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Investigating the Inception Mechanism of Pulsed X-ray Triggered Partial Discharges by Time Resolved Measurements

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ABSTRACT

In this work, the effect of ultra-short (50ns) X-ray pulses on the triggering and the discharge mechanism of partial discharges (PD) in voids of solid insulation is investigated by time-resolved PD current measurements with an ultra-wideband detection circuit and a photomultiplier tube. PD current pulses from naturally incepted and X-ray incepted voids at different doses and different field strengths are compared. The PD pulse shapes of each inception are compared for rise-time, pulse-width and peak current amplitude. In addition, the potential effects of X-rays on the solid insulation material itself are discussed. It is shown that no negative effect of the X-ray pulse on the solid insulation is expected and that no significant differences are found between X-ray and naturally incepted PD. However, the first pulse of each PD inception is distinctly different compared to all subsequent pulses, especially with varying applied field strengths at the instant of inception. 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.

Index Terms — partial discharges, insulation testing, time-resolved PD measurements, X-ray applications, X-ray measurements.

1 INTRODUCTION

Partial discharge 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. PDs are gas discharge events in a cavity which may lead to material degradation and 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_{inc} and a start electron is available.

The conventional PD measurement technique according to IEC-60270 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 [1-4]. Experiments have shown that it is in the order of 30 minutes for $d = 1$ mm and around

3 days for $d = 200$ μm [1]. This is especially problematic for factory outgoing or commissioning tests, where measurement time is limited to typically a few minutes.

The use of X-rays during PD measurements allows the simultaneous ionization of the gas volume in a potential void while the test voltage is applied to the insulation. In this way, the start electrons for PD development are given and the statistical time delay is eliminated.

First reports on X-ray application to PD detection were published in the 60's [5], but a more comprehensive attempt was made towards the end of the 80's at Ontario Hydro [6-8]. 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 effected directly the height/phase distributions and patterns. They were tightened and at overrated X-ray doses PDs were suppressed completely [7-8]. 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 [9] used continuous X-rays for PD inception at artificially produced spherical voids (~ 0.2 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 in this size range. The same effects were observed for a spherical void of 0.6 mm diameter in [10].

The detection of insulation defects with the help of X-rays does not necessarily mean that these defects will be the sites of permanent PD activity when the equipment will be in operation under nominal voltage. Moreover, a strong continuous X-ray irradiation would have an effect on the insulation material, which absorbs the X-ray leading to different mechanisms like ionization, chemical bond-breaking, increase in the bulk conductivity, effects which are not well understood.

The pulsed X-ray induced PD measurement technique (PXIPD) uses very short X-ray pulses (~ 50 ns) in a PD measurement in order to minimize the influence of X-rays on the insulation material and PDs [11-14]. This method proposes ionizing the gas in a void, while the AC voltage is applied and detecting the PD activity immediately after the decay of the X-ray pulse. In this way, the interactions such as those of a continuous X-ray beam with the PD and the insulation are avoided, and PDs on real insulators [11] and laboratory samples with delamination defects and spherical voids can be reliably detected [12-14]. It was observed that even voids in the range of ~ 0.5 mm diameter could be detected without any statistical time lag at the expected theoretical discharge inception level. The measured phase resolved PD patterns did not differ from the naturally triggered ones [13]. The main difference of PXIPD to the XIPD shown in [6-10] is that the X-ray pulse supplies only the start electrons for the first PD, the subsequent PDs are not supported by the X-ray beam.

In [14] it was 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 was experimentally determined and verified theoretically. To do so, both the interaction of X-rays with gas molecules along with the attenuation phenomena of X-rays by matter was taken into consideration.

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. In [14], also the guidelines and fundamental steps necessary for the design of a PXIPD setup are given.

Among different PD measurement techniques, the time resolved PD discharge measurements were used to study the temporal development and discharge mechanism of individual PDs occurring in metallic gas gaps and dielectric-bounded voids [15-18]. Main PD parameters (PD current magnitude, rise-time and pulse-width) have shown to change in each temporal stage of PD activity. The type of the discharge is taken as an indication of the aging stage of the high voltage component showing PD [19-24].

Thus, time-resolved X-ray induced PD measurements (TRXPD) with a wide-band measurement circuit 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 work, the study is restricted to the effect of the X-ray pulse on the first PD pulses in a void with no PD activity, thus on the inception mechanism. The time resolved study gives insight into the PD mechanism and the possible traces of X-ray to the PD pulses. This X-ray induced inception occurs at theoretical inception field and zero time delay, as shown in [12-13]. Measurements are performed on a spherical void in transparent epoxy. A direct comparison of X-ray triggered first PD pulse characteristics and the first PD induced by natural radiation is possible for voids > 1 mm, where the statistical time lag for a natural inception is less than 1 hour.

After giving a brief background about the nature of PDs in dielectric bounded geometries and presenting a theoretical background about PDs in Section 2, the experimental setup, the measurement procedure and the used equipment are described in Section 3. In Section 4 the X-ray impact on the epoxy bulk characteristics is discussed. The results of the time resolved measurements with minimum and maximum X-ray dose and natural dose are shown in Section 5. In Section 6 these results are discussed briefly.

2 THEORETICAL BACKGROUND

Different discharge pulse shapes have been observed in dielectric bounded cavities. An overview of the experience and the related phenomena to partial discharges is given in [25-28].

Figure 1. X-ray application to a void in a solid insulation. E_0 is the background field, $f \cdot E_0$ the field inside the void and V_{eff} is the effective volume for first electron production by X-ray according to [14].

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 [1, 3, 29] has shown to describe well the initial stage of PD in spherical or spheroidal voids.

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. This charge displacement can be measured as

an apparent charge on the electrodes of the sample [2-3, 16, 29].

For a PD to develop in a void, the electric field fE_0 within (cf. Figure 1) must exceed the inception field strength E_{str} . In addition, a starting electron must be available. This critical electric field is given as a threshold criterion and is usually called *streamer criterion* [29]:

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

where E_0 is the applied background field. For air $(E/p)_{crit} = 25 \text{ V/(Pa}\cdot\text{m)}$, $B = 8.6 \text{ m}^{1/2} \text{ Pa}^{1/2}$ 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 of the surrounding bulk material [3, 29]. For spherical voids in epoxy ($\epsilon_r=4$) $f \sim 1.33$, p is the pressure in the void and is typically assumed to be in the range of $p=50\text{-}100 \text{ kPa}$ [1].

The start electron is mainly provided by gas ionization through natural irradiation. In our experiments, we create additional electrons by artificial X-ray irradiation (cf. Figure 1).

3 EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The classical PD detection system makes use of a relatively small bandwidth and records the apparent discharge magnitude and its phase position. 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 order to achieve a high-bandwidth measurement setup, a new compact ring capacitor was built for our experiments (cf. Figure 2). 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 [15, 16]. A ring epoxy block with $\epsilon_r \sim 4$ (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 [18]:

$$D \leq 0.25 * (D_m - d) \quad (2)$$

For the sample used in these measurements $D = 3 \text{ mm}$ and $d = 1.2 \text{ mm}$, hence condition (2) is fulfilled. The resistor R_D is $10 \text{ M}\Omega$ (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 [21], a time constant of about 230 ps was calculated (cf. Figure 3). This is well acceptable, since the PD pulses measured show a time constant of several hundreds of picoseconds, mostly around 1 ns .

Figure 3. Equivalent circuit of the TRXPD Setup

A LeCroy digitizing oscilloscope with a bandwidth of 1 GHz with 10 GS/s was used. The PD current through the 50Ω resistor R_m is transmitted as a voltage signal by the 50Ω transmission cable. The terminal connection to the oscilloscope is done over 50Ω , so that reflections are avoided. The resulting resistance for the detected discharge current in this way is 25Ω (cf. Figure 2).

The X-ray source generates a short pulse of $30\text{-}50 \text{ ns}$ duration with maximum photon energy of about 300 keV , see [14]. It can be triggered with a time delay of about $2.5 \mu\text{s}$ upon receiving a trigger signal. The X-ray beam irradiates the sample while simultaneously the ac voltage is applied.

Figure 2. 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.

A measurement procedure was defined and transparent epoxy samples of rod-rod geometry containing a single spherical void were prepared as in [13]. The results shown in this paper are for a 1.2 mm spherical void in a 3 mm electrode gap.

The ac voltage was brought to $U_{0inc}/3$ (rms value) and it was increased in 1 kV steps.

At each voltage step, a single X-ray pulse was shot at the instant of peak voltage (phase angle of 90°). At inception, a sequence of 100 pulses was recorded and the voltage was

immediately shut down afterwards. By doing so, we restrict our investigation to the initial processes and no aging is expected like in [21-22].

This whole procedure was repeated for 2 different X-ray doses at minimum inception voltage and at different overvoltages.

PDs reveal themselves also in other forms like emitting radiation by excited particles, photons, ultrasonic sound, heat from particle impact and chemical reactions [26].

The light emitted by the PDs was detected by a photomultiplier tube (PMT, Hamamatsu) module, consisting of a photomultiplier tube with a build in high voltage power supply. To bundle the light emitted from the void, a 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 temporal and spatial resolution of individual PD pulses in epoxy voids was measured in [20] 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 our measurements too (see Section 5).

The electroluminescence processes taking place in a discharge have been mostly studied with respect to their spectral characteristics [36-39], 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 [38]. Their 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.

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 analysed 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 4). 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.

4 X-RAY IMPACT ON EPOXY BULK PROPERTIES

For reliable use of the PXIPD technique as a testing method, it is 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 [30-33] and is also a problem within large particle accelerators [34]. 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 $\sim 10^5$ 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 10^8 Gy/s [35]. From this reference we can estimate an average photoconductivity of $\sigma = 3 \cdot 10^{-11}$ S/m for dose rates on the order of 10^4 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 $\sigma_{\text{first}} = 3 \cdot 10^{-11}$ S/m in the case of first PD pulses and analogously $\sigma_{\text{sub}} = 0.05 \cdot \sigma_{\text{first}}$ 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 ΔQ flowing to the electrodes by:

$$E' = -\frac{\Delta Q}{C \cdot D} = -\frac{\Delta Q}{A \epsilon_0 \epsilon_r} = -\frac{j \tau}{\epsilon_0 \epsilon_r} = -\frac{\sigma E_0 \tau}{\epsilon_0 \epsilon_r} \quad (3)$$

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, $\epsilon_0=8.85 \cdot 10^{-12}$ C²/Jm and $\epsilon_r=4$, the total contribution of the induced charge to the electric field is estimated to be $E'/E_0=2 \cdot 10^{-09}$.

In the case of subsequent PD pulses we obtain $E'/E_0=4 \cdot 10^{-4}$. 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.

5 RESULTS

The results shown in this paper are for a spherical void of 1.2 mm diameter, as mentioned in Section 3. 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 paper 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 1) to be $U_{inc} = 5.5$ kV_{rms}, if the X-ray pulse is applied at phase angle of 90° which gives an absolute background field value of $E_{inc} = 2.6$ kV/mm if $p=75$ kPa is taken as void gas pressure.

The experimentally reproducible inception voltage for this sample was always 4 kV_{rms} at phase angle of 90° (absolute background field value of $E_{inc} = 1.9$ kV/mm). This gives a void pressure of about 50 kPa, which is comparable with the pressure range estimated for spherical voids [1].

The minimum X-ray dose of 2 µSv at 2.6 kV/mm gives $Ne \approx 5$ start electrons and the maximum X-ray dose of 70 µSv provides $Ne \approx 150$. At 1.9 kV/mm (4 kV_{rms} at 90°), the minimum X-ray dose still gives $Ne \approx 3$ and the maximum dose $Ne \approx 130$.

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, at least for the results shown in this paper. 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 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 (rms value) 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 4. Left: First-PD with minimum X-ray dose at $E_{inc} = 1.9$ kV/mm. Electrical pulse and PMT pulse (dashed line). The electrical pulse has a rise-time of 1.3 ns pulse and pulse-width 1.4 ns. The PMT pulse has a rise-time 2.9 ns and pulse-width of 10.6 ns. Right: 5 subsequent-PDs with minimum X-ray dose. Average rise-time of subsequent pulses is 2.3 ns and pulse-width 2.3 ns.

Figure 4 (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 4. These subsequent-PD pulses are all similar but differ from the first-PD. They have a smaller amplitude of ≈ 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 Figures 4. 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 2).

Figure 5. Current peak values and time delay between subsequent PDs for the first 20 PDs at inception with minimum X-ray dose.

Figure 5 shows the peak current of each PD and the time-delay between PDs for the sequence of Figure 4. The time delay 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 ≈ 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 5. In fact, all 99 recorded PDs at each new PD inception were similar.

Figure 6 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 4 is depicted with the absolute value of applied background electric field $E_0 = 1.9$ kV/mm (cf. Figure 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 7.

Figure 6. 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.

Figure 7. PD inceptions with minimum X-ray dose. Dependence of first-PD rise-time on the electric field at inception instant.

However, there is a certain scatter in the values of the current peak 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 5.

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

In Figure 6 a single measurement at inception field of $E_{inc} = 1.7$ kV/mm is shown (3.5 kV_{rms} at phase angle of 90°).

This is slightly lower than the always reproducible minimum inception field $E_{inc} = 1.9$ kV/mm. It was recorded after all the series of measurements for >1.9 kV/mm of Figure 6 was completed and was only a non-reproducible one time occurrence. For this reason it is not considered here as the minimum E_{inc} for the void.

In Figure 8, 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 measurement setup (see Section 3).

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 6. The time delay between subsequent pulses is between 7 ms and 35 ms with most of the pulses having a time delay between 7 and 10 ms.

Figure 8. Example of first PD Pulses at inception at 1.9 kV/mm. Left: with maximum X-ray dose. Right: at natural inception.

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 6.

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 6) and maximum X-ray dose inceptions. The subsequent PDs of a natural inception showed the same characteristics as the ones at minimum and maximum X-ray dose inception at every field level.

Figure 9. Example of first PD pulses at overvoltage factor 1.2 (2.3 kV/mm). Left: with minimum X-ray dose. Right: with maximum X-ray dose.

An example of the first-PD shape at overvoltage is given in Figure 9. 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 6 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 characteristics 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.

6 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 [1].

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 modelling of dynamic processes occurring in a void is possible. This is subject of further research. 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 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 6.

The results allow us to conclude that that the number of start electrons of ≈ 5 at minimum dose and ≈ 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_{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 [22-23], 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 [20] 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.

7 SUMMARY AND CONCLUSION

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 angles 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, $E < E_{inc}$ and $E > E_{inc}$.

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