in the model. These models consider surface charge memory effects like the loss of electrons by being trapped into deeper traps of the insulating material and in [ICL11] additionally the charge decay through conduction along the void walls is considered in the FEM model.

### 9.2.2 Deterministic PD Model

TRXPD offers the possibility of combining the deterministic PD occurrence approach with the stochastic approach (Monte Carlo) used in the mentioned PD models. The validation of PD models is possible with higher precision than before. The main advantages of
this approach are the following:

- the minimum inception field of the void is determined experimentally and is known very precisely (cf. figure 9.2).

- by the controlled inception of the first-PD and the acquisition of each PD occurrence the time delay between subsequent discharges is known (cf. figure 9.4). With this, the time of each individual PD is known and can be related to the ac phase.

Still, it is expected that the parameters show a statistical behavior especially with increasing PD activity in the void. Since we restrict our investigation to the initial phase of PD activity in a new void, this will not be of significant importance. The start electrons for the first-PD are supplied by the X-ray pulse. The discharge initiates at the chosen phase angle, provided that $E_{\text{void}} \geq E_{\text{inc}}$ (cf. figure 2.3). The discharge electrons of this first-PD are injected on/in the anodic void surface and are available for a next discharge. This may happen at the same half-wave if $E_{\text{void}}$ exceeds $E_{\text{inc}}$ again or at field reversal at the next half-wave. However, some of these trapped charges may diffuse into energetically deeper traps in the insulating material so that they cannot be de-trapped at $E_{\text{inc}}$ or only at sufficient overvoltage. This loss of electrons may be roughly accounted for by an exponential decay term $\exp\left(-\frac{t}{\tau_{\text{tr}}}\right)$, where $\tau_{\text{tr}}$ is a time constant giving the effective lifetime of an electron in a detrappable trap [GN95].

Another phenomenon occurring is that the deployed charges by a PD that are not trapped have a limited lifetime mainly because of conduction along the void walls but also ion drift in the gas volume. This depends on the conductivity of the void surface and studies [HBW93, MK90, Mor95] have shown that the surface conductivity increases significantly at longer (up to some hours) PD activity and during the PD event itself. This surface charge decay happens with a time constant that is dependent not only on the surface conductivity but also on the geometric dimensions of the void [GN95].
The PD model presented in this section is based on the equations presented in section 2.1.

The factor $\gamma$ is given in the literature to be $\gamma_+ \approx 0.2$ for positive streamers and $\gamma_- \approx 0.5$ for negative polarity streamers [Nie95]. We have found a better agreement of the experimental results to the PD model using $\gamma_\pm \approx 0.2$ (see section 9.5).

9.3 Precise experimental determination of minimum inception voltage

9.3.1 Direct Comparison of PRXPD and TRXPD Measurements

![Graph showing inception field (background rms) vs. void diameter with PRXPD and TRXPD measurements. The refined measurement procedure at TRXPD allows a more precise determination of $E_{inc}$.]

**Figure 9.1:** Inception field (background rms) vs. void diameter with PRXPD and TRXPD measurements. The refined measurement procedure at TRXPD allows a more precise determination of $E_{inc}$.

Figure 9.1 the $E_{inc}$ vs. void size for the MP session X1 shown in figure 6.2 in section 6.3 and later TRXPD measurements with another set of sample. The black diamond points show the results of
the first session X1 of figure 6.2. The open circles show the results of the TRXPD measurements with minimum X-ray dose. The crosses inside the circles give the inception field of the same samples when a high X-ray dose was used. There is no difference in the inception field. At this session the smallest void to show PD at any X-ray dose and even at high overvoltage was 0.8 mm. Voids < 0.8 mm showed no PD activity at any time and overvoltage factor. The inception fields for the TRXPD voids are closer to the theoretical inception curve for 50 kPa whereas for the PRXPD voids the inception fields are closer to the 100 kPa line and show a higher scatter. This may be due to the improved measurement procedure for the TRXPD tests but also pressure differences in individual voids cause differences in $E_{inc}$.

### 9.3.2 Minimum inception voltage

The results shown in this subsection and all the following sections are for a spherical void of 1.3 mm diameter. The minimum X-ray dose of $\approx 2 \mu Sv$ at $U_{inc} = 7.1$ kV gives $N_e \approx 5$ start electrons and the maximum X-ray dose of $\approx 70 \mu Sv$ provides $N_e \approx 180$. The experimental determination of the minimum inception voltage by applying the X-ray pulse at different phase angles of the ac voltage is depicted in figure 9.2. It shows different levels of the applied voltage with each marked point as a single TRXPD measurement. The full circles are the points where PD incepted, the open circles show the points where the X-ray pulse was applied (both minimum and maximum X-ray dose) but no PD inception occurred. From figure 9.2 the minimum inception level is clearly visible with a scatter of about 0.5 kV. This is $U_{inc} = 7.1$ kV, which corresponds to a phase angle of 90° at 5 kV$_{rms}$. By using the streamer-criterion (equation (2.3)), this corresponds to a void pressure of about 50 kPa, which is comparable with the pressure range estimated for spherical voids [GN95]. Each point in figure 9.2 refers to a new PD test after a previous measurement with X-ray is made and the voltage is shut down to stop the PD activity.
9 Characterization of PD Behavior

Figure 9.2: Upper figure: voltage on sample vs. phase angle instant of single X-ray pulse application. Each point in the graph represents a new TRXPD measurement. The full circles refer to a successful PD inception and the open circles give the voltage levels where no PD inception occurs. Lower figure: a magnified view of the $U_{\text{inc}}$ level.

9.4 PD behavior at various field conditions

9.4.1 Effect of electric field

Generally, throughout the text the term “first-PD” refers to the first-PD that is detected at an inception. It is the discharge that is incepted directly by the X-ray pulse. The subsequent-PDs are the ones following the first-PD, meaning PD pulse number 2 to PD number 100.

Figure 9.3 (left) shows the first-PD pulse that incepted with a minimum dose of X-ray at 9.9 kV. It has a peak value of about 55 mA and rise-time of 0.8 ns, the pulse-width is 1.3 ns. The corresponding PMT pulse is shown as a dashed line and is always broadened, this one having a rise-time of 2.2 ns and pulse-width of 9 ns. The general observation of longer PMT signals was made throughout all
9.4 PD behavior at various field conditions

Figure 9.3: Example of a single TRXPD sequence (with minimum X-ray dose, X-ray pulse applied at 9.9 kV which corresponds to 7 kV$_{\text{rms}}$ at 90$^\circ$). Left: first-PD as electrical pulse and PMT pulse (dashed line). The electrical pulse has a rise-time of 0.8 ns pulse and pulse-width of 1.3 ns. The PMT pulse has a rise-time of 2.2 ns and pulse-width of 9 ns. Right: 5 subsequent-PDs with minimum X-ray dose. Average rise-time of subsequent pulses is 1.4 ns and pulse-width of 1.6 ns.

measurements. As we only used the PMT signals for reliable triggering, it is only shown as an example. The first five subsequent-PDs following the first-PD pulse are depicted on the right side of figure 9.3. These subsequent-PD pulses are all similar but differ from the first-PD. They have a smaller amplitude, slower rise-time and longer pulse-width than the first pulse. Their peak values are nearly constant.

In figure 9.4, the peak current of each PD and the time-delay between PDs for the sequence in figure 9.3 are shown. The time delay between subsequent pulses is less than 5 ms for the first 3 PDs and then sets to an almost constant time delay of 10 ms for later discharges. A PD pulse repetition rate of $\approx 1$ pulse/halfwave is evident for this voltage level.

Figure 9.5 shows the dependence of the peak current of the first-
Figure 9.4: Current peak values and time delay between subsequent PDs for the first 40 PDs of the PD sequence in figure 9.3.

Figure 9.5: Dependence of first-PD current peak on the electric field at inception instant.
9.4 PD behavior at various field conditions

PD on the electric field at the moment of PD inception. Despite a certain scatter there is a clear indication that the higher the electric field the higher the peak current and at the same time the lower the rise-time of the pulses as depicted in figure 9.6. It was also observed that for the first-PD with increasing electric field the pulse-width tends to decrease.

![Figure 9.6: Dependence of first-PD rise-time on the electric field at inception instant.](image)

Figure 9.7 gives the PD charge magnitude of the first-PD and the mean value of the corresponding set of 99 subsequent discharges in dependence of the applied background electric field $E_0$ (cf. figure 2.3). The PD magnitude of the first PD is directly proportional to the electric field at the time of inception but the subsequent PDs are not affected by the height of the field. They show an almost constant PD magnitude at each applied background electric field.
9 Characterization of PD Behavior

Figure 9.7: Dependence of PD charge magnitude on the electric field at inception instant.

9.5 PRPD modeling with X-ray inception

In our simplified PD model the minimum inception field (cf. figure 9.2) and the time instant of the first-PD and each subsequent PD are known. The total field in the void at any inception time $t_i$ ($i$ indicates the PD number) is the sum of the by the factor $f$ enhanced background field $E_0(t_i)$ and the field $E_q(t_i)$ caused by the accumulation of the discharges deployed on the void surface during the previous PD events. Two subsequent discharges of the same polarity increase the absolute value of $E_q$. If a PD has the opposite polarity with its preceding PD, then it has a negative contribution to its absolute value.

At the time instant of the first-PD which is incepted by the X-ray pulse application at a known phase angle, the field in the void is only the contribution of the background field since $E_q(t_1) = 0 \text{kV/mm}$. When the first-PD occurs at time $t_1$ the electric field caused by the charges deployed on the void surface after the PD is the field collapse
in the void and can be expressed as:

\[ E_q(t_1) = -(E_{\text{void}}(t_1) - E_{\text{res}}). \] (9.1)

\( E_{\text{void}}(t_1) = E_{\text{inc}} \) is only valid for the case that the X-ray pulse applied at the minimum inception voltage level, as shown in figure 9.2. \( E_{\text{res}} \) is calculated according to Equation (2.10). The resulting \( E_q(t_1) \) from the first-PD is added to \( E_{\text{void}}(t_1) \) and gives the total electric field in the void at any time instant \( t \) after the occurrence of the first-PD. Since the time of the next PD event is known, one can easily calculate \( E_{\text{void}}(t_i) \) at which the next PD inception occurs. In our model, this is done by keeping \( E_q(t_{i-1}) \) constant when calculating \( E_{\text{void}}(t_i) \).

**Figure 9.8:** Occurrence time instant of the first-PD and 2 subsequent discharges (crosses) at 5 kVrms with \( \gamma_{\pm} = 0.2 \). The solid line shows \( fE_0 \), the electric field in the void without PD. The dashed line is \( E_{\text{void}} \) with PD. \( E_{\text{void}} \) follows \( fE_0 \) in the areas where it is not marked as a dashed line. The diamond points show \( E_{qi} \) after the corresponding PD\(_i\). \( E_{\text{void}} = fE_0 + E_q - E_{\text{res}} \)
The figures in this section show the implementation of the described simplified PD model on different applied voltages and phase angles of X-ray pulse application. In each figure, the first 3 half-waves of the applied electric field are shown. In the plots, the occurrence instant of all PDs within the first 3 half-waves of the electric field is plotted. For each PD inception time the resulting $E_{qi}$ is plotted as a diamond point.

Figure 9.8 shows the first-PD at $5 \text{kV}_{\text{rms}} 90^\circ$ and 2 subsequent PDs. For this sequence $\gamma_{\pm} = 0.2$ was taken, which shows that the subsequent PDs occur as soon as $E_{\text{void}}$ reaches $E_{\text{inc}}$ again. The inception field of subsequent PDs is within the scatter of $E_{\text{inc}}$ shown in figure 9.2. It is obvious that no time delay occurs for the subsequent PDs, at least for the initial phase of PD activity.

Figure 9.9: Occurrence time instant of the first-PD and 3 subsequent discharges (crosses) at $8 \text{kV}_{\text{rms}}$ with $\gamma_{\pm} = 0.2$. The solid line shows $fE_0$, the electric field in the void without PD. The dashed line is $E_{\text{void}}$ with PD. $E_{\text{void}}$ follows $fE_0$ in the areas where it is not marked as a dashed line. The diamond points show $E_{qi}$ after the corresponding PD$_i$. $E_{\text{void}} = fE_0 + E_{q} - E_{\text{res}}$
9.5 PRPD modeling with X-ray inception

Figure 9.9 shows the first-PD at 8 kV_rms 38° and 3 subsequent PDs. The next 3 subsequent PDs occur without time delay and incept as $E_{\text{void}}$ reaches $E_{\text{inc}}$. The slightly lower $E_{\text{inc}}$ of PD$_2$ and PD$_4$ are within the scatter of $E_{\text{inc}}$ shown in figure 9.2. $E_{\text{void}}$ exceeds $E_{\text{inc}}$ for a relatively long period after PD$_4$ but no PD inception occurs.

**Figure 9.10:** Occurrence time instant of the first-PD and 3 subsequent discharges (crosses) at 8 kV_rms with $\gamma_\pm = 0.2$. The solid line shows $fE_0$, the electric field in the void without PD. The dashed line is $E_{\text{void}}$ with PD. $E_{\text{void}}$ follows $fE_0$ in the areas where it is not marked as a dashed line. The diamond points show $E_{q_i}$ after the corresponding PD$_i$. $E_{\text{void}} = fE_0 + E_q - E_{\text{res}}$

Figure 9.10 shows the first-PD at 8 kV_rms 90° and 3 subsequent PDs. The subsequent PDs occur as soon as $E_{\text{void}}$ reaches $E_{\text{inc}}$ again. The inception field of subsequent PDs is within the scatter of $E_{\text{inc}}$. It is obvious that almost no time delay occurs for the first 3 subsequent PDs. $E_{\text{void}}$ exceeds $E_{\text{inc}}$ for a short time after PD$_4$ but no PD inception occurs.

Figure 9.11 shows the first-PD at 10 kV_rms 151° and 3 subsequent PDs. PD$_2$ to PD$_4$ occur as soon as $E_{\text{void}}$ reaches $E_{\text{inc}}$ again. No
time delay occurs for the first 3 subsequent PDs. $E_{\text{void}}$ exceeds $E_{\text{inc}}$ for a relatively long time after PD$_4$ but no PD inception occurs.

**Figure 9.11:** Occurrence time instant of the first-PD and 3 subsequent discharges (crosses) at 10 kV$_{\text{rms}}$ with $\gamma_{\pm} = 0.2$. The solid line shows $fE_0$, the electric field in the void without PD. The dashed line is $E_{\text{void}}$ with PD. $E_{\text{void}}$ follows $fE_0$ in the areas where it is not marked as a dashed line. The diamond points show $E_{qi}$ after the corresponding PD$_i$. $E_{\text{void}} = fE_0 + E_q - E_{\text{res}}$

Figure 9.12 shows the first-PD at 10 kV$_{\text{rms}}$ 30° and 6 subsequent PDs. The subsequent PDs incept without time delay at $E_{\text{inc}}$ or slightly below. It is obvious that no time delay occurs for the first 6 subsequent PDs. $E_{\text{void}}$ exceeds $E_{\text{inc}}$ for a short time after PD$_4$ but no PD inception occurs. This example clearly shows the increased pulse repetition rate with increasing the applied electric field.
Figure 9.12: Occurrence time instant of the first-PD and 3 subsequent discharges (crosses) at 10 kV\textsubscript{rms} with $\gamma \pm = 0.2$. The solid line shows $fE_0$, the electric field in the void without PD. The dashed line is $E_{\text{void}}$ with PD. $E_{\text{void}}$ follows $fE_0$ in the areas where it is not marked as a dashed line. The diamond points show $E_{qi}$ after the corresponding PD\textsubscript{i}. $E_{\text{void}} = fE_0 + E_q - E_{\text{res}}$

9.6 Discussion

The minimum inception field for every void could be determined very precisely by applying the X-ray pulse at different phase angles of the ac half-wave. It was shown that even a high number of start electrons produced slightly below $U_{\text{inc}}$ is not sufficient to start sustainable PD when only a few milliseconds later the minimum inception level is reached. Below $U_{\text{inc}}$ no PD activity of any kind was observed, neither with the electrical signal nor the PMT. The determined $U_{\text{inc}}$ can be well explained by the streamer criterion [CKP89].

Investigating the PD-mechanism, the first-PD pulse shows a strong dependence on the electric field at inception instant and mostly has a higher peak current than the subsequent-PD pulses and a rise-time below 1 ns with a pulse-width of about 1 ns. The subsequent-PDs are
more diffuse and show rise-times and pulse-widths between 1 ns and 2 ns. The first-PD pulse deploys charges on the void surface, which on polarity reversal serve as start electrons for the subsequent-PDs. This difference between the first-PD and subsequent-PDs was also observed at a natural inception and with a maximum X-ray dose, i.e. at every inception regardless of the inception conditions.

The rise-time, current-peak and charge magnitude of the first PD pulse is very much affected by the electric field in the void at the moment of X-ray application. The study of PD mechanism in dielectric gaps [Dev84, BN93, Mor93, Her94, HBW93, BN95, Bar05, Bar08, HBFS91, BLT89] has shown that the overvoltage factor has a great impact on the PD pulse shape. Based on the numerous discussions and the widely accepted idea of Townsend-like discharges in dielectric bounded gaps and the appearance of streamer-like discharges beginning at very small overvoltages, our result supports the latter one.

The charge magnitude and pulse characteristics of the subsequent PDs are not affected by the applied overvoltage. This was also confirmed by the presented deterministic PD model. This is an indication that the subsequent PDs occur directly when $E_{\text{inc}}$ is reached inside the void and no substantial overvoltage can build up. By the controlled inception of the first-PD and the acquisition of the trigger time of each subsequent PD, the exact phase distribution of the detected PDs was possible. It was shown that after the first-PD incepted at a defined phase angle, the electric field in the void where subsequent PDs occur can be estimated. This makes it possible to determine the statistical time delay for subsequent PDs. Again, no significant statistical time delay is observed and PD activity occurs as soon as $E_{\text{inc}}$ is reached inside the void. In contrast to literature, we cannot confirm the large difference between $\gamma_+$ and $\gamma_-$. Our results agree well with $\gamma_+ = \gamma_- = 0.2$.

The way presented here aims to show the potential of this approach.

In a more advanced implementation, the model is to be extended
for considering more PD parameters. This includes the consideration of the slight changes on $E_{\text{inc}}$ of subsequent PDs by considering the PD charge of the corresponding PD signal, since PD charge is directly proportional to $E_{\text{inc}}$. Moreover, statistical analyses can be done for a large set of measurements with various geometrical configurations and overvoltage levels. By doing so, other parameters like effective work function, charge decay time and other material characteristics can possibly be determined.

9.7 Summary

The TRXPD setup makes it possible to determine the minimum inception voltage of a void very precisely. The test setup offers the possibility of providing start electrons by the X-ray pulse at any phase angle of the applied ac voltage. By doing so, also the effect of the electric field to the mechanism of PDs was studied. It was shown that the detected PDs are of streamer-like mechanism and show an almost linear dependence of the rise-time and pulse-height on the electric field (overvoltage) in the void at the instant of inception. The generally accepted behavior is that the streamer-like discharges occur at overvoltage conditions as results of a lack of electrons. Applying an X-ray pulse at levels below the minimum inception field showed that no Townsend-type (glow) discharges are developed, as far as they are detectable with the presented detection system. The transition from no-PD to PD occurs directly via a streamer-like discharge, showing rise-times of several hundreds of picoseconds and pulse-widths of a few nanoseconds. Further, it was shown how this measurement procedure can be used for a deterministic approach of modeling PD activity in voids. All relevant parameters influencing the PD activity can be estimated by an extended PD model based on the one presented in this work.
10 Summary and Conclusion

In this chapter the main results are summarized.

The detection of the spheroidal shaped voids with one sided contact to an electrode and a diameter less than 0.5 mm was successful only with the PXIPD measurements.

The PXIPD measurements of the self-made samples with single spherical voids confirmed that short pulsed X-ray application reliably incepts sustainable PD at low electric fields and without any statistical time delay. The inception field of each void corresponds very well to the theoretical streamer-inception field.

These measurements showed:

- X-rays incepts PDs at voids Ø ≥ 0.5 mm,
- a previous PXIPD inception favors a later conventional PD inception but $E_{\text{inc}}$ are still very high,
- no pattern difference between X-ray triggered and conventional PD was observed; X-ray pulses supply only initial electrons.

The built TRXPD setup makes it possible to detect the PD current and its light emission simultaneously. The time constant of the setup is small so that sub-ns PD pulses can be detected successfully.

Individual PD pulses that incepted at different conditions were compared according to defined criteria like rise-time, pulse-width and peak current. The measurements confirmed that pulsed X-rays inception supply only initial electrons and the further PD development shows no difference to a natural PD inception without X-ray application.
Further, the ultra-short X-ray pulse has no destructive impact on the mechanical and chemical characteristics of the solid insulation under test. The contribution of the accumulated X-ray dose to the background electric field is negligible.

We conclude that using pulsed X-rays to incept PD is generally applicable and only those voids are triggered that would have incepted naturally with longer waiting times. No particular overvoltage stress is needed to test the insulation system and the statistical time-lag is eliminated.

The minimum dose measurements seem to justify the assumption that an X-ray beam interacts with the void gas in a predictable way and even with a small number of electrons produced, can successfully lead to a PD development. The statistical variations of the minimum dose were within the measurement accuracy.

On the basis of minimum dose measurements it was also demonstrated how any X-ray source can be successfully used for a PXIPD setup. The energy spectrum of any X-ray source beam can be estimated by simple attenuation measurements and the dose at every insulation location can be estimated. Measurement and calculation steps were provided that are considered as guidelines and fundamental steps necessary for the design of a PXIPD setup.

The TRXPD setup makes it possible to determine the minimum inception voltage of a void very precisely. The TRXPD setup offers the possibility of providing start electrons by the X-ray pulse at any phase angle of the applied ac voltage. By doing so, also the effect of the electric field to the mechanism of PDs was studied.

It was shown that the detected PDs are of streamer-like mechanism and show an almost linear dependence of the rise-time and pulse-height on the electric field (overvoltage) in the void at the instant of inception. The generally accepted behavior is that the streamer-like discharges occur at overvoltage conditions as results of a lack of electrons. Applying an X-ray pulse at levels below the minimum inception field showed that no Townsend-type (glow) discharges are developed, as far as they are detectable with the pre-
sented detection system.

Further, it was shown how this measurement procedure can be used for a deterministic approach of modeling PD activity in voids. All relevant parameters influencing the PD activity can be estimated by an extended PD model based on the one presented in this work.
11 Outlook

The results of this work lead to some further questions which would be of great interest to be studied in terms of PRPD routine testing of insulation.

The built measurement setup and the method of producing voids of known size and shape open new ways for further fundamental study of the PD mechanism and behavior in different materials.

The author finds the following main topics as very promising to be studied with the built methodology and measurement setups:

- The minimum void size to develop PD is very much effected by the bulk material. Production of epoxy samples as they are used in industrial environment would be very interesting for the manufacturers. In this way research on materials would be done that are more resistant to PD development and thus safer for long term operation. This would be accompanied by parallel research on the mechanical, thermal and other dielectric properties.

- The temporal development of PD mechanism and the effects of void walls could be studied in more detail. This would give more information about the charge dynamics within a void and the surrounding dielectric. The characteristics of different epoxy materials with respect to charge trapping and detrapping can be studied.

- The latter is to be accompanied by analytic and numerical models of the Townsend mechanism.

- The interface between different fiber/matrix materials can be studied with respect to delaminations and cracks.
• The PXIPD method should be applied to real HV equipment (GIS, Cables). Here, the attenuation of X-rays has to be considered and the appropriate X-ray source and PD equipment has to be chosen.

• Further improvement of sensitivity of the TRXPD setup would be of interest if long-term studies (aging) are to be done. This would possibly require the slight change of the geometry of the samples by using the same production method shown in this work.
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Curriculum Vitae

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