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Conduction Processes in Gas-Insulated HVDC Equipment: 
From Saturated Ion Currents to Micro-Discharges

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ABSTRACT
Charge generation in gas-insulated high-voltage direct current (HVDC) equipment has been investigated since surface charge accumulation was detected as the main challenge to insulation coordination. Over the years, researchers have made enormous progress using continuous ion current measurements or surface charging experiments with model spacers downscaled from gas-insulated components. Whereas the low sensitivity of the former method limits its measurement range, the latter method is time-consuming and demands comprehensive modeling. In this paper, more than 3,000 hours of surface charge measurements are presented, covering the full range of charge generation processes from ion currents owing to natural ionization to the inception of micro-discharges. In accordance with gas-insulated equipment, Al₂O₃-filled epoxy resin was used for the solids, and sulfur hexafluoride (SF₆) was used for the gaseous insulation. It has been demonstrated that the ion pair generation from natural ionization in the gas is significantly influenced by the surrounding solid materials, and therefore, scales with the insulation volume. From the onset of micro-discharges, sharp and locally limited charge patterns are formed, as surface conductivity does not appear to influence the investigated charge distributions. Whereas the primary charge dissipation from surface areas centered at the distribution could be explained in terms of the gas volume size, the discharge currents could not be reproduced with common ion-current models. At low electric fields, the observed charge decay indicates the presence of low-field conduction processes that cannot be explained by charge generation from natural ionization in the gas.

Index Terms — Ionization, surface charging, gas discharges, ion current, charge measurement, SF₆, epoxy resin insulators, switchgear, HVDC insulation

1 INTRODUCTION
The development of gas-insulated components has reduced the size and improved the reliability of power equipment relative to conventional air-insulated devices. Gas-insulated alternating current (AC) devices are already widely used and gas-insulated high-voltage direct current (HVDC) devices could become increasingly important in future energy networks. Because of the growing demand for long-distance power transmission and large transmission capacities, HVDC facilities such as gas-insulated switchgears (GIS) or gas-insulated lines (GIL) are expected to play a major role in high-power connection as well as in distribution, switching, and transmission devices.

The main challenge facing the implementation of gas-insulated HVDC equipment is the need to control the surface charging of solid-gas interfaces to prevent field enhancements in cases of voltage polarity reversals or transient over-voltages [1-3]. The main processes that cause conduction currents through the insulation, which is the main source of surface charge accumulation, can be categorized into two groups: processes that are dominant in low electric fields that are far below those that initiate the onset of charge injection and charge multiplication at interfaces, hereafter called the subcritical regime (SCR); and processes that are dominant in high electric fields that are sufficient to activate micro-discharges at local field enhancements, hereafter called the partial critical regime (PCR).

Despite some studies indicating a volume scaling of charge generation—which is, in a physically correct sense, a charge separation from natural ionization in gas [4]—volume-independent ion pair (IP) generation rates are commonly used to determine the dimensions of gas-insulated HVDC components [5-8], to model initiatory electron provisions for partial discharges in small volumes, and to explain statistical time lags for breakdown inception in gaseous insulations [9]. Furthermore, the contradictory conclusions of investigations...
on the influence of surface conductivity on the charging of solid-gas interfaces give rise to the question whether a distinct surface property that cannot be explained by volume conduction along the interface must be considered for the dimensioning of gas-insulated devices.

This study focuses on both the conduction currents in low electric fields and the locally limited surface charge accumulations caused by micro-discharges. The high sensitivity of surface charging experiments enables the investigation of the clearance distances required for gas-insulated equipment, which may be up to tens of centimeters large, as well as subsections of insulation systems on a single-millimeter scale. Based on their measurements using voltages in a range of two orders of magnitude, these experiments are suited to addressing the field dependency and volume scalability of conduction processes in the subcritical and partial critical regimes.

2 SURFACE CHARGING PROCESSES

Figure 1 shows an example of a mixed insulation bounded by a metal electrode and a polymeric plate separated by an insulating gas gap. The polymer is grounded on the bottom by a conductive layer, and high-voltage is applied to the metal electrode. Therefore, the electric field spans an insulation volume comprising gaseous and a solid domains with metal-gas, gas-polymer, and polymer-metal interfaces. Applying HVDC to the insulation causes charge accumulation at the insulator surface as a result of the movement of the free and bound charges. The charging current appears unipolar with respect to the applied voltage if the surface charge accumulation is dominated by charge transport and charge generation in the gas; however, the reverse is true if the charge accumulation is dominated by charge transport and charge generation in the polymeric bulk. In contrast to bound charges, which are usually modeled with isotropic permittivities, the generation and transport of free charge carriers can show a highly anisotropic distribution. Nevertheless, at low HVDC fields, solid materials are usually modeled as having a homogeneous volume and surface conductivity. The contributing gas domain, connected via field lines to the surface charges, is called the active gas volume.

2.1 CONDUCTION THROUGH SOLID INSULATION AND ALONG INSULATOR SURFACES

In general, the capacity of an insulating medium to conduct a current if subjected to an electric field can be expressed as the product of charge density and mobility. In gas-insulated equipment, aluminum oxide (Al₂O₃)-filled epoxy resins are commonly used as material for barrier or support insulators. A number of studies have analyzed the volume and surface conductivities of such epoxy resins as functions of temperature, the electric field, and humidity [10-14]. Their measurements suggest that, for temperatures less than and greater than the glass transition temperature, the volume conductivity increases by approximately one and two decades per 40°C, respectively [10-14], in accordance with the properties of other polymers [15]. Therefore, an inhomogeneous temperature distribution is expected to strongly influence the insulation characteristic of gas-insulated devices [16]. Moreover, some authors have observed the presence of an ohmic conduction regime in electric fields of up to 3 kV/mm, followed by characteristics that may pertain to space-charge-limited currents [10, 11, 14]. In contrast, other authors have observed an ohmic conduction regime in fields of up to 20 kV/mm [12, 13].

The non-linear surface conductivity of the insulator surfaces has been characterized by some authors as the main parameter determining the surface charge accumulation of untreated small-scale GIS-spacers [17, 18]. The results of other studies indicate that a distinct surface property can be measured only under high levels of humidity [10, 20]. This property’s influence on surface conductivity was characterized to be particularly significant at humidity levels greater than 20% RH at 40°C and atmospheric pressure. This environment is unlikely to be exhibited in equipment under operation [10, 20]. Sandblasting the insulator surface to change the interface’s roughness has also been suggested to strongly influence the surface conductivity and its dependency on humidity [11]. In recent studies, a smoothening of the surface charge accumulation under DC voltage was achieved by Cr₂O₃-coating of insulator surfaces [21].

2.2 CHARGE GENERATION AND TRANSPORT IN GASEOUS INSULATION

In low electric fields, the minimum gas conductivity is assumed to correspond to IP generation from natural ionization, which has generally been investigated through continuous ion current measurements method [4, 10] or surface charging experiments [22]. Owing to its low sensitivity, the continuous ion current measurement method has a limited measurement range and requires gas volumes that are normally impractical for a detailed modeling of the conduction processes in gas-insulated devices. The surface charge method is time-consuming and necessitates comprehensive modeling; nonetheless, it offers a powerful technique for studying charge generation and transport in gaseous insulation.

To date, basic research on low field gas conduction with respect to pressure and volume has been based on continuous...
ion current measurements. To derive a reasonable signal-to-noise ratio, an ion current signal larger than 100 femtoampere (fA) is preferable. Under the maximum published IP rates of 70 IP cm\(^{-3}\) s\(^{-1}\) at 0.45 MPa SF\(_6\), this limits to a minimal gas volume of 9×10\(^3\) cm\(^3\), which is investigated in electrical fields smaller than 300 V/m. The volumes are larger and the fields are lower than the technically relevant parameters when modeling initial electron supply in small voids or the surface charging of GIS or GIL insulators. Moreover, because of a lack of spatially resolved information, ion currents are assumed to be homogeneous and mostly proportional to the gas volume. However, some ion current measurements have indicated that a perfect proportionality cannot be assumed and that the contribution of the surrounding solids, such as metal encapsulations, to the IP generation may be significant [4]. In contrast to these basic parameter studies, surface charging experiments are generally conducted to validate the knowledge gained from continuous ion current measurements in an applied insulation system. In contrast to continuous ion current measurements, finite element simulations that neglect the volume scaling of the IP rates have successfully validated surface charging experiments conducted on down-scaled GIS arrangements [11, 23].

Various ion-current investigations have been conducted in the PCR to analyze additional charge provisions by field emission and micro-discharges at interfaces. Fields in the range of 1 to 20 kV/mm were applied to ensure comparability with technical conditions. The results showed that, even below 5 kV/mm, significantly more charges occur than could be explained by natural ionization alone [24-27]. Some of these measurements also indicate a considerable increase in the ion currents under enhanced levels of humidity [26,27]. Moreover, dust particles adhere to solid-gas interfaces, forming micro-protrusions or contributing to charge transport, and may therefore significantly impact surface charge accumulation [2, 24, 25, 29-31].

### 3 MEASUREMENT SYSTEM

#### 3.1 GENERAL SETUP

Figure 2 shows the setup constructed to measure two-dimensional (2D) surface potential distributions. The surface potentials of the solid sample are scanned with a contactless electrostatic probe (Trek 341B) and digitalized with a 20-bit multimeter. The sensor adjusts the voltage applied to the probe to minimize the electric field at the location centered below the sensor head.

In the case of a homogeneous surface charge distribution, the electric field between the sample surface and the sensor becomes zero, and the measured potential corresponds to the surface potential [32]. However, in the case of an inhomogeneous distribution, charges contribute as a function of distance to the sensor potential [33]. Therefore, a 2D potential scan is required to calculate inhomogeneous charge densities by deconvoluting the measured potential distribution with the sensor response function. For this purpose, a three-axis positioning system was developed to control the vertical and rotational position of the sample and the horizontal position of the sensor head. The vertical axis can be used to adjust the electrode distance and scale the gas-volume of the investigated insulation system. The scanning system was built inside a sealed metallic chamber, allowing experiments under gas pressures of up to 0.6 MPa. The gas pressure, temperature, and humidity were continuously monitored using a dew point meter (MBW 973) and a combined capacitive sensor (WIKA GDHT-20).

![Figure 2. Schematic of the experimental setup.](image)

#### 3.2 INVESTIGATED INSULATION SYSTEM

The insulation volume can be subdivided into gaseous and solid domains. In this study, SF\(_6\) was used as the insulation gas, and the solid samples were manufactured using epoxy resin filled with aluminum oxide (Al\(_2\)O\(_3\)) micro-filler. Two different high-voltage electrodes were used:

**EL1:** A polished spherical electrode with a 7.5-mm radius, made of aluminum.

**EL2:** A spherical electrode with a 7.5-mm radius, made of aluminum and embedded with a 10-\(\mu\)m radius micro-tip made of steel.

![Figure 3. SEM picture of a micro-tip embedded on a sphere with a 7.5-mm radius.](image)
by a 60 kV DC source (Heinzinger PNCshp 60000-3mA) that was monitored with a 16-bit digital interface.

To produce a sample surface such as that used in gas-insulated equipment, rectangular epoxy plates (200 × 200 × 4 mm³) were cast under vacuum in an upright position, using a mirror polished mold coated with silicone based release agent. To fit the epoxy samples into the grounded electrode, the plates were water-cut to a round shape with a 65-mm radius. The backsides of the plates were roughened with fine sandpaper and conductive-coated to ensure a proper electrical connection to the ground electrode and to suppress discharges in gas cavities. The front sides, used for the surface charging experiments, were cleaned exclusively with ethanol and lint-free paper. Before placing the samples inside the chamber, they were pre-dried and degassed under vacuum at 80°C for at least three days.

3.3 EXPERIMENTAL PROCEDURE

Each experiment began with an initial scan of the potential distribution to determine the initial condition before the sample was moved to the experimental position. Subsequently, the sample was alternately charged or discharged, and the surface potential was scanned. In this study, a sensor distance of 2 mm and a scan resolution of 0.25 × 0.25 mm² were found to be an optimal compromise between the overlap of the sensor response function and the signal amplitude. The scan of a surface area with a 20-mm radius from the sample center required 15 min to complete. For each scan, the surface charge distribution was calculated by first adjusting the measured potential distribution to a uniformly distributed grid by applying a biharmonic spline interpolation with half of the scan resolution. The inverse model described in Section 4 was then applied to calculate the surface charge distribution with a spatial resolution of 0.1 × 0.1 mm².

4 INVERSE CALCULATION OF SURFACE CHARGE DENSITIES

Solving an inverse problem means calculating from a set of observations the causal factors that produced them. In our situation that means calculating the surface charge density distribution from the measured potential distribution caused by these charges.

4.1 SENSOR RESPONSE FUNCTION (SRF)

The sensor response function (SRF) correlates the measured sensor potentials with surface charges at different distances from the sensor axis. The obtained function can be used to calculate the reciprocal surface capacities in the presence of the sensor head and to construct the sparse inversion matrix A. For this purpose, the measurement principle of the electrostatic probe was simulated using finite element methods. For each charge position, an optimization algorithm was used to calculate the corresponding sensor potential. To do so, the electric field centrally below the sensor head was minimized as described in Section 3.1. Figure 4 shows an example SRF determined for a sensor distance of 2 mm using a 4-mm-thick epoxy sample. In this particular case, the sensor potential is primarily influenced by surface charges up to a distance of 10 mm from the sensor axis. In general, the SRF depends on the sensor position, sensor distance, sample thickness, and system permittivities. However, for radii smaller than 50 mm from the sample center, the SRF is found to be independent from the radial sensor position.

4.2 SIGNAL PROCESSING TECHNIQUE

Whereas the inversion matrix A correlates each measured surface potential with the corresponding surface charge densities $q$, the exact surface potentials $u_{exact}$ are usually blurred by measurement noise $e$. Therefore, a direct calculation of the surface charge densities cannot be achieved, and regularization methods are required to solve the inverse problem:

$$q = A^{-1}u_{exact} + A^{-1}e.$$  (1)

In this particular case, regularization refers to the introduction of additional information to solve an ill-posed problem and to prevent overfitting disturbances. The information might introduce a penalty for complexity, add restrictions for smoothness, or bound the vector space norm. The problem is very similar to that of image deblurring and can be solved with standard routines [34, 35]. In the case of insufficient regularization, the measured noise would be transferred to the calculated charge distribution, and thus the data would be overfitted to the disturbances. In contrast, too much regularization causes excess smoothing and loss of detail, thus underfitting the charge information.

In this study, Tikhonov regularization [35] was found to be the most convenient regularization method. This method is applied by first converting the 2D inverse problem into a one-dimensional problem, reshaping the measured surface potential matrix into a vector $u_{exact}$. The measurement position, which must be known when considering neighboring surface charges, is preserved by filling the sparse inversion matrix in the Toeplitz block structure [35]. A singular value decomposition is then applied to the inversion matrix A, and the regularization parameters $\alpha$ are determined using the L-curve criteria. Finally, the surface charges are calculated by solving the minimization problem.

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Figure 4. Normalized SRF determined for a sample thickness of 4 mm, $\varepsilon_r$ of 5.63, and sensor distance of 2 mm. The graphic scaling does not correspond to the given dimensions.
The interface, were calculated to determine the impacts of the charging currents were only fitted for measurement times processes, these bipolar charging currents were neglected, and from polarization. Because this study focused on conduction and transport in the solid insulation and most probably result these currents can be directly assigned to charge generation to the applied voltage, was found. Because of their polarity, measurements, a small charging current, bipolar with respect linear regression model. Within the first hour of all the sample center. The obtained time series was fitted with a series. The experiments were conducted at gas pressures in the range of 0.4 to 0.45 MPa while placing electrode EL1 at 200-mm distance and applying a slightly accentuated microstructure obtained from surface charging experiments in the PCR. With increasing charging time, the microstructures become more pronounced and the overall plateau rises.

5 EXPERIMENTAL RESULTS

To investigate the conduction processes in gas-insulated systems, six surface charging and two charge decay experiments were performed. The first charging series included measurements with the electrodes EL1 and EL2 covering the full range of electric field from the SCR until the inception of discharges from the micro-tip. The subsequent seven experiments were exclusively conducted with EL2, focusing on the formation and decay of spatially limited surface charge distributions generated in the PCR from the micro-tip embedded to EL2.

All measurements were taken in an SF6 atmosphere at temperatures of 22 ± 1°C and humidity below 200 ppmv, which corresponds to a maximum relative humidity of approximately 3.5% RH at 0.45 MPa. Each experiment used a different epoxy sample, handled and manufactured as described in Section 3, and the charging currents were compared, defined as the time derivative of the surface charge densities integrated over an area with a radius of 12-mm from the sample center. The obtained time series was fitted with a linear regression model. Within the first hour of all measurements, a small charging current, bipolar with respect to the applied voltage, was found. Because of their polarity, these currents can be directly assigned to charge generation and transport in the solid insulation and most probably result from polarization. Because this study focused on conduction processes, these bipolar charging currents were neglected, and the charging currents were only fitted for measurement times of more than one hour.

5.1 SURFACE CHARGE ACCUMULATION IN THE SUBCRITICAL REGIME (SCR)

Figure 5 shows the currents obtained from the SCR charging experiments performed in the first measurement series. The experiments were conducted at gas pressures in the range of 0.4 to 0.45 MPa while placing electrode EL1 at distances of 40, 90, 200, and 300 mm from the sample surface. These distances define active gas volume sizes of 11, 22, 24, and 87 cm³, respectively, producing slight changes in the field inhomogeneity. During the experiments, positive voltages from 0.5 to 50 kV were applied for at least 3 h.

Before each experiment the sample was fully discharged to residual charge densities below 0.1 pC/mm². Numerous gas handlings were performed between the experiments, and the chamber was opened various times, with the electrodes and sample remaining unchanged. Extracting the insulation gas and temporarily filling the chamber with ambient air did not influence the subsequent experiments. The electrostatic fields, averaged for both the gas ($E_{avg,gas}$) and solid sides ($E_{avg,solid}$) of the interface, were calculated to determine the impacts of the gas volume size and applied voltage stress. For the SCR experiments, the finite-element simulations did not reveal significant self-field of the measured surface and space charges.

![Figure 5](image1.png) **Figure 5.** Charging currents for different electrode distances in the SCR with respect to the voltage (a), and the averaged electric field at the gas side of the sample surface $E_{avg,gas}$ (b).

The currents follow a linear field dependency with similar slopes over all distances, decreasing with increased applied field and tending to change their polarities. This change corresponds to dominant gas conduction in low electric fields and to a dominant bulk conduction in high electric fields. Moreover, the current increases with respect to the gas volume. Figure 6 shows a typical flat charge distribution with a slightly accentuated microstructure obtained from surface charging experiments in the SCR. With increasing charging time, the microstructures become more pronounced and the overall plateau rises.

![Figure 6](image2.png) **Figure 6.** Surface charge densities obtained from the first measurement series when charging the sample with EL1 at a 200-mm distance and applying a voltage of 10 kV.

5.2 SURFACE CHARGING IN THE PARTIALLY CRITICAL REGIME (PCR)

Figure 7 shows results from experiments that were conducted in the PCR by placing electrode EL2, with the embedded micro-tip, at a 40 mm distance from the sample surface. The focus of these investigations has been on the shape of the obtained charge pattern rather than on determining the inception of micro-discharges at certain field strengths. Before each experiment, the high-voltage electrode was cleaned with ethanol and adjusted and a new sample was introduced to the chamber. Similar current shapes were found for all six experiments. However, the current deviations between the series increased with the applied voltage. Figure
7b compares experiments conducted with EL1 and EL2. In contrast to the linear decrease of the charging current in the SCR, the PCR experiments show a significant current increase from the onset of micro-discharges at the protrusion.

One example of the surface charge distributions obtained in this regime is shown in Figure 8. The sample was charged for 5 hours by placing EL2 at a 40 mm distance and applying a voltage of 27 kV. Starting from a discharged sample with residual surface charge densities smaller than 0.1 pC/mm², a spatially limited surface charge accumulation was observed. The accumulated charges formed a plateau with an average charge density of 20 pC/mm². Whereas the plateau radius grew with increasing charging times, its amplitude remained constant and its edges remained steep and clearly defined. For all PCR measurements a slightly higher charge density was measured in the edge of the charge plateau.

Figure 7. (a) PCR charging currents with respect to voltage, and (b) comparison of measurements taken with EL1 and EL2 at a 40 mm distance.

Figure 8. Surface charge densities when charging the sample by placing EL2 at a 40 mm distance and applying a voltage of 27 kV.

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Figure 8. Surface charge densities when charging the sample by placing EL2 at a 40 mm distance and applying a voltage of 27 kV.

5.3 DECAY OF SPATIALLY LIMITED SURFACE CHARGE DISTRIBUTIONS

To analyze the charge decay of spatially limited surface charge distributions, two experiments using EL2 were conducted using the parameters listed in Table 1. Whereas the surface charging was performed under a 0.44-MPa gas pressure, the charge decay was measured for either 0.44 MPa or 0.22 MPa.

During the discharge sequences, a voltage of 100 V was applied to the high-voltage electrode to prevent connecting field lines from the investigated sample surface to the microtip. In this manner, micro-discharges in front of the high-voltage electrode, which might otherwise have contributed to the discharging currents at the sample surface, could be avoided.

Figure 10 shows the residual surface charges during decay with respect to the discharge time and current. The current decreased with the residual charges starting from a linear conduction regime at high values and progressing to nonlinear behavior towards zero charge. Figure 11 presents typical surface charge distributions measured during discharging. Starting from the previously shown plateau-like distribution, the centered charges decay to form a volcano-like pattern, followed by the removal of the remaining charge ring.

Figure 10. Residual surface charges during decay with respect to discharge time and current. The current decreased with the residual charges starting from a linear conduction regime at high values and progressing to nonlinear behavior towards zero charge.

Figure 11. Typical surface charge distributions measured during discharging. Starting from the previously shown plateau-like distribution, the centered charges decay to form a volcano-like pattern, followed by the removal of the remaining charge ring.
Figure 10. Residual surface charges with respect to time (top), and discharge current measured for 0.22 and 0.44 MPa and simulated ion currents in accordance to Section 6.3, assuming different IP rates and a gas pressure of 0.44 MPa (bottom).

Figure 11. Surface charge decay when placing EL2 at a 100 mm distance and applying a voltage of 100 V. The sample was previously charged with EL2 at a 40 mm distance and a voltage of 27 kV.

6 DISCUSSION

The changes in the surface charge, excluding the contribution of polarization within the first measurement hour, might have been a result of conduction currents originating from the gaseous domain $I_{\text{solid}}$, ion-currents through the gaseous domain $I_{\text{gas}}$, or surface currents flowing along the interface $I_{\text{surface}}$. By defining the direction of volume currents from the gaseous to the solid domain, changes in the surface charges can be described as

$$\frac{dQ_{\text{surface}}}{dt} = I_{\text{gas}} - I_{\text{solid}} - I_{\text{surface}}.$$  \(3\)

However, surface conductivity may play a minor role in surface charging and charge decay in gas-insulated HVDC equipment under operation. Some publications have indicated that, for untreated epoxy spacers under dry conditions, the charge transport along the interface can be neglected \[10, 20\]. This suggestion is confirmed by the discharging sequences shown in Section 5, which do not show changes in flank slopes or location, despite significant tangential field stress. Therefore, the current $I_{\text{surface}}$ flowing along the interface will be neglected in the following discussion.

6.1 ION PAIR GENERATION FROM NATURAL IONIZATION

In low electric fields, the conduction current through the gaseous insulation is currently assumed to be caused by ion pair (IP) generation from both terrestrial and cosmic natural ionization \[36\]. According to the literature, muons, as a part of the secondary cosmic radiation, are the main contributor \[36\], resulting in an overall IP generation of 26 to 70 IP cm$^{-3}$ s$^{-1}$, measured at 0.4 MPa SF$_6$ \[4, 8, 37\]. These rates were calculated from continuous ion current measurements using coaxial electrode arrangements with dimensions typical of gas-insulated equipment. For electric fields below 100 V/m a linear increase of the ion current as a function of the applied voltage was observed. An increase in the field increases the ion drift velocity and thus decreases both the space charge density and ion-ion recombination until the latter becomes negligible and the current becomes saturated. The saturated current can then be used directly to determine the ion pair generation rates. In accordance with the established nomenclature for saturated ion currents, assuming an ohmic conduction behavior of Al$_2$O$_3$-filled epoxy resins, the charging current can be described as

$$\frac{dQ_{\text{surface}}}{dt} = e \cdot V_{\text{avg}} \cdot p \cdot IP - \int \sigma_{\text{V}} \cdot E_{\text{avg,solid}} \cdot dA.$$  \(4\)

Figure 12. (a) IP-rates obtained from measurements in the SCR when placing EL1 at different distances from the sample surface, (b) Mean IP rates calculated for the flat current regime.

Whereas the current through the solid insulation ($I_{\text{solid}}$) shows a dependency on the electric field, $I_{\text{gas}}$ scales linearly with the IP generation rate per unit volume, pressure and time,
gas pressure, and gas volume. However, significant charge densities in the insulation volumes or at interfaces may change the electric field distribution and in turn, affects the active gas volume.

In accordance with previously published volume conductivities [10, 11], the conductivity of the solid samples was found to be $9.8 \times 10^{-5} \text{ S/m}$ at $22\degree$C. This parameter was derived independently of the electrode distance by a linear fit of the saturated ion currents, using Equation (4). An example of the calculated current through the solid insulation is shown in Figure 7b. The close agreement with the measured currents in high electric fields confirms the assumption of an ohmic conduction regime of the solid as measured by other researchers [10-14]. By applying the derived volume conductivity of the solid to Equation (4), the IP generation rates were calculated by subtracting the conduction current carried through the solid sample from the changes in the surface charges presented in Figure 5b, and by dividing the remaining current by the active gas volume and elementary charge. The rates for different electrode distances with respect to the electric field at the gas side of the interface are shown in Figure 12a.

Contradicting the volume-independent ion pair (IP) generation rates that are often used to model gas-insulated equipment [6, 11, 12, 23], a distance-dependent characteristic was found in accordance to [4]. The IP rate, shown in Figure 12b increased as the electrode distance decreased and showed enhanced fluctuation in low electric fields. For an electrode distance of 40 mm, a large rate scattering of up to $\pm 25 \text{ IP cm}^{-3} \text{s}^{-1} \text{bar}^{-1}$ was measured, also appearing to a lesser extent in fields higher than $5 \times 10^4 \text{ V/m}$. Figure 12b shows the mean IP rates derived for a distance of 40 mm in fields higher than $5 \times 10^4 \text{ V/m}$ and for larger distances in fields higher than $8 \times 10^3 \text{ V/m}$. The volume dependency is comparable to the linear relation previously derived from continuous ion current measurements at TU Munich [4]. This behavior might be attributable to the supply of additional gas ions owing to the stopping of high-energy electrons in the gas released by the interaction of cosmic radiation with the surrounding solids [38]. Because of the primarily vertical direction of cosmic radiation [36] and the linear scaling of the active gas volume with the electrode distance, the surface area of the high-voltage electrode, connected via electric field lines with the analyzed sample surface, could be used to approximate the IP contribution at $0.85 \text{ IP cm}^{-3} \text{s}^{-1} \text{bar}^{-1}$ per square millimeter of the surface area. Nevertheless, this generation may also show a dependency on the interface orientation because the muon flux decreases significantly for angles higher than $70\degree$ with respect to the vertical axis [36]. Furthermore, the IP rate depends on the altitude [36], shielding, and type of surrounding materials [38], hindering a location-independent comparison of absolute rates. The values presented here closely approximate those determined in the outdoor experiments conducted at TU Munich [4]. In general, the additional IP generation owing to the solid materials may be important in determining the discharge time constants or calculating charge distributions that may alter the electric field.

### 6.2 FORMATION OF LOCALIZED SURFACE CHARGE DISTRIBUTIONS

Whereas the subcritical charging currents showed high reproducibility, the experiments in the PCR revealed an increasing current deviation with voltage. This may have been caused by the inhomogeneous field arrangement, which formed a high field region in front of the micro-tip, in which the smallest changes in surface structure or tip adjustment may significantly influence the PCR current. The changes could have been caused by the cleaning of the electrode between experiments.

Because of the unipolar charge polarity with respect to the applied voltage, the surface charge accumulation was dominated by gas conduction and formed a charge plateau that tended to nullify the normal electric field at the gas side of the interface. The growth of the pattern toward a higher radius with increasing charging time was therefore attributed to field displacement caused by the surface charges. The slightly enhanced surface charge densities in the edge of the distributions might be owed to charge dissipation in the time between switching of the high-voltage and before screening the sample with the surface potential probe during measurement. This phenomena is comparable with the volcano-like charge decay shown in Figure 11. As depicted in Figure 13, the center of the distribution spans a larger active gas volume, causing an enhanced charge dissipation. Similar discharge pattern of localized surface charges were measured in [23].

### 6.3 NON-LINEAR CHARGE DECAY

Comparing the charge decay obtained from charging experiments at different electrode distances and gas pressures leads to the conclusion that the shape of the localized charge pattern, rather that the pressure, defines the discharge current. Moreover, the localized charge pattern was found to decay selectively, with charges dissipating primarily from surface areas where the electric field lines spanned the largest gas volume.

![Figure 13. Gas conductivity and electrical field lines for different residual surface charges that span the active gas volume contributing to charge decay.](image)
surface charges as the field distribution becomes more defined by the external applied potential, as shown in Figure 13. Moreover, the influence of gas-ion recombination on the discharging currents was found to be negligible, as was the altering of the field arising from the space charge effects in the gas.

Nevertheless, the discharge currents could not be reproduced qualitatively using the IP rates obtained from charging experiments. Non-linear behavior that significantly exceeded the calculated discharge current was observed. The simulated currents shown in Figure 10 indicate that even applying the maximal measured IP generation of 25 IP · cm⁻³ · s⁻¹ · bar⁻¹ undercut the measured discharge current by a factor of 3.7. This was observed during surface charging experiments for smaller gas volumes than those derived for discharging. Moreover, owing to the questionable nature of the upward-directed contribution of electrons released from solid materials to ionization in the gas, considering the angle dependency of the muon flux, it is unlikely that the epoxy sample influences the IP generation in the gas. In Section 6.1 a linear scaling of the contribution of solid materials to IP generation in the gas was found. This indicates that emitted electrons stopped closer than 40 mm from the interface. Therefore, it is unlikely that electrons emitted from the HV-electrode contribute to IP generation in the gas volume connected via field lines to the surface charge during discharging. IP rates in the range of 10 to 15 IP · cm⁻³ · s⁻¹ · bar⁻¹ seem to be more realistic. However, this leads to calculated currents that deviate significantly from the values needed to reproduce the discharge experiments. One reason for the increased discharge currents may be electrophoretic conduction owing to microscopic dust particles [2, 29-31, 39] or humidity [26, 27].

7 CONCLUSION

This study presented surface charging and charge decay experiments conducted with a gas-solid mixed insulation system. From currents derived experimentally at different gas pressures, gas volumes, and electric fields, the following conclusions can be drawn.

- Charging experiments revealed the linear volume scaling of IP rates. The solids contribute to the ion pair generation from natural ionization in the gas, with a value of 0.85 IP · cm⁻³ · s⁻¹ · bar⁻¹ per square millimeter of surface area.
- The localized charge pattern decays selectively, showing charge dissipation primarily from surface areas centered at the distribution.
- The charge decay of localized charge distributions could not be qualitatively explained by IP rates that are consistent with values obtained from charging experiments or the literature.
- In low electric fields, below 70 · 10⁴ V/m in the bulk, and in accordance with the literature, solid samples made of epoxy resin filled with Al₂O₃ show ohmic conduction behavior.
- Surface conductivity was found to have no significant influence on the accumulated charge pattern. Therefore, micro-discharges form sharp distributions that increase the tangential field stress but tend to suppress its normal component at the interface.

Further investigations are needed to gain a better understanding of low field charge generation and transport processes.

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