Partial discharges, breakdown and leader propagation in SF$_6$

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)
presented by

MARKUS BUJOTZEK
Dipl.-Ing., RWTH Aachen

born on 12 February 1979
citizen of Germany
accepted on the recommendations of:

Prof. Dr. Christian M. Franck,
Prof. Dr.-Ing. Stefan Tenbohlen,
Dr. Martin Seeger

2015
Abstract

Compressed SF$_6$ gas is, due to its excellent insulation and arc quenching properties, widely used in high voltage (HV) equipment, such as gas insulated switchgear (GIS) or high voltage circuit breakers. Commonly, the design of HV equipment is based on semi-empirical rules which have been established through several years of experience. With the demand for more compact gas insulated switchgear this approach reaches its limits and the prediction of withstand and breakdown voltage is required for more efficient development and improvements of the HV equipment. Precise predictions are difficult, however, due to various parameters influencing the strength of the gaseous insulation and require a better understanding and modelling of the involved discharge and breakdown processes.

The work presents a comprehensive picture of the discharge and breakdown processes in SF$_6$ for technically relevant electric field configurations under various conditions relevant for practical applications. It aims to enable the reliable prediction of the breakdown voltage and the partial discharge inception voltage. This is addressed by experimental methods and theoretical considerations.

In order to represent technically relevant conditions, experimental investigations have been performed for small protrusions in uniform and weakly non-uniform background fields for a variety of pressures, different protrusion sizes and at both polarities. Such conditions are representative for particulate contamination and surface roughness in practical applications. Optical and electrical diagnostics was used to obtain a consistent picture of the pre-breakdown phase and the breakdown, which occurs by stepped leader propagation. It was found that the pre-breakdown partial discharge activity at both po-
larities is decisive for the insulation performance of the system.

It is shown that a theoretical leader inception model, which is based on a critical charge criterion and which was derived from earlier models for strongly non-uniform gaps, can satisfactorily describe the measured corona charges and the measured leader inception background fields. Based on these investigations and on the experimental results, a physical leader propagation model that consistently describes the observed phenomena in uniform background fields in SF$_6$ was established. The model explains two different types of leader breakdown; these can be associated with the precursor and the stem mechanisms. It also yields the parameters of stepped leader propagation, which include step lengths, associated step charges, step times, and fields and temperatures in the leader channel. The model predicts the range of parameters under which arrested and breakdown leaders occur in good agreement with experimental data. It is shown that for small protrusions the parameter controlling the discharge is not the applied voltage but the background field in which the protrusion is embedded. Later, the leader propagation model was applied and extended to weakly and strongly non-uniform fields and validated with additional experimental data.

In a next step, models for first electron production, streamer inception, and leader propagation have been systematically combined to evaluate the partial discharge inception and breakdown fields in compressed SF$_6$. The dependence of the three criteria (first electron, streamer inception, leader propagation) on parameters like pressure, geometry, voltage wave shape and polarity is presented and decisive criteria for breakdown and partial discharge inception were identified for a given configuration. The results show that only by taking into account all these physical mechanisms the known parameter dependencies of gaseous SF$_6$ insulation can be quantitatively explained. It is shown that the model can be used to predict critical particle lengths, inception and breakdown fields for AC and lightning impulse (LI) voltage wave shapes.

Furthermore, details of the streamer dimensions have been in-
investigated. The streamer radius is an important input parameter for the breakdown prediction models and no direct experimental information was available so far for negative polarity. Optical measurements of the streamer and leader channel dimensions are presented and compared to theoretical predictions and data from literature. The results demonstrate the validity of these input parameters used in the leader propagation model and the 1/p pressure (p) dependence of the streamer radius. For negative polarity, experimentally obtained streamer radii are presented for the first time and confirm indirectly determined values from breakdown measurements for weakly non-uniform background fields and disprove the indirectly determined values for strongly non-uniform background fields. As a consequence, the results indicate that the leader propagation model cannot be fully applied for cases with strongly non-uniform background fields and negative polarity without adaptions. Different results are obtained for strongly and weakly nonuniform field arrangements regarding the initial streamer corona extension. For the strongly non-uniform field arrangement the first streamers extend into the gap until the potential drop across the streamer equals the potential drop resulting from the background field. The average streamer channel field is equal to the critical field in cold conditions. For the weakly non-uniform field arrangement a significant deviation from the expected corona extension was found.
Zusammenfassung


Die experimentellen Untersuchungen wurden an kleinen Spitzen, welche im homogenen oder schwach inhomogenen Hintergrundfeld platziert wurden, durchgeführt, um technisch relevante Bedingungen herzustellen. Sie wurden für eine Vielzahl von Drücken, verschiedene Längen der Spitzen, sowie für beide Polaritäten durchgeführt. Solche Bedingungen sind repräsentativ für Partikel und
Oberflächenrauigkeit in technischen Anwendungen. Es wurde optische und elektrische Diagnostik verwendet, um ein konsistentes Bild der Vorentladungsphase und des Durchschlags, welcher durch einen Leader erfolgt, zu erlangen. Es zeigte sich, dass die Teilentladungsaktivitäten während der Vorentladungsphase in beiden Polaritäten entscheidend für Isolationsfähigkeit des Gases sind.


In einem nächsten Schritt wurden Modelle für die Bereitstellung des Erstelektrons, den Streamereinsatz und die Lederausbreitung systematisch kombiniert, um die Teilentladungs- und Durchschlagsfelder in SF$_6$ für technisch relevante Anordnungen auszuwerten. Die Abhängigkeit der drei Kriterien (Erstelektron, Streamereinsatz, Lederausbreitung) von Parametern wie Druck, Geometrie, Span-

dingungen. Für die schwach inhomogene Feldanordnung wurde eine signifikante Abweichung von dieser erwarteten Korona-Ausdehnung gefunden.
Contents

Abstract iii

Zusammenfassung vii

Table of Contents xi

1 Introduction 1
   1.1 Aim of this work ........................................ 4
   1.2 List of publications ...................................... 7
   1.3 Thesis outline ............................................ 11
      1.3.1 Experimental methods ............................... 11
      1.3.2 Theoretical considerations and modelling ........ 13
      1.3.3 Application and validation of the derived models 14
   1.4 References ................................................ 17

2 Pre-discharges and breakdown at small protrusions 23
   2.1 Introduction ................................................. 24
   2.2 Theoretical considerations ............................... 25
      2.2.1 Basic physical processes ............................ 25
      2.2.2 Streamer corona ...................................... 26
      2.2.3 Leader inception criterion .......................... 28
   2.3 Experiments ................................................ 29
      2.3.1 Experimental set-up .................................. 29
      2.3.2 Experimental results ................................ 30
   2.4 Discussion .................................................. 32
   2.5 Conclusions ................................................. 35
   2.6 Acknowledgment ............................................ 36
   2.7 References .................................................. 37
3 Formative time lag and breakdown at small protrusions 39
  3.1 Introduction ............................................. 40
  3.2 Physical processes during PD and breakdown .......... 41
  3.3 Formative time-lag ...................................... 43
  3.4 Conclusions .............................................. 49
  3.5 References ............................................. 50

4 Partial discharges and breakdown at protrusions in uniform background fields 51
  4.1 Introduction ............................................. 52
  4.2 Experiments .............................................. 55
    4.2.1 Experimental set-up ................................. 55
    4.2.2 Diagnostics .......................................... 55
    4.2.3 Experimental results ................................. 57
  4.3 Discussion .............................................. 72
    4.3.1 Overview of physical picture ........................ 72
    4.3.2 Streamer inception field ............................ 73
    4.3.3 Statistical time lags ................................ 74
    4.3.4 Corona Model ........................................ 78
    4.3.5 Leader channel model ............................... 79
    4.3.6 Time scales for space charge and leader channel decay ........................................... 84
  4.4 Conclusions .............................................. 87
  4.5 Acknowledgements ........................................ 89
  4.6 References ............................................. 90

5 Leader propagation in uniform background fields 95
  5.1 Introduction ............................................. 96
  5.2 Basic processes ........................................ 97
    5.2.1 Electric field ....................................... 97
    5.2.2 Corona charge ...................................... 100
    5.2.3 Leader channel dynamics ............................ 100
  5.3 Numerical model for leader inception and propagation 105
    5.3.1 Model features ...................................... 105
    5.3.2 Input parameters .................................... 106
5.3.3 Output data ........................................ 107 
5.3.4 Examples .......................................... 109 
5.4 Results of the model and discussion ............. 115 
5.4.1 Leader types and ranges ......................... 115 
5.4.2 Features of arrested leaders .................... 119 
5.4.3 Step time, leader propagation velocity and gap 
crossing time .......................................... 121 
5.5 Conclusions .......................................... 123 
5.6 Acknowledgements .................................. 125 
5.7 References .......................................... 126 

6 Partial discharges and breakdown at sub-millimeter defects 131 
6.1 Introduction ......................................... 132 
6.2 Theoretical considerations ......................... 133 
  6.2.1 Basic processes .................................. 133 
  6.2.2 Numerical model ................................. 136 
  6.2.3 Statistical time lag .............................. 137 
6.3 Experiments ......................................... 137 
  6.3.1 Experimental set up ............................. 137 
  6.3.2 Experimental results ............................ 139 
6.4 Discussion .......................................... 142 
6.5 Conclusions ......................................... 147 
6.6 Acknowledgement ................................... 148 
6.7 References .......................................... 149 

7 Leader propagation in non-uniform background fields 151 
7.1 Introduction ......................................... 152 
7.2 Leader propagation model ......................... 154 
7.3 Results ............................................. 155 
7.4 Discussion .......................................... 158 
7.5 Conclusions ......................................... 159 
7.6 Acknowledgement ................................... 159 
7.7 References .......................................... 160
8 Parameter Dependence 161
8.1 Introduction ............................................ 162
8.2 Breakdown Mechanism in SF6 ......................... 164
  8.2.1 General Considerations ......................... 164
  8.2.2 First Electron .................................. 166
  8.2.3 Streamer Inception .............................. 169
  8.2.4 Leader Propagation ......................... 170
8.3 Results ................................................. 172
  8.3.1 Statistical Time Lag .............................. 172
  8.3.2 Streamer Inception .............................. 177
  8.3.3 Leader Criterion ............................... 178
  8.3.4 Combined Breakdown Criterion .............. 178
8.4 Discussion ............................................. 182
8.5 Conclusions ........................................... 191
8.6 Acknowledgement ..................................... 192
8.7 References ............................................ 193

9 Streamer radius and length 199
9.1 Introduction ............................................ 200
9.2 Physical Picture ...................................... 202
9.3 Experimental setup ................................... 205
  9.3.1 Diagnostics ...................................... 207
9.4 Results ................................................ 211
  9.4.1 Visualization of first streamer corona ....... 211
  9.4.2 Streamer Radius .................................. 213
  9.4.3 Length of the first streamer corona .......... 218
9.5 Discussion ............................................. 221
  9.5.1 Streamer Radius .................................. 221
  9.5.2 Streamer Length .................................. 223
9.6 Conclusions ........................................... 225
9.7 References ............................................ 227

10 Summary and Outlook 233

Acknowledgments 239
Curriculum Vitae 241
1 Introduction

Gas insulated high voltage switchgear (GIS) is one key element of today’s electric power transmission system. The metal encapsulated switchgear consists of components like circuit breakers and disconnectors and uses compressed sulfur hexafluoride ($\text{SF}_6$) for insulation. The excellent insulation and arc quenching properties, beside from its greenhouse warming potential, make it most suitable for the use as gaseous dielectric [1][2].

With the demand for smaller and thus more cost effective gas insulated systems the need for a better understanding of the discharge and breakdown processes arises. Improvements in design can only be achieved when limits of the gas insulation are understood and quantified, thus can be predicted. Therefore, the mechanisms of partial discharges (PD) and breakdown in compressed SF$_6$ are of high relevance for high voltage gas insulation systems.

Although the field of gaseous insulation and its application side are mature, the physical understanding is not sufficient and still unknowns even in the very basic processes exist. The strength of electrical insulation in gaseous compressed SF$_6$ is determined by complex processes which are influenced by various parameters, like pressure, polarity, field homogeneity, surface roughness of the electrodes, particulate contamination, and voltage wave shape. In the past, mainly strongly non-uniform field gaps, such as point-to-plane gaps have been studied. These configurations hardly represent technical gas insulation systems, where relatively small protrusions, like surface roughness or small particles, are embedded in a quasi-uniform background field. Many of the involved processes have been investigated in the past and are relatively well understood, but the
combination and interaction of the single processes for such configurations has not yet been presented sufficiently in a quantitative way. A further motivation for new research in this field is the availability of new measurement devices compared to the equipment used in the 1970s and 1980s, when a major part of the research on the dielectrics of SF$_6$ and other gases was carried out. Finally, also the increasing demand for alternatives to SF$_6$ demands basic understanding of dielectrics in electronegative gases.

The electrical insulation characteristics of SF$_6$ have been studied extensively in the past and the relevant specific literature is reviewed in the corresponding main chapters of this work. The most relevant and general literature is summarized in the following. The standard reference book about high voltage insulation with SF$_6$ of Mosch and Hauschild [3] contains all relevant investigations since the introduction of SF$_6$ in high voltage applications in the 1950s until the publication year of 1979. The majority of the investigations of the physical phenomena were conducted in the 1980s [4-19], where the leading research groups on SF$_6$ insulation from academia and industry have significantly advanced the understanding also by joined activities, see e.g. [13][15-18]. During this period a consistent physical picture of the individual involved processes and an adequate theoretical description with focus on non-uniform field gaps, see e.g. [18-20], was established which served as basis for further research [21-31]. A very comprehensive overview about conduction and breakdown in gases is presented in [32], which summarizes the state of knowledge in 1999. In many of these investigations positive polarity and strongly inhomogeneous fields have been studied, since they resulted in lowest breakdown voltages under these conditions. In the last 15 years the interest decreased but further investigations have been performed on the topic of electrical insulation in SF$_6$ [33-40] and especially in the recent years the research interest increased again and has focused on the alternatives to SF$_6$ [37-40]. The recently published PhD thesis from Koch [40] was conducted in parallel to the present work and has used the findings and applied
the developed model described in the present work to novel gases for high voltage insulation.
1.1 Aim of this work

The scientific objective of the overall presented work is to extend and to provide a comprehensive picture of the discharge and breakdown processes in SF$_6$ for technically relevant electric field configurations. It is aimed to enable the reliable prediction of the breakdown voltage and the partial discharge inception voltage, which is of interest for practical applications.

The major contribution of the work presented in this PhD thesis lies on the experimental methods and on the validation and application of the developed models for the pre-breakdown and breakdown phase under various conditions relevant for technical gas insulation systems.

To achieve the overall goal the following main points with the corresponding steps are addressed together with co-authors in dedicated publications, which are listed and described in the next section.

1. Experimental investigations of partial discharge inception and breakdown in technical relevant geometries – represented by different fixed protrusions in uniform and weakly non-uniform background fields at various pressures and at both polarities:

- Construction and extension of an experimental setup to perform discharge and breakdown measurements in different electric field configurations
- Setup of optical (photo multipliers, high speed imaging, image intensifier, photographs) and electrical (current, voltage) diagnostics of the pre-discharge and breakdown phase
- Measurements of characteristic quantities during the pre-breakdown partial discharge phase, such as: discharge currents, corona and leader charges, discharge inception and breakdown voltages, light emission, and discharge
1.1 Aim of this work

- Measurement of streamer radii and length, and visualization of discharges

2. Modelling of the pre-breakdown and breakdown phase:

- Description of the first electron production, the corresponding statistical time lag, and the processes during the formative time lag
- Extension of the basic physical picture developed for gaps with strongly non-uniform electric field distribution to gaps in which a quasi-uniform background field is disturbed by small particulate contamination
- Derivation of a streamer corona charge scaling and a leader inception model, which is based on a critical charge criterion for streamer corona
- Interpretation of measurement results by quantitative models and order-of-magnitude estimates and definition of a simple leader propagation model
- Development of a physical leader propagation model, which yields the parameters of stepped leader propagation

3. Validation and application of the derived models to various conditions and protrusions length:

- Sub-millimeter to millimeter range
- Uniform and weakly non-uniform background fields
- Extension and application of the leader propagation model for point-to-plane gaps (strongly non-uniform background fields)
- Identification of the decisive criteria for breakdown and partial discharge inception and the investigation of their dependence on design parameters
• Validation of the predicted inception and breakdown voltages with own measurements and data from literature
1.2 List of publications

This thesis comprises in total eight scientific publications that address the aims described in the section above. It is based on the following journal and conference contributions.


VI. Bujotzek M, Seeger M, “Leader propagation in non-uniform background fields in SF6”, 18th Int. Conf. on Gas Discharges and their Applications, Greifswald, Sept 2010


I. Seeger M, Niemeyer L, Bujotzek M and Votteler T, “Pre-discharges and breakdown in SF6 at small protrusions”, 15th

Contributions from the author of this thesis to each publication

VIII. The experimental setup was designed by MB and extended with an image intensifier. The experiments have been performed and the results post-processed by MB and by FS under supervision of MB. The analysis of the results was done by MB. The results have been discussed by MB and MS together with MK and CF. The manuscript was written by MB with support from MS, MK and CF.

VII. The simulations for first electron, streamer inception and leader propagation have been setup and performed by MB under supervision of MS. The results have been analysed by MB and discussed with MS. The comparison of the results to data from literature and the application to a GIS example was done by MB. The manuscript was written by MB with support from MS and review from MS.

VI. An adapted leader propagation model was applied to non-uniform gaps by MB under supervision of MS. The simulations have been performed by MB and the experiments have been carried out and supervised by MB and MS. The results have been discussed by MB and MS. The manuscript was written by MB with support and review from MS.

V. All experiments have been setup and executed by MB or under supervision of MB with support from MS. The analysis of the experimental data and simulations have been performed by MB with guidance from MS. The results have been discussed by MB and MS. The manuscript was written by MB with support and review from MS.
IV. The leader propagation model was developed and implemented by MS with contributions through frequent discussions between MS and LN as well as between MS and MB. MB contributed to the validation of simulations results with experimental data. The manuscript was written by MS with support from LN and contributions from MB.

III. The experimental setup was extended by MB with support from MS (new current measurement and high speed video). The majority of the experiments have been performed and supervised by MB with support from MS. Major parts of the analysis was performed by MB with support and under supervision of MS. The results have been discussed between MS, LN and MB. The theoretical considerations and the model were developed by MS and LN. The manuscript was written by MS with support from LN and contributions from MB.

II. MB executed all experiments and performed the data analysis with support and under supervision of MS. The results have been discussed between MS, MB and LN. The manuscript was written by MS with support from MB and LN.

I. MB has setup, performed and supervised parts of the experiments and was involved in the analysis of the results. The theoretical considerations and the model were developed by MS and LN. The manuscript was written by MS with support from LN and reviewed by all authors.

---

| MB | Markus Bujotzek |
| MS | Martin Seeger |
| LN | Lutz Niemeyer |
| FS | Fabian Schmidt |
| MK | Myriam Koch |
| CF | Christian Franck |
During the work on this thesis contributions to the following additional publication have been made, which is related to the research topic but which is not contained in this thesis:

1.3 Thesis outline

The scientific publications are included in chronological order in chapters 2–9 below which also reflects the list of publications (I.–VIII.). In the following sections the content of the publications is briefly described and related to the three main topics listed in section 1.1.

Overall, the basis of the present thesis are the first four publications (I.-IV.), especially the contribution on the leader propagation model (IV.). Based on these investigations, the model was applied, extended and validated for further relevant applications (V. and VI.). One major part of the present thesis is represented by the investigation of the overall applicability of models for first electron, streamer inception and leader propagation to technically relevant electrical insulation systems and the systematic evaluation of the dependence of the involved physical phenomena on accessible design parameters (VII.). Further, details of the streamer dimensions which have remained open in the course of the research have been investigated separately (VIII.).

1.3.1 Experimental methods

The experimental methods and the experimental results presented in this thesis are the first key part of the overall investigation. The main features of the experimental methods are:

- A test device, which is flexible for various electrode setups, different pressures, voltages, and offers optical and electrical access to the area of interest.

- Electrical measurements: High resolution measurement devices for pre-discharge currents and voltage, capable to withstand breakdown events.

- Optical measurements: Detection of light emitted by pre-discharges with UV sensitive fast photo multiplier tubes, op-
tical imaging of pre-discharges by high speed video and high resolution single pictures. Use of an image intensifier for recording of low light pre-discharge events.

- The corresponding data acquisition system: The observation of short discharge phenomena (several 10 ns) which occur in random sequence separated by long time intervals (several 10 ms to seconds) requires the use of data acquisition systems with high sample rates and high storage capacities.

The experimental setup was continuously modified and extended in the course of the work. The details are given in the corresponding publications and the main (experimental) features of each publication are listed below.

I.–III. Investigations on pre-breakdown partial discharges and breakdown in compressed SF$_6$ at small protrusions in a uniform background field are performed. This configuration was studied for artificial protrusions with different lengths at various pressures from 0.1 to 0.5 MPa and both polarities using electrical and optical diagnostics. The experimental results include observations in current and video measurements, statistical and formative time lags, time interval between arrested leaders, first corona and arrested leader charges, leader lengths and diameter, and inception and breakdown fields.

V. The experimental setup and methods described in (I.–III.) has been adapted to a sub-millimeter protrusion and a new photo multiplier tube was introduced.

VI. Extension of the electrode setup to strongly non-uniform background fields and additional use of single frame imaging in combination with high speed video and a photo multiplier tube.

VIII. The leader propagation model requires a few physical input parameters and one of the less precisely known ones is the
streamer radius. To provide input data for the model and to check assumptions made previously the streamer radius and the propagation length in SF\textsubscript{6} for strongly and weakly non-uniform field arrangements are experimentally investigated. The optical setup is modified to improve the image scale and an electrode setup for weakly and strongly non-uniform background field is used. The image intensifier is introduced for optical imaging of low light pre-discharges.

1.3.2 Theoretical considerations and modelling

The theoretical considerations and modelling of the pre-breakdown and breakdown phase are essentially contributions of the co-authors or originate from standard literature, e.g. the streamer criterion or the modelling of the first electron production. These contributions are considered as state of the art and form the theoretical basis of the thesis.

I. A general theoretical approach is presented to describe leader inception at protrusions for positive and negative polarity in a homogeneous background field. It is found that the model satisfactorily describes the measured corona charges and the breakdown fields.

II. A further investigation on pre-breakdown partial discharges and breakdown in compressed SF\textsubscript{6} at small protrusions in a uniform background field is performed. A significant formative time lag of up to several seconds was observed, depending on polarity and pressure. The role of the dominating pulses during the pre-breakdown phase, which are arrested leaders, on the formative time lag and the breakdown is discussed.

III. The basic physical processes from first electron generation to stepped leader propagation are discussed, and approximate quantitative models describing statistical time lags, corona
and leader charges and breakdown fields, are given. The investigation focuses on streamer and leader inception mechanisms.

IV. A physical leader propagation model that consistently describes the observed phenomena in uniform background fields in SF\textsubscript{6} is presented. The model explains two different types of leader inception; these can be associated with the precursor and the stem mechanisms. It also delivers the parameters of stepped leader propagation, which include step lengths, associated step charges, step times and fields, and temperatures in the leader channel. The model predicts the range of parameters under which arrested and breakdown leaders occur in good agreement with the experimental data.

In VII. the models for first electron production, streamer inception and leader propagation are recaptured and combined systematically to deduce discharge inception and breakdown fields in technically relevant electrical insulation systems.

1.3.3 Application and validation of the derived models

The validation and application of the developed models for the pre-breakdown and breakdown phase in various conditions relevant for technical gas insulation systems represent the second key part of the present work.

V. The leader propagation model is applied for defects with sizes typical of very small particles in the sub-millimeter range. The model is validated for weakly non-uniform fields with new experimental data for a protrusion length of 410 \( \mu \text{m} \), both polarities and different pressures. This protrusion length represents very small particles, but may account also for extreme values of surface roughness. Statistical and formative time lags together with breakdown voltage-time characteristic are
discussed. Some general consequences for technical applications are listed.

VI. In a next step the leader propagation model is extend and applied to non-uniform background fields. Although such configurations are usually different from technical gas insulation systems, examples for practical application exist, e.g. disconnector switching in GIS or large particulate contamination. Experimental data is presented for positive and negative polarity at a pressure of 0.3 MPa SF$_6$. Special attention is paid to the temporal evolution of the propagating leader, i.e. step times and lengths, and the leader channel field. These are compared to the predictions of the model together with the parameter ranges within which arrested leaders, delayed breakdown leaders and immediate breakdown leaders occur.

VII. The experimental investigations and the model predictions presented above have been carried out for well-defined protrusions. All experiments have been performed at DC step pulses. This basic results and the physical description of the involved processes are now used to deduce the partial discharge inception and breakdown fields in technically relevant electrical insulation systems, e.g. GIS, and for various voltage wave shapes. The dependence of the involved physical phenomena on accessible design parameters, like e.g. pressure, geometry, is discussed. Models for first electron production, streamer inception and leader propagation are combined systematically to deduce partial discharge inception and breakdown fields. The results show that only by taking into account these three physical mechanisms the parameter dependence of gaseous SF$_6$ insulation can be quantitatively explained. Consequences for practical applications are discussed.

VIII. The major objective is to confirm the previous assumptions and measurements regarding streamer radius and to provide input data for the model (IV.). It is found that the streamer
radius scaling agrees with previous experimental results for positive polarity. For negative polarity, experimentally obtained streamer radii are presented for the first time and confirm indirectly determined values from breakdown measurements for weakly non-uniform background fields (III.) and disprove the indirectly determined values for strongly non-uniform background fields (VI.). Further, it was found that for strongly non-uniform fields the streamer length scales as expected with the critical electric field, but with a different field for weakly non-uniform background fields.
1.4 References


2 Pre-discharges and breakdown at small protrusions

Martin Seeger, Lutz Niemeyer, Markus Bujotzek, Torsten Votteler

Full publication title: Pre-discharges and breakdown in SF$_6$ at small protrusions

Abstract: A general theoretical approach is presented to describe leader inception at protrusions for positive and negative polarity in a homogeneous background field. Under these conditions leader inception is sufficient to produce breakdown. Experimental data is presented for positive and negative polarity and is compared to the theoretical considerations. The experimental data includes pre-breakdown discharge currents and breakdown voltages for artificial protrusions with length scales in the range 1...30 mm and pressures 1...4 bar. It is found that the model satisfactorily describes the measured corona charges and the breakdown fields.

2.1 Introduction

Leader breakdown in SF$_6$ has been extensively studied in the past, mostly for strongly non-uniform (e.g. point-to-plane) gaps and at positive polarity. This has led to a consistent physical picture of the involved processes and an adequate theoretical description, see [1] and [2] for a summary. Negative polarity breakdown has attracted much less interest because negative breakdown voltages are usually substantially higher than positive [3].

In gas insulation technology, where smooth field configurations are used, particle induced breakdown is of particular interest. In this case the relevant electrode configuration is a quasi-uniform background field which is locally disturbed by a particle acting as small electrode protrusion. Although some empirical breakdown data have been published for this case, mainly for positive polarity (see e.g. [4] for one of the most recent publications), a consistent model has not yet been presented.

The scope of this paper is to extend the basic physical picture developed for strongly non-uniform gaps to gaps in which a quasi-uniform background field is disturbed by small particulate contamination. Under these conditions it is found that the models developed for strongly non-uniform gaps cannot be applied. Modifications are required to account for the particular features of the field at the pro-
trusions. The paper presents a theoretical concept and experimental data gained with artificial protrusions at both polarities. The data comprise the measurement of breakdown voltages, pre-breakdown discharge currents and the observation of light emission by a CCD video camera.

2.2 Theoretical considerations

2.2.1 Basic physical processes

The basic processes controlling the leader process in SF$_6$ were discussed in [1]: Streamers develop in a zone of enhanced electric field and form a streamer corona, consisting of many streamers (Figure 1a). The candidate for leader formation is a single streamer of high extension and charge. The per-length energy input into this candidate streamer channel is given by $q \cdot E$, with the channel field $E$ and the charge $q$ flowing through the channel. As the field along a streamer is approximately equal to the critical field $E_{cr} = p_0 \cdot 89$ [V/m] ($p_0$ = pressure [Pa]) the energy criterion $(q \cdot E_{cr})$ reduces to a charge criterion, so that leader inception is controlled by a critical charge criterion

$$q > q_{cr}$$ (1)

The critical charge $q_{cr}$ is controlled by the energy balance in the streamer channel: $E_{cr} \cdot q_{cr} = \pi \cdot R_s^2 \cdot \rho \cdot \Delta h_d$ where $R_s$ is the streamer channel radius, $\rho$ the initial gas density in the channel and $\Delta h_d$ the enthalpy reached at the end of the heating process and corresponding to the dissociation temperature $T_d$. The channel heating leads to an over-pressure which expands the channel. This is accompanied by a reduction of the critical field, which decreases with decreasing gas density and increasing gas temperature. The original streamer channel is thus transformed into a gaseous conductor with a decreasing voltage drop so that it acts as an electrode, at the tip of which a further corona can be formed and lead to a further corona and a
leader propagation step.

As was shown in [1] the critical charge can be expressed:

\[ q_{cr} = \frac{C_q}{p_0^2} \]  

(2)

with the initial gas pressure \( p_0 \). The proportionality constant \( C_q \) depends sensitively on \( T_d \) and the initial channel radius \( R_c \), which is polarity dependent. The channel heating model exposed in [5] indicates that \( T_d \) is typically in the range 1700...2400 K. The corresponding range for the proportionality factor is then \( C_q \approx 10...60 \) [As·Pa\(^2\)].

![Figure 1: a) Photograph of a typical streamer corona (left), b) simplified geometrical structure of a streamer corona in an applied background field \( E \) (right).](image)

2.2.2 Streamer corona

In the case of small protrusions of length \( L \) on an electrode in a (locally) uniform background field \( E_0 \), the structure of the streamer corona can be roughly characterised by a radial and a longitudinal extension \( r_c \) and \( l_c \) (Figure 1b). The longitudinal extension \( l_c \) of the streamers can be deduced from the fact that the field along the pro-
pagating streamer channel is equal to the critical field $E_{cr}$, leading to $E_{cr} \cdot l_c = \int_0^{l_c} E(z) \cdot dz$ where $E(z)$ is the field distribution from the protrusion $(z=0)$ tip along the longitudinal direction $z$. An approximate analytical solution can be obtained by using a mono/dipole approximation for $E(z)$ and by neglecting the difference between $E(z)$ and the background field $E_0$ at the streamer tip $x = l_c$, i.e. $l_c \cdot E_{cr} \approx E_0 \cdot L + E_0 \cdot l_c$ which leads to

$$l_c \approx L \cdot \frac{x}{1-x}$$

with the abbreviation $x = E_0 / E_{cr}$ for the reduced background field. Thus, the length $l_c$ of the corona increases over-proportional with $x$. The radial extension $r_c$ is approximately determined by the Laplace field along which the corona streamers propagate and will be less sensitive to the applied background field. Tentatively we assume therefore $l_c / r_c \sim x$, i.e. the aspect ratio of the corona is expected to increase with the reduced background field. This has the consequence that the total corona charge $Q$ is increasingly concentrated towards the axis, i.e. towards the “strongest” streamer. We can therefore expect that the ratio $q/Q$ increases approximately in proportion to $(l_c / r_c)^2$: $q/Q \propto x^2$. At the critical field $x=1$ a direct streamer breakdown occurs; i.e. only one, namely the strongest, streamer crosses the gap. To first approximation we can assume $Q/q(x=1) \approx 1$ and it follows:

$$\frac{q}{Q} \approx x^2$$

The space charge $Q$ contained in the corona would have to be determined by solving the Poisson equation and subsequent integration over the space charge density. As a simple analytical approximation, we consider the corona shape as a semi-ellipsoid within which the field is critical, see Figure 1b. For this geometry, analytical solutions
are available [6], which allows calculating the dipole moment $P$ of an ellipsoid in a uniform field. Interpreting $P$ as the product $P = l_c Q$ this yields an approximation for the corona charge:

$$Q \approx \frac{P}{l_c} = g \cdot \varepsilon_0 \cdot E_{cr} \cdot l_c^2 \cdot (1 - x) = g \cdot \varepsilon_0 \cdot \left(\frac{E}{p}\right)_{cr} \cdot p_0 \cdot L^2 \cdot \frac{x^2}{(1-x)} \quad (5)$$

with a dimensionless geometry factor $g$, which depends only weakly on the aspect ratio ($l_c/r_c$). The typical value for $g$ can be estimated for large aspect ratios to $g \approx 0.17$.

### 2.2.3 Leader inception criterion

As the charge $q$ flowing through a single streamer in the corona can not be determined experimentally, one has to find a measurable related quantity. In [1] it was shown that the total charge $Q$ of the streamer corona can be used in the case of point-to-plane gaps. We generalise this concept to arbitrary electrode geometries so that the leader inception criterion can be formulated

$$Q > Q_{cr}. \quad (6)$$

However, $Q_{cr}$ will not be the same as in point to plane gaps, but will have to be modified to account for the geometric particularities of the leader inception zone.

Using the leader inception criterion (6), introducing the ratio $q/Q = q_{cr}/Q_{cr}$ by eq(4) and using eq(2) and eq(5) for the critical charge and the corona charge $Q$, we obtain an implicit relation between the reduced leader inception field $x_{linc} = (E_0/E_{cr})_{linc}$ and the protrusion length $L$ and gas pressure $p_0$:

$$\frac{x_{linc}^4}{(1 - x_{linc})} = \frac{C_q}{g \cdot \varepsilon_0 \cdot \left(\frac{E}{p}\right)_{cr} \cdot p_0^3 \cdot L^2} \quad (7)$$

From this relation the reduced leader inception field $x_{linc}$ can be determined for a given protrusion length $L$ and pressure $p_0$. The pa-
rameter $C_q$ has to be determined from experiments. For the limit of high pressures and long protrusions, corresponding to $(E_0/E_{cr})<<1$, this relation reduces to $x_{\text{lin}c} \sim p_0^{-1/4}/\sqrt{p_0 \cdot L}$. The reduced leader inception field thus decreases with the product $(p_0 \cdot L)$ (with an additional weak pressure dependence) and can thus be plotted in the same way as the streamer criterion, which depends only on $(p_0 \cdot L)$.

2.3 Experiments

2.3.1 Experimental set-up

The experimental set up of the test gap is shown in Figure 2. An artificial protrusion (aluminium) with a length $L$ of 1mm, 2mm, 3mm, 5.5mm, 30mm and diameter of 1mm, was placed between two smooth plate electrodes (aluminium) of 200mm diameter each. The radius at the tip of the protrusion was roughly 250 $\mu$m, i.e. the tip had a conical shape over a length of approximately 0.5 mm. The distance between the plate electrodes was set to $D=20$ mm for the smaller protrusions of 1...3 mm length and 50mm and 80mm for the 5.5 mm and 30 mm length, respectively. Ground potential was applied to the plate electrode at the opposite electrode a high voltage step pulse (of positive or negative polarity) of 100 ns rise time was applied for 10s. This step was produced by a high voltage circuit, consisting of a charged capacitor ($2nF$), which was switched onto the electrode arrangement via a resistor (600$\Omega$). The whole set up including the high voltage circuit was placed into gas insulated switchgear (GIS) compartments containing SF$_6$. In the test gap compartment with the electrodes, the gas pressure was varied from 1...4 bar. The protrusion was insulated from the plate electrode by an insulating tube of 0.5 mm wall thickness, covered by a conductive layer for avoiding surface charges. Only 1-2 mm on the top of the needle was not insulated. This allowed determining pre-discharge currents with a current transformer (IPC Type CM-100-M). The current signal was recorded on a digital storage
oscilloscope (DSO), type LeCroy LT 374 and time integrated. The
accuracy of the current measurement was calibrated before each test
by a fast square wave current generator. The gap at the protrusion
was observed by a video camera through a window in the test com-
artment. The frame rate was 500...1000 fps.

Figure 2: Experimental set up of the test gap.

2.3.2 Experimental results

Pre-breakdown discharge currents and breakdown voltages were de-
termined for the various protrusion lengths. An example of a mea-
sured current waveform and the integrated corona charge is shown
in Figure 3 for negative polarity. These charges were determined
for the first pulse after application of the voltage, i.e. when they
occurred into a space charge free gas.

At negative polarity the discharge activity started without signi-
ficant statistical time lag. At positive polarity, however, a signifi-
cant statistical time lag was observed, which depended on protru-
sion length and pressure. At both polarities the size and repeti-
tion frequency of the current pulses increased with applied voltage.
Usually, large pulses were followed by smaller pulses, indicating a
space charge influence on the discharge activity. At positive polarity, leaders could not be observed by the video camera, i.e. leader inception immediately lead to breakdown. At negative polarity arrested leaders could sometimes be observed very close to the breakdown voltage. Thus, for both polarities the breakdown voltage is practically equal to the leader inception voltage in the given set-up. The

![Image of measured current waveform and deduced charge](https://via.placeholder.com/150)

**Figure 3:** Measured current waveform (upper plot) and deduced charge (lower plot) for a 2mm protrusion at a pressure of 2 bar.

corona charges were typically in the range of some pC to some 100 pC. According to eq (5) the quantity $Q/(p_0 \cdot L^2)$ should scale only with the reduced background field $x=E_0/E_{cr}$. Figure 4 shows the experimentally determined values (points) together with the model prediction of eq(5) (solid line). The experimental data are seen to
collapse to the model prediction within the experimental scatter, particularly for the smaller protrusion lengths.

Reduced (background) breakdown fields $x=E_0/E_{cr}$ were determined from the measured breakdown voltages $U_{bd}$, using $E_0=U_{bd}/D$. The resulting values for the various protrusion lengths and pressures are shown in Figure 5 for positive and negative polarity. The figure shows also the curves predicted by the model (eq (7)). These curves were fitted to the experimental data with only one single value for $C_q$ for each polarity: $C_q^+=0.8 \, [\text{As}\cdot\text{Pa}^2]$ and $C_q^-=1.5 \, [\text{As}\cdot\text{Pa}^2]$ for the positive and negative polarity, respectively. With this one fit all the experimental data is satisfactorily described.

2.4 Discussion

Small protrusions are representative for small particulate contamination and surface roughness in gas insulation. Since leader inception in most practical applications leads to breakdown, the understanding and prediction of leader inception under these conditions is of large practical interest.

The proposed model satisfactorily describes the corona charges and the reduced leader inception/breakdown fields.

Typical measured corona charges were in the range of some pC to some 100 pC, which is significantly less than observed in point-to-plane gaps [1], where corona charges amounted to some nC. The corona model of section 2.2 explains this difference by the concentration of the corona to fewer streamers by the background field (eq(4)).

Leader inception was observed in the experiments at breakdown voltage. Leader inception background fields were determined from that. Both, the measurements and the model show that the background field for leader inception and breakdown decrease with pressure and protrusion length, see Figure 5. This behaviour is reproduced by the model and can be directly seen from eq(7). The pressure dependence is due to the critical charge criterion (eq(2)) and the
protrusion length dependence follows from the increase of the corona charge with protrusion length.

The only free parameter of the model, \( C_q \) (see eq (7)) was determined by fitting to the measurements for each polarity. This yields a satisfactorily overall agreement of the measurement with the model for all pressures and protrusion lengths studied. For positive

![Scaled corona charges (Q/(p⋅L^2)) deduced from measured corona current pulses for various protrusion lengths and pressures at positive and negative polarity (symbols). Solid line: Model eq(5).](image)

**Figure 4:** Scaled corona charges \((Q/(p\cdot L^2))\) deduced from measured corona current pulses for various protrusion lengths and pressures at positive and negative polarity (symbols). Solid line: Model eq(5).

polarity \( C_q \) was about a factor of two lower than for negative polarity. The lower value of \( C_q \) for positive polarity corresponds to a lower leader inception field at positive polarity, assuming that a first electron is available. Due to the long time of voltage application of several seconds, this was always the case in our experiments.

A lower value for \( C_q^+ \) was also hypothesised in [1] for point-to-plane gaps and was thought to be about a factor 10 lower than \( C_q^- \). Obviously this difference is less for protrusions, i.e. leader inception fields at protrusions are less polarity dependent than those in point-to-plane gaps.

The values for \( C_q \) are lower than the expected range \( C_q \approx 10...60 \text{[As}\cdot\text{Pa}^2\text{]} \) by at least an order of magnitude. Within the accuracy of
Figure 5: Measured reduced breakdown fields (symbols) in dependence of pressure for various protrusion lengths at positive and negative polarity. The model predictions are shown by the lines.
the model and the expectations for $C_q$ (which resulted from very simple basic assumptions) this discrepancy is not surprising, however. Note that also the corona charges were reproduced within an order of magnitude only. Further, it might be possible that the heating of the candidate leader channel does not occur in a single step, but by a sequence of smaller discharge pulses. This would allow a lower value for $C_q$. This hypothesis is supported by the observation of the discharge activity in the experiments, where several large current pulses occurred in regular time intervals of some $\mu$s to some 10 $\mu$s before the breakdown. These time intervals are too large to be interpreted as propagating leaders. In the corresponding video pictures only one discharge channel could be observed. Similar observations are reported by [4].

### 2.5 Conclusions

The leader inception in SF$_6$ at small protrusions in homogeneous background fields were investigated for positive and negative polarity. A theoretical leader inception model is presented, which is based on a critical charge criterion. This model is similar to the earlier model presented in [1], but, additionally, takes the particular features of the electric field at the protrusion into account.

Experimental data is presented for positive and negative polarity. In the experiments the pre-breakdown discharge currents and the breakdown voltages were measured. The measurements were accompanied by optical observation of the pre-breakdown discharges using a CCD video camera.

The investigated protrusion lengths were in the range of 1...30 mm and the SF$_6$ pressure was in the range 1...4 bar. This is the parameter range of practical interest for gas insulation with particulate contamination. The model satisfactorily describes satisfactorily both, the measured pre-breakdown corona charges and the measured leader inception background fields. The only free parameter of the model $C_q$ was fitted to the experiments for positive and negative
polarity. These values are lower than those found in point-to-plane gaps. Possible reasons were discussed.

The leader inception and breakdown occur almost at the same reduced background fields and decrease with pressure and protrusion length. This behaviour is explained by the model. For large values of pressure $p_0$ and protrusion length $L$ the reduced leader inception/breakdown field scales approximately as $E_0/E_{cr} \sim p_0^{-1/4}/\sqrt{p_0 \cdot L}$. This is a similar parameter dependence as for the streamer inception criterion.

## 2.6 Acknowledgment

The authors thank A. Hayati Soloot for performing parts of the experiments during his internship at ABB Switzerland Ltd., Corporate research.
2.7 References


3 Formative time lag and breakdown at small protrusions

Martin Seeger, Markus Bujotzek and Lutz Niemeyer

Full publication title: Formative time lag and breakdown in SF₆ at small protrusions

Abstract: Pre-breakdown partial discharges (PBPD) and breakdown in compressed SF$_6$ at small protrusions in a uniform background field were investigated at pressures of 0.1...0.5 MPa for both polarities. Such geometry is close to technically relevant configurations of compressed gas insulation systems, which are locally disturbed by small defects. Optical and electrical diagnostics allowed us to obtain a consistent picture of the pre-breakdown phase and the breakdown, which occurred by stepped leader propagation. It is found that the PBPD activity at both polarities is decisive for the insulation performance of the system. A significant formative time lag of up to several seconds could be observed, depending on polarity and pressure. The role of the dominating pulses during this phase, which are arrested leaders, on the formative time lag and the breakdown will be discussed.

3.1 Introduction

Breakdown of compressed SF$_6$ insulation occurs via a sequence of processes beginning with the generation of a first electron to initiate a streamer and streamer corona, followed by PBPD and ending with stepped leader propagation across the gap, resulting in breakdown. These processes mostly have been studied in strongly non-uniform field gaps (point-to-plane) and at positive polarity [1-4]. In compressed gas insulation systems, e.g. gas insulated switchgear (GIS) [3], the field configuration of practical interest is completely different from point-to-plane gaps. The insulation gap is only weakly non-uniform and its field is only locally disturbed by small-scale defects, such as particles or surface roughness. For such field configuration we have found that the partial discharge activity at both polarities is decisive for the insulation performance of the system. In recent publications [5, 6] we presented the results of measurements which have led to an improved understanding of PBPD and breakdown development in uniform background fields with protrusion lengths L=1...30 mm and pressures in the range p=0.1 MPa...0.5 MPa.
at both polarities. In [6] the focus was set on a protrusion length of 1 mm. The basic physical processes from first electron generation to stepped leader propagation were discussed, and approximate quantitative models describing statistical time lags, corona and leader charges and breakdown fields, were given [6]. The present paper summarises the physical understanding obtained (section 3.2) and will focus on the formative time-lag at a pressure of 0.2 MPa (section 3.3). In the presentation of the data the ratio of the background field $E_0$ to the critical field $E_{cr} = (E/p)_{cr} = 89p$ [V/m] will be used, where $p$ [Pa] is the pressure. This reduced background field $x = E_0/E_{cr}$ is important, since $x=1$ constitutes the theoretical limit to which the insulation can be exploited in the absence of defects.

3.2 Physical processes during PD and breakdown

The field geometry investigated is shown in Fig.1. For details see [6]. A high voltage step pulse was applied for a duration of 60 s. Positive and negative polarity at the protrusion were investigated. The PBPD activity was monitored by a sensitive current transformer (CT), connected to a digital storage oscilloscope (DSO). Optical observation of the discharge gap was performed by a high speed video camera.

For both polarities the following physical picture emerged from the measurements, see Fig.2: The first corona (Fig.2, event (a)), triggered by a first electron after a statistical time lag $t_s$, develops into a space-charge-free gap and consists of several streamers. It leaves behind an ionic space charge, which reduces the electric field and decays by ion drift in the field. Further coronae may develop during the space charge decay with smaller charges than the first corona. Such smaller coronae were observed over the whole PBPD time. Streamer coronae are only very weakly visible in the video frames due to insufficient sensitivity of the video camera. If the electric field at the tip of a streamer channel is sufficiently high,
42  3 Formative time lag and breakdown at small protrusions

Figure 1: Experimental set-up: $L=$ protrusion length, $D=20\ldots80$ mm.

Further ionization activity can start from it, and a further corona may develop at this tip (Fig.2, event (b)). The charge injected into the narrow streamer channel heats it further. This process may repeat a few times. Note that this is a simplified picture; the detailed physical processes are much more complex [1-2, 7-8]. The charge injection into the channel generally occurs in the form of a sequence of current pulses, leading to a stepwise heating. As the current pulse sequence typically occurs within 100 ns, energy losses from the channel are low and its total temperature increase at the end of the pulse sequence is approximately determined by the sum of the pulse charges over the sequence. As long as the channel temperature remains sufficiently low and the electric field in the channel remains correspondingly high, the voltage drop along the channel keeps the voltage at its tip low. This, together with the field reduction by space charges at the channel tip, limits the corona activity and further energy input into the channel. Such events will be denoted as arrested leaders. The arrested leader channel decays mainly by heat conduction. Only if a new corona occurs at the leader tip before the channel has decayed the latter can be reheated and may further elongate into the gap (Fig.2, event (c)). These events will be denoted as restrike-leaders. If, however, the channel has decayed, a new leader has to be started (Fig.2, event (d)). Breakdown occurs if the channel heating exceeds a level above
which the electric field at its tip is sufficiently high to initiate further propagation (Fig.2, event (e)). Since the corona activity at the leader tip varies randomly, the transition from arrested leaders to leader propagation across the gap is characterized by a substantial statistical variance. At low electric fields the transition can occur only after several arrested leaders have formed, i.e. after an extended PBPD time. At higher applied fields it may occur immediately after the first corona.

3.3 Formative time-lag

The total time to breakdown $t_{bd}$ after voltage application is the sum of the statistical time lag $t_s$, the PBPD time $t_{pd}$ during which arrested leaders occur and the propagation time lag $t_p$, see Fig.2:
$t_{bd} = t_s + t_{pd} + t_p$. In the experiments the propagation time $t_p$ was in the range of some 100 ns for both polarities and over the entire pressure range studied. Fig. 3 shows the measured statistical time lag $t_s$ and the formative time lag $t_f = t_{pd} + t_p$ for both polarities at a pressure of 0.2 MPa. The horizontal dashed lines in the figure indicate when the applied voltage pulse has reached 90% of its amplitude. The vertical dashed lines indicate the theoretical reduced streamer inception field $x_{inc}$ based on the avalanche criterion. Reduced breakdown fields $x_{bd}$ (50% probability) are indicated by the arrows. The statistical time lag decreases with increasing applied field with a slope which is steeper for positive polarity and is higher for positive polarity than for negative polarity at the same background field. At negative polarity there is a limiting field above which the statistical time lag is negligible with respect to the total formative time lag $t_{pd} + t_p$.

**Figure 3:** Statistical time lag $t_s$ and formative time lag $t_f$ versus reduced background field $x$. 
3.3 Formative time-lag

Figure 4: Leader charge $Q_L$ versus reduced background field $x$ for arrested leaders (open symbols) and for the first leader step at breakdown (full symbols).

For both polarities the formative time lag is significant and can amount to up to seconds. It decreases with increasing field. At background fields which exceed $x_{bd}$ by about 25% (positive) and 40% (negative) the breakdown occurs directly after the statistical time lag, i.e. the formative time lag reduces to the propagation time $t_p$. Fig.4 shows the leader charge determined from the current measurements at a pressure of 0.2 MPa, see [6] for details. The leader charge increases with increasing reduced field. Minimum leader charges at breakdown are indicated by the dashed lines in the figure. They amount to 200 pC and 600 pC for positive and negative polarity, respectively.

Fig.5 shows the average number of leaders in the PBPD time $t_{pd}$ as a function of the reduced background field $x$ for both polarities. For lowest breakdown fields the number of leaders is much higher for
the negative polarity than for the positive polarity. Some 10 leaders can occur until the propagating leader occurs. For higher fields this number reduces to only a few leaders within $t_{pd}$ and for the highest fields, when the breakdown occurs immediately after the statistical time lag, it becomes unity for both polarities. This single leader then becomes the first leader step of the immediately propagating leader.

Fig.6 shows the distribution of times between successive leaders $t_L$ for both polarities and for selected ranges of the reduced field $x$. The lines indicate the relevant time scales for the space charge decay $t_{sc}$ and the leader channel decay $t_{\lambda}$, which were estimated to 1...15 $\mu$s and 7...80 $\mu$s, respectively [6]. Since the space charge decay time is lower than the channel decay time large coronae can reheat the channel after a few microseconds. This explains the occurrence of restrike-leaders. The video observation revealed that leaders following within less than 30 $\mu$s of the previous leader were always restrike-leaders [6]. For the lowest breakdown fields (upper plots in Fig.6) the time between successive leaders $t_L$ ranges from a few $\mu$s to several 10 ms, i.e. leaders can follow within a short time inter-
Figure 6: Distribution of $t_L$ for selected ranges of the reduced background field $x$. The total number of leader events per distribution is denoted by $N_L$.

In the same channel (restrike-leader) or occur independently in new channels after a long time interval. For $0.5 < x < 0.55$ most of the leaders are independent. With increasing field $t_L$ decreases. This is valid for both polarities.

The results of Fig.4-Fig.6 can be interpreted as follows: With increasing field the time between successive leaders decreases (Fig.6), i.e. within the same time interval the number of breakdown attempts increases. With increasing field the charge in the leaders also increases (Fig.4), which facilitates the propagation and, therefore, breakdown. Both effects lead to a decrease in the number of leaders within $t_{pd}$ (Fig.5) and to a decrease of $t_{pd}$ with increasing background field. This explains qualitatively the decrease in the formative time lag with increasing background field $x$ in both polarities (Fig.3).
Fig. 7 shows the fraction of breakdowns produced by restrike-leaders as a function of the reduced field $x$. For negative polarity and lowest breakdown fields, the breakdown is dominantly initiated by restrike-leaders, i.e. it is the effect of cumulative heating of the same channel which enables the breakdown at low fields. This fraction decreases with increasing field, which can be explained by the increasing leader charge. The probability of a single leader to propagate is higher at higher fields and the importance of successive heating of the same channel is less important for the breakdown. Since restrike-leaders are relatively rare events a large number of leaders are needed before breakdown occurs.

For positive polarity, where we should note that the uncertainty is larger, only a small fraction of the breakdowns is produced by restrike-leaders (Fig. 7). This may be the result of the lower leader charge necessary for propagation at the same electric field (Fig. 4) at positive polarity, i.e. the breakdown can be initiated by a single leader and cumulative heating is not necessary. This reduces the number of arrested leaders until breakdown.
3.4 Conclusions

The experimental results presented in this paper and in [6] show that at protrusions in uniform background fields a significant formative time lag can be observed. This time lag is not only the time needed for stepped leader propagation, but consists of an extended PBPD time.

The detailed analysis results in a “fractal-like” behaviour over the involved time scales: On short time scales of a few 10 ns sequential pulses lead to sequential heating of a streamer channel. These can be observed as arrested leaders. On larger time scales of microseconds the sequential restrikes into the same leader channel can lead to sequential heating and propagation of the leader.

On even larger time scales of 100 $\mu$s and more new leaders are started.

The observed decrease of the formative time lag with increasing field can be qualitatively explained by a decrease of the time interval between leaders, i.e. an increased number of breakdown attempts, in combination with an increasing leader charge.

The result is that for negative polarity the minimum breakdown field is determined by restrike-leaders. We believe that this is caused by the charges of single leaders being too low. Only for higher fields can one leader efficiently initiate propagation through the gap. This is different for positive polarity, where at the minimum breakdown field the charge of a single leader is already sufficient. Thus, it is a stochastic process which determines when this leader occurs and which defines the formative time lag.
3.5 References


4 Partial discharges and breakdown at protrusions in uniform background fields

Martin Seeger, Lutz Niemeyer and Markus Bujotzek

Full publication title: Partial discharges and breakdown at protrusions in uniform background fields in SF₆

doi: 10.1088/0022-3727/41/18/185204
Abstract: The breakdown mechanism of compressed SF$_6$ in gas insulation is known to be controlled by stepped leader propagation. This process is reasonably well understood for strongly non-uniform insulation gaps (“point-to-plane”) and in the absence of pre-breakdown discharge activity (“corona stabilization”). Open questions still remain for weakly non-uniform insulation gaps with small electrode protrusions (particles, surface roughness), in which pre-breakdown partial discharge (PD) activity is present. This paper presents a first attempt to derive a consistent picture under these conditions, which are characteristic for practical gas insulation systems. Experiments were carried out in a uniform field gap with a short protrusion on one electrode. This configuration was studied at various pressures from 0.1 to 0.5 MPa and both polarities using electrical and optical diagnostics. The results are interpreted using a quantitative model and order-of-magnitude estimates. The emerging picture allows prediction of most of the technically relevant aspects of the discharge processes and their main parameter dependencies. It comprises statistical time lags, formative time lags including pre-breakdown PD activity and breakdown fields as a function of gas pressure, protrusion length and polarity.

4.1 Introduction

Breakdown of compressed SF$_6$ insulation occurs via a sequence of processes starting with the generation of a first electron to initiate a streamer and streamer corona, followed by pre-breakdown PD and ending with stepped leader propagation across the gap, resulting in breakdown. So far, these processes have mostly been studied in strongly non-uniform field gaps of the point-to-plane type. Most studies concentrate on positive polarity (e.g. [1-12]) at the high field electrode, for which the breakdown voltage is much lower than for negative polarity (e.g. [13-15]). The results of these studies have usually been presented in the form of voltage-pressure diagrams (figure 1(a)), in which streamer inception (broken curve), PD activity
(shaded area) and breakdown voltage (solid curve) are the main references. The point-to-plane experiments have helped to understand some basic features of the breakdown process in the absence of pre-breakdown PD activity, namely leader initiation and stepped leader propagation (e.g. [5]). In the presence of pre-breakdown PD activity, usually denoted as corona stabilised breakdown, only some qualitative explanations have been discussed (e.g. [7-12, 16, 17]).

![Diagram](image)

**Figure 1:** Breakdown and PD characteristics in a) point-to-plane and b) uniform background field geometries with a protrusion.

In compressed gas insulation systems, e.g. gas insulated switchgear (GIS) [4], the field configuration of practical interest is completely different from point-to-plane gaps. The insulation gap is characterised by a weakly non-uniform electric field distribution, in which the ratio between maximum and minimum electric field in the gap is in the range between 2 and 3. This field distribution will be denoted as the background field $E_0$ and is determined by the geometry of ideally smooth electrodes. In reality the electrodes are not ideally smooth and the background field may be locally disturbed by small-scale defects, such as particles or surface roughness [18]. The scale of these defects is typically several $10 – 100 \, \mu\text{m}$ in the case of surface roughness and a few mm in the case of particles. These defects, when located on an electrode, can be idealised as small electrode protrusions embedded in the locally almost uniform background field $E_0$ (figure 1(b)). For this specific configuration it
turns out that the PD activity at both polarities is decisive for the insulation performance of the system. Although some experimental data for relatively long protrusions in a quasi-uniform background field have been published (e.g. [8-12]), a comprehensive understanding of the involved processes, to our knowledge, has not yet been presented. In particular, short protrusions in and below the mm range have not been studied because of experimental difficulties in sample preparation and local diagnostics.

This paper presents a first attempt to extend the physical understanding developed for point to plane gaps and long protrusions to technically more relevant small protrusions. The experimental study focuses on protrusions of 1 mm length in a uniform background field. This restriction is not essential as the derived concepts are based on physical considerations and allow extrapolation to smaller and larger protrusions. The latter case has already been treated in [19].

In section 4.2 we will present experimental data for both polarities and will use these data to identify the relevant discharge processes. A discussion of the qualitative features from first electron generation to breakdown will be given in section 4.3. A model for quantification of corona and leader charges, breakdown fields and estimates of the involved time scales will also be given in section 4.3. Focus will be put on the distinction between the various pre-breakdown discharge phenomena, their random features and polarity differences. To represent the data, the voltage versus pressure plot used for point-to-plane gaps (figure 1(a)) will be replaced by the scheme of figure 1(b). Instead of the voltage $U$ as the discharge driving quantity, the background field $E_0$ referred to a reference value, which is a property of the gas and is called the critical- or limit-field, will be used. This reference field scales with the gas pressure $p$ [Pa] as $E_{cr,0} = (E/p)_{cr,0} \cdot p = 89 \cdot p$ [V/m] at ambient temperature [18]. This reduced background field $x = E_0/E_{cr,0}$ is of importance, since $x = 1$ constitutes the theoretical limit to which the insulation could be exploited in the absence of defects.
4.2 Experiments

4.2.1 Experimental set-up

The experimental set-up of the test gap is shown in figure 2. An artificial protrusion (steel) with a length $L = 1$ mm and radius 0.5 mm, was placed between two smooth plate electrodes (aluminium) of 200 mm diameter. The protrusion had a conical shape over a length of approximately 1 mm and a tip radius of 250 $\mu$m. The distance between the plate electrodes was set to $D = 20$ mm. Ground potential was applied to the plate with the protrusion. At the opposite electrode a high voltage step pulse (of positive or negative polarity) of 100 ns rise time was applied for a duration of 60 s. This step was produced by a high voltage circuit, consisting of a capacitor (2 nF), which was charged by a Van-de-Graaf generator (VdG) and was switched onto the electrode arrangement via a damping resistor (600 $\Omega$). The whole set-up including the high voltage circuit was placed into GIS compartments containing SF$_6$. In the test gap compartment the gas pressure was varied from 0.1...0.5 MPa SF$_6$ (>99 % purity) at ambient temperature. Most measurements were carried out at 0.2 MPa and 0.4 MPa. The protrusion was insulated from the plate electrode by an insulating tube of 0.5 mm wall thickness. Since for both polarities the results (time lags and breakdown voltages) were influenced by the time interval between successive voltage applications, a sufficient long pause time of about 300 s [4] between the voltage applications was used.

4.2.2 Diagnostics

As the short discharge phenomena (several 10 ns) occurred in random sequence separated by long time intervals (several 10 ms to seconds) it was necessary to use data acquisition systems with high sample rates and high storage capacities.

The pre-discharge currents passing through the tip of the needle were measured with a current transformer (Pearson model 6585,
Figure 2: Experimental set-up. DSO=Digital storage oscilloscope, VdG=Van de Graaf generator, CT=current transformer. The protrusion length and gap distance were $L = 1\, \text{mm}$ and $D = 20\, \text{mm}$, respectively.

analogue bandwidth 400 Hz...250 MHz) and were recorded on a digital storage oscilloscope (DSO) type LeCroy LC574AL (analogue bandwidth 1 GHz). The sequence trigger mode of the DSO allowed the main events during a full sequence of short discharge events separated by long time intervals to be captured. The trigger level was set to record current pulses exceeding some mA. The recorded time per segment was 50...100 $\mu$s and the processing time between two segments was between 15...45 $\mu$s. Except for the events occurring in this dead-time all discharge events were recorded. The number of recorded sequences was adjusted to record all events until breakdown. The pulse charges were obtained by time integration of the current signal. In contrast to PD measurements, which only record the apparent charge [18], these charges are true, physical charges.

The initial phase of the rapidly rising step voltage caused very fast transients (VFT) in the GIS test set-up, which show up as high amplitude displacement current transients superimposed on the discharge current for about 1 $\mu$s. After this time the discharge pulses could be measured without disturbance.
In some experiments the protrusion was also observed by a high speed video camera Phantom v7.3 through a window in the compartment. The frame rate was 74074 fps, i.e. one frame per 13.5 µs with an exposure time of 11.5 µs. The recording time covered several 10 s. In these experiments only, a 10% N$_2$ admixture to the SF$_6$ was used to increase the light emission from the discharges. This reduces the critical field by about 2% [20] and had negligible influence on the current signals.

4.2.3 Experimental results

Observations in current and video measurements

Examples of measured current waveforms and time-correlated video frames are shown in figures 3 and 4 for a pressure of 0.2 MPa and negative and positive polarity, respectively. Instead of current amplitudes the corresponding pulse charges will be discussed. For negative polarity (figure 3) the discharge activity starts after a statistical time lag of 80 µs in the example shown. The first pulse often takes the form of a large, single pulse (see event (a)) of some 10 pC. It is followed, after a time of some µs, by smaller pulses with charges of a few pC and pulse intervals of the order of a microsecond. On the video frames the first pulse only appears as a very weak and diffuse discharge pattern. These frames are not shown. This first large pulse will be denoted as first corona. After a delay (4 ms in the example shown), the video frames show narrow, luminous channels, which do not cause breakdown. These will be denoted as “arrested” leaders. The current measurements show a large pulse for such arrested leaders (see enlarged current waveforms in figure 3, event (b)) followed by smaller pulses of decreasing magnitude over a duration of about 100...200 ns and with a pulse interval of about 10 ns. The highest pulse within that sequence is of similar magnitude as the first corona and is often preceded by a small pulse of a few pC, as already observed by [8-12]. This current signature was used to identify leaders in the measured current waveforms in
the case when video frames were not available. Occasionally this pulse sequence was followed by a regular sequence of a few pulses with time separation of about 100 ns (see figure 3, event(c)). This discharge activity ceased completely after about 500 ns. In the time intervals between subsequent arrested leaders only weak corona activity at the protrusion tip can be observed. The video frames show that subsequent arrested leaders nearly always occur in the same, or in part of the same, channel when they follow within less than about 30 $\mu$s; see events (c) and (d). In this case, the magnitudes of successive pulses often increased. This phenomenon was correlated with an increase of the channel length. Finally (figure 3, event (e)), breakdown occurs by several successive leader steps with pulse separations of the order of 100 ns.

For positive polarity long statistical time lags are observed. In the example shown in figure 4 the first corona (see event (a)) occurred after 143 ms, and similarly to the case of negative polarity the initial pulse was followed by a sequence of pulses with charges of a few pC and pulse intervals of the order of a microsecond. After 155 ms two successive arrested leaders (events (b) and (c)) can be observed, which are separated by a time interval of 2.3 $\mu$s. As the video frame could not resolve this time separation, the frame shows the superposition of both events. As in the case of negative polarity, both discharges occur in the same channel and are associated with a sequence of pulses. The number of such pulses and the duration of the sequence was less than for negative polarity. Generally, arrested leaders of positive polarity were much less intense in the video frames than those of negative polarity. Breakdown occurred 7 ms later in this example by a sequence of leader steps and with a total gap crossing time of about 130 ns. At fields significantly higher than the 50% breakdown field, immediate breakdown occurred after the first corona for both polarities.
Figure 3: Measured current waveforms and related video frames for negative polarity at $p = 0.2$ MPa. The applied voltage was 200 kV. The first pulse close to $t = 0$ s before event (a) is the VFT signal.
Figure 4: Measured current waveforms and related video frames for positive polarity at \( p = 0.2 \) MPa. The applied voltage was 185 kV. The pulse in the top left graph is the VFT signal.
Statistical and formative time lag

The picture of the breakdown process for negative and positive polarities described above was observed consistently over the investigated range of reduced background fields $x$ and pressures $p$. A schematic of the sequence of events from voltage application to breakdown is shown in figure 5(a). After application of the fast rising voltage step a statistical time lag occurs, which represents the time necessary for a first electron to start an avalanche and produce a streamer corona in the high field region close to the protrusion tip [21, 22]. This first corona initiates a pre-breakdown PD phase during which streamer coronae and also arrested leaders can be observed. At sufficiently high background field these leaders eventually propagate through the gap and cause breakdown after the propagation time. The time scales are denoted by:

- $t_s$: statistical time lag
- $t_{pd}$: pre-breakdown PD time
- $t_p$: leader propagation time
- $t_f = t_{pd} + t_p$: total formative time lag
- $t_{bd} = t_s + t_{pd} + t_p$: total time to breakdown.

A schematic of the dependence of these time scales on the reduced background field $x$ is shown in figure 5(b). Two characteristic reduced background fields have to be distinguished:

- $x_{min}$: reduced background field below which no breakdown occurs
- $x_{max}$: reduced background field above which leader propagation is immediately started from the first corona. This case will be denoted as “immediate breakdown” in the following.
Partial discharges and breakdown at protrusions in uniform background fields

Figure 5: Schematics of discharge processes and related time scales. (a) Discharge processes and time scales. The times $t_{sc}$, $t_L$, $t_\lambda$ denote space charge decay time, time between successive leaders and thermal leader decay time, respectively. Typical pulse charge levels are indicated by the horizontal dashed lines. (b) Dependence of time scales on reduced background field $x = E_0/E_{cr,0}$. $x_{inc}$, $x_{min}$ and $x_{max}$ denote fields for PD inception, minimum breakdown and immediate breakdown ($t_{bd} = t_p$), respectively.
Note that there is a substantial gap between $x_{\text{min}}$ and $x_{\text{max}}$.

Figure 6 shows, as symbols, the measured statistical and formative time lags $t_s$ and $t_{pd} + t_p$ as a function of $x$ for both polarities and for pressures of 0.2 MPa and 0.4 MPa. Both time lags decrease with increasing applied field with a slope which is steeper for positive polarity. The decrease is higher for positive polarity than for negative polarity for the same background field. At negative polarity there is a limiting field above which the statistical time lag is negligible with respect to the total formative time lag. The propagation time $t_p$ was in the range of some 100 ns for both polarities and over the entire pressure range studied. Both statistical and formative time lags may reach values up to several seconds close to $x_{\text{min}}$. 

![Diagram showing the relationship between time lags and $x$ for both polarities and pressures.](image-url)
Figure 6: Statistical time lag $t_s$ and formative time lag $t_{pd} + t_p$ as a function of the reduced background field $x$. The horizontal dotted line indicates the leader propagation time $t_p$. The theoretical reduced background fields ($x_{inc}$ (2), $x_{min}$ (20) and $x_{max}$ (22)) are indicated by arrows below the x-axis. $x_{inc}$ is additionally marked by the vertical dotted line. The experimental values of $x_{* min}$ and $x_{* max}$ are indicated by the vertical dashed lines derived from the distribution of the experimental data (full circles): $x_{* min}$ is the lower boundary and $x_{* max}$ is the intersection of the descending slope with the horizontal line $t = t_p$. 
Figure 7: Average time interval between successive arrested leaders as a function of the reduced background field \( x \) for pressures of 0.2 MPa and 0.4 MPa and both polarities. Predicted reduced breakdown fields \( x_{\text{min}} \) from (20) are indicated by the arrows below the x-axis. The vertical dotted line indicates the predicted streamer inception background field \( x_{\text{inc}} \).
**Time interval between arrested leaders**

The time interval $t_L$ between arrested leaders (as defined in figure 5(a)) varied stochastically. Minimum intervals were, for all investigated pressures and both polarities, of the order of a microsecond. The average time interval $<t_L>$ between successive arrested leaders of is shown in figure 7 as a function of the applied field for both polarities. This time decreases with increasing field and decreases with increasing pressure. For positive polarity the decrease with the field is much steeper than for negative polarity. At the minimum reduced breakdown field $x_{min}$, indicated by the arrows in the figures, the average time interval between arrested leaders is around 10 $\mu$s and 100 $\mu$s for negative and positive polarity, respectively. At the highest fields the leader starts to propagate immediately and the number of leader steps during propagation is typically between 2 and 6.

**First corona and arrested leader charges**

As derived in our previous publication [19] the first corona charge $Q_c$ is proportional to $p \cdot L^2$ and is a function of the reduced background field $x = E_0/E_{cr,0}$ (see also equation (10) in section 4.3.4 below), where $L$ is the protrusion length and $p$ the pressure. First corona charges scaled according to this law are shown in figure 8 together with the theoretical curve from (10) below.

Arrested leaders are associated with a sequence of pulses. The cumulated charge $Q_L$ of this sequence was evaluated over 150 ns (50 ns before and 100 ns after the largest pulse). Additionally, the charge of the largest single pulse $Q_{L,s}$ during the pulse sequence was determined. This largest pulse was usually one of the first pulses of the sequence and was found to scale with the cumulated charge $Q_L$ as

$$Q_{L,s}/pC \approx (Q_L/pC)^{0.8}$$

(1)
4.2 Experiments

Figure 8: Scaled corona charges \( Q_c/(pL^2) \) as a function of the reduced background field \( x \).

Figure 9 shows \( Q_L \) plotted with the same scaling as the corona charge, i.e. \( Q_L/(p\cdot L^2) \), for comparison. Leaders which initiated the breakdown are marked by full symbols and have the highest charges. Especially at low fields, large charges often resulted from arrested leaders re-striking the same channel. This re-striking could repeat a few times and was observed for both polarities. It was much more frequent at negative polarity. Minimum values for \( Q_L/(p\cdot L^2) \) at breakdown are marked by the horizontal arrows in figure 9. The corresponding charges are the same for 0.2 MPa and 0.4 MPa and are 200 pC and 600 pC for positive and negative polarity, respectively. For the highest fields, at which the breakdown is immediately triggered by the first corona, the charges could not be determined due to the overlaid VFT signal.

**Leader lengths and diameter**

The lengths of arrested leaders were roughly evaluated from the video frames and are plotted in figure 10(a) as a function of the reduced background field \( x \). The much better visibility and higher
Figure 9: Scaled cumulated leader charges $Q_L/(pL^2)$ as a function of reduced background field at 0.2 MPa and 0.4 MPa for both polarities. The minimum charges leading to breakdown are indicated by the horizontal arrows. Predicted reduced breakdown fields $x_{min}$ from (20) are indicated by the arrows below the x-axis.
frequency of occurrence of negative leaders explains that mainly negative leaders could be evaluated. Figure 10(a) shows an increase of the leader length with the applied background field. Maximum observed leader lengths amounted to only 2...3 mm. The large scatter of the leader length for similar applied fields indicates an additional influence parameter, which can be expected to be the cumulated leader charge $Q_L$. This is confirmed by figure 10(b), which shows that the arrested leader length increases with the cumulated leader charge. The diameter of the leaders could be estimated very roughly from the video frames and was typically about 1...2 pixels with a pixel size of about 70 $\mu$m. This allows estimation of an upper limit for the leader diameter of about 70...140 $\mu$m.

**Inception and breakdown fields**

The minimum reduced breakdown field $x_{min}$ in the experiments is shown in figure 11 for both polarities as a function of pressure. For reference, the theoretical reduced streamer inception background field $x_{inc} = E_{inc}/E_{cr,0}$, determined by (2) below, is shown by the full curve. In both polarities leader inception occurred at fields below breakdown. At negative polarity and pressures $\geq 0.3$ MPa leader inception was observed already at the theoretical streamer inception field. Only at 0.1 MPa negative and positive inception background fields were the same. Minimum reduced breakdown fields were lower for positive polarity at pressures $\geq 0.3$ MPa. At lower pressure $p \leq 0.2$ MPa, the minimum reduced breakdown fields in both polarities were equal.
Figure 10: Scaling of arrested leader length with reduced background field $x$ and cumulated leader charge $Q_L$. (a) Arrested leader length as a function of reduced background field $x$ for $p=0.2$ MPa and 0.4 MPa and both polarities. (b) Arrested leader length as a function of leader charge $Q_L$ for negative polarity and $p=0.2$ MPa.
Figure 11: Reduced streamer inception field $x_{inc}$ and reduced minimum breakdown field $x_{min}$ as a function of pressure for both polarities. Curves: prediction (2) and (20). Points: measurements.


4.3 Discussion

4.3.1 Overview of physical picture

The usual understanding of breakdown in SF\textsubscript{6} as described in [18] is a sequence of phenomena starting with the generation of a first electron after a statistical time lag $t_s$ and followed by a first streamer-corona, streamer-to-leader transition, leader propagation to the opposite electrode and leader-to-spark transition, which ends in breakdown. Under the particular conditions studied here, the process is more complex. The essential phenomena are summarized in figure 5(a). The additional phenomena of interest to be discussed are the extended pre-breakdown PD phase of duration $t_{pd}$ during which arrested leaders occur. This type of PD activity is reported in several investigations, e.g. [8-13, 23], but the controlling mechanisms were not discussed comprehensively.

The first corona leaves behind an ionic space charge, which reduces the electric field and decays by ion drift in the field. Further coronae may develop during the decay of the original space charge [8-12, 17]. The higher the residual space charge the lower the charge of a new corona. If the field at the tip of a streamer channel is sufficiently high, a corona may develop at this tip and inject its charge into the streamer channel and heat it further, see figure 5(a), event (b). This process may repeat a few times. The time between the events is controlled by the decay of the space charge deposited by each corona at the channel tip. The sequence of current pulses injected into the channel leads to a stepwise heating and also some further elongation of the channel into the gap. A similar process has been simulated in a point-to-plane gap by [24]. The repeated charge injection into the narrow channel increases significantly the integrated intensity of the emitted light, which explains that these arrested leaders can be observed with the video camera. As the current-pulse sequence occurs within a few 100 ns typically, energy losses from the channel are low and its total temperature increase at the end of the pulse sequence is approximately determined by the
4.3 Discussion

sum of the charge pulses over the sequence. As long as the channel temperature remains sufficiently low and the electric field in the channel remains correspondingly high, the voltage drop along the channel keeps the field at its tip low. This limits the corona activity and further energy input.

The arrested leader channel decays mainly by heat conduction. Only if a further corona occurs at the leader tip before the channel has decayed, can the latter be reheated and elongate into the gap; see figure 5(a), event (c). Such processes may ease the conditions for breakdown. If, however, the channel has decayed, the next arrested leader develops in a new channel, see figure 5(a), event (d).

Breakdown occurs if the channel heating reaches a level at which the corona at its tip has sufficient charge to initiate stepped leader propagation [5]. Since the corona activity is subject to random variations in space and time, the transition from arrested leaders to stepped leader propagation is characterized by a substantial statistical variance. The transition may occur after several trials of arrested leaders resulting in an extended time delay $t_{pd}$ between first corona and breakdown. Under these conditions the time to breakdown is no longer controlled by first electron statistics but instead by the statistical features of the repetitive arrested leader process. Only at sufficiently high electric fields does breakdown occur by immediate leader inception from the first corona, and only in this limiting case are the time to breakdown statistics controlled by first electron statistics.

As the physical processes involved are extremely complex and their quantitative simulation is not yet feasible, we will attempt to quantify them approximately and to make order of magnitude estimates.

4.3.2 Streamer inception field

According to [18], streamer inception has to be determined by evaluating the streamer criterion for the field distribution at the protrusion. The result can be represented, according to [25], as a reduced
streamer inception background field

\[ x_{inc} = f(p \cdot L, \text{protrusion geometry}), \]  

(2)

which is a dimensionless function of the product \( p \cdot L \) and the protrusion geometry. This function was determined numerically for the specific shape of the protrusion used in the experiments. To describe the dependence of the effective ionisation coefficient \( \bar{\alpha} \) on the particle density \( (N) \) reduced electric field \( E/N \) [26] the following approximation was used:

\[ \bar{\alpha} = C \cdot \left[ \frac{E}{N} - \left( \frac{E}{N} \right)_{cr,0} \right] \cdot N, \]  

(3)

with \( C \approx 0.028 \text{ V}^{-1} \) and \( (E/N)_{cr,0} = 3.6 \cdot 10^{-19} \text{ Vm}^{-2} \).

4.3.3 Statistical time lags

Positive polarity

The statistical delay for a first corona is determined by the availability of a first electron close to the protrusion tip within a critical volume. The inner boundary of this volume is given by the condition that a critical avalanche can be formed [26]; see length \( l_s \) in figure 12. The outer boundary is determined by the surface on which the field falls to the critical value \( E_{cr,0} \); see length \( l_{cr} \) in figure 12. Outside of this boundary no avalanching can occur [18]. The lateral extension of the critical volume \( V \) was approximated by an equivalent spherical segment of solid angle \( \Omega \). The axial dependence of the electric field \( E(z) \) was taken from an electrostatic field calculation, from which the equivalent solid angle was also determined to be \( \Omega \approx 0.1 \).

The mechanism for production of a first electron is collisional field detachment, which is strongly field dependent [4, 22]. We approxi-
Figure 12: Integration range of the critical volume for determination of the statistical time lag for positive polarity.

mate the rate of detached electrons within the critical volume as

$$\dot{N}_e = n^- \int_V \delta \cdot dV \approx \Omega \cdot 4 \cdot \pi \cdot n^- \int_{l_s}^{l_{cr}} \delta(E(z)) \cdot (z + R)^2 \cdot dz \quad (4)$$

with the detachment rate coefficient $\delta = \delta(E(z))$ depending on the field distribution $E(z)$ ahead of the protrusion in the direction of $z$; see figure 12. The equilibrium concentration of negative ions is denoted by $n^-$ and the protrusion radius is $R$. The field dependence of the detachment rate coefficient $\delta$ is approximated by piecewise fitting of the data from [22] by power laws:
Partial discharges and breakdown at protrusions in uniform background fields

\[
\delta = 10 \cdot \left( \frac{E}{E_{cr,0}} \right)^{26} \text{ (s}^{-1}\text{)} \quad \text{for } E/E_{cr,0} < 1.6,
\]

\[
\delta = 5 \times 10^4 \cdot \left( \frac{E}{E_{cr,0}} \right)^{7} \text{ (s}^{-1}\text{)} \quad \text{for } E/E_{cr,0} \geq 1.6
\]

with a maximum value of \( \delta = 2 \times 10^8 \text{ s}^{-1} \).

The equilibrium concentration of negative ions \( n^{-} \) is controlled by the natural volume ionisation rate and is taken from [4]:

\[
n^{-} = 2.2 \times 10^{9} \cdot \frac{p}{p_{0}} \cdot \frac{T_{0}}{T} \text{ (m}^{-3}\text{)}
\]

with \( p_{0} = 0.1 \text{ MPa} \) and \( T_{0} = 300 \text{ K} \) as reference values. The average time for production of a first corona is then

\[
t_{s} = \frac{1}{N_{e}}
\]

The result is shown by the curves in figures 6a and 6c together with the experimental data. The theoretical reduced streamer inception field \( x_{inc} \) is indicated in the figures. In the range between \( x_{\text{min}} \) and \( x_{\text{max}} \) and for both pressures, the experimental values are consistent with the prediction. Below \( x_{\text{min}} \) the experimental statistical time lags are systematically above the prediction for both pressures. A sensitivity analysis of the parameters entering (4) shows that the only reason for this could be an over-estimate of the electric field at the protrusion tip, as this is the only parameter entering the detachment rate coefficient \( \delta \) extremely sensitively (5). We suspect that a field reduction due to positive space charge accumulation close to the protrusion might be the reason for this discrepancy.
4.3 Discussion

Negative polarity

In the experiments significant statistical time lags of up to some seconds were observed, which is much higher than in [23, 27]. At negative polarity first electrons are produced by field emission from the protrusion tip. Field emission is quantified by the “Fowler Nordheim” equation [28], which gives the electron production rate \( \dot{N}_e \) emitted from an area with a surface field \( E_t \). The corresponding statistical time lag is

\[
    t_s = (\dot{N}_e)^{-1} = \left( A_{eff} \cdot \frac{10^{4.52} \cdot \sqrt{\Phi} \cdot 1.54 \times 10^{-6} \cdot (\beta \cdot E_t)^2}{\Phi} \right)^{-1} \exp \left( -\Phi^{1.5} \cdot 2.84 \times 10^9 / (\beta \cdot E_t) \right) / e
\]

where \( \Phi \approx 4.5 \) eV is the work function, \( e \) the elementary charge, \( \beta \) a field enhancement factor due to micro-surface roughness, \( A_{eff} \) the effective emitting area, which was set to the geometric tip surface \( A \approx 10^{-8} \) m\(^2\). For the field \( E_t \) the Laplace field at the tip surface was used. The parameter \( \beta \), which is the most sensitive parameter in (8), was fitted to the experimental data at \( p = 0.2 \) MPa (figure 6(b)), yielding \( \beta=7 \) and \( \beta=10 \) for the upper and lower limits of the data range, respectively. These limits are shown by the curves in figure 6(b) and show that even slight variations in the surface structure lead to large variations in the first electron production. The same limit values for \( \beta \) were used in figure 6(d) for a pressure of 0.4 MPa. In this case it can be seen that the long statistical time lags fall into the area between \( x = x_{inc} \) and the upper limit curve. The only exception are the data points around \( x = 0.4 \), which are above the prediction, probably due to field reduction by space charge accumulation, as in the case of positive polarity. No experimental data has to be expected below \( x_{inc} \) because the streamer criterion is not fulfilled.
4.3.4 Corona Model

In [19] we recently presented an approximate analytical model for a streamer corona from a protrusion of length $L$ developing in a uniform background field $E_0$ into a space charge free gap. The main results of this model are as follows: The structure of the streamer corona can be roughly characterised by a radial and a longitudinal extension. The longitudinal extension $l_c$ can be derived from the redistribution of the Laplace field by the streamer channel, in which the field is equal to the critical field $E_{cr,0}$. This results in

$$l_c \approx L \cdot \frac{x}{1-x}, \quad (9)$$

where $x$ is the reduced background field. The space charge $Q_c$ contained in the corona is given by

$$Q_c \approx g \cdot \varepsilon_0 \cdot \left( \frac{E}{p} \right)_{cr,0} \cdot p \cdot L^2 \cdot \frac{x^2}{(1-x)} \quad (10)$$

with a dimensionless geometry factor $g \approx 0.5$. $\varepsilon_0$ is the vacuum permittivity. This charge, relative to the product $p \cdot L^2$, is plotted in figure 8 and shows satisfactory agreement with the measured data. From (9) and (10) the relation between the difficult to measure corona length $l_c$ and the easily measured charge $Q_c$ can be derived:

$$l_c \approx \sqrt{\frac{1}{g \cdot \varepsilon_0 \cdot \left( \frac{E}{p} \right)_{cr,0} \cdot (1-x)} \cdot \frac{1}{p} \cdot \frac{Q_c}{p}} \quad (11)$$

Note that from this relation the corona length is expected to scale essentially with the square root of $Q_c/p$. 
4.3 Discussion

4.3.5 Leader channel model

The total energy input into a streamer channel of cross section $\pi \cdot R_0^2$ by a charge pulse $q$ leads to a temperature increase $(T - T_0)$, which can be derived from a simple energy balance [5] of the form

$$q \cdot E_c = \pi \cdot R_0^2 \cdot \rho_0 \cdot c_p \cdot (T - T_0), \quad (12)$$

with $T_0$ the initial temperature, $E_c$ the electric field in the streamer channel, $\rho_0 = (\rho/p)_0 \cdot p$ the initial gas density, $c_p$ the average specific heat and $R_0$ the pressure dependent streamer radius. For SF$_6$ it is $(\rho/p)_0 = 6 \times 10^5$ kg Pa$^{-1}$m$^{-3}$, $c_p \approx 950$ J kg$^{-1}$ K$^{-1}$ ($T \leq 1500$ K) and

$$R_0 \approx \frac{C_s}{p} \quad (13)$$

with $C_s(+) \approx 2$ mPa and $C_s(-) \approx 3$ mPa. The constant $C_s(+) \approx$ was deduced from Schlieren measurements of the streamer channel diameter [29]. For negative polarity $C_s(-) > C_s(+) \approx$ is expected [5], but no data is available. The above value is a tentative assumption.

The temperature increase $(T - T_0)$ is accompanied by a fast pressure rise in the channel, which produces an expansion as described in [30]. With a similar but simplified model (to be published) the expansion was modelled for various sequences of charge injection into the channel. For rapid pulse sequences, the final temperature of the channel depends mainly on the cumulated injected charge. This justifies using the cumulated charge in the discussions below.

When current flows through a streamer or leader channel, the channel field $E_c$ re-arranges itself such that conduction electrons are available. In strongly electronegative gases this condition is met when this field is equal to the critical field [26, 31], which can be expressed as [5]
4 Partial discharges and breakdown at protrusions in uniform background fields

\[ E_c \approx E_{cr}(p, T) = \left( \frac{E}{p} \right)_{cr,0} \cdot \frac{T_0}{T} \cdot p \cdot f(T, p) \] (14)

with the pressure reduced critical electric field \((E/p)_{cr,0}=89\ \text{Vm}^{-1}\text{Pa}^{-1}\) at \(T_0=300\ \text{K}\). The function \(f(T, p)\) accounts for the reduction of the critical field by dissociation and is \(f(T, p) = 1\) for \(T \leq 1500\ \text{K}\). In this limit the reduced channel field \(E_c/E_{cr,0}\) is simply related to the channel temperature \(T\) by

\[ \frac{E_c}{E_{cr,0}} \approx \frac{T_0}{T} \] (15)

This has the consequence that with increasing channel temperature the voltage drop \(\Delta U_c = E_c \cdot l\) over a channel of length \(l\), decreases and the corona activity at the channel tip increases. This allows us to define a simple leader propagation criterion: For propagation it is necessary that the field at the channel tip, which generates the second corona, is at least the same as at the protrusion tip before the start of the first corona. This condition is fulfilled when the voltage drop along the channel is overcompensated by the voltage gain from the background field, i.e.

\[ \frac{E_c}{E_{cr,0}} \leq \frac{E_0}{E_{cr,0}} = x. \] (16)

This very simple criterion is the breakdown criterion. Inserting (14) into (12) and using (15) and (16) the critical charge \(q_{crit}\) for breakdown can be derived:

\[ q_{crit} = K \cdot \frac{C_s^2}{p^2} \cdot \frac{1-x}{x^2}, \] (17)
where $K = (\pi \cdot (\rho/p) \cdot c_p \cdot T_0)/(E/p)_{cr,0} \approx 0.6 \text{ Cm}^{-2}$ is a material constant.

According to the physical picture presented in section 4.3.1 this charge $q_{crit}$ has to be supplied by a corona. Two limiting cases can be considered; see figure 13.

![Figure 13: Schematic of first and second corona, defining a) $x_{min}$ (20) and b) $x_{max}$ (22).](image)

At low fields the charge of a second corona $Q_{c,2nd}$ is fed into a streamer or arrested leader channel of a previous discharge (figure 13(a)). The breakdown criterion can then be written as

$$Q_{c,2nd} \geq q_{crit}. \quad (18)$$

This leads to the minimum reduced breakdown field $x_{min}$. The charge $Q_{c,2nd}$ can be approximately described by (10), taking as “effective” protrusion length the sum $L + l$ of the real protrusion length and its extension $l$ by the leader channel (9):

$$Q_{c,2nd} \approx g \cdot \varepsilon_0 \cdot \left(\frac{E}{p}\right)_{cr,0} \cdot p \cdot L^2 \cdot \frac{x^2}{(1-x)^3}. \quad (19)$$

In figure 9 the charges $Q_{c,2nd}$ are plotted (dashed curves) in comparison to the experimental data in dependence on the reduced back-
Partial discharges and breakdown at protrusions in uniform background fields

A good agreement with the measured charges leading to breakdown (full symbols) can be observed. Inserting (17) and (19) into (18) the breakdown criterion can be solved for $x = x_{\text{min}}$:

$$x_{\text{min}} = \left[ 4 \sqrt{\frac{g \cdot \varepsilon_0 \cdot (E/p)_{c,0}^2}{\pi \cdot (\rho/p)_0 \cdot c_p \cdot T_0 \cdot C_s^2} \cdot p^{0.75} \cdot L^{0.5} + 1} \right]^{1/4}. \quad (20)$$

At high fields the first corona is already sufficient to start propagation of the breakdown leader; see figure 13(b). In this case, the breakdown condition is given by

$$k \cdot Q_c \geq q_{\text{crit}} \quad (21)$$

Here $Q_c$ is the charge of the first corona (10) and $k$ is the fraction of this charge which is fed into the streamer channel to be heated. The value of $k$ depends on the background field $x$ as described in our previous publication and is approximately $k \approx x^2$ [19]. Typically $k$ is in the range 0.2-0.5 for the conditions investigated here. Inserting (17) and (10) into (21) we obtain the cubic equation

$$1 - \frac{x_{\text{max}}}{x_{\text{max}}^3} = \left[ \sqrt{\frac{g \cdot \varepsilon_0 \cdot (E/p)_{c,0}^2}{\pi \cdot (\rho/p)_0 \cdot c_p \cdot T_0 \cdot C_s^2} \cdot L \cdot p^{1.5}} \right] \quad (22)$$

from which $x_{\text{max}}$ can be determined.

Figure 14 shows, as an example, the dependence of $q_{\text{crit}}$, $k \cdot Q_c$ and $Q_{c,2nd}$ on $x$ for $p = 0.2$ MPa for positive polarity. The intersection points of $Q_{c,2nd}$ and $k \cdot Q_c$ with $q_{\text{crit}}$ yield the reduced breakdown fields $x_{\text{min}}$ and $x_{\text{max}}$ and the related charges. The values for $x_{\text{min}}$ and $x_{\text{max}}$ obtained in this way are indicated in figure 6 for 0.2 MPa and 0.4 MPa and both polarities by the arrows. They agree with the experimental values $x^{*}_{\text{min}}$ and $x^{*}_{\text{max}}$ (dashed vertical lines) within the variance of the data points.
Figure 14: Dependence of critical charge $q_{\text{crit}}$ and corona charges $k \cdot Q_c$ and $Q_{c,2nd}$ on the reduced background field $x$ for a pressure of 0.2 MPa and positive polarity. The intersection points marked by the dots define $x_{\text{min}}$ and $x_{\text{max}}$. The corresponding charges are indicated by the horizontal arrows.

Figure 11 shows the reduced breakdown fields $x_{\text{min}}$ over the pressure range 0.1..0.5 MPa. The curves show the prediction and the symbols represent the measured values. For pressures above 0.2 MPa the agreement is good for both polarities. Deviations are within the accuracy of the measurement. At 0.2 MPa the measured positive breakdown field is slightly higher than predicted by the model. However, this is still nearly within the accuracy of the measurement. The discrepancy may be caused by the long statistical and formative time lags for positive polarity, due to which the voltage application time of 60 s was not sufficient to produce the first electron and breakdown at the lower field. At 0.1 MPa the measured breakdown fields are 10-20% lower than predicted. The reason for this is not clear at present.

The model was also applied to experimental data with protrusions up to 30 mm length for both polarities and pressures between 0.1
MPa and 0.4 MPa [19]. These data were also correctly described by the model. This is to be expected since the model does not contain empirical factors. This also suggests that it may be extrapolated towards smaller protrusions, such as surface roughness.

The observable length of the arrested leaders is expected to be between the length of the first corona \( l_1 = L \cdot x/(1-x) \) and the sum of the first and second corona \( l_1 + l_2 \) with \( l_2 = (L+l_1) \cdot x/(1-x) \) from (9). This is roughly confirmed by the optical observation, see figure 10(a), where the predictions are shown by the curves. The large scatter of the leader lengths is due to the statistical variations of charge amplitudes. The scaling of the leader length with the leader charge according to (11) is confirmed by figure 10(b).

### 4.3.6 Time scales for space charge and leader channel decay

**Space charge decay**

The ionic space charge generated by the corona mainly decays by ion drift. The corresponding time scale \( t_{sc} \) is proportional to the corona length scale \( l_c \) and inversely proportional to the ion drift velocity \( v_d = v_{d,cr} \cdot (E_0/E_{cr,0}) = v_{d,cr} \cdot x \), where \( v_{d,cr} = 600 \) m/s for SF\(_6\) [32]. Using (11) to obtain \( l_c \), the decay time \( t_{sc} \) is

\[
t_{sc} \approx C_{sc} \cdot \sqrt{\frac{Q}{(1-x) \cdot p}} \cdot \frac{1}{x} \propto \frac{1}{x \cdot \sqrt{p}},
\]

where \( C_{sc} = (v_{d,cr} \cdot \sqrt{g \cdot \varepsilon_0 \cdot (E/p)_{cr,0}})^{-1} \approx 84 \) Pa\(^{0.5}\)s\(^{0.5}\)A\(^{-0.5}\). Note that \( t_{sc} \) increases with \( \sqrt{Q} \), decreases with \( \sqrt{p} \) and is inversely proportional to the reduced background field \( x \). For \( p = 0.2 - 0.4 \)MPa, \( x \approx 0.5 \) and \( Q = 10 \) pC-600 pC, the space charge decay time \( t_{sc} \) is expected to be in the range 1-15 \( \mu s \).
**Leader channel decay**

The origin of a leader channel is always a streamer, with an initial channel radius according to (13). Its transition into a leader channel occurs by the throughput of charge pulse(s), supplied by streamer corona(e), which have a duration of the order of a few nanoseconds (see figure 15(a)). The energy input increases the channel temperature according to (12), creates a corresponding overpressure and causes an expansion to a final radius

\[ R_f = R_0 \cdot \sqrt{T/T_0} \]  \hspace{1cm} (24)

when the channel pressure has fallen to ambient pressure \( p \) (figure 15(b)). The expansion initially occurs approximately with sonic velocity \( c_0 \) at ambient temperature (\( c_0=138 \text{ m/s for SF}_6 \ [33] \)), so that the time scale of the expansion process \( t_{ex} \) is approximately

\[ t_{ex} \approx \frac{R_f - R_0}{c_0} = \frac{C_s}{c_0} \left( \sqrt{\frac{T}{T_0}} - 1 \right) \cdot \frac{1}{p}. \]  \hspace{1cm} (25)

For \( T_0=300 \text{ K}, p=0.2-0.4 \text{ MPa} \) and \( T=600-1500 \text{ K} \), the expansion time \( t_{ex} \) is in the range 15-135 ns.

After the channel expansion the temperature in the channel decays by radial thermal conduction in combination with radial gas inflow (figure 15(c)). The thermal decay time scale \( t_\lambda \) is of the order \( t_\lambda \approx R_f^2/\chi \), where \( \chi \) is an average heat diffusivity, which is proportional to \( 1/p \). With the initial channel radius from (13) and (24) one obtains

\[ t_\lambda \approx \frac{C_{CFD} \cdot C_s^2}{p} \cdot \frac{T_0}{T} \propto \frac{C_s^2}{p}, \]  \hspace{1cm} (26)

where \( C_{CFD} \approx 3.5 \text{ sm}^{-2}\text{Pa}^{-1} \) is a proportionality factor determined
from computational fluid dynamic (CFD) simulations of the expansion process [34], using material data from [33]. The simulations were initialised with a rectangular temperature profile and account not only for thermal conduction but also for the radial inflow associated with the cooling. For $T_0$=300 K, $p$=0.2-0.4 MPa, $T$=600-1500 K the thermal decay time $t_\lambda$ results in the range 7-80 $\mu$s.

**Figure 15:** Schematic of time scales of leader channel development and decay: a) Current input by corona pulse, b) Channel expansion, c) Thermal decay.

**Comparison of time scales**

Comparing the above time scales one observes:

$$t_c (-1 \text{ ns}) \ll t_{\text{ex}} - 15 - 135 \text{ ns} \ll t_{\text{sc}} - 1 - 15 \mu\text{s} \leq t_\lambda - 7 - 80 \mu\text{s}$$

with $t_c$: corona pulse, $t_{\text{ex}}$: channel expansion, $t_{\text{sc}}$: space charge decay, $t_\lambda$: thermal channel decay

The time scales $t_c$ and $t_{\text{ex}}$ are much smaller than the time
scales $t_{sc}$ and $t_\lambda$. This means that only these last two time scales and their relation to each other affect the leader sequence.

Any large space charge left by a previous leader inhibits the formation of a new corona of sufficient charge to initiate a new leader. Therefore, the space charge decay time $t_{sc}$ is a lower limit for the time between arrested leaders $t_L$. This is confirmed by the experimental data in figure 7, where the average time between arrested leaders $<t_L>$ tends towards $t_{sc}$ as the reduced background field $x$ increases. This is more pronounced for negative polarity (figure 7(b)), where $<t_L>$ reaches $t_{sc}$ when the reduced background field reaches or exceeds $x_{min}$. Under these conditions the leader sequence is controlled by space charge decay.

For conditions where $t_\lambda > t_{sc}$, it can be expected that a subsequent leader can re-strike in the channel of a previous leader. This was observed in the experiments for both polarities (figure 3 and 4).

A further condition for the occurrence of such re-strikes is that the time between the leaders $t_L$ is lower than $t_\lambda$. For positive polarity (figure 7(a)), on average, $t_L$ exceeds $t_{sc}$ and $t_\lambda$. In this case the previous leader leaves neither a space charge nor a thermal memory, and the following leader develops along a new trajectory. Therefore, re-strike leaders are rare events for positive polarity.

For negative polarity the leader decay time $t_\lambda$ is higher than for positive polarity, due to the higher value of $C_s$ for negative polarity (24), see figure 7(b). When the reduced background field is $x_{min}$, the leader decay time is higher than $t_L$, on average. In this case leaders can re-strike in the same channel. This cumulative channel heating favours the transition to a breakdown leader. This is the dominant breakdown mechanism for a reduced breakdown field equal to $x_{min}$ for negative polarity.

### 4.4 Conclusions

The experimental data and theoretical considerations presented in this paper provide a consistent understanding of the discharge acti-
Partial discharges and breakdown at protrusions in uniform background fields

vity controlling PD and breakdown in SF$_6$ under typical conditions in gas insulation systems, namely in the presence of small protrusions (small conducting particles and electrode surface roughness). These conditions differ substantially from the point-toplane (or similar) geometries that are usually studied. For small protrusions the parameter controlling the discharge is not the voltage applied to the gap, but the background field in which the protrusion is embedded. All discharge criteria, therefore, have to be expressed as a function of this quantity. This background field is best normalised to the critical field as the relevant gas property controlling the dielectric strength.

Above the PD inception level, corona and arrested leader discharges occur which increase in magnitude and repetition frequency with increasing background field, the arrested leaders providing the highest pulse charges. For sufficiently high background fields, breakdown occurs after a time lag, consisting of a statistical and a formative contribution. Both these time lags decrease with increasing background field. It is particularly noteworthy that the formative time lag not only consists of the time for leader propagation through the gap, but also contains a pre-breakdown PD phase which is dominant at low background fields and becomes negligible at high background fields. Only in the latter limit does the usual concept apply that the time to breakdown is controlled by first electron statistics.

A general model has been derived which consistently explains the major features of the observations and their parameter dependen-
cies. The model uses the reduced background field $x = E_0/E_{cr,0}$ and the protrusion length $L$ as the relevant parameters controlling all discharge activities. It describes:

- the major parameter dependencies of first electron production for both polarities,

- the main features of pre-breakdown corona activity, namely, inception fields, charge and spatial extension of the PD and average time interval between successive PD events,
• the main features of leader channel development and decay in the case of arrested leaders,

• the minimum background field above which breakdown occurs with time delay,

• the background field above which breakdown is immediately triggered by the first discharge from the protrusion.

The model thus predicts, for given gas pressure and protrusion length, the main design-relevant quantities.

The discharge processes are characterised by an intrinsic randomness, which is reflected by a relatively large scatter of the time lag data. For time lags due to first electron generation, the agreement between experiment and model is not yet satisfactory, so that a more detailed modelling will be required. The statistics of pre-breakdown PD and with it the formative time lag is controlled by the randomness of space charge generation/drift/decay in the gap. This requires further investigation. The details of stepped leader propagation across the gap have not been described here and will be treated in a future publication.

Further work will include the exploration of the dependence of breakdown fields on particle size and applied voltage waveform, the interpretation of PD measurements and an attempt to develop a deeper understanding of surface roughness induced breakdown.

4.5 Acknowledgements

The authors would like to thank R. Bini of ABB Switzerland Ltd., Corporate Research for doing the CFD simulations, P. Stoller of ABB Switzerland Ltd., Corporate Research for proofreading of the manuscript and S. Post and A. Reingruber for helping in the experiments and the data analysis during their internship at ABB Switzerland Ltd., Corporate Research.
4.6 References


Partial discharges and breakdown at protrusions in uniform background fields


[23] Thalji J Y and Nelson J K (1989),”Impulse waveform effects on negative point breakdown phenomena in SF₆”. Conf Electr Ins and Diel Phenom, Leesburg, VA, USA, 81-86


5 Leader propagation in uniform background fields

Martin Seeger, Lutz Niemeyer and Markus Bujotzek

Full publication title: Leader propagation in uniform background fields in SF$_6$

doi: 10.1088/0022-3727/42/18/185205
Abstract: The breakdown mechanism of compressed SF$_6$ in gas insulation is known to be controlled by stepped leader propagation. This process is still not well understood in uniform and weakly non-uniform background fields with small electrode protrusions, such as particles or surface roughness. In a previous publication an investigation of partial discharges and breakdown in uniform background fields that focused on streamer and leader inception mechanisms was presented [Seeger M at al J. Phys. D: Appl. Phys. 41 (2008) 185204]. In this paper we present for the first time a physical leader propagation model that consistently describes the observed phenomena in uniform background fields in SF$_6$. The model explains two different types of leader breakdown; these can be associated with the precursor and the stem mechanisms. It also yields the parameters of stepped leader propagation, which include step lengths, associated step charges, step times and fields and temperatures in the leader channel. Further, it explains the features of arrested leaders in uniform background fields. The model predicts the range of parameters under which arrested and breakdown leaders occur in good agreement with experimental data.

5.1 Introduction

The behaviour of leaders in SF$_6$ has mainly been studied in non-uniform field gaps, such as point-to-plane gaps or relatively short gaps with relatively long protrusions [1-15]. Most of these studies concentrated on positive polarity [1-13], which exhibited lower breakdown voltages than negative polarity [14-16]. These configurations are very different from technical gas insulation systems, where relatively small protrusions, like surface roughness or small particles, are present as defects and are embedded in approximately uniform background fields defined by the electrode configurations [17].

A first study on leader breakdown from small protrusions under uniform field conditions was presented in [18-20]. The experiments presented in these papers showed a breakdown behaviour substan-
5.2 Basic processes

5.2.1 Electric field

For leader discharge propagation the controlling macroscopic field parameter is the uniform background field in the gap $E_0 = U_0/D$, where $U_0$ is the applied voltage and $D$ the gap distance. As shown in [19], it is practical to refer this field to the critical field of the gas $E_{cr,0}$ at ambient temperature $T_0$ and to introduce the dimensionless
field parameter

\[ x_0 = \frac{E_0}{E_{cr,0}}, \]  

(1)

\( E_0 \) controls the local field enhancement created by a conducting protrusion extending from an electrode into the gap. The protrusion can be a conducting particle on the electrode aligned in the direction of the background field by electrostatic forces, or it can be a surface roughness feature. Generally, the conducting protrusion can be accompanied by a discharge channel that extends from it into the gap. The background field \( E_0 \) reduces to zero inside a metallic protrusion. In the discharge channel, the background field reduces to the channel field \( E \). The presence of a protrusion redistributes

Figure 1: Field re-distribution in a uniform background field by a conductive protrusion (length \( L \)) and a conducting channel (length \( z_L \)). \( E(z) \) denotes the channel field. \( \Delta U \) is the field integral defined by (2) which determines the field enhancement at the tip of the channel. The length of a streamer developing in this field enhancement is denoted by \( \ell \).
the electric field so that a field enhancement ahead of the protrusion is created that can be integrally characterised by a voltage difference $\Delta U$; see figure 1. For the general case where the field varies over the total length of the protrusion and discharge channel $L'$,

$$\Delta U = E_0 \cdot L' - \int_0^{L'} E(z) \cdot dz$$  \hspace{1cm} (2)

where $L' = L + z_L$; $L$ denotes the length of the metallic protrusion and $z_L$ is the length of the discharge channel (see figure 1). The length $\ell$ of a streamer channel developing in the enhancement zone ahead of the protrusion can be determined by the following consideration: In strongly electronegative gases the streamer channel field $E$ is equal to the critical field $E_{cr,0}$ [21]. The voltage drop in the enhancement zone, described by $\Delta U$, is thus redistributed such that

$$\Delta U = \ell \cdot (E_{cr,0} - E_0) + \Delta u$$  \hspace{1cm} (3)

The term $\ell \cdot (E_{cr,0} - E_0)$ is the voltage drop along the streamer of length $\ell$ and $\Delta u$ is the voltage drop in the enhanced field remaining ahead of the streamer tip (see figure 1). Numerical field simulations have shown that $\Delta u$ is only a few percent of $\Delta U$, so that it will be neglected in the following. Equation (3) together with equation (1) can then be solved for the streamer length $\ell$ to yield

$$\ell = \left( \frac{\Delta U}{E_{cr,0}} \right) \cdot \frac{1}{(1 - x_0)}.$$  \hspace{1cm} (4)

This length defines the length scale of the streamer corona in the direction of the background field. For the special case of a first corona starting from a conducting protrusion of length $L$ one has, from (2), $\Delta U = E_0 \cdot L$ and one obtains the length scale of the first corona

$$\ell = L \cdot \frac{x_0}{(1 - x_0)}.$$  \hspace{1cm} (5)
5.2.2 Corona charge

As discussed in [18], the streamer corona is a spatial structure filled with streamer channels in which the field is equal to the critical field \(E_{cr,0}\). This volume has a length scale \(\ell\) according to (4) and (5). The space charge distribution in this volume can be approximated by a prolate ellipsoid (spheroid) with a diameter \(2 \cdot \ell\) in the field direction, within which \(E = E_{cr,0}\). An analytical expression for the dipole moment of this charge distribution is given in [22] as the product \(\ell \cdot Q_c\) of the length scale \(\ell\) and a charge \(Q_c\). This finally yields the corona charge

\[
Q_c \approx g \cdot \varepsilon_0 \cdot E_{cr,0} \cdot \ell^2 \cdot (1 - x_0) \quad \text{with} \quad g \approx 0.5. \tag{6}
\]

The dimensionless geometry factor \(g\) is approximately independent of the eccentricity of the ellipse (in symmetry plane of the spheroid) in the parameter range of interest for the present application. Using equation (4) to substitute for \(\ell\) yields the corona charge in terms of the potential difference \(\Delta U\) and the reduced background field \(x_0\):

\[
Q_c \approx g \cdot \varepsilon_0 \cdot \frac{\Delta U^2}{E_{cr,0}} \cdot \frac{1}{(1 - x_0)}. \tag{7}
\]

5.2.3 Leader channel dynamics

Initial conditions

The leader channel is created by heating of a streamer channel that is initially at ambient temperature \(T_0 = 300\) K and has an initial radius \(R_0\) that scales inversely with the gas pressure \(p\):

\[
R_0 = \frac{C_s}{p} \quad \text{with} \quad C_s^+ \approx 2 \text{m} \cdot \text{Pa} \quad \text{for positive polarity,} \quad C_s^- \approx 3 \text{m} \cdot \text{Pa} \quad \text{for negative polarity} \tag{8}
\]

\(C_s\) is higher for negative polarity than for positive polarity for reasons discussed in [5]. For positive polarity absolute values were
estimated from schlieren photographs [23]. For negative polarity $C_s$ was indirectly inferred from discharge measurements [19]. Theoretical data for SF$_6$ are not available and $C_s$ might also depend on further parameters such as the divergence of the electric field in which the streamer develops.

The mass per length contained initially in the streamer channel is then

$$m_0 = \pi \cdot R_0^2 \cdot \rho_0 = \pi \cdot (\rho/p)_0 \cdot C^2_s/p.$$  \hspace{1cm} (9)

Due to the rapidity of the heating and expansion of the channel, with time scales typically below some 100 ns, its mass exchange with the surrounding cold gas is negligible. Mass conservation in the expanding channel can therefore be assumed [24].

**Leader inception**

Leader inception is the transition of a streamer channel to a leader channel and is caused by ohmic heating of a streamer channel when a charge pulse $Q$ passes through it [5]. The deposited energy per length is the product $Q \cdot E$ of the charge and the channel field $E$ and raises the channel temperature $T$. This creates an initial over-pressure $\Delta p$, which drives the channel to expand. Channel expansion, in turn, causes a gas density reduction and a corresponding decrease of the channel field $E$. Note that in our simplified model any heated channel enabling propagation is considered as a leader. Similar processes are described in [27, 28] for stepped streamer propagation. However, to our understanding for a stepped propagation via a heated channel the denotation leader is more appropriate (see also [21]).

In SF$_6$ the two main mechanisms have been identified by which charge is fed into a channel, namely, the precursor [3] and the stem mechanism [15]. In the precursor mechanism, the longest streamer in the corona is activated by a bipolar ion drift process; see figure 2(a). In this case only a small fraction $\alpha \cdot Q$ of the total corona
charge $Q$ is fed into a single channel so that $\alpha$ is typically in the range of a few percent, corresponding to the fact that the corona contains several tens of streamers. The experimental data suggests that the value of $\alpha$ is approximately 0.02. In the stem mechanism the streamer corona contains branched streamers which feed their charge into common stem(s) see figure 2(b). A substantial part of the total corona charge may be fed into one single channel, so that the fraction $\alpha$ may reach values up to the order of unity. We will therefore study the two limiting cases

\begin{align*}
\alpha &= 1 \quad \text{the stem mechanism}, \\
\alpha &= 0.02 \quad \text{the precursor mechanism}.
\end{align*}

It has to be noted, that these are two extreme cases and that, in reality, both mechanisms may compete or combine [15]. Such effects are not covered by the simple model presented here.

**Figure 2:** Schematic charge channelling mechanisms at leader inception. (a) Precursor mechanism, limiting case $\alpha = 0.02$; the precursor is marked by an arrow. (b) the stem mechanism, limiting case $\alpha = 1$; the charge injection into the stem is indicated by arrows.
5.2 Basic processes

Channel field

As pointed out above, the streamer field is stabilised to the critical value $E_{cr}$. This is also a good approximation for the leader channel, so that $E = E_{cr,0}$ [21, 24]. This field can be expressed as [19]

$$E = E_{cr} = (E/p)_{cr,0} \cdot p \cdot (T_0/T) \cdot f(T, p)$$

with the pressure reduced critical field $(E/p)_{cr,0} = 89 \text{ V m}^{-1}\text{Pa}^{-1}$ for SF$_6$ at $T_0=300 \text{ K}$ and where $f(T, p)$ is a dimensionless function that accounts for thermal dissociation (see figure 3).

![Figure 3: Material functions $f(T, p)$ and $h = h(T, p) - h(T_0, p)$ for SF$_6$.](image)

Channel heating

When a charge pulse $Q$ is fed through a channel at temperature $T$ and with a field $E$, the per-length energy balance becomes

$$m \cdot \Delta h \approx m_0 \cdot \Delta h = (\rho/p)_0 \cdot p \cdot \pi \cdot R_0^2 \cdot \Delta h = E \cdot Q$$

Here, $\Delta h$ is the increase of the enthalpy $h$ in the channel, which is related to gas temperature $T$ and pressure $p$ by the material function.
$h = h(T,p)$ [25], which is shown in figure 3. With (8) and (12) the above equation can be solved for $\Delta h$ and yields, after channel expansion to ambient pressure $p$

$$\Delta h = C_{\Delta h} \cdot f(T,p) \cdot \frac{T_0}{T} \cdot \frac{p^2}{C_s^2} \cdot Q$$

(14)

with the material constant

$$C_{\Delta h} = \left(\frac{E}{p}\right)_{cr,0}/(\pi \cdot (\rho/p)_0) = 4.8 \times 10^5 \text{ V kg}^{-1}\text{m}^2$$

(15)

From the enthalpy increase $\Delta h$ the temperature increase $\Delta T$ can be determined from the material function $h(T,p)$.

**Channel expansion**

A channel heated from an initial temperature $T_0$ to a temperature $T_1 = T_0 + \Delta T$ and expanded to the ambient pressure $p$ reaches an equilibrium radius

$$R(T_1) = R_0 \sqrt{T_1/T_0}.$$  

(16)

When the initial temperature $T_i$ of a pre-heated channel of radius $R(T_i)$ is increased by a charge pulse to $T_i + \Delta T$ the initial over-pressure ratio is

$$\frac{(p + \Delta p)}{p} = \frac{(p/\rho)_{T_i+\Delta T,p}}{(p/\rho)_{T_0,p}} \cdot \frac{T_0}{T_i}.$$  

(17)

Here, $(p/\rho)_{T,p}$ is the thermal equation of state for the gas including dissociation effects. After expansion to equilibrium pressure the increase of the channel radius $\Delta R$, using (8) and (16), becomes

$$\Delta R = R(T_i) \cdot \left(\sqrt{1 + \frac{\Delta T}{T_i}} - 1\right) = \frac{C_s}{p} \cdot \sqrt{\frac{T_i}{T_0}} \cdot \left(\sqrt{1 + \frac{\Delta T}{T_i}} - 1\right).$$  

(18)
The expansion is a complex gas-dynamic flow process involving shock- and rarefaction waves. Its Mach number is determined by the initial over-pressure ratio \((p + \Delta p)/p\) according to (17). Numerical simulations with a computational fluid dynamics (CFD) solver [26] under the conditions of interest here (channel radii of the order of 10 \(\mu\)m and time scales up 100 ns) show, that the average channel expansion velocity \(v_{ex}\) scales as

\[
v_{ex} \approx c_0 \cdot C_{ex} (\Delta p/p)^\beta \tag{19}
\]

with \(c_0=\)velocity of sound \(\approx 140\) m s\(^{-1}\) (SF\(_6\) at \(T_0\)) and \(C_{ex} (\Delta p/p)^\beta\) as an average expansion Mach number with \(C_{ex} \approx 0.6\)and \(\beta \approx 0.1\). From (17), (18) and (19) the expansion time scale becomes

\[
t_{ex} = \frac{\Delta R}{v_{ex}} \approx \frac{C_s}{p} \cdot \sqrt{\frac{T_i}{T_0}} \cdot \left(\sqrt{1 + \frac{\Delta T}{T_i}} - 1\right) \cdot \frac{1}{c_0 \cdot C_{ex} \cdot (\Delta p/p)^\beta}, \tag{20}
\]

which is inversely proportional to the gas pressure \(p\), increases with increasing temperature rise \(\Delta T\) and is higher for negative polarity than for positive. This relation can be used to derive an estimate for the propagation step time \(\tau\). As a leader propagation step proceeds into ambient gas, one has \(T_i = T_0\) and a lower limit estimate for the propagation step time follows from (20)

\[
\tau > \frac{C_s}{p} \cdot \left(\sqrt{1 + \frac{\Delta T}{T_0}} - 1\right) \cdot \frac{1}{c_0 \cdot C_{ex} \cdot (\Delta p/p)^\beta}. \tag{21}
\]

### 5.3 Numerical model for leader inception and propagation

#### 5.3.1 Model features

The model uses the following major simplifications:

- It disregards the spatial randomness of the leader propagation
direction by assuming propagation along the axis of symmetry of the protrusion parallel to the background field $E_0$.

- It disregards leader branching.
- It assumes that the electric field distribution is Laplacian and neglects the effects of space charges.
- It disregards the inherent randomness of the streamer discharges by assuming fixed values for the parameter $\alpha$.

All these assumptions make the model deterministic so that it cannot predict random features.

Leader inception and propagation are constructed step-by-step by using the relations derived in section 5.2. The index $i$ is used to designate the propagation step and the index $j \leq i$ the leader sections left behind the propagating leader tip. Thus $Q_i$ is the corona charge associated with the $i$-th propagation step and $E_{ij}$ is the field in the $j$-th leader section after the leader has propagated $i$ steps. The construction of the $i$-th propagation step starts by determining the corona length $\ell_i$, the corona charge $Q_i$, and the step time $\tau_i$. The charge $Q_i$ is then fed into the channel sections behind the leader tip to update the section temperatures $T_{ij}$ and fields $E_{ij}$ for all $j < i$.

For leader inception, i.e. for the first propagation step, the two options discussed in section 5.2.3 (see (10) and (11)) will be studied. The case $\alpha = 1$ implies the maximal possible charge injection and determines the lower limit background field $x_{min}$ for leader breakdown. The case $\alpha = 0.02$ implies a minimal charge injection and determines the background field $x_{max}$ for immediate breakdown. The subsequent leader propagation steps use $\alpha = 1$ because the leader tip corona then feeds all of its charge into the channel.

5.3.2 Input parameters

The input parameters of the model are protrusion length $L$, gap distance $D$, reduced background field $x_0$, polarity, ambient gas pressure $p$ and temperature $T_0$ and the material functions of the gas,
namely, the thermal equation of state function \((p/\rho)_{T,p}\), the enthalpy \(h(T, p)\) (figure 3), the pressure-reduced critical field \((E/p)_{cr,0}\) and \(f(T, p)\) (figure 3). A second set of parameters characterising the streamer corona are summarised in table 5.1.

### 5.3.3 Output data

For the step number \(i\) and section number \(j\) the following output data are produced:

- Propagation step length \(\ell_i\), see (4).
- Step corona charges \(Q_i\), see (6).
- Temperatures \(T_{ij}\) and channel fields \(E_{ij}\), see (14) and (12).
- Propagation step time \(\tau_i\), see (21).

From these, the following further quantities can be derived:

- The leader propagation curve \(z_L(t)\) from
  \[
  z_{L,i} = \sum_{j=1}^{i} \ell_j \tag{22}
  \]
  and
  \[
  t_i = \sum_{j=1}^{i} \tau_j. \tag{23}
  \]
- The initial values of temperature \(T_{11}\) and channel field \(E_{11}\) in the first channel section \(\ell_1\) (i.e. after leader inception).
- The cumulated leader charge at step \(i\):
  \[
  Q_{L,i} = \sum_{j=1}^{i} Q_j. \tag{24}
  \]
- The temporal development of the average reduced channel field \(<x> = <E>/E_{cr,0}\) during propagation:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry factor for the determination of the corona charge</td>
<td>$g$</td>
<td>0.5</td>
<td>(6)</td>
</tr>
<tr>
<td>Scaling factor for initial channel radius at positive (negative) polarity</td>
<td>$C_s$</td>
<td>2 (3) m Pa</td>
<td>(8)</td>
</tr>
<tr>
<td>Fraction of corona charge fed into channel for stem mechanism</td>
<td>$\alpha$</td>
<td>1</td>
<td>(10)</td>
</tr>
<tr>
<td>Fraction of corona charge fed into channel for precursor mechanism</td>
<td>$\alpha$</td>
<td>0.02</td>
<td>(11)</td>
</tr>
<tr>
<td>Fraction of corona charge fed into channel for precursor mechanism</td>
<td>$\alpha$</td>
<td>0.02</td>
<td>(11)</td>
</tr>
<tr>
<td>Scaling parameters for average expansion Mach number</td>
<td>$C_{ex}$</td>
<td>0.6</td>
<td>(18)</td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td>0.1</td>
<td>(18)</td>
</tr>
</tbody>
</table>
\[
\langle x \rangle = \frac{\sum_{j=1}^{i} (E_{ij} \cdot \ell_{j})}{E_{cr,0} \cdot z_{L,i}}.
\] (25)

- The leader length \(z_{L}^{*}\) and cumulative charge \(Q_{L}^{*}\) of an arrested leader at the breakdown limit from (22) and (24), respectively, when summing over all steps until the leader is arrested.

- The leader gap crossing time from (23)

\[
t_{p} = \sum_{i=1}^{i_{\text{max}}} \tau_{i},
\] (26)

where \(i_{\text{max}}\) is the number of steps after which the leader reaches the opposite electrode.

### 5.3.4 Examples

Simulations were performed at negative polarity, \(p=0.2\) MPa and at background field values \(x\) just below and above the breakdown limit, for both \(\alpha=1\) and \(\alpha=0.02\). The gap distance \(D\) was chosen according to experiments in [19] to be 20 mm.

Figure 4(a) shows the propagation curves \(z_{L}(t)\) below the breakdown limit. For the stem mechanism (\(\alpha=1\)) the leader propagates with an average velocity of about \(4 \times 10^{4}\) m s\(^{-1}\) and stops after 6 propagation steps at a total length of \(z_{L}^{*} = 4\) mm. For the precursor mechanism (\(\alpha=0.02\)) the leader propagates a similar total length but with a higher average velocity of about \(3 \times 10^{5}\) m s\(^{-1}\). The dominant propagation occurs in the first step already.

Figure 4(b) shows the leader propagation curves above the breakdown limit. The precursor mechanism (\(\alpha=0.02\)) can now produce the transition from streamer to leader and the leader propagates through the gap. It can be observed that the time for crossing the gap is much lower for the precursor case in comparison to the stem case. The average propagation velocities are about \(2 \times 10^{5}\) m s\(^{-1}\) and \(6 \times 10^{4}\) m s\(^{-1}\) for the precursor and stem case, respectively.
Figure 5(a) shows the step charge sequence $Q_i$ just below the breakdown limit. For stem mechanism the $Q_i$ values are of the order of a few 10 pC and drop off steeply when propagation stops. The full symbols are measured charges from [19] and show a reasonable agreement with the simulation. Only the first pulse is higher in the experiments, which may be due to branching of the streamer corona (see figure 2(b)). For the precursor mechanism the leader stops propagating after a short time of a few ns, associated with a very steep drop of the step charge. The measured streamer corona charge (full symbol) is of the same order of magnitude as the charge of the simulated first step. Figure 5(b) shows the step charge sequence $Q_i$ slightly above the breakdown limit. For the stem mechanism the step charges $Q_i$ resulting from the model are in the range of 50 to 100 pC with a rising tendency at later steps. The experimental data (full symbols) are of the same order of magnitude. Again, the first pulse is higher in the measurements. The fact that the steps occur more frequently in the experiments than predicted from the third step onward is most probably due to leader branching, which is frequently observed in the high speed video frames. For the precursor mechanism the step charge values of the propagating leader initially drop after the first corona charge $Q_1$ and then rise steeply by more than two orders of magnitude, exceeding the corresponding charges for the stem mechanism. For this case no experimental data are available.

Figures 6(a) and 6(b) show the time development of the reduced channel field $x(z,t)$ along the leader for an arrested and a breakdown leader started by the stem mechanism. Similar features also occur for the precursor mechanism (not shown in the figure). Below the breakdown limit for arrested leaders (figure 6(a)) $x$ increases towards the leader tip. When it reaches the critical value $x=1$ at the tip propagation stops. Above the breakdown limit (figure 6(b)) the channel field $x(z,t)$ initially rises towards the leader tip but flattens out after about five propagation steps, lowering its average level with further propagation. The corresponding development of
5.3 Numerical model for leader inception and propagation

Figure 4: Simulated leader propagation curves $z_L(t)$ for precursor ($\alpha = 0.02$) and stem ($\alpha = 1$) leader inception mechanism in a uniform background field for pressure $p=0.2$ MPa, protrusion length $L=1$ mm and negative polarity. The symbols mark the different steps during propagation. The gap distance is $D=20$ mm. (a) Arrested leaders for $\alpha = 1$ at $x = 0.56$ and for $\alpha = 0.02$ at $x = 0.74$. (b) Breakdown leaders for $\alpha = 1$ at $x = 0.58$ and for $\alpha = 0.02$ at $x = 0.76$.

Figure 5: Simulated step corona charge sequence $Q_i$ of leader propagation for precursor ($\alpha = 0.02$) and stem ($\alpha = 1$) leader inception mechanism in a uniform background field for a pressure $p=0.2$ MPa, protrusion length $L=1$ mm and negative polarity. The open symbols mark the different steps during propagation. For comparison, measured charges from [19] are given by the full symbols. (a) Arrested leaders for $\alpha = 1$ at $x = 0.56$ and for $\alpha = 0.02$ at $x = 0.74$. (b) Breakdown leaders for $\alpha = 1$ at $x = 0.58$ and for $\alpha = 0.02$ at $x = 0.76$. 
Figure 6: Simulated reduced field $x(z,t)$ along the channel during leader propagation in a uniform background field for stem leader inception mechanism ($\alpha = 1$), $p=0.2$ MPa, protrusion length $L=1$ mm and negative polarity. The symbols mark the different steps during propagation for each propagation step $i$. The total leader length is denoted by $z_L$. (a) Arrested leader at $x = 0.56$. (b) Breakdown leader at $x = 0.58$. 
5.3 Numerical model for leader inception and propagation

Figure 7: Simulated channel temperature distribution $T(z, t)$ during leader propagation in a uniform background field for stem leader inception mechanism ($\alpha = 1$), $p=0.2$ MPa, protrusion length $L=1$ mm and negative polarity. The symbols mark the different steps during propagation for each propagation step $i$. The total leader length is denoted by $z_L$. (a) Arrested leader at $x = 0.56$. (b) Breakdown leader at $x = 0.58$. 
the channel temperature distribution $T(z, t)$ is shown in figures 7(a) and 7(b). It is interesting to note that there is a sharp limit temperature in the first step which decides between arrest and breakdown. This temperature limit depends on the leader inception mechanism and is around 500 K for the stem mechanism and about 310 K for the precursor mechanism. Below the breakdown limit the channel temperature at the tip drops towards ambient temperature $T_0$ during propagation and the leader stops. Above the breakdown limit it rises steeply, reaching and exceeding the SF$_6$ dissociation temperature ($\approx 1600$ K).

Figure 8: Simulated reduced average channel field $<x>$ during leader propagation in a uniform background field for stem ($\alpha = 1$) and precursor ($\alpha = 0.02$) inception mechanism for $p=0.2$ MPa, protrusion length $L=1$ mm and negative polarity. The gap distance is $D=20$ mm. The symbols mark the different steps during propagation. The total leader length is denoted by $z_L$.

Figure 8 shows the temporal development of the reduced average channel field $<x>$ for both leader inception mechanisms. Below the breakdown limit for the stem mechanism the channel field $<x>$ remains at about the same level close to the applied field $x_0$. Above
the breakdown limit it drops steeply during the first few propagation steps and then asymptotically drops towards zero. For the precursor mechanism this behaviour is different. At leader inception there is no such distinct difference between leader arrest and breakdown. In case of breakdown the average channel field falls to about the same level independently of the inception mechanism.

5.4 Results of the model and discussion

The model provides some deeper insight into the leader formation and propagation process and allows an improved interpretation of the experimental data presented in our previous publications [18, 19].

5.4.1 Leader types and ranges

In [19] three leader types were identified, namely, arrested leaders, delayed breakdown leaders and immediate breakdown leaders. Delayed breakdown leaders and immediate breakdown leaders occurred at reduced background fields $x_{\text{min}}$ and $x_{\text{max}}$, respectively. The model presented here allows us to relate these leader types to leader inception mechanisms and to predict the background field ranges in which they occur. A summary is shown in table 5.2.

Arrested leaders. When the field is above the streamer inception field, a first corona occurs after a statistical time lag. This first corona was only very weakly visible in the video frames and exhibited a single large pulse with a tail in the current measurements [19]. For reduced fields below $x_{\text{max}}$ the model with $\alpha=0.02$ explains this as follows: The charge injection in the first step is too small to significantly heat a streamer channel, which explains why the first corona was not visible in the video frames. The very weak pulses that follow within only a few nanoseconds cannot be resolved by the current measurement, which explains that only a single pulse with a tail was measured.
Table 5.2: Summary of leader types, related inception mechanisms and ranges of reduced background field.

<table>
<thead>
<tr>
<th>Leader type</th>
<th>Inception mechanism</th>
<th>Reduced field range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrested leader</td>
<td>Precursor ($\alpha=0.02$)</td>
<td>$x_{inc}^\alpha &lt; x &lt; x_{max}$</td>
</tr>
<tr>
<td></td>
<td>Stem ($\alpha=1$)</td>
<td></td>
</tr>
<tr>
<td>Delayed leader breakdown</td>
<td>Stem ($\alpha=1$)</td>
<td>$x_{min} &lt; x &lt; x_{max}$</td>
</tr>
<tr>
<td>Immediate leader breakdown</td>
<td>Precursor ($\alpha=0.02$)</td>
<td>$x \geq x_{max}$</td>
</tr>
</tbody>
</table>

$^a x_{inc}$ streamer inception field.

During subsequent discharge activity a corona can develop at the tip of a previous streamer channel, as explained in [19]. This can be identified with the stem mechanism, i.e. $\alpha=1$. The current concentration of a corona into a single stem can explain why these events were clearly visible in the video frames. In case the leader cannot propagate through the gap, this mechanism leads to arrested leaders, which can be observed at fields between the streamer inception field $x_{inc}$ and the immediate breakdown field $x_{max}$; see table 5.2.

Delayed leader breakdown. Above the reduced background field $x_{min}$, when the conditions for leader propagation according to the stem mechanism are fulfilled, delayed breakdown occurs after a stochastical time delay [19, 20]. This delay cannot be treated by the deterministic model described here and is most probably due to stochastical processes in the discharge activity, e.g. successive leaders re-striking the same channel [20] and spatio-temporal variations of the electric field distribution, produced by variations in the ionic space charge distribution left by previous discharges. These mechanisms are not well understood yet.
Figure 9: Ranges for the different leader discharge types and model predictions for $x_{\text{min}}$ and $x_{\text{max}}$ as a function of the gas pressure $p_0$ for both polarities. Simulation results are plotted as curves. The measured ranges are given by the vertical bars. The theoretical streamer inception field from [19] is also plotted for comparison.
Immediate leader breakdown. Above the reduced background field \( x_{\text{max}} \), immediate transition from streamer to leader occurs after the first corona via the precursor mechanism. At such fields, the precursor mechanism is the dominant leader mechanism, since for the stem mechanism previous discharge activity would be necessary. This is in agreement with previous observations in point-toplane gaps [3, 5, 15] from which it was deduced that the precursor mechanism is the dominant leader mechanism in SF\textsubscript{6}. However, in the case of uniform background fields, this is only the case above \( x_{\text{max}} \). At lower fields the stem mechanism seems to be the dominant leader breakdown mechanism under such conditions.

The values for \( x_{\text{min}} \) and \( x_{\text{max}} \) predicted by the model are plotted in figure 9 versus the gas pressure \( p \). The experimentally observed discharge ranges are represented by bars. It is seen that the model predictions are in good agreement with the experimental data. In particular, the pressure dependence and polarity differences are correctly represented. Being deterministic, the model is not able to describe stochastic features such as the partial overlapping of the experimental discharge type ranges.

It is interesting to note that the breakdown criterion at the limit \( x_{\text{min}} \), (i.e. for \( \alpha = 1 \)) can also be formulated in terms of a local field condition, namely, in terms of the field \( x_{21} \) of the first leader section \( \ell_1 \) after the input of the charge of the second corona \( Q_2 \). The simulations show (see figure 6(a) and 6(b) for an example) that this breakdown criterion for \( x_{\text{min}} \) is

\[
x_{21} < x_0. \tag{27}
\]

In other words, when the leader channel field in the first section—after the energy input from the second corona—is below the background field \( x_0 \), the leader can propagate. This is in agreement with the breakdown criterion (20) in [19]. For \( x_{\text{max}} \) a similar criterion cannot be given because the breakdown decision is only made after several steps and thus depends on integral parameters.

Condition (27) can also be formulated equivalently in terms of a
corresponding critical channel section temperature $T^* = T_{21}$. The resulting values are plotted in figure 10 as a function of the gas pressure $p$ for both polarities. This temperature increases with increasing pressure and is in the range of 350 K to 900 K. This temperature is much less than the leader-channel temperatures expected based on measurements in point-to-plane gaps (temperatures above the SF$_6$ dissociation temperature) \cite{5, 24}. Thus, leader inception and propagation can occur well below the dissociation temperature.

### 5.4.2 Features of arrested leaders

Arrested leaders are high level partial discharges; understanding them is relevant for partial discharge interpretation and gas decomposition issues. Although arrested leaders have been shown to exist in experiments (e.g. \cite{9, 12, 14}), their properties have not been described quantitatively, and the physical mechanism that leads to them has not been well understood. The leader propagation model presented here provides for the first time a quantitative model for this phenomenon.
Figure 11: Limiting values of cumulative charge $Q_L^*$ and arrested leader length $z_L^*$ vs gas pressure $p$: Simulations (curves) and experiments (symbols). (a) Cumulative charge of arrested leaders. (b) Arrested leader length.
The main observable parameters of arrested leaders are their length $z_L$ and their total charge $Q_L$. These quantities can be determined from the model by summing up the step lengths (23) and charges (24) up to leader arrest. Of particular interest are the values $Q_L^*$ and $z_L^*$ close to the breakdown limit $x_{\text{min}}$. Figure 11 shows these data for a protrusion length of $L=1$ mm at various pressures and for both polarities; the curves represent the model prediction and the symbols represent the measurements. It should be noted that the cumulative charge $Q_L^*$, which is essential for partial discharge diagnostics, is approximately independent of both gas pressure and polarity (figure 11(a)). This is in agreement with the measurements. The critical length $z_L^*$ is a few times the protrusion length $L$. It decreases with increasing pressure but is approximately polarity-independent (figure 11(b)). The experimental data lie systematically below the prediction but follow the predicted pressure trend. This systematic deviation is possibly due to an insufficient sensitivity of the framing camera used in our experiments.

Figure 12 shows, as a prediction, the simulated values for $x_{\text{min}}$, $Q_L^*$ and $z_L^*$ for various protrusions lengths $L$ at a pressure of 0.4 MPa and both polarities. With increasing protrusion length the reduced background field $x_{\text{min}}$ decreases (figure 12(a)) and the cumulative charge of arrested leaders increases (figure 12(b)). For all protrusion lengths the positive polarity exhibits lower minimum breakdown fields $x_{\text{min}}$ and higher charges $Q_L^*$. Note that the effect of the statistical time lag as described in [19] is not taken into account here. This may have an influence on the minimum breakdown field, especially for small protrusions. The length of arrested leaders $z_L^*$ (figure 12(c)) increases only slightly with protrusion length and is nearly independent of polarity.

### 5.4.3 Step time, leader propagation velocity and gap crossing time

The leader propagation step time $\tau$ is controlled by a combination of channel expansion, ion-drift and local ionisation processes [3]. The
Figure 12: Reduced background field $x_{\text{min}}$ (a) and limiting values for cumulative arrested leader charge $Q^*_L$ (b) and arrested leader length $z^*_L$ (c) versus protrusion length at a pressure of 0.4 MPa.
experimental data suggest that channel expansion is the dominant process, so that (21) can be used as a lower limit for the propagation step time \( \tau \).

![Leader propagation time \( t_p \) versus gas pressure \( p \). Simulation results (curves) and experimental data (symbols) are shown.](image)

**Figure 13:** Leader propagation time \( t_p \) versus gas pressure \( p \). Simulation results (curves) and experimental data (symbols) are shown.

Figure 13 shows a plot of the propagation time of an un-delayed leader across a 20 mm gap as a function of the gas pressure. The predicted curves are only weakly dependent on polarity and show a systematic increase of \( t_p \) with gas pressure. The experimental data are in rough agreement with the model. With the given gap distance of 20 mm, an average leader propagation velocity of \( 0.5 \times 10^5 - 2 \times 10^5 \) m s\(^{-1} \) can be deduced for the pressure range 0.1 to 0.5 MPa, which is in good agreement with previous investigations (e.g. [29, 30]).

### 5.5 Conclusions

A one-dimensional numerical model is presented, which describes the propagation of leaders in SF\(_6\) triggered by a small electrode protrusion embedded in a uniform background field. It assumes rectilinear propagation of the leader along the background field and is
strictly deterministic, so that it cannot predict the random aspects of leader propagation. It also does not account for ionic space charges.

It takes into account the following parameters: applied background field, protrusion length, gas pressure and polarity. The model has the following main features:

- Option to choose the stem or the precursor mechanism to initiate the first discharge step.
- Step-by-step simulation of the propagation process through the gap.
- Modeling of propagation step lengths, step charges and step times.
- Modeling of the time dependent field and temperature distribution along the leader channel.

The model correctly predicts the parameter ranges within which the three leader types that have been previously observed [19] (namely, arrested leaders, delayed breakdown leaders and immediate breakdown leaders) occur. It relates the observed leader modes to the stem and the precursor leader inception mechanisms. At both polarities the stem mechanism determines the minimum breakdown field $x_{\text{min}}$. At higher field $x_{\text{max}}$, when immediate breakdown occurs, the precursor mechanism determines leader inception and breakdown. Between $x_{\text{min}}$ and $x_{\text{max}}$ the precursor mechanism leads only to arrested leaders.

The model can explain the main features of arrested leaders—their length scale and charge—as a function of applied background field, gas pressure, polarity and protrusion length. The simulations are in agreement with our previously [19] published experimental data.

The model allows calculation of the leader propagation step times and related quantities such as the propagation velocity and the gap crossing time.
The model is not restricted to uniform background fields but can be readily extended to non-uniform background field distributions. This will be treated in a future publication.

The model could principally be useful for other strongly electronegative gases where the leader channel field can be approximated by the critical field.

5.6 Acknowledgements

The authors would like to thank R Bini of ABB Switzerland Ltd., Corporate Research for doing the CFD simulations and P. Stoller of ABB Switzerland Ltd., Corporate Research for proofreading the manuscript.
5.7 References


“conduction and breakdown in gases” and “gaseous insulation”.


6 Partial discharges and breakdown at sub-millimeter defects

Markus Bujotzek and Martin Seeger

Full publication title: Partial Discharges and breakdown in SF$_6$ at sub-millimeter defects

Abstract: An improved understanding and modelling of partial discharges, leader-inception and breakdown in practically relevant SF$_6$ gas-insulation configurations is presented. In such configurations the background field is nearly uniform and defects have a typical length of a few 10...100 µm (surface roughness) to a few millimeters (particles). This paper addresses the partial discharge and breakdown at defects with sizes typical of very small particles and surface roughness. Experimental data is presented for positive and negative polarity and pressures of 0.2 MPa and 0.4 MPa. The length of the investigated protrusion, which was of well-defined shape, was 410 µm. Measured breakdown fields agree well with predictions from a new leader propagation model. Special attention is paid to the statistical and formative time lags, resulting in breakdown voltage-time characteristics. Some general consequences for technical applications are discussed.

6.1 Introduction

The mechanisms of partial discharges (PD) and breakdown in compressed SF$_6$ are of high relevance for the design of high voltage insulation systems, e.g. gas insulated switchgear (GIS). They have been mainly studied for positive polarity and in strongly non-uniform field gaps, such as point-to-plane gaps [1-3]. These configurations hardly represent technical gas insulation systems, where relatively small protrusions, like surface roughness or small particles, are embedded in a quasi-uniform background field [4]. The PD and breakdown processes in uniform and weakly non-uniform background fields are therefore of special interest for technically relevant applications.

In recent publications [5-8] a study on partial discharges, leader inception and leader breakdown at small protrusions in uniform background fields was presented. The investigations [5-8] covered protrusions of length 1...30 mm at both polarities in the relevant pressure range 0.1...0.5 MPa. A physical leader propagation model [6] could consistently describe the observed phenomena and showed
6.2 Theoretical considerations

The basic processes and the leader inception and propagation model are discussed in detail in [5, 6]. Their main aspects together with the modelling of the statistical time lag are described in the following sections.

6.2.1 Basic processes

The breakdown mechanism of compressed SF$_6$ in gas insulation is controlled by stepped leader propagation. It starts with the generation of a first electron to initiate a streamer corona, is followed by the transition to a leader (leader inception) and ends with stepped leader propagation across the gap.

For small protrusions the parameter controlling the discharge is not the voltage applied to the gap, but the background field $E_0$ in which the protrusion is embedded. All discharge criteria, therefore, have to be expressed as a function of this quantity. This background field is best normalized to the critical field as the relevant gas property controlling the dielectric strength.

$$x = \frac{E_0}{E_{cr,0}}$$  \hspace{1cm} (1)

Where: \( E_{cr,0} = p_0 \cdot 89 \) (V/(m·Pa)) \hspace{0.5cm} p_0 = \text{pressure (Pa)} \hspace{0.5cm} E_0 \) controls the local field enhancement created by the protrusion, which can be conducting particle, a surface roughness feature or

a good agreement with the experimental data from [5, 7-8].

In the present paper we apply our model to the sub-millimeter range and validate it for weakly non-uniform fields with new experimental data for a protrusion length of 410 µm, both polarities and different pressures. This protrusion length represents very small particles, but may account also for extreme values of surface roughness. Furthermore, statistical and formative time lags will be discussed.
a discharge channel. The electric field is redistributed by the presence of the protrusion, see Figure 1. The field enhancement ahead of the protrusion can be integrally expressed as a voltage difference:

\[ \Delta U = E_0 \cdot L' - \int_{0}^{L'} E(z) \cdot dz \approx \ell \cdot (E_{cr,0} - E_0) \]  

(2)

Where:
- \( L' = L + z_L \)
- \( L = \) length of protrusion
- \( z_L = \) length of the discharge channel
- \( \ell = \) length of a streamer channel

Figure 1: Field re-distribution in a uniform background field by a conduction channel.

Equation (1) together with equation (2) can be solved for the length \( \ell \) of a streamer developing in the field enhancement zone
6.2 Theoretical considerations

ahead the protrusion and a previous discharge channel, respectively.

\[ \ell = \left( \frac{\Delta U}{E_{cr,0}} \right) \cdot \frac{1}{(1 - x)} \]  

(3)

The charge of a streamer corona can be calculated with the given length of a streamer corona from equation (3) according to the following expression.

\[ Q_c \approx 0.5 \cdot \varepsilon_0 \cdot E_{cr,0} \cdot \ell^2 \cdot (1 - x) \]  

(4)

Leader inception is the transition of a streamer channel to a leader channel and is caused by ohmic heating of a streamer channel when a charge pulse \( Q \) passes through it [1]. The deposited energy per length is the product \( Q \cdot E \) of the charge and the channel field \( E \) and raises the channel temperature \( T \). This creates an initial over-pressure \( \Delta p \), which drives the channel to expand. Channel expansion, in turn, causes a gas density reduction and a corresponding decrease of the channel field \( E \). This field is stabilized to the critical value \( E_{cr} \) [9].

In \( \text{SF}_6 \) two main mechanisms have been identified by which charge is fed into a channel, namely, the precursor [3] and the stem mechanism [10]. In the precursor mechanism, only a small fraction of the total corona charge \( \alpha \cdot Q_c \) is fed into a single channel so that \( \alpha \) is typically in the range of a few percent. From our experiments we deduced \( \alpha \approx 0.02 \). In the stem mechanism the streamer corona contains branched streamers which feed their charge into common stem(s). A substantial part of the total corona charge may be fed into one single channel, so that the fraction \( \alpha \) may reach values up to the order of unity.

The two charge injection mechanisms can be used to describe the minimum and maximum breakdown fields. For leader inception, i.e. for the first propagation step, the two options \( \alpha = 0.02 \) and \( \alpha = 1 \) are regarded. The case \( \alpha = 1 \) implies the maximal possible charge injection and determines the lower limit background field \( x_{min} \) for
leader breakdown. The case $\alpha = 0.02$ implies a minimal charge injection and determines the background field $x_{max}$ for immediate breakdown.

6.2.2 Numerical model

Leader inception and propagation are constructed step-by-step by using the relations described above, i.e. first the inception mechanism is chosen (stem or precursor), then the channel heating and expansion is calculated from the corona charge and the channel field. After the first propagation step $\alpha = 1$ is used in the subsequent leader propagation steps because the corona at the leader tip then feeds all of its charge into the existing channel. The construction of each propagation step starts by determining the corona length $\ell$, the corona charge $Q_C$, and the step time resulting from the time needed for channel expansion. The charge is fed through the channel sections behind the leader tip and the temperature and field of each section is recalculated.

The model delivers for each step the propagation step length, step corona charge, temperatures and fields of all channel sections, and the propagation step time. From these quantities several further quantities, e.g. cumulated leader charge, leader length and charge in the case of an arrested leader, or leader crossing time, can be deduced. Within the present paper only the minimum and maximum breakdown fields are calculated and compared to experimental results. The minimum breakdown field $x_{min}$ results from the lowest applied background field using the stem mechanism for leader inception, i.e. if the leader which was initiated from the full first corona charge manages to cross the gap. The immediate breakdown at the field $x_{max}$ occurs when the minimal charge injection from the first corona is sufficient to produce a leader which crosses the gap, i.e. leader inception from the pre-cursor mechanism. Between $x_{min}$ and $x_{max}$ the precursor mechanism leads to arrested leaders.
6.2.3 Statistical time lag

The effect of the statistical time lag as described in [5] was not taken into account in the leader propagation model presented in [6]. This may have an influence on the minimum breakdown field, especially for small protrusions, and is therefore considered for the present case with a protrusion length of 410 µm.

At positive polarity the statistical time lag for a first corona is determined by the availability of a first electron close to the protrusion tip within a critical volume. The inner boundary of this volume is given by the condition that a critical avalanche can be formed [5, 11]. The outer boundary is determined by the surface on which the field falls to the critical value $E_{cr,0}$. The mechanism for production of a first electron is collisional field detachment, which is strongly field dependent [5, 11]. At negative polarity first electron are produced by field emission from the protrusion tip. Field emission is quantified by the ‘Fowler-Nordheim’ equation [5, 12], which gives the electron production rate $\dot{N}_e$ emitted from an area with a given surface field. For both polarities the corresponding statistical time lag $t_s$ is calculated according:

$$t_s = \frac{1}{\dot{N}_e}$$  \hspace{1cm} (5)

6.3 Experiments

6.3.1 Experimental set up

The experimental set-up of the test gap is schematically shown in Figure 2 together with a photograph of the protrusion. An artificial protrusion (steel) with a length $L=410$ µm was mounted on a rod with spherical cap with length 165 mm and radius 16 mm. The rod with the protrusion was placed between two smooth plate electrodes (aluminium) of 200 mm diameter. The protrusion had a conical shape and a tip radius of 250 µm. The distance between the rod and
the plate electrode was set to $D=20$ mm. Ground potential was applied to the rod. At the opposite electrode a high voltage step pulse (of positive or negative polarity) of 100 ns rise time was applied for 60 s. This step was produced by a high voltage circuit, consisting of a capacitor ($2 \text{nF}$), which was charged by a Van-de-Graaf generator (VdG) and was switched onto the electrode arrangement via a damping resistor ($600 \ \Omega$). The whole set-up including the high voltage circuit was placed into GIS compartments containing SF$_6$. In the test gap compartment the gas pressure was varied between 0.2 MPa and 0.4 MPa SF$_6$ ($>99 \%$ purity) at ambient temperature. Since for both polarities the results (time lags and breakdown voltages) were influenced by the time interval between successive voltage applications, a sufficient long pause time of minimum 300 s between the voltage applications was used.

![Diagram](image)

**Figure 2:** Experimental set-up. VdG=Van de Graaf generator, the protrusion length and gap distance were $L=410 \ \mu\text{m}$ and $D=20$ mm, respectively.

The gap was observed by a photomultiplier (Hamamatsu R456) and the signal was recorded on a digital storage oscilloscope (Le-Croy LC574AL) to determine the instant of discharge activity after
application of the voltage (statistical time lag). Additionally, the applied voltage was recorded and from the breakdown of the voltage the total time to breakdown was determined. The formative time lag was evaluated from the difference between total time to breakdown and statistical time lag.

The protrusion was placed on a rod to ensure a maximum electric field at the protrusion tip. The background field in which the protrusion was embedded is defined by the rod and the plate electrodes and is weakly non-uniform. The field enhancement of the background field is a factor of two in comparison to the uniform field at given electrode distance \((U/D)\), where \(U\) is the applied voltage.

### 6.3.2 Experimental results

The total time to breakdown after voltage application is the sum of the statistical time lag and the formative time lag. The formative time lag consists of the leader propagation time, which is in the range of some 100 ns, and the pre-breakdown phase during which partial discharges in from of streamer coronae and arrested leaders occur. Figure 3 shows the measured statistical time lag and the formative time lag as a function of the reduced background field \(x\) for both polarities at pressures of 0.2 MPa and 0.4 MPa.

Both time lags decrease with increasing applied field with a slope which is steeper for positive polarity. The statistical and the formative time lags may reach values up to several seconds close to \(x_{min}\). At the lower pressure and positive polarity the lack of a first electron is very dominant and yields long statistical time lags.

The vertical dashed lines indicate the calculated reduced background field \(x_{min}\) and \(x_{max}\). Very good agreement between the prediction and the measurement can be observed for the minimum breakdown field (below which no breakdown occurs) for both polarities and pressures. The immediate breakdown field \(x_{max}\) is the field above which the leader propagation is immediately started from the first corona and thus the formative time lag is reduced to the propagation time, i.e. it amounts some 100 ns. Except for the pressure
Partial discharges and breakdown at sub-millimeter defects

a) Negative, p=0.2 MPa

b) Positive, p=0.2 MPa
Figure 3: Statistical time lag and formative time lag as a function of the reduced background field $x$. 
of 0.4 MPa and positive polarity also a good agreement between the theoretical values and the measurements can be observed. The reduced breakdown fields, $x_{min}$ and $x_{max}$, decrease with pressure. This behaviour is also reflected by the model. Note that there is a substantial gap between $x_{min}$ and $x_{max}$.

The statistical time lags according to (5) are plotted together with the measured data in Figure 3. For negative polarity, see Figure 3a) and 3c), the theoretical curves were calculated for a lower and an upper limit with different field enhancement factors $\beta$ within the ‘Fowler-Nordheim’ equation, see [5] for details. For 0.2 MPa $\beta=5.5$ and $\beta=10$, and for 0.4 MPa $\beta=4$ and $\beta=5.5$ were used for the upper and lower limit, respectively. For positive polarity, the calculated statistical time lag is significantly below the measured times at 0.2 MPa, Figure 3b), and represents the minimum time for the statistical time lag at 0.4 MPa, Figure 3d).

### 6.4 Discussion

The comparison of measured and calculated statistical time lags in Figure 3 show a reasonable agreement at negative polarity when assuming moderate field enhancement factors. This is in agreement with [5]. At positive polarity the calculated statistical time lags describe only the lowest measured level at 0.4 MPa. At 0.2 MPa the measured values are many orders of magnitude higher than the prediction. These discrepancies are larger than observed for longer protrusions [5]. Possible reasons may be field distortions by space charges, as discussed in [5]. This is not understood yet.

Figure 4 shows the dependence of the measured background breakdown fields $x_{min}$ and $x_{max}$ on pressure in comparison to the simulation results. Both, the measurements and the model show that the background field for minimum and immediate breakdown decrease with pressure and show the lowest values for positive polarity. As mentioned before a good agreement between measurement and simulation can be observed. Only at 0.4 MPa there is a dis-
Figure 4: Ranges for the different leader discharge types and model predictions for $x_{min}$ and $x_{max}$ as function of pressure for both polarities.
crepancy for $x_{\text{max}}$ at positive polarity. This was observed similarly for a protrusion length of 1 mm [6] and is not understood yet. It may be related to the chosen value of $\alpha$, which was the same for both polarities and all pressures. This may be a too strong simplification. Choosing $\alpha=0.15$ can reproduce the experimental value for $x_{\text{max}}$ at 0.4 MPa.

The total time to breakdown is shown for 0.2 MPa and 0.4 MPa in Figure 5 for both polarities. It can be seen that at lower pressures (0.2 MPa, Figure 5a)) at negative polarity the time to breakdown is shorter than at positive polarity. For short time voltage application, e.g. lightning impulse (LI), which is in the range of 1E-6 s, this produces that the negative polarity will be decisive for the breakdown. This can be explained by the long statistical time lag in the positive polarity, see Figure 3b). At lowest breakdown fields the time to breakdown is in the range of 0.1 s to several seconds. This time is in the range of typical AC voltage application times. Thus, for both polarities breakdown is possible under AC applications. The polarity differences of the leader breakdown (see Figure 4) determine then the polarity at breakdown, which is the positive in this case.

At higher pressures, see Figure 5b), this behaviour is different. Due to the higher absolute electric fields at this pressure the statistical time lags are smaller, see Figure 3c) and 3d) (note that the absolute field at $x=1$ and 0.2 MPa is the same at $x=0.5$ and 0.4 MPa, see (1)). At short voltage application times (LI) the positive polarity is now the decisive one. At longer voltage application times (AC) the behaviour is similar to the case of 0.2 MPa. Thus, at 0.4 MPa the positive polarity is the decisive one under LI and AC applications for the investigated protrusion length. However, it can be expected that for smaller protrusion lengths the statistical time lack at positive polarity will produce that the negative polarity will be decisive for LI applications, e.g. [13].

In [5] three types of leader were identified, namely arrested leaders, delayed breakdown leaders and immediate breakdown leaders.
Figure 5: Time to breakdown as a function of the reduced background field $x$ for both polarities and 0.2 MPa and 0.4 MPa.
In the present experiments the same discharge behaviour is observed. Delayed breakdown leaders and immediate breakdown leaders occur at reduced background fields $x_{\text{min}}$ and $x_{\text{max}}$, respectively (see Figure 4). The model presented in [6] and summarized here allows us to relate these leader types to leader inception mechanisms and to predict the background field ranges in which they occur. A summary is shown in Table 6.1.

**Table 6.1:** Summary of leader types, related inception mechanisms and ranges of reduced background field.

<table>
<thead>
<tr>
<th>Leader type</th>
<th>Inception mechanism</th>
<th>Reduced field range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrested leader</td>
<td>Precursor ($\alpha=0.02$)</td>
<td>$x_{\text{inc}}^a &lt; x &lt; x_{\text{max}}$</td>
</tr>
<tr>
<td></td>
<td>Stem ($\alpha=1$)</td>
<td></td>
</tr>
<tr>
<td>Delayed leader breakdown</td>
<td>Stem ($\alpha=1$)</td>
<td>$x_{\text{min}} &lt; x &lt; x_{\text{max}}$</td>
</tr>
<tr>
<td>Immediate leader breakdown</td>
<td>Precursor ($\alpha=0.02$)</td>
<td>$x \geq x_{\text{max}}$</td>
</tr>
</tbody>
</table>

$^a x_{\text{inc}}$ streamer inception field, see Figure 4

**Arrested leaders:** When the field is above the streamer inception field, a first corona occurs after a statistical time lag. For reduced fields below $x_{\text{max}}$ (immediate reduced background field) this can be explained by the model with the precursor mechanism for leader inception, i.e. $\alpha=0.02$. The longest streamer in the first corona is activated and only a small fraction of the total corona charge is fed into a single channel. During subsequent discharge activity a corona can develop at the tip of this previous streamer channel. This can be then identified with the stem mechanism since the total corona charge is fed through the existing channel, i.e. $\alpha=1$. In case the leader cannot propagate through the gap, this mechanism leads to ar-
rested leaders, which can be observed at fields between the streamer inception field $x_{\text{inc}}$ and the immediate breakdown field $x_{\text{max}}$. Arrested leaders are high level partial discharges; understanding them is relevant for partial discharge interpretation and gas decomposition issues. Although arrested leaders have been shown to exist in experiments (e.g. [14]), their properties have not been described quantitatively, and the physical mechanism that leads to them has not been well understood.

**Delayed leader breakdown:** Above the reduced background field $x_{\text{min}}$, when the conditions for leader propagation according to the stem mechanism are fulfilled, delayed breakdown occurs after a stochastical time delay [5, 7]. This delay is not treated by the deterministic model and is most probably due to stochastical processes in the discharge activity, e.g. successive leaders re-striking the same channel [7] and spatio-temporal variations of the electric field distribution, produced by variations in the ionic space charge distribution left by previous discharges. These mechanisms are not well understood yet.

**Immediate leader breakdown:** Above the reduced background field $x_{\text{max}}$, immediate transition from streamer to leader occurs after the first corona via the precursor mechanism. At such fields, the precursor mechanism is the dominant leader mechanism, since for the stem mechanism previous discharge activity would be necessary. This is in agreement with previous observations in point-to-plane gaps [1, 3, 10] from which it was deduced that the precursor mechanism is the dominant leader mechanism in SF$_6$. However, in the case of uniform and weakly non-uniform background fields, this is only the case above $x_{\text{max}}$. At lower fields the stem mechanism is the dominant leader breakdown mechanism under such conditions.

### 6.5 Conclusions

The leader inception and breakdown in SF$_6$ at sub-millimeter defects in weakly non-uniform background field was investigated at
positive and negative polarity. The protrusion length was 410 µm and the SF$_6$ pressure was 0.2 MPa and 0.4 MPa. This is the parameter range of practical interest for gas insulation with particulate contamination and surface roughness features, respectively.

A theoretical leader inception and propagation model was presented in [6] and could describe well the measured minimum breakdown fields $x_{min}$ and immediate (after the statistical time lag) breakdown fields $x_{max}$. This indicates that the model is also valid for very small protrusions and surface roughness in weakly non-uniform background fields. The model relates $x_{min}$ and $x_{max}$ to the stem and the precursor leader inception mechanism, respectively. In agreement with the model the measured leader breakdown fields $x_{min}$ and $x_{max}$ were lowest at positive polarity.

However, the model does not include any effect of statistical time lags on the breakdown field. From the experiments very large statistical time lags resulted at positive polarity for a pressure of 0.2 MPa. This produces that for very short voltage application times, e.g. LI applications, the negative breakdown field is lower than the positive breakdown field. The range where this occurs depends on protrusion size, pressure and voltage application time. This explains that the negative polarity might be decisive for the breakdown, although leader breakdown is favoured at positive polarity.

### 6.6 Acknowledgement

The authors thank J. Knauel for performing the experiments during his internship at the ABB Switzerland Ltd., Corporate Research.
6.7 References


7 Leader propagation in non-uniform background fields

Markus Bujotzek and Martin Seeger

Full publication title: Leader propagation in non-uniform background fields in SF₆”

18th International Conference on Gas Discharges and their Applications, Greifswald, Germany, 2010.
Abstract: Leader propagation and breakdown (BD) in SF$_6$ in a point-to-plane gap was experimentally investigated for both polarities at a pressure of 0.3 MPa. The experimental results are compared to a recently presented leader propagation model, which is extended for non-uniform background fields and validated with this new experimental data. The one-dimensional model describes the observed phenomena and yields the parameters of stepped leader propagation. It satisfactory describes the stepped leader propagation process.

7.1 Introduction

The phenomena of leader inception and propagation in SF$_6$ have been studied extensively in the past, because of their importance for high voltage insulation systems, e.g. [1-3]. The focus was mostly set on positive polarity and on point-to-plane gaps, since there lowest breakdown voltages are reached.

In recent publications [4-5] an improved understanding and a physical model of the breakdown mechanism of compressed SF$_6$ was presented for uniform and weakly non-uniform background fields [6]. The breakdown mechanism is controlled by stepped leader propagation. The presented one-dimensional model describes the observed phenomena and yields the parameters of stepped leader propagation, which are step lengths and charges, step times, electric fields and temperatures inside the leader channel.

In the present contribution we extend the model to non-uniform background fields and validate it with new experimental data for a point-to-plane gap. Although such configurations are usually different from technical gas insulation systems, examples for practical applications exist, e.g. disconnector switching in GIS or large particulate contamination.

The experimental data is presented for positive and negative polarity at a pressure of 0.3 MPa SF$_6$. Special attention is paid to the temporal evolution of the propagating leader, i.e. step times and lengths, and the leader channel field.
The investigated field geometry is shown in Fig. 1. A high voltage step pulse of positive or negative polarity was applied for 30 s at the protrusion. The applied voltage pulse was measured by a damped capacitive voltage divider. A photomultiplier (PM) tube (Hamamatsu R456), a SLR camera (Canon EOS 350D) and a high speed camera (Phantom v7.3) were placed to observe the light emitted between the electrodes. The gap distance between the point-to-plane electrodes was $D=105$ mm. The point electrode (steel) had a spherical tip with a radius of 2 mm and an overall length of $L=190$ mm. The plane electrode was made of aluminum and had a diameter of 270 mm. The voltage divider and the PM tube were connected to a digital storage oscilloscope (LeCroy LC574AL).

**Figure 1:** Experimental set-up. VdG=Van de Graaf generator.
7.2 Leader propagation model

The physical leader propagation model for uniform background fields is described in detail in [4]. It is a one-dimensional numerical model, which describes the processes from leader inception to stepped leader propagation. Recently the model was also validated for weakly non-uniform background fields and protrusions in the sub-millimeter range [6]. This model is now extended to strongly non-uniform background fields. It will be described in the following only qualitatively.

Within the model leader inception and propagation are constructed step-by-step using the non-uniform background field from electrostatic field calculations. This background field describes the length of a streamer corona by the re-distribution of the electric field; similarly as described in detail in [4], but adapted to the non-uniform field. From this length a total streamer corona charge can be deduced. In the first step only a fraction of this corona charge heats one of the streamer channels. The heating leads to a pressure rise followed by a radial expansion of the channel, which defines the step time. The electric field inside the channel is set to the critical field at the corresponding pressure and temperature [7]. At the tip of the first channel further coronae can develop if the electric field is sufficiently high. In the subsequent steps the step length and step time is calculated in the same way using the total corona charge, which is fed through the channel sections behind the leader tip. The temperature and electric field of each section is recalculated after each step. The model parameters were the same as given in [4]. Only the polarity dependent channel radius \( R_0 = C_s/p \), with \( p = \text{pressure} \) was adapted to the measured data at negative polarity resulting in \( C_s^- = 8 \, \text{m Pa} \). For uniform background fields \( C_s^- = 3 \, \text{m Pa} \) was used. The constant for positive polarity remained unchanged with \( C_s^+ = 2 \, \text{m Pa} \).
7.3 Results

The propagating leader can be quantified in terms of length, propagation time, number of steps, step charge, leader channel field, channel temperature and radius. Some of these quantities have been measured and are shown together with the model predictions in Fig. 2.

In Fig. 2a) the total leader length in dependence of the applied voltage is shown for both polarities. The total length was deduced from photographs and high speed videos of the leaders. The length increases with the applied voltage for both polarities. Leaders up to 70 mm (corresponding to ca. 70 % of the gap distance) are observed for the highest applied voltages. Further increase in voltage leads to breakdown, i.e. complete bridging of the gap. At positive polarity the length increases faster with the applied voltage and BD is reached at voltages exceeding 110 kV. This is significantly lower than at negative polarity with BD voltages at about 260 kV. The model predictions agree satisfactorily with the experimental results at both polarities. At negative polarity the predicted total leader length is slightly overestimated. This may result from the evaluation of the leader lengths in the experiments. The opening angle of the propagating leaders is about 45° around the axis of symmetry. In the projection on the observation plane the leaders appear then with a reduced length, which may be up to 30% less than the real length. Additionally, weak streamers at the leader tip may not be recorded by the camera. At positive polarity such discrepancy is not visible due to the steep rise of the curve.

The total propagation time in dependence of the applied voltage is shown in Fig. 2b). This time was deduced from the PM signal. For negative polarity significantly higher values are observed than for positive polarity, suggesting a higher propagation velocity since similar lengths have been reached. The model predictions agree well with the experimental data at negative polarity. At positive polarity too long propagation times are predicted. This is produced
Figure 2: Experimental results and model predictions at both polarities and 0.3 MPa SF$_6$. 
by the prediction of a too high number of short steps. The (not shown) average step time, which was measured to about 200 ns at negative and 35 ns at positive polarity, is predicted correctly for both polarities.

The number of steps in dependence of the applied voltage is shown in Fig. 2c). Again, much ‘steeper’ characteristics can be observed at positive polarity. Typically up to 12 steps are reached at both polarities and the corresponding maximum voltage without BD. The model prediction is only shown for negative polarity and satisfactorily agrees with the measurement. At positive polarity step numbers in the range of 20 have been predicted. In general, it can be observed that there is a larger voltage range between leader inception and BD at negative polarity.

The leader propagation model provides further parameters, which have not been measured in the experiments, e.g. step charges and the leader channel field.

![Simulated average leader channel field](image)

**Figure 3:** Simulated average leader channel field for an arrested and a BD leader at negative polarity and 0.3 MPa SF$_6$.

Corona charge measurements can be found in literature [1] for similar point-to-plane arrangements and pressures. The measured charges agree well with the charges predicted by the model, which
are typically in the range of 1...3 nC at negative polarity and a few hundred pC at positive polarity, respectively.

The average channel field is shown in Fig. 3 for the case of an arrested leader and a BD leader at negative polarity. A BD leader reaches significantly lower average channel fields (≥ 25 kV/cm) than an arrested leader (≥ 60 kV/cm). This is related to a higher channel temperature, which is also predicted by the model and is in good agreement with data reported in literature, e.g. [1].

7.4 Discussion

The comparison of the experimental data with the model predictions shows a good overall agreement. This was reached by adapting the parameter (describing the streamer radius) in the model. As discussed in [4], we assume that this is physically justified since the streamer radius may depend on the divergence of the electric field. However, data for the streamer radius at negative polarity is missing. There are no other parameters of which an adaption would be justified. For the positive polarity such adaption was not necessary. A higher polarity dependence of $C_s$ in strongly non-uniform fields may be explained by the development of the electron avalanche when it propagates towards an increasing and decreasing field, corresponding to positive and negative polarity at the tip, respectively.

From the leader length and the propagation time the average propagation velocity can be deduced. Average values at positive and negative polarity are $5 \times 10^5$ m/s and $1.5 \times 10^4$ m/s, respectively. For positive/negative polarity this is higher/less than found in uniform background fields [4], where the velocity was in the range of $1 \times 10^5$ m/s and was not distinctly different for both polarities. According to the model, at negative polarity the lower propagation velocity is produced by the larger streamer radius; resulting in a longer channel expansion time. Since the total leader length is correctly predicted, at positive polarity the model would reproduce the measured pro-
pagation velocity if less but longer steps would be predicted. This shows that in strongly non uniform fields the leader propagation is different from the situation in uniform background fields and needs further investigation.

7.5 Conclusions

Experimental data for leader propagation in SF$_6$ at 0.3 MPa and both polarities in a point-to-plane gap haven been presented. These data have been used for validation of a recently presented leader propagation model, which was extended for strongly non-uniform background fields. The reasonable agreement of the model with the experimentally observable quantities for both field configurations (uniform and strongly non-uniform) indicates that the model can be used generally. However, some discrepancies remain which may be explained by physical effects, e.g. the variation of the streamer radius with field non-uniformity. The model helps, therefore, to indentify the importance of such effects. Further investigations will be done to clarify this in detail.

7.6 Acknowledgement

The authors would like to thank S Burow for performing the experiments and for helping in the data analysis during his internship at ABB Switzerland Ltd, Corporate Research.
7.7 References


8 Parameter Dependence

Markus Bujotzek, Martin Seeger

Full publication title: Parameter Dependence of Gaseous Insulation in SF₆

IEEE Transactions on Dielectrics and Electrical Insulation, Volume 20, Number 3, pp. 845–855, 2013.
doi: 10.1109/TDEI.2013.6518954
Abstract: The strength of electrical insulation in gaseous compressed SF$_6$ is determined by various parameters, like pressure, polarity, field homogeneity, surface roughness of the electrodes, particulate contamination, and voltage wave shape. The dependence of the involved physical phenomena on accessible design parameters, like e.g. pressure, geometry, is of interest for the prediction of partial discharge inception and breakdown fields. Models for first electron production, streamer inception and leader propagation are presented, which are combined systematically to deduce these fields in technically relevant electrical insulation systems.

8.1 Introduction

Compressed SF$_6$ gas is widely used for insulation in high voltage (HV) equipment, such as gas insulated switchgear (GIS) or high voltage circuit breakers. The excellent properties, beside from its greenhouse warming potential, make it most suitable for the use as gaseous dielectric [1].

The prediction of withstand and breakdown voltage is required for efficient development and improvements of HV equipment. Precise predictions are difficult, however, due to the numerous parameters influencing the strength of the gaseous insulation, e.g. pressure, polarity, field homogeneity, surface roughness of the electrodes, particulate contamination and voltage wave shape, e.g. power frequency (AC), constant voltage (DC), lightning impulse (LI), switching impulse (SI) and very fast transients (VFT) wave shapes [2, 3].

Commonly, the design of HV equipment is based on semi-empirical rules, which have been established through several years of experience. These rules are usually based on the surface electric field inside the SF$_6$ filled equipment, which is obtained from electric field calculations. This field will be in the following referred to as the background field. From this field the breakdown fields are estimated taking into account parameters like surface roughness, electrode surface area, pressure, polarity and voltage wave shape. The para-
meter dependencies have to be determined experimentally. These breakdown fields are usually expressed by scaling laws [1, 4, 5].

The push towards limits of compactness of high voltage equipment and higher voltage ratings require a precise understanding of the involved physical phenomena and its quantitative description. Especially the knowledge of the breakdown decisive parameters and their dependencies on the accessible design parameters, like e.g. pressure, geometry, is of importance. Due to the abovementioned number of parameters a variety of possible limits of the gaseous insulation system may occur, e.g. one cannot generally state which polarity is the more critical one for breakdown since this depends sensitively on pressure, voltage wave shape, surface roughness etc. (e.g. [1, 4]). Similarly one cannot generally state which voltage wave shape is the more critical one for testing, since this depends on pressure, surface roughness etc. Furthermore, it is important to know under which conditions partial discharges occur. Also this depends on many parameters like pressure, surface roughness, particulate contamination, voltage wave shape and polarity. These examples show the complexity of gaseous insulation in practical applications. A systematic evaluation of all the physical effects in the parameter range of practical relevance is, therefore, needed. This can only be achieved by a sufficiently precise description of the physical processes involved, i.e. semi-empirical approaches are usually not sufficient. In the present contribution an overview of the relevant physical processes will be given and these processes will be combined systematically to evaluate the breakdown and partial discharge fields in compressed SF$_6$ insulation. To our knowledge no such systematic evaluation was done so far.

The electrical insulation characteristics of SF$_6$ were studied extensively in the past, e.g. [4]. The major investigations of the physical phenomena were conducted in the 1980’s, e.g. [6-9]. A review from 1991 can be found in [10]. In many of these investigations positive polarity and strongly inhomogeneous fields have been studied, since they resulted in lowest breakdown voltages under these conditions.
In the last decades further investigations have been performed on the topic of electrical insulation in SF$_6$ [11-18]. In [19] a new leader propagation model was presented, which was validated for different cases [20, 21].

The physical phenomena which dominate the breakdown in SF$_6$ insulation can be identified when considering the temporal evolution of the breakdown itself. It is known that the breakdown in SF$_6$ in technically relevant electrode arrangements and pressures occurs via stepped leader propagation [6, 7, 11]. It is initiated from a first electron, followed by a streamer, streamer to leader transition, stepped leader propagation across the gap, and finally after reaching the opposite electrode the breakdown occurs after transition from a leader to a spark. In the present paper the parameter dependencies of the three abovementioned criteria (first electron, streamer inception, leader propagation) will be presented. The decisive criteria for breakdown and partial discharge inception will be identified for given configurations, i.e. given polarity, pressure, electrode arrangement, and applied voltage wave form.

The paper is structured as follows: In section 8.2 the breakdown mechanism in SF$_6$ is addressed and the models required for its description are introduced. Section 8.3 presents the results of the parameter variations and is followed by a discussion in section 8.4. Section 8.5 concludes the findings and identifies needs for future investigations.

**8.2 Breakdown Mechanism in SF$_6$**

**8.2.1 General Considerations**

For practical applications, the primary interest is the prediction of the breakdown voltage and the partial discharge inception voltage. We first define practically relevant cases, which are discussed in the following. These cases represent the typical possible configurations in compressed SF$_6$ insulation systems at operating conditions.
These are regarded to be pressures in the range of 0.1-0.6 MPa, weakly non-uniform fields, both polarities and standard voltages wave shapes: AC, DC and impulse (LI, SI). We chose 0.1 MPa as the lowest pressure example, representing conditions for applications like ring main units (RMU) in distribution systems and 0.6 MPa representing the upper limit and e.g. high voltage circuit breakers.

Five cases for the electrode configurations are chosen, which are:

1. Low surface roughness: This configuration represents the ideal, ”smooth” electrode arrangement.

2. Technical equivalent surface roughness: This case represents typical technical electrodes, which can be for example found in coaxial electrode arrangements, e.g. GIS.

3. High technical equivalent surface roughness: This case represents extreme surface roughness and should be regarded as the upper limit for “undisturbed” technical electrode arrangements. An example are the surfaces of worn arcing contacts in circuit breakers or disconnectors.

4. Protrusion: This is together with case 2 probably the most typical technical arrangement. A protrusion can be a small particle or some other structure (e.g. screw, edge, electrode defects) locally enhancing the otherwise homogenous or weakly inhomogeneous background field.

5. Oblong particle: This arrangement is the most undesired one of the five cases. It represents e.g. large particulate contamination of GIS.

The following table summarizes the parameters of the cases described above, which are used in the simulations, and defines the denotation for the figures. The parameters are introduced in the corresponding following sections. All cases have been simplified for modeling as a single idealized micro-protrusion with the height $L$ and the tip radius of curvature $R$. The protrusion is placed in a homogenous background field.
Table 8.1: Overview of the considered cases and their corresponding parameters.

<table>
<thead>
<tr>
<th>No</th>
<th>Name</th>
<th>L</th>
<th>L/R</th>
<th>FE* factor β</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Smooth</td>
<td>20 µm</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>TR100</td>
<td>100 µm</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>TR400</td>
<td>400 µm</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Protrusion</td>
<td>1 mm</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>Particle</td>
<td>3 mm</td>
<td>10</td>
<td>180</td>
</tr>
</tbody>
</table>

*FE: field enhancement, cf. section 8.2.2

8.2.2 First Electron

The prerequisite for avalanche formation is the existence of a first electron. Among several physical processes for electron production the two major ones, which come into consideration for compressed \( \mathrm{SF}_6 \) gas insulation, are electron detachment from negative ions \([9, 22, 23]\) and electron emission from the cathode \([4]\). The latter one is assumed to be the dominating mechanism for cases with negative polarity at the field enhanced electrode or in the case of homogenous field, where due to this effect the breakdown usually starts at the cathode. If the electrode is at positive polarity, the first electron has to be provided from the gas volume in front of the electrode.

The dominating mechanism for electron emission from the negative electrode is cold field emission \([4]\), which can be described by the Fowler-Nordheim equation \([24, 25]\). Typical values for the microscopic electric field necessary for field emission are in the range of \(10^9 \) V/m, i.e. 10 MV/cm \([4, 26]\), which is far above typical macroscopic electric fields in compressed gas insulation systems. Such high electric fields can only be reached at microscopic inhomogeneities like imperfections of the electrode surface, which can create local field...
enhancements of up to several orders of magnitude. The electron production rate $\dot{N}_e(1/s)$ emitted from an effective area $A_{\text{eff}}(\text{m}^2)$ can be calculated according to [24]:

$$\dot{N}_e = A_{\text{eff}}/e \cdot C_1 \cdot (\beta \cdot E_0)^2 \cdot \exp (-C_2/(\beta \cdot E_0))$$

$$C_1 = 1.54 \cdot 10^{-6} \cdot \frac{10^{4.52/\sqrt{\Phi}}}{\Phi}$$

$$C_2 = 2.84 \cdot 10^9 \cdot \Phi^{1.5}$$

(1)

where $\Phi \approx 4.5 \text{ eV}$ is the work function, $e$ the elementary charge, $\beta$ a field enhancement factor due to microscopical surface roughness and $E_0(\text{V/m})$ the applied background field. The parameter $\beta$ is the most sensitive one in equation (1) and is reported in literature with the typical values $\beta < 1000$ [24, 27]. This factor was varied for the five different cases according to Table 8.1. The chosen values for $\beta$ result from a field enhancement factor $\beta_1$, motivated by the shape of the idealized protrusion, and a second field enhancement factor $\beta_2$ which is due to microscopic roughness of the protrusion surface. The field enhancement ($\beta_1$) can be characterized to a good approximation with $\beta_1 \approx 2 + L/R$ [24]. The factor $\beta_2$ was fitted to experimental data with $\beta_2 = 5 \ldots 20$. The resulting total field enhancement is $\beta = \beta_1 \cdot \beta_2$. The effective area was kept constant at $A_{\text{eff}} = 10^{-16} \text{ m}^2$, which is a typical value reported in literature [24, 27].

At positive polarity the first electron is generated in front of the field enhanced electrode. Initial electrons provided from the inter-electrode gas space are mainly supplied by detachment from negative SF$_6$ ions [4, 9, 23, 28]. The collisional field detachment from negative ions is strongly field dependent. The electron production rate $\dot{N}_e$, i.e. the number of detached electrons per unit time and unit volume is determined with the detachment rate coefficient $k_d$ and the negative ion concentration $n^-$ [23]:

$$\dot{N}_e = k_d \cdot n^-$$

(2)
The ion concentration is controlled by the natural ionization leading to an equilibrium concentration of negative ions, which can be determined from measured ionization rates [9]. The assumption of an equilibrium concentration of ions between the electrodes is generally only valid for larger electrode systems, e.g. GIS, since the ion concentration is diffusion-limited within a few centimeters of an electrode [9, 23]. Further, for the calculation of the statistical time lag also the transient ion distribution has to be considered, since the negative ions move towards the anode with velocity $\mu \cdot E$, where $\mu$ is the ion mobility and typical velocities are in the order of some mm/$\mu$s. In this paper these considerations are taken into account in a simplified way. We distinguish between impulse voltage applications and AC or DC voltage applications by choosing two different negative ion concentrations $n^-$ in equation (2). For impulse voltages with application times in the $\mu$s range the steady state equilibrium ion concentration of $2.2 \times 10^{10} \text{m}^{-3} \text{MPa}$ [9, 23] is used. This is reasonable, since the diffusion limited ion distribution moves towards the anode as soon as the voltage is applied. For the duration of voltage application one can assume that the ion density is constant within the critical volume and is equal to the equilibrium ion density. This is only valid if before the voltage application no field was applied across the electrodes for sufficiently long time (typically in the range of several minutes). Only then the equilibrium ion concentration is reached. For typical technical electrode arrangements and voltage application times $> \text{ms}$ (i.e. AC or DC) the initial ion density distribution can be neglected and the ion density distribution for the corresponding electrode distance and applied voltage has to be calculated. From spatio-temporal calculations of the ion distribution for different distances and voltages it resulted that an average constant ion concentration of $1.0 \times 10^5 \text{m}^{-3} \text{MPa}$ in front of the anode should be used for the initial ion density. This number originates from reasonable values for the electrode distance of about 50 mm and for the applied voltage yielding an electric background field of 50% of the critical electric field. Detachment rate coeffi-
cients published by Xu et al [23] were used to calculate the electron production rate.

The two decisive quantities for the statistical time lag at positive polarity are the electron production rate within the critical volume and the size of the critical volume itself. Both quantities depend on the electric field distribution, thus the geometry of the electrode arrangement. The boundaries of the critical volume are determined by two surfaces [18]. The outer boundary is determined by the condition that the electric field falls to the critical field, since the field must exceed the critical field for formation of an avalanche. The inner boundary of the critical volume it is given by the condition that a critical avalanche can be formed, i.e. the streamer criterion must be fulfilled.

\[ 8.2 \text{ Breakdown Mechanism in SF}_6 \]

\[ 8.2.3 \text{ Streamer Inception} \]

The streamer criterion describes the necessary size of an avalanche to become critical and is defined as:

\[
\int_{0}^{x_{cr}} \bar{\alpha}(x) \cdot dx = K
\]

where \( \bar{\alpha} \) is the effective ionization coefficient and \( K = \ln(N_e) \) with \( N_e \) being the number of electrons in the avalanche. For SF\(_6\) \( \bar{\alpha} \) can be described in dependence particle density reduced electric field \( E/N \) [18] with the particle number density \( N \) by [29, 30]:

\[
\bar{\alpha}(E/N) = 0.0277 \cdot (E/N - (E/N)_{cr,0}) \cdot N
\]

with \( (E/N)_{cr,0} = 3.6 \times 10^{-19} \ \text{Vm}^2 \). Streamer inception is reached if the applied field is sufficiently high to fulfill equation (3), where \( K = 10.5 \) [30, 31] is used.
8.2.4 Leader Propagation

The physical leader propagation model is described in detail in [19]. It is a one-dimensional numerical model, which describes leader propagation triggered by a protrusion embedded in a uniform background field. Recently, the model was also validated for weakly non-uniform background fields and protrusions in the sub-millimeter range [20] and later also extended to strongly non-uniform background fields [21]. For small protrusions the parameter controlling the discharge is the background field $E_0$ in which the protrusion is embedded. This background field can be normalized to the critical field as the relevant gas property controlling the dielectric strength.

$$x = \frac{E_0}{E_{cr,0}}$$  \hspace{1cm} (5)

Where at ambient temperature: $E_{cr,0} = p_0 \cdot 89$ (V/m), $p_0$=pressure (Pa) and $E_0$ controls the local field enhancement created by the protrusion, which can be a conducting particle, a surface roughness feature (metallic protrusion) or a discharge channel starting from a metallic protrusion. The electric field is redistributed by the presence of such protrusion such that the potential change ahead of the protrusion can be integrally expressed as a voltage difference:

$$\Delta U = E_0 \cdot L' - \int_0^{L'} E(z) \cdot dz \approx \ell \cdot (E_{cr,0} - E_0)$$  \hspace{1cm} (6)

Where: $L' = L + z_L$ the total length of the protrusion $L$=length of metallic protrusion, $z_L$=length of a discharge channel starting from the metallic protrusion, $\ell$=length of a streamer channel at the tip of the discharge channel and $E(z)$ is the unperturbed, capacitive electric field.

Equation (5) together with equation (6) can be solved for the length $\ell$ of a streamer developing into the field enhancement zone.
ahead the protrusion and a previous discharge channel, respectively.

\[ \ell = \left( \frac{\Delta U}{E_{cr,0}} \right) \cdot \frac{1}{(1 - x)} \]  

(7)

The charge of a streamer corona can be calculated with the given length of a streamer corona from equation (7) according to [18]:

\[ Q_c \approx 0.5 \cdot \varepsilon_0 \cdot E_{cr,0} \cdot \ell^2 \cdot (1 - x) \]  

(8)

Leader inception is the transition of a streamer channel to a leader channel and is caused by ohmic heating of a streamer channel when a charge pulse \( Q \) passes through it [6]. The deposited energy per length is the product \( g \cdot Q_c \cdot E \) of the charge and the channel field \( E \) and raises the channel temperature \( T \). The factor \( g \) describes the fraction of the total corona charge which leads to heating of the channel. The heating creates an initial over-pressure \( \Delta p \), which drives the channel to expand. Channel expansion, in turn, causes a particle number density \( N \) reduction and a corresponding decrease of the channel field \( E \), since this field is stabilized to the critical field \( E_{cr} \) [7]. Note that the critical field depends linearly on \( N \) for temperatures below 1500 K, see e.g. [19].

In SF\(_6\) two mechanisms are known for charge injection into a channel; the precursor and the stem mechanism. The two charge injection mechanisms are taken into account in the model by variation of \( g \). For leader inception, i.e. for the first propagation step, the two options \( g=0.02 \) and \( g=1 \) are regarded. The case \( g=1 \) implies the maximal possible charge injection by the stem mechanism and determines the lower limit background field \( x_{min} \) for leader propagation. Usually this is associated with a significant formative time lag [18, 19]. The case \( g=0.02 \) implies a minimal charge injection by the pre-cursor mechanism and determines the background field \( x_{max} \) for immediate leader propagation.

Within the numerical model leader inception and propagation are constructed step-by-step by using the relations described above, i.e.
first the inception mechanism is chosen (stem or precursor), then the channel heating and expansion is calculated from the corona charge and the channel field. After the first propagation step \( g=1 \) is used in the subsequent leader propagation steps assuming that the corona at the leader tip feeds all of its charge into the existing channel. The charge is fed through the channel sections behind the leader tip and the new temperature and field of each section is recalculated. The model delivers for each propagation step the propagation step length, step corona charge, temperatures and fields of all channel sections, and the propagation step time. The leader channel expansion is calculated from initial conditions and the subsequent channel heating. The polarity dependence of the channel radius \( R_0 = C_s / p \) is accounted for by the constant \( C_s \) [19]. For negative and positive polarity \( C_s^- = 3 \) m Pa and \( C_s^+ = 2 \) m Pa, respectively was used. In the following we will assume that leader propagation through the gap is a sufficient criterion for breakdown.

8.3 Results

8.3.1 Statistical Time Lag

The statistical time lag \( t_s \) is the average time for production of the first electron, which is the reciprocal value of the electron production rate \( (t_s = 1 / \dot{N}_e) \). For simplicity, the electron production rate at the maximum field is assumed.

Negative Polarity

The statistical time lag at negative polarity for two selected cases ‘TR400’ (\( \beta = 40 \)) and ‘Protrusion’ (\( \beta = 120 \)), is shown in Figure 1 for a pressure of 0.4 MPa together with experimental data. For comparison the statistical time lag for both cases is also plotted for different effective emitting areas \( A_{eff} = 10^{12} \) m\(^2\) (dashed lines) and \( A_{eff} = 10^{16} \) m\(^2\) (solid lines). It can be seen the effect of area increase is negligible in comparison with the impact of the field enhancement.
8.3 Results

Figure 1: Time to first electron for case ‘TR400’ and case ‘Protrusion’ at 0.4 MPa at negative polarity.

factor $\beta$. In Figure 1 further the typical application times of LI voltage and AC voltage are indicated by the horizontal lines. From this representation it can be followed that for the ‘Protrusion’ case and $p=0.4$ MPa a first electron is expected to be usually available in the reduced electric field range of interest, i.e. at $x > 0.4$. For the case ‘TR400’, especially for lighting impulse voltage application roughly 80% of the critical electric field is needed to generate an electron within the required time, i.e. the first electron criterion can be decisive for breakdown if all other criteria (streamer, leader) are fulfilled at lower values of $x$.

Postive Polarity

The dependency of the statistical time lag at positive polarity on the electrode structure and pressure was calculated for a single idealized protrusion embedded in a homogenous background field $E_0$. The electric field in $z$ direction ahead of a protrusion of length $L$ and radius $R$ on a plate electrode was approximated by a multipole
expansion [32]:

\[
\frac{E(z)}{E_0} = 1 + \frac{L/R - 1}{(z/R + 1)^2} + \frac{2}{(z/R + 1)^3}
\]  

(9)

Figure 2: Time to first electron at pressures 0.1-0.6 MPa for case (a) ‘TR400’ and case (b) ‘Protrusion’ at positive polarity.

Figure 2 shows the average time for production of a first electron for protrusions of lengths \(L=400\ \mu m\), \(L/R=2\) (‘TR400’) and \(L=1\ mm\), \(L/R=6\) (‘Protrusion’), in dependence on the applied background field \(E_0/E_{cr,0}\) with the pressure varied from 0.1-0.6 MPa. Experimental results for \(p=0.2\ MPa\) are included in the figure for
both cases. The time to first electron is calculated from two initial ion concentration corresponding to impulse and AC or DC voltage applications, cf. 8.2.2.

Note that for the case ‘Protrusion’ (\(L=1 \text{ mm}\)) in Figure 2, the ratio \(L/R=6\) was chosen for comparison to experimental data only. In the following calculations \(L/R=4\) will be used, as denoted in Table 8.1 for this case. Figure 2 shows that the statistical time lag decreases with applied background field, increasing pressure and increasing \(L/R\) ratio. Thus, the shortest statistical time lags are expected for high roughness, represented by high \(L/R\) ratios, e.g. sharp edges, and at high pressures. The pressure, indicated by the arrows in Figure 2, has the least effect of the three abovementioned parameters.

Comparing the times to first electron again with typical voltage application times, indicated by the horizontal lines in Figure 2, it can be observed that for ‘TR400’ a lack of first electron can be expected at lower pressures for LI applications. Interestingly, there is not much difference in the reduced background field needed for the first electron for AC and LI applications for both cases (see intersection of the time to first electron curves with the LI and AC lines). This is caused by the difference in the ion concentrations used for calculation of the statistical time lag for the two different voltage applications. The ratio of the ion concentrations \((n^{-}_{(LI)}/n^{-}_{(AC)})\) is close to the ratio between the voltage application times assumed for AC and LI wave shapes.

Figure 3 shows the pressure dependence of the reduced background field \(x\) required for a first electron for AC and LI at positive and negative polarity. For AC and LI, average times within which a first electron should occur were chosen to 1 s and 1 \(\mu\)s, respectively. These time scales can be regarded as representative. In AC applications withstand tests are usually performed in the time range of several 10 s, whereas in LI the impulse peak duration is of the order of a few microseconds only. For AC applications we consider the peak voltage, i.e. the maximum field.
It can be clearly seen, that for the smooth and low technical roughness cases a much higher field is necessary to obtain a first electron than for large protrusions or particles. The pressure dependence is more pronounced at negative polarity. The curves in Figure 3 are clipped at a maximum of $E_0/E_{cr,0}=1$, since above this value the background field in the whole electrode gap becomes overcritical. It is assumed that the probability for the occurrence of a first electron by the previously described mechanisms is then strongly increased. This is, therefore, regarded as an upper limit.
8.3.2 Streamer Inception

The necessary reduced fields for streamer inception can be calculated from equation (3) for the different pressures and idealized geometries, using the electric field from equation (9). This is shown in Figure 4 for the five different cases in the pressure range 0.1-0.6 MPa. Note that for the streamer criterion no polarity dependence exists, since it is irrelevant if the avalanche is directed towards the protrusion or away from it.

Figure 4 shows that the pressure dependence of the reduced streamer inception field is more pronounced for smaller protrusions, i.e. for low roughness. For the ‘smooth’ case and low pressures nearly the critical field needs to be applied to fulfill the streamer criterion. For a particle or a protrusion in the millimeter range only 20% to 30% of the critical (background) field is sufficient to create a streamer. If no leader propagation occurs this defines the onset of partial discharges, provided that a first electron is available, c.f. 8.3.1.

Figure 4: Pressure dependence of the reduced streamer inception field $E_0/E_{cr,0}$ for different cases.
8.3.3 Leader Criterion

In section 8.2.4 two limiting cases for leader breakdown ($x_{\text{min}}$ and $x_{\text{max}}$) have been introduced corresponding to the minimum reduced background field required for breakdown and the reduced background field leading to immediate breakdown, respectively. In between these two limits delayed breakdowns are expected due to the statistical nature of the involved processes [33, 34]. Note that the delay refers to the formative time lag and not to the statistical time lag, cf. section 8.3.2. The lower limit $x_{\text{min}}$ is decisive for DC and AC applications, whereas $x_{\text{max}}$, i.e. the immediate breakdown, is of interest for impulse voltage stresses (LI, SI). Figure 5 shows the resulting pressure dependence of the leader breakdown fields at both polarities for the different cases.

In this example, leader propagation is calculated for a 20 mm gap and breakdown is defined when the leader reaches the opposite electrode. This is justified since streamer crossing occurs at fields much higher than those for leader propagation and in the present configurations leader crossing is a sufficient criterion for breakdown. These results are also valid for larger electrode distances since the dependence on the gap distance is low for homogenous background field. The reduced leader breakdown fields decrease with increasing roughness and pressure comparable to the streamer criterion. Additionally, the leader propagation depends on polarity and has lower breakdown fields at positive polarity. The polarity effect results from the difference in the streamer channel radius for both polarities, which is considered within the model by the constant $C_s$, c.f. section 8.2.4.

8.3.4 Combined Breakdown Criterion

The superposition of the results from sections 8.3.1-8.3.3 determines the breakdown fields for the various cases. The decisive criterion, leading to lowest breakdown fields is identified for different conditions, i.e. pressure, polarity, roughness/protrusion length, voltage
Figure 5: Dependence of the minimum and maximum reduced leader breakdown field $E_0/E_{cr,0}$ on pressure for different cases and different voltage applications: (a) positive AC, (b) negative AC, (c) positive LI, (d) negative LI.

wave shape. In the following this superposition of the results for one selected case (‘Protrusion’) will be presented in detail. All relevant effects can be discussed on this example.

Figure 6 shows the reduced background fields for the different criteria for this case in the pressure range 0.1...0.6 MPa. The results for AC voltages are presented in Figure 6a. The breakdown is determined by the positive leader criterion for pressures below 0.27 MPa. Note that for breakdown all criteria have to be fulfilled and, thus, the criterion needing the highest applied field is decisive. For higher
Figure 6: Dependence of the reduced background field $E_0/E_{cr,0}$ required for first electron/streamer/leader breakdown on pressure for the ‘Protrusion’ case at both polarities for (a) AC and (b) LI voltages.
pressures the breakdown occurs at negative polarity and is determined by the negative 1\textsuperscript{st} electron criterion up to 0.4 MPa and by the leader criterion at higher pressures. Partial discharges are expected at all pressures below the breakdown field if streamer and 1\textsuperscript{st} electron criterion are fulfilled. The polarity at which PD occurs depends on pressure and applied field and is distinguished in Figure 6a by different shadings. PD is expected at both polarities for pressures below 0.28 MPa. It starts at positive polarity below 0.15 MPa and at negative polarity between 0.15 and 0.28 MPa. Above 0.28 MPa the PD occurs at negative polarity only. There, the onset of PD is determined by the streamer criterion, i.e. PD is expected to occur without significant statistical time lag.

The different criteria for LI voltage applications are compared in Figure 6b. The breakdown field at pressures below 0.36 MPa is determined by the positive leader criterion. Between 0.36 and 0.53 MPa the breakdown is determined by the positive 1\textsuperscript{st} electron criterion and above 0.53 MPa by the negative leader criterion.

In Figure 7 the resulting reduced breakdown fields for all the cases described in Table 8.1 is shown for positive LI (LI\textsuperscript{+}), negative LI (LI\textsuperscript{-}) and AC voltages. Experimental results are included from literature for comparison. It can be observed that the reduced breakdown fields decrease with increasing pressure and increasing roughness/protrusion size. The reduction of breakdown field with increasing pressure is more pronounced for high roughness and protrusions, which reflects the known sensitivity of SF\textsubscript{6} insulation systems to surface roughness. It explains the breakdown critical voltage waveform and polarity. For example, AC breakdown is predicted to occur always at fields below LI breakdown. The critical polarity for LI depends on pressure and on the roughness/protrusion case. For protrusions and particles mostly the positive LI is decisive, since a first electron is available and the leader criterion determines the polarity dependence. For technical equivalent roughness TR400 the critical polarity changes at around 0.4 MPa from positive to negative. This behavior occurs at higher pressures the higher the
roughness or protrusion size is.

The critical polarity for all cases for LI and AC voltages is summarized in Table 8.2. For AC the occurrence of partial discharges is indicated by the shaded areas. In addition to the shading, the PD inception field in percentage of the breakdown field is given for both polarities.

For the ‘smooth’ case the critical polarity cannot be identified by the model since the breakdown is predicted at the critical field, i.e. there is no significant polarity difference expected. This is caused by the lack of a 1st electron for background fields below the critical field, cf. Figure 3. For the ‘TR100’ case and LI voltages this is similar. Partial discharges are predicted for technical equivalent roughness (TR100 and TR400) at negative polarity for pressures above 0.4 MPa. For the ‘Protrusion’ and ‘Particle’ case PD is expected for all pressures within the investigated range. There, the polarity at which PD occurs depends on pressure. It is negative at higher pressures and positive and/or negative at lower pressures with different onset voltages. It should be noted that the occurrence of PD is mainly decided by the availability of the 1st electron, since the streamer criterion is fulfilled at relatively low fields for the mentioned cases. Thus, PD will occur after a statistical time lag and are predicted to occur more likely in the given polarity. PD is not excluded for the other polarity.

8.4 Discussion

The different criteria decisive for breakdown and their comparison were presented in section 8.3. The first electron criterion determines the breakdown for smooth electrodes and low technical equivalent roughness at lower pressures. With increasing pressure and roughness or protrusion size, the breakdown field is determined by the leader criterion. The 1st electron criterion can be still decisive at higher pressures, especially at positive polarity since at positive polarity the pressure dependence of the 1st electron is significantly less
Figure 7: Dependence of the reduced breakdown field on pressure for different cases for positive and negative LI and for AC voltages: (a) Smooth, (b) TR100, (c) TR400, (d) Protrusion, (e) Particle. Experimental results from literature are included for comparison with model predictions.
Table 8.2. Polarity of the breakdown field for LI and AC voltage applications for different pressures and cases. Occurrence of PD is marked with shading, the PD onset field in percentage of the breakdown field is given polarity dependent (positive / negative) in the second line of the corresponding rows.

<table>
<thead>
<tr>
<th>Case</th>
<th>LI</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 2 3 4 5 6</td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>+/- +/- +/- +/- +/- +/-/-</td>
<td>+/- +/- +/- +/- +/- +/-/-</td>
</tr>
<tr>
<td>TR100</td>
<td>+/- +/- +/- +/- +/- +/-/-</td>
<td>+ + -</td>
</tr>
<tr>
<td>TR400</td>
<td>+ + + + + + -</td>
<td>+ + +</td>
</tr>
<tr>
<td>Protrusion</td>
<td>+ + + + + + -</td>
<td>+ + + + +</td>
</tr>
<tr>
<td>Particle</td>
<td>+ + + + + +</td>
<td>+ + + + +</td>
</tr>
</tbody>
</table>
pronounced than at negative polarity and the 1\textsuperscript{st} electron criterion intersects with the leader criterion, e.g. see Figure 6a. This intersection causes the pressure dependent change of the critical polarity for these cases. The streamer criterion is not decisive for breakdown in the investigated pressure range, but determines, especially for protrusions and particles, the onset of partial discharges. For these cases and pressures above 0.6 MPa it is expected that the streamer criterion becomes also decisive for the breakdown, due to the relatively weak pressure dependence of the reduced streamer inception fields. Then the 1\textsuperscript{st} electron and leader criterion may be fulfilled at lower fields than streamer inception.

Partial discharges are expected for AC voltage applications for all cases, except for the “smooth” ideal case. The prediction of PD even for the relatively low technical roughness case might be unexpected but is reasonable. PD will always occur when approaching the breakdown field, if breakdown is not decided by the 1\textsuperscript{st} electron or the streamer criterion. This definition of PD onset and its prediction does not refer to a measurable PD activity in the context of classical PD diagnostic. The streamer charges are the lower the lower the roughness or the protrusion is, since the charge scales quadratically with the protrusion length [18]. Further, the PD inception field for the low roughness case is relatively high (since also the breakdown level is high) and not reached in typical technical arrangements and at typical test voltages. This will be demonstrated with an example later in this section. In general, the relative PD inception levels (Table 8.2) are typically in the range of 60-90\%, i.e. PD inception is expected at voltages which are 10\%-40\% below the breakdown voltage.

The results indicate the importance of the availability of the first electron for breakdown and for inception of partial discharges. It has to be noted that the prediction of the first electron has the largest uncertainty among the presented criteria. It was shown that for both polarities some of the model parameters have been adapted to experimental data for two different cases. Especially at positive polarity,
the scatter of these data is relatively large and the agreement with the model is not fully satisfactory. But despite these uncertainties, which will be mainly reflected in absolute numbers, the qualitative parameter dependency of the criterion should be predicted correctly.

In the following, we will compare the predicted breakdown values with experimental results from literature and with test standard values. In [4] several experimental results for breakdown fields for AC and LI voltage applications are reported for various technical rough surfaces and different electrode arrangements at different pressures. These results are inserted in Figure 7 for the ‘TR100’ case. The error bars represent the scatter of the results from various arrangements and electrode surfaces. For AC voltage application the predicted reduced breakdown field is within this scatter and the pressure dependence is reproduced correctly. For negative LI the agreement is satisfactory for 0.2 MPa, but the prediction deviates at 0.4 MPa from the measurement. Nevertheless, the drop in breakdown field is predicted correctly, but at a slightly higher pressure. This is probably caused due to uncertainties in the prediction of the 1st electron. In general, the agreement justifies to consider the ‘TR100’ case to be realistic for typical, clean technical electrode systems.

The ‘TR400’ case can be considered as representative for extreme surface roughness and should be regarded as the upper limit for “undisturbed” technical electrode arrangements. In [20] breakdown measurements of a 410 µm protrusion in a weakly non-uniform background field have been presented. The experiments were performed for DC voltage with application times in the 10 s range and can be regarded as representative for AC applications. They are inserted in Figure 7 for the ‘TR400’ case. The agreement between model prediction and experiment is satisfactory and the pressure dependence is predicted correctly. A further comparison of the ‘TR400’ case can be done with empirical scaling laws reported in [1, 4, 34]. These laws are reported to represent extreme surface roughness with an average height of the profile in the order of 300 µm. The comparison of the prediction for the ‘TR400’ with the empirical scaling
law is also shown in Figure 7 (dashed lines). The agreement between model prediction and the scaling law is satisfactory for AC and positive LI. For negative LI the model prediction deviates from the scaling law, especially at lower pressures. There the prediction of the availability of the 1st electron is probably too pessimistic, leading to higher breakdown fields. Interestingly, the technical brochure 360 from CIGRE [35] lists these empirical scaling laws for the 50% breakdown fields for LI and AC voltages as breakdown fields in SF$_6$ for a technical electrode surface without mentioning the extreme surface roughness.

In [36, 37] measurements of breakdown fields for AC and LI at both polarities are reported for fixed defects with different length at 0.45 MPa SF$_6$. The results for 1 and 3 mm are inserted in Figure 7 for the ‘Protrusion’ and ‘Particle’ case, respectively. The agreement with the model prediction is reasonable, except for the ‘Protrusion’ case and AC voltage applications. The reason for this discrepancy is not clear, especially since further experimental results from [18] are presented for this case, which show good agreement with the model predictions. In general, from experience AC voltage breakdown is expected to be below the LI breakdown level [35], as predicted by the model. It should be noted that the present model does not take into account any field distortions by space charges due to partial discharge activities. Usually space charges lead to lower fields and, therefore, higher breakdown voltages. This is sometimes referred to as “corona stabilization”. To our understanding, however, this is not relevant here, since the breakdown decision for AC voltage applications is taken at instants when the space charge has drifted away from the contact, i.e. under nearly space charge free conditions. Thus, the present model predicts partial discharge activity but this has no influence on the breakdown voltage.

For further comparison with literature and test standard values three of the investigated cases are used. These are regarded as the most common and technically interesting ones, representing typical SF$_6$ insulation systems. These are the technical equivalent rough-
ness cases (TR100 and TR400), which represent “clean conditions” in e.g. GIS or gas circuit breakers (GCB). Further, the ‘Protrusion’ case is considered in the comparison to account for disturbances of these “clean conditions”. The typical pressure range for GIS and GCB applications is 0.4...0.6 MPa. It can be seen from Table 8.2 that the critical polarity for these cases is the negative polarity for AC voltage applications. For LI voltages the critical polarity is negative for the technical equivalent roughness cases. This is in agreement with literature, where usually the breakdown in weakly non-uniform fields of technical electrode arrangements is reported at negative polarity, e.g. [1, 35, 38].

The test standard values [2, 3] specify the required test voltages for AC and LI for high voltage switchgear. Figure 8 shows the comparison of predicted breakdown voltage ratios for LI and AC_rms voltages with those values from standards. The test standards define for a given rated voltage a corresponding power frequency and LI withstand voltage level. The ratios from the standards for the rated voltages of 72/145/245/362/420 kV are within the shaded grey area in Figure 8.

The comparison of the predicted breakdown voltage ratios with the ratios from standards can be interpreted in the following way: if the predicted ratio is below the ratio given by the standard, the LI voltage test will be more critical to pass. If it is above the standard ratio, the AC test is more critical. From Figure 8 it can be seen that the model predicts the LI test to be decisive for all three cases over the whole pressure range of interest. Additionally it can be deduced that in most of the cases the negative LI should be decisive above 0.4 MPa (cf. red curve below corresponding black curve). These results agree with the experience as mentioned above.

In the following the model predictions are discussed for a given technical application of an industrial GIS bus duct. In this example the model predictions for all cases are summarized and presented in an alternative way. The following parameters have been assumed: \( U_r = 420 \) kV (rated voltage), coaxial electrode system with
8.4 Discussion

Figure 8: Comparison of the predicted breakdown voltage ratios \( \text{LI/AC}_{\text{rms}} \) for pressures 0.1-0.6 MPa with ratios from test standards.

\( R_{\text{inner}} = 8 \text{ cm and } R_{\text{outer}} = 26 \text{ cm.} \) This numbers originate from [39] and represent a typical industrial GIS for 420 kV. The electric field at the inner conductor can be calculated from the dimensions for a given voltage which can be normalized to the rated voltage in per unit values (p.u.), where 1 p.u. corresponds to \( U = 420 \text{ kV} \cdot \sqrt{2} / \sqrt{3}. \) The model predictions from above are scaled accordingly to the p.u. values and compared in the following again with standard test voltages.

Figure 9 shows the predicted breakdown voltages for positive LI (LI+), negative LI (LI-), AC and PD inception voltage for the different cases in p.u. voltage for the given example. The rated operating voltage, power frequency withstand voltage (PFWV) and LI withstand voltage test according to standards are included in the figure by horizontal lines. For protrusions and surface roughness with a length up to 1 mm all voltage tests required by the test standard are below the prediction and, therefore the corresponding tests would
Figure 9: Comparison of the predicted breakdown voltages for positive LI, negative LI, AC and PD inception voltage for the different cases with the rated operating voltage, power frequency withstand voltage (PFWV) and LI withstand voltage test according to standards for a 420 kV GIS bus duct.

be passed. No PD is expected at the PFWV test, since the test level is below the predicted inception level. At protrusion lengths of roughly 1.6 mm, assuming a linear interpolation between different protrusion lengths, the LI withstand voltage prediction crosses the test level, i.e. this test becomes critical and breakdown is expected at positive polarity. PDs are expected to occur in the PFWV test for protrusion length above 1.6 mm, i.e. such protrusions can be detected at the standard PFWV test. No PD is predicted for protrusions up to 3 mm at nominal voltages, however. Breakdown is expected in the PFWV test and for protrusions with length of 3 mm and above. Note that all the discussed behavior is only valid for the given example. In the assumed design particles or protrusions should be below 1.6 mm to pass all the required tests. It should be kept in mind also that not only the length of the protrusion, but also the aspect ratio $L/R$ plays an important role and a change of this
ratio would affect the results. This would mainly influence the 1\textsuperscript{st} electron criterion, which is decisive for the LI withstand prediction.

SI voltage wave shape was not addressed in the present investigation but can be described in a similar way as shown for the AC and LI voltage waveforms. Since the time to peak of SI voltage waveform (250 µs) is significantly larger than that of LI (1.2 µs) and due to the first electron statistics, it is expected that SI breakdown voltage is closer to AC breakdown voltage than to LI breakdown voltage. This is in agreement with the experience [35].

8.5 Conclusions

Parameter dependencies of gaseous insulation in SF\textsubscript{6} were investigated. These parameters comprise: pressure, field enhancement, voltage wave shape (AC, LI) and voltage polarity. Models for first electron production, streamer inception and leader propagation are presented, which allow to deduce the partial discharge inception and breakdown fields in technically relevant electrical insulation systems, e.g. GIS. The results show that only by taking into account all these physical mechanisms the known parameter dependencies of gaseous SF\textsubscript{6} insulation can be quantitatively explained. The largest uncertainty is observed for the first electron production rates, which depend not only sensitively on the polarity and field enhancement, but also on the details of the test conditions. The description of the first electron production may be improved in the future. For practical applications the main predictions from the model are:

a) For technical equivalent roughness partial discharges occur only above 0.4 MPa. The operating or test voltage has to be relatively high for PD onset and the PD level is small, therefore not easily detectable. Thus, PD is not relevant for technical equivalent surface roughness.

b) Protrusions and particles show always PD activity with onset levels at typical test (protrusion) and operating voltages (particles). The onset voltages and polarity depend on pressure and are typically
20%-40% below the breakdown voltage.

c) The LI test is always more critical to pass compared to the PFWV test. The decisive voltage polarity is negative for most of the relevant cases and pressures above 0.4 MPa.

d) On an example of a gas insulated bus duct it is shown that the model can be used to predict critical particle lengths, inception and breakdown fields for AC and LI voltage wave shapes.

8.6 Acknowledgement

The authors would like to thank C. M. Franck for carefully proofreading the manuscript and his helpful suggestions for improvements as well as R. Koerner for performing of measurements in the framework of his bachelor thesis.
8.7 References


9 Streamer radius and length

Markus Bujotzek, Martin Seeger, Fabian Schmidt, Myriam Koch, Christian Franck

Full publication title: Experimental investigation of streamer radius and length in SF$_6$

doi: 10.1088/0022-3727/48/24/245201
**Abstract:** $SF_6$ has for decades been widely used in high voltage insulation and switching applications, e.g. in gas insulated switchgear. Despite its widespread use some important parameters, like the properties of streamers, are still not sufficiently understood. Since breakdown in $SF_6$ always occurs via the streamer-leader transition the streamer properties are decisive for leader inception and, therefore, breakdown of the insulation. Important parameters are, for example, the streamer radius and the streamer propagation length of arrested streamers. Such properties enter in breakdown prediction models. In the present study the streamer radius and the propagation length were investigated experimentally at 50 and 100 kPa for both polarities using strongly and weakly non-uniform background fields. No experimental information was available so far for negative polarity. The resulting streamer radius scaling agrees with previous experimental results for positive polarity and with expectations from breakdown models for negative polarity. These results were similar for strongly non-uniform and weakly non-uniform background fields. A difference between the two setups was observed for the streamer lengths. It was found that for strongly non-uniform fields the streamer length scales as expected with the critical electric field but with a different field for weakly non-uniform background fields. This was similar for both polarities.

**9.1 Introduction**

Compressed $SF_6$ is commonly used in high voltage (HV) gas insulated switchgear (GIS) and in high voltage gas circuit breakers due to the excellent insulation and arc quenching properties. Although this technology is mature and investigated since the 1960’s, an improved understanding of the electrical breakdown and the involved processes is of high importance for efficient development and reliable operation of HV equipment using $SF_6$. Since $SF_6$ is known to be a strong greenhouse gas the search for alternatives is ongoing in research and development [1][2][3]. The modelling of the breakdown
process in SF$_6$ and alternatives is, therefore, of high interest. A recently developed 1-dimensional model could successfully describe the measured breakdown voltages under the relevant operating conditions of HV switchgear using SF$_6$ [4][5][6]. This model is currently also successfully applied to SF$_6$ alternatives [7]. The previous studies have shown that the breakdown in compressed SF$_6$ in technically relevant electrode arrangements occurs via stepped leader propagation [8][9][10][11]. The recent model [4][5] delivers, among several other quantities, the breakdown voltage and the length of the discharge for a given configuration, i.e. electric field, pressure, polarity and ambient temperature. It requires a few physical input parameters. One of the most unknown parameters in the model is the streamer radius. Previous measurements of discharge channels at positive polarity were done by Torshin using Schlieren techniques [12]. These results were used for the model [4][5]. At negative polarity no information was available and the streamer radius could only be indirectly estimated from breakdown measurements [4]. The mentioned Schlieren measurements of Torshin [12] focused on leaders and only limited information about streamer radius is given. The results were obtained at 304 kPa, where an initial radius of about 6-8 $\mu$m was reported for the initial stage of the discharge formation. This was attributed to the first streamer. Previous experiments of Torshin [13] for 203 kPa, 405 kPa and 811 kPa report similar numbers and are comparable with data of leader precursor radius measurements in [14]. Further, Chalmers et al [15] investigated the development of leader discharges in a point-plane gap in SF$_6$ up to 500 kPa and report a streamer radius (during leader step development) of 25 $\mu$m at 100 kPa. All these experiments were done in point-plane gaps at positive polarity. A further experimental study, where breakdown measurements in a point-plane arrangement have been performed [16], indicated that at negative polarity the streamer radius might depend on the homogeneity of the electric background field revealing higher streamer radii for strongly non-uniform background fields.

The objective of the present contribution is to confirm the pre-
vious assumptions and measurements for negative and positive polarity, respectively, and to provide input data for the model [4][5]. This is done by optical measurements of the streamer and leader channel radius in weakly non-uniform and strongly non-uniform electric field arrangements at both polarities. Further, the experimentally obtained length of the initial streamer corona is presented and compared to theoretical predictions.

The physical picture and the relevant theoretical considerations are introduced in section 9.2, the experimental setup is presented in section 9.3, the results are reported in section 9.4, discussed in section 9.5, and concluded in section 9.6.

9.2 Physical Picture

The breakdown in compressed SF$_6$ is a sequential process of the production of an initial electron close to the high field electrode, the development of streamer corona, the streamer to leader transition, the stepped leader propagation towards the opposite electrode, and the leader to spark transition. During stepped leader propagation a streamer corona develops at the tip of the propagating leader [8][9]. The properties of single streamers and of streamer corona, in particular the radius and the spatial extension of the streamers and streamer corona are of importance for the modelling of stepped leader propagation. The physical picture and the nomenclature used in the present contribution are similar to [4]-[20]: The streamer [8][9] is a filamentary discharge which develops from an avalanche if the streamer criterion is fulfilled [17][18]. The diameter of a streamer is controlled by the radial diffusion of electrons and photoionization from the streamer head [8][9]. The radial extension of the streamer in SF$_6$ is expected to be independent of the applied voltage [8]. Further, it was assumed in [8] for SF$_6$ that the radial extension depends on the polarity, arguing that positive streamers, where avalanches are oriented towards the streamer head, have more narrow channels than negative streamers, where avalanches emerge from the streamer.
head. Moreover, the streamer radius $R^\pm$ is expected to scale inversely proportional with the number density of the gas. For constant temperature this is equivalent to a scaling with pressure $p$ [8][15][23]. For our model and for practical applications where the temperature is close to an ambient temperature of 300 K this is more convenient. In the following we use, therefore, the pressure dependence of the streamer radius according:

$$R^\pm = C_s^\pm / p$$

(1)

where $C_s^\pm$ is a constant. This pressure dependence motivates a determination of $C_s^\pm$ at low pressures, since the radial extension becomes smaller with increasing pressure. The constant $C_s^\pm$ can be determined experimentally [5] either directly through radius measurements or indirectly through breakdown measurements, or it can be deduced from numerical simulations [19]. Different values are reported from previous investigations: $C_s^- = 3$ m-Pa and $C_s^+ = 2$ m-Pa were used for leader propagation modelling in uniform background fields [5], later $C_s^-$ was adapted to 8 m-Pa for non-uniform background fields [16]. In [8], initially these constants were roughly estimated with $C_s^- = 15$ m-Pa and $C_s^+ = 5$ m-Pa.

For the model we are interested in a thermally active radius of the streamer channel since this determines the transition to a leader. The thermally active radius can be measured by Schlieren techniques. Gallimberti et al report that the self-luminous radius coincides with its corresponding Schlieren value [14][20]. This justifies to measure the optical radius and to use the obtained values in the model. Further, in SF$_6$ the streamer radius is nearly one order of magnitude smaller than in air [21][22][23], e.g. at 100 kPa and 300 K we expect a streamer radius of only 20 $\mu$m in SF$_6$ and about 100 $\mu$m in air at positive polarity. Within the limited experimental accuracy possible differences between self-luminous, thermally active and electrical radius are neglected in the present work. In the following, the radius of the streamer refers to the optical radius of the discharge filament without any halo, i.e. the self-luminous core.
The length of a streamer and the extension of the first streamer corona, respectively, is another parameter of interest, which can be deduced from optical measurements. With sufficient accuracy the streamer channel field in SF$_6$ can be assumed to be equal to the critical field $E_{cr}$ [8][10][17][24]. This is a characteristic of strongly electronegative gases, where attachment lengths and attachment times are so small that electron current can only be maintained if attachment is compensated by ionization, i.e. at critical field [25]. This is different from air where the streamer channel field, more often referred to as streamer stability field, is significantly lower than the critical field, e.g. [22][23][26]. The approximate length of a streamer $l_s$ in direction of the electric field line can be determined by the following consideration. The streamer extends in one dimension, i.e. along an electric field line, into the gap until the potential drop across the streamer equals the potential drop from the undisturbed background field $E(z)$[8][20][27]:

$$\int_0^{l_s} (E(z) - E_{cr}) \cdot dz = 0$$

(2)

This describes that the streamer propagates until there is no remaining field enhancement at the streamer tip.

Another estimation of the streamer length yielding the maximum possible corona extension is [24]:

$$l_{s,\text{max}} = \frac{U}{E_{cr}}$$

(3)

The consequence of (3), following the consideration regarding the potential drops, is that the applied voltage $U$ is completely consumed by the streamer and no more potential drop across the remaining gap to the opposite electrode remains. This can only be true in vanishing background fields in the streamer head location or when the gap is completely bridged. It can be used as an upper limit and for discussion of the obtained results in the following. Further, it can be expected from the above considerations, that the streamer length
should be independent of polarity to first approximation. Polarity effects might be produced by the different streamer head size leading to differences in the electric field at the streamer tip. Also the interaction of streamers \[28\] during propagation might be different at positive or negative polarity. However, such polarity differences are not reported in literature and we assume, therefore, that such effects are small.

9.3 Experimental setup

The experimental setup for the strongly and the weakly inhomogeneous field arrangements are shown in Figure 1(a) and Figure 1(b), respectively. In both cases the electrode arrangement was placed into a coaxial GIS test compartment (vessel inner diameter ca. 400 mm, length ca. 600 mm), which was filled with SF$_6$ (>98% purity) at 50 kPa or 100 kPa at ambient temperature. A high voltage step pulse of 100 ns rise time and a constant voltage in the tail of positive or negative polarity was applied for 30 s at the field enhanced electrode. The voltage step was generated by a high voltage circuit consisting of a closing switch, a pre-charged capacitor (2 nF) and a damping resistor (600 Ω). Due to the statistical time lag the discharge inception always occurred after the voltage rise during the constant part of the applied voltage. Therefore the rise of the voltage and the inception time are of no importance for the discharge development, which occurs into a space charge free gap. No relevant voltage decay occurred until discharge inception. To ensure independence of successive voltage applications and similar conditions in the test gap, a pause time of at least 100 s followed by a small DC voltage (below inception voltage) to remove residual ions were applied. The GIS compartment was equipped with two UV transparent quartz (Herasil® 102) windows for optical diagnostics. The windows have been mounted in special flanges to enable as close as possible optical access to the electrode setup without distortion of the electric field in the region of interest.
Figure 1: Experimental set-up for the (a) strongly non-uniform field arrangement with $D=50$ mm, $L=190$ mm and (b) weakly non-uniform field arrangement with $D=30$ mm, $L=125$ mm. PMT=Photo Multiplier Tube, II=Image Intensifier. The electric field lines and the voltage reduced electric field along the rotational symmetry axis are shown on the right-hand side.
For the strongly non-uniform field arrangement, cf. Figure 1(a), the gap distance between the electrodes was \( D = 50 \text{ mm} \). The point electrode was made of stainless steel and had a spherical tip with a radius of \( 2 \text{ mm} \) and an overall length of \( 190 \text{ mm} \). The counter-electrode was an aluminium plate of \( 200 \text{ mm} \) diameter, where a spherical cap (stainless steel) with a radius of \( 125 \text{ mm} \) was mounted on. The intention was to have a relatively small counter-electrode for the tip to have mainly discharges around the rotational axis of symmetry, which is perpendicular to the axis of optical observation. The electric field lines from the spherical tip of the point electrode towards the counter-electrode are depicted on the right-hand side of Figure 1(a). Further, the voltage reduced electric field along the rotational axis of symmetry (dashed-dotted line in the field line plot) \( e' = E/U \) is shown, where \( E \) is the electric field and \( U \) the applied voltage.

In the weakly non-uniform field arrangement a plug-plane gap was used. The plug with a hemispherical tip was made of aluminium and had a length of \( L = 125 \text{ mm} \) and a radius of \( 9.5 \text{ mm} \). In the centre of the tip an artificial protrusion (steel) was mounted. The protrusion had a conical shape with a tip radius of \( 250 \mu \text{m} \), a length of \( 500 \mu \text{m} \) and was electrically connected to the plug. The plug was placed between two smooth aluminium plate electrodes of \( 200 \text{ mm} \) diameter. The distance between the plug and the plate electrode was set to \( D = 30 \text{ mm} \). The electric field lines and the voltage reduced electric field of the background field, i.e. the undisturbed plug-plane field without protrusion, are shown on the right-hand side of Figure 1(b).

### 9.3.1 Diagnostics

The applied voltage step was measured with a damped capacitive voltage divider. For optical diagnostics a photomultiplier tube (PMT) and a commercial D-SLR camera (Nikon D7000) in combination with an image intensifier were used. The PMT (Hamamatsu model R11568) was used to identify the discharges as well as a trig-
Streamer radius and length

In cases when the statistical time lag, i.e. the time delay between voltage application and the first streamer, was long. The operating voltage was set to -750 V. The PMT signal was recorded together with the voltage signal on a digital storage oscilloscope type LeCroy WavePro 960 with an analogue bandwidth of 2 GHz.

The image intensifier, type HiCATT18 from Lambert Instruments, was equipped with a UV sensitive lens 100 F/2.8 (type CERCO® 2178). The lens was coupled to the image intensifier with macro extension tube rings (in total 69 mm) resulting in a magnification factor of 1.3. The photocathode at the input of the two stage hybrid intensifier is type S20 with a maximal response at 270 nm to 450 nm. The phosphor at the output is type P46 with a decay time to 10% of 200 ns to 400 ns. The resolution at output to the D-SLR was 28 lp/mm (lp= line pairs), which can be translated to 17 µm, which is above the 4.7 µm pixel pitch of the CMOS chip of the D-SLR. Thus, the image intensifier was decisive on the overall limit of the spatial resolution, which was estimated to 13 µm (17 µm / 1.3). This optical setup was used for determination of radius and length of the discharges. These dimensions were evaluated with standard image processing software (GIMP [29]) using the translation 6.15 µm/px.

For the determination of the luminous radius of a streamer several methods are reported in literature, e.g. [30][31][32], and the resulting radius might depend on the method. The chosen procedure in the present investigation is illustrated in Figure 2 and Figure 3 for two examples, which are also shown later in section 9.4.2. The streamer channel appears as a bright channel in the images, see Figure 2. This signal is overlaid by an optical artefact (halo) caused by the optical chain. This can be seen in Figure 2(a) and Figure 2(c). This artefact is assumed to originate from optical crosstalk inside the image intensifier [33]. Therefore measuring of the brightness profile and the determination of the radius from the full width at half maximum (FWHM) of the raw intensity profile is not meaningful, see Figure 3(a) and Figure 3(c). Instead the images have been
Figure 2: (a) original image and (b) post-processed (normalized, brightness $-15$, contrast $+45$) image of streamer channel examples of Figure 5(c); (c) original image and (d) post-processed (normalized, brightness $-100$, contrast $+110$) image of streamer channel examples of Figure 5(d). The images are shown in false colours.

Figure 3: Intensity profiles at positions indicated by the dotted lines in Figure 2. The shown profiles result the averaging of ten adjacent evaluation lines.
post-processed by varying contrast and brightness to evaluate the luminous core radius and the extension of the channel. The contrast and brightness settings have been chosen for each image to have a high contrast ratio but no saturation in the luminous core and eliminating in this way the halo and the background noise of the image, see Figure 2(b) and Figure 2(d). A threshold for the brightness was applied to determine the dimensions. For many cases it was checked that this procedure is equivalent to fitting a parabolic intensity profile to the centre of the radial intensity distribution without taking into account the halo, see Figure 3(b) and Figure 3(d). The FWHM of the parabolic profile corresponds to the radius determined by the threshold method. A parabolic intensity profile is expected for a cylindrical homogenous emitting body which is only a first order approximation of the streamer channel. The radius determined from the parabolic profile corresponds to a threshold of 70%-80% of the normalized raw intensity profile. The uncertainties of the radius determination procedure are covered by the variation of the results and are reflected in the error bars. The streamer length was defined by a straight line, starting from the electrode surface until the end of the luminous channel.

The gate pulse width of the image intensifier was varied for various conditions and was in the range of few hundreds ns to some µs. The MCP (micro-channel plate) voltage of the image intensifier was varied between 800 V±100 V. Further, the settings of the ISO speed of the D-SLR was varied for various conditions and was set to ISO 1000 for most cases. The results did not significantly depend on these settings.

The test procedure sequence was the following. The D-SLR was activated for 10 s during which the voltage pulse was applied. The image intensifier was triggered either on the voltage rise of the applied high voltage pulse in cases of short statistical time lags (below some µs) or on the PMT signal in cases of longer statistical time lags. In some cases an additional time delay for the image intensifier gate pulse, in combination with triggering on the voltage signal, was
set to compensate for the statistical time delay.

9.4 Results

9.4.1 Visualization of first streamer corona

<table>
<thead>
<tr>
<th>Field arrangement</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>strongly non-uniform field</td>
<td><img src="image1.png" alt="Image" /> 81 kV $t_g=100 \text{ ns}$ $t_s=180 \text{ ns}$</td>
<td><img src="image2.png" alt="Image" /> 83 kV $t_g=10 \mu\text{s}$ $t_s=1.8 \mu\text{s}$</td>
</tr>
<tr>
<td>50 kPa</td>
<td><img src="image3.png" alt="Image" /> 52 kV $t_g=40 \mu\text{s}$ $t_s=210 \text{ ns}$</td>
<td><img src="image4.png" alt="Image" /> 53 kV $t_g=1 \mu\text{s}$ $t_s=120 \text{ ns}$</td>
</tr>
<tr>
<td>weakly non-uniform field</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>50 kPa</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 4**: Images of first streamer corona in strongly and weakly non-uniform background fields for negative and positive polarity at 50 kPa; $t_g$ is the gate time of the image intensifier and $t_s$ is the statistical time lag.

The recorded first streamer corona in both field arrangements are shown in Figure 4 for both polarities at 50 kPa. Typical duration of such events shown are in the range of a few 10 to a few 100 ns. This time is less than the typical gate time of the image intensifier. In the evaluated events no further discharge occurred during the gate time. The occurrence of discharges and the duration of the events was recorded with the PMT signal. The gate time of the image intensifier ($t_g$) and the statistical time lag ($t_s$) of the shown first streamer corona are given in Figure 4. The field enhanced electrode is located
at the bottom edge of each image. In the strongly non-uniform field arrangement (cf. upper row in Figure 4) the first streamer corona exhibits a spherical overall shape around the spherical tip electrode. The structure consists of several tens of streamers. The formation of a few stems can be observed at both polarities. We interpret this as the feeding of several streamers into one common channel \[8\][34]. The overall extension of the streamer corona is similar for both polarities at similar voltages. At negative polarity the corona, especially the ends of the discharges, appear more diffuse than at positive polarity where the discharges have more confined ends.

In the weakly non-uniform field arrangement the streamers are “pinned” to the electrode protrusion, but also additional streamers appear from the plug if the applied voltage was sufficiently high to fulfil the streamer criterion also at the plug surface. This was the case in the examples shown in the lower row of Figure 4. At positive polarity it was not possible to trigger on the voltage step pulse to “capture” the complete first streamer corona due to large statistical time lags. Instead, the PMT signal was used for triggering of the image intensifier. Due to an intrinsic time delay between the PMT signal and the gate of the image intensifier of approximately 30 ns only the decay of the emitted light signal could be recorded. This decay appears as a few individual discharge tracks, which end in the same distance from the plug electrode as the whole streamer corona structure. This was checked at negative polarity, where images of complete first streamer corona have been compared to images of the decay at similar conditions. These structures have been used for length and diameter determination. In comparison to the strongly non-uniform field arrangement less branching, i.e. also no stems, and a lower total number of streamers are observed for the weakly non-uniform field arrangement. The overall shape of the streamer corona is like a brush with a few fingers oriented outwards the plug electrode. The extension is similar at comparable voltages.

In both field arrangements and at both polarities the streamers are oriented along the field lines, cf. Figure 4 in comparison to Figure 1.
Further, also in both field arrangements and at both polarities, the increase of pressure to 100 kPa leads to less diffuse channels with a lower total number of streamers within the streamer corona.

### 9.4.2 Streamer Radius

The radius evaluation for both field arrangements is presented in the following. The procedure for determination of the mean values of the streamer radius together with the individual measurements are presented for the strongly non-uniform field arrangement. For the weakly non-uniform field only the mean values are shown.

Figure 5 shows typical examples of discharge channels which were used for the evaluation of the streamer radius for the strongly non-uniform field arrangement at positive polarity at 50 kPa. As described in section 9.3.1 the recorded images have been post processed for this purpose. Figure 5 shows examples of the original (Figure 5(a) and (b)) and the post processed images (Figure 5 (c) and (d)) together with exemplary radius measurements.

Since each streamer corona consists of several single streamers, several radius determinations have been performed for each image and the minimum and the maximum radius for each shot were recorded. This approach was chosen to minimize uncertainties and variations of the results, which might be caused by the applied threshold method for radius determination described in section 9.3.1 but also by the variations of the streamer channels in the images due to projection and focus variations. These results for the strongly non-uniform field are shown for positive and negative polarity in Figure 6. For the determination of the radius only streamers in the focused plane have been evaluated, see for example Figure 5. A discharge channel in the focused plane is characterized by the sharpness of the image and minimum diameter. The evaluation was performed at different positions along the streamer and no significant differences of the radius during streamer propagation were observed, see for example Figure 5(d). In cases, where the determination of the radius of a single streamer inside the complete first streamer corona was not
Figure 5: Typical examples of first streamer corona for the strongly non-uniform field arrangement at positive polarity at 50 kPa; (a) original image of the first streamer corona (recorded with enabled noise reduction of the camera), (b) original image of a subsequent discharge, (c) and (d) post-processed and zoomed in part of the image with single streamers (c) and of the subsequent discharge (d) used for streamer radius evaluation; \( t_g \) is the gate time of the image intensifier, \( t_s \) is the statistical time lag, \( t_{sd} \) is the time of occurrence of the subsequent discharge (\( t = 0 \) at beginning of voltage rise).

possible the radius of a “subsequent discharge” was evaluated. This was required either when the full first corona was not (fully) captured (Figure 5(b)) or when the whole corona was diffuse. The reason why the full first corona was not captured might be either the need to trigger on the PMT signal or if corona inception happened within a time shorter than the intrinsic time delay of the image intensifier.

A “subsequent discharge” might be a second streamer corona or the first stage of leader development, which happens at the tip of a first streamer and leads to illumination of the channel [8]. During this process the channel might slightly expand due to the thermal heating process. Therefore, the radius determined from this “subsequent discharge” can be regarded as an upper limit for the streamer radius. Also, regardless of the type of this “subsequent discharge”, it has to originate from a streamer, since this is, after the availability
of the initial electron, the first step in the discharge process. The results at positive polarity, cf. Figure 6(a), justify this assumption since the radii evaluated directly from first streamers and the “subsequent discharges” yield similar values, i.e. channel expansion was still negligible. This can be also seen in the comparison of Figure 5(c) and Figure 5(d).

For the strongly non-uniform field arrangement the “subsequent discharges” occurred within the first streamer corona during the abovementioned decay of the emitted light signal. At negative polarity, cf. Figure 6(b), it was only possible to deduce the radius from these “subsequent discharges”. The dashed lines in both figures correspond to the expected values for the two tested pressures according to (1) with $C_s^- = 3 \text{ m-Pa}$ and $C_s^+ = 2 \text{ m-Pa}$. The evaluated radii are in the expected range for both pressures and both polarities. Further, within the scatter the radius is not dependent on the applied voltage. This justifies the averaging of all evaluated radii for a given arrangement, i.e. different voltages but one polarity and given pressure, to obtain a mean value for the minimum and maximum radius together with the corresponding standard deviation. The results for the strongly non-uniform field are shown in Figure 7 as a function of pressure. The radius at negative polarity is in the range between $47 \pm 4 \mu m$ and $58 \pm 6 \mu m$ at 50 kPa and between $34 \pm 5 \mu m$ and $43 \pm 6 \mu m$ at 100 kPa. At positive polarity the radius is in the range between $41 \pm 6 \mu m$ and $53 \pm 6 \mu m$ at 50 kPa and between $17 \pm 3 \mu m$ and $22 \pm 3 \mu m$ at 100 kPa. The solid and dashed lines correspond to the expected values according to (1).

The same evaluation was performed for the weakly non-uniform field arrangement and the results are shown in Figure 8. The radius at negative polarity is in the range between $70 \pm 11 \mu m$ and $90 \pm 15 \mu m$ at 50 kPa and between $32 \pm 4 \mu m$ and $40 \pm 4 \mu m$ at 100 kPa. At positive polarity the radius is in the range between $48 \pm 7 \mu m$ and $59 \pm 5 \mu m$ at 50 kPa and between $21 \pm 6 \mu m$ and $28 \pm 5 \mu m$ at 100 kPa. The evaluated radii are in a similar range as for the strongly non-uniform background field with the largest difference at 50 kPa and
Figure 6: Evaluated minimum and maximum radii of streamers in the first streamer corona and “subsequent discharges” as a function of applied voltage for the strongly non-uniform field arrangement at (a) positive polarity and (b) negative polarity. The dashed lines correspond to the expected values according to (1).
Figure 7: Mean minimum and maximum radii of streamers as a function of pressure for the strongly non-uniform field arrangement.

Figure 8: Mean minimum and maximum radii of streamers as a function of pressure for the weakly non-uniform field arrangement.
at negative polarity. For both field arrangements the evaluated ranges overlap with the lines for the expected radii according (1). The largest deviation is observed at 50 kPa and at negative polarity for the weakly non-uniform field arrangement, where also the largest experimental scatter is present and only a low number of shots was recorded due to experimental difficulties to “capture” the first streamer corona.

9.4.3 Length of the first streamer corona

The evaluated length of the first corona, i.e. the corona which develops into a space charge free gap, are shown in Figure 9 for the strongly non-uniform field arrangement. The lengths are shown for positive and negative polarity and for the two tested pressures in the same figure. The representation of the length as a function of the maximum reduced field \( x = E_0/E_{cr,0} \) enables the comparison for different pressures. \( E_0 \) corresponds to the background field \( E(z) \) at \( z = 0 \), i.e. at the electrode surface on the axis of rotational symmetry, and \( E_{cr,0} = p_0 \cdot 89 \left( \frac{V}{m} \right) \) the critical field of SF\(_6\) at \( T=300 \) K \[35\] with \( p_0 \)=pressure in Pa.

For comparison the expected streamer lengths according to the physical picture, cf. section 9.2, are also shown in Figure 9. The dashed line corresponds to the streamer length \( l_s \) according to (2) and the solid line refers to the maximum streamer length \( l_{s,max} \) according to (3). The experimentally determined streamer lengths are in the expected range and agree well with the theoretical values according to (2). The streamer lengths increase with the reduced background field almost linearly. Due to the strongly non-uniform field arrangement relatively high values, up to \( x = 9 \), for the reduced background field at the tip surface of the point electrode were obtained. At 100 kPa less scatter than at 50 kPa can be observed and the lengths are independent on polarity. At 50 kPa the scatter is larger and a slight difference between positive and negative polarity emerges with slightly higher lengths at positive polarity. Beside this observation, there is no distinct pressure dependence in this pressure
Figure 9: Length of the first streamers as a function of the reduced background field for the strongly non-uniform field arrangement at positive and negative polarity.

The same evaluation was performed for the weakly non-uniform field arrangement, c.f. Figure 10. The total number of experiments performed for this arrangement was lower and for each pressure and polarity the applied voltage was only varied by some kV if at all. The reason is that in weakly non-uniform field arrangements the voltage range between streamer inception and breakdown, i.e. where the first corona can be investigated best, is much smaller than for strongly non-uniform fields. To avoid overexposure and thus a potential damage of the image intensifier, breakdowns have been avoided, which additionally limits the voltage range to be tested. The lengths of the first streamers are shown in Figure 10 as a function of the maximum reduced undisturbed field, i.e. the field at the tip without protrusion. Note that due to the lower field enhancement the $x$ values are much lower compared to the previous case (Figure 9). Similar to the strongly non-uniform field arrangement the measured
lengths increase almost linearly with the reduced background field and no distinct pressure and polarity dependence is observed.

The streamer lengths are again within the expected range, i.e. between \( l_s \) and \( l_{s,max} \). But, contrary to the case of the strongly non-uniform field, the streamer lengths for the weakly non-uniform field do not follow the theoretical prediction for \( l_s \) according to (2). The values are close to \( l_{s,max} \) at higher reduced background fields and at the lower pressure, respectively, and closer to \( l_s \) for lower background fields. Two additional lines are included in Figure 10 for later discussion. These lines correspond to \( l_s \) according to (2), but are calculated assuming a lower average streamer channel field. An average channel field of \( 3/4 \cdot E_{cr,0} \) and \( 2/3 \cdot E_{cr,0} \) was used for these two cases. The experimentally determined streamer lengths are close to these two lines, being closer to the \( 2/3 \cdot E_{cr,0} \) line at lower background fields and to the \( 3/4 \cdot E_{cr,0} \) line at higher background fields.

![Figure 10](image_url)

**Figure 10**: Length of the first streamers as a function of the reduced background field for the weakly non-uniform field arrangement at positive and negative polarity.
9.5 Discussion

In the following the results of the streamer radius and streamer length determination will be discussed in the context of the physical picture described in section 9.2 considering the expectations mentioned in the motivation. In general, the optical observations made during the present investigation are in agreement with the description of the physical processes.

9.5.1 Streamer Radius

Overall, for both field arrangements the evaluated radii are in the expected range according to (1). This is especially the case if only the minimum values of the determined radii are considered. It can be argued that all uncertainties of the optical measurement, e.g. due to evaluation of a discharge in a slightly defocused plane, overlaid discharges, smearing and halo effects, but also due to successive discharges, will lead to a higher evaluated radius than the real radius of the streamer. Thus, the minimum values and the corresponding standard deviations can be regarded as more meaningful and should be compared to the theoretical predictions. The maximum values give an indication of the uncertainty of the experimental results. These minimum values, cf. Figure 7 and Figure 8, agree within the error bars with the theoretical prediction according to (1) with $C^-_s = 3 \ \text{m-Pa}$ and $C^+_s = 2 \ \text{m-Pa}$ for both field arrangements, both tested pressures and for both polarities, except for one case. For the strongly non-uniform field arrangement and a pressure of 50 kPa, the determined minimum radii for negative polarity are lower than expected and instead the maximum values agree with the prediction. This is also evident from Figure 6(b). The reason for this difference is not clear, but since the deviation is not large it is not further addressed.

The found voltage independence of the streamer radius in the strongly non-uniform field arrangement agrees with the expectations [8], but is different from the behaviour known in air [21][22][23]. The
reason for this is assumed to be produced by the different properties of SF$_6$ and air. In this respect it is assumed that the most important one is the high electronegativity of SF$_6$.

One of the intentions of the present investigation was to check the assumption made in a previous investigation [16] that the streamer radius in strongly non-uniform fields at negative polarity may depend on the non-uniformity of the electric field. It was assumed that larger streamer radii are present for this condition and the corresponding constant used for modelling was $C_s^- = 8$ m·Pa. This was necessary to obtain an agreement between measured and calculated breakdown voltages. This assumption is disproved with the presented results and thus the adaption of $C_s^-$ is not justified to obtain such agreement. Therefore, the results indicate that the model [5] cannot be fully applied to strongly non-uniform background fields and negative polarity without adaptions. A possible explanation for a discrepancy might be the effect of the presence of space charges, which might change the electric field distribution and by this change the discharge behaviour. This is usually referred to as “corona stabilization” [15][36] and is not taken into account in the model. It is unlikely that this effect is of relevance here, since the large polarity effect was observed without pre-breakdown discharge activity. Another explanation could be the corona charge approximation in the model [5], which could be different for strongly and weakly non-uniform fields. This might be related to the field divergence, which leads to a more sphere-like corona in strongly non-uniform fields and a more focused corona in weakly non-uniform fields. It is possible that the leader inception mechanism is influenced by these differences in the corona structure.

Further, the results confirm $C_s^- = 3$ m·Pa for weakly non-uniform fields, which was so far only indirectly estimated from breakdown measurements [4][5]. The results are also in agreement with Schlieren measurements for positive polarity [12], where Torshin reported 6–8 µm at 304 kPa, which corresponds to $C_s^+ = 1.8–2.4$ m·Pa, as well as with [15], where Chalmers et al report a streamer radius of 25 µm.
at 100 kPa, which corresponds to $C_s^+ = 2.5 \text{ m-Pa}$, and with [20], where Gallimberti and Wiegart determine 13 $\mu$m at 200 kPa, which corresponds to $C_s^+ = 2.6 \text{ m-Pa}$. Thus, the validity of $C_s^- = 3 \text{ m-Pa}$ and $C_s^+ = 2 \text{ m-Pa}$ is confirmed with the results of the present investigation. This is of great relevance for modelling and prediction of breakdown voltages in practical applications [5][6].

### 9.5.2 Streamer Length

The results for the strongly non-uniform background field, cf. Figure 9, are in agreement with the physical picture described in section 9.2. The agreement of the experimentally determined lengths with $l_s$ according to (2) confirms that the streamer extends into the gap until the potential drop across the streamer equals the potential drop resulting from the undisturbed background field $E(z)$ and that the streamer channel field is equal to the critical field $E_{cr}$ in cold conditions. Also, it confirms that there is no pressure dependence, beside the trivial effect on the critical field, which scales linearly with the pressure. The slight differences between positive and negative polarity at 50 kPa might originate from uncertainties in the length determination. At negative polarity the anode directed streamers shows a more diffuse boundary than at positive polarity, cf. Figure 4. This is related to the direction of the electron avalanches which are directed towards the pin electrode for positive polarity and towards the plate electrode for negative polarity.

The results for the weakly non-uniform background field are less distinct and require more discussion. In general, the same physical picture is assumed for weakly and strongly non-uniform background fields regarding the length of the streamers. But since the experimentally obtained lengths do not follow $l_s$ according to (2), several possibilities for the deviation are discussed in the following.

The simplest explanation for any kind of deviation could be the presence of the protrusion at the tip of the plug electrode. One could argue that the weakly non-uniform field is disturbed and that the effect of the protrusion is not negligible. This possibility can be
excluded due to two reasons. First, a similar setup was used in a previous investigation [36], where the plug electrode was prepared with and without a (similar) protrusion. No differences regarding the streamer length have been found for both cases. Second, electric field calculations confirm that the protrusion has no significant effect on the background field at a distance in the millimeter range from the plug surface. Thus, the protrusion serves only as a (very) local field enhancement to start the first corona at a defined location.

The average streamer channel field is assumed to be equal to the critical field \( E_{cr,0} \), cf. section 9.2. It was shown in Figure 10 that if this average field is reduced to \( 3/4 \cdot E_{cr,0} \) or \( 2/3 \cdot E_{cr,0} \) a better agreement between the experimentally obtained streamer lengths and the theory according to (2) is reached. There might be several reasons for a lower average streamer channel field. An increased temperature would result in a lower critical field. The two chosen values for the critical field correspond to an average channel temperature of 400 K and 450 K, respectively. Such a temperature effect is unlikely since streamers are ionizing waves, which leave a thin ionized channel in the cold, neutral gas [24] and are therefore usually considered as cold discharges. This was also confirmed experimentally with Schlieren measurements [15] and with light measurements with interference filters [20]. Also, especially the streamers of the first streamer corona develop into the cold gas gap, i.e. no pre-heated channels are present. A reasonable change of the average channel field might be caused by interaction or the superposition of several streamers. A streamer corona consists of several tens of streamers and the consideration of single streamers might be too simplistic, cf. also [20]. If several streamers feed one common channel it might also be denoted as “stem” [8][34]. This would represent the transition into a leader, which might lead to sufficient heating of the channel and the corresponding reduction of the critical electric field. Further, it was shown for air with the help of a quasi-2D model that taking into account the interaction of streamers simultaneously propagating in the discharge gap influences streamer parameters and that strea-
mer interaction decreases the field in the channel [28]. Recently it was shown that for strongly branched streamers in air complicated field distributions in the streamer channels can occur [37]. It is not clear, however, if this is valid also for SF$_6$. These arguments would also be valid for the strongly non-uniform field arrangement, where deviations from $l_s$ according to (2) have neither been observed in the present investigation nor by other authors [8][20][34]. However, from the images of the first streamer corona, one can see that the streamers are more concentrated and form a more narrow structure in the plug-plane case, whereas they are more divergent and have larger distances in the pin-plane case. This might promote the interaction of streamers in the case of the plug-plane electrode arrangement. Also, the deviation from $l_s$ according to (2) is largest at lowest pressure, where the streamer radius is highest, which also would favour “overlapping” or interaction of streamers. This is also in agreement, qualitatively and quantitatively regarding the length, with previous investigations [36].

Another explanation might be the possibility that the experimentally deduced lengths include a further step of the discharge process. If immediately after the first streamer corona, i.e. within tens of ns after the first streamer, a leader precursor is initiated in front of the streamer corona it would appear on an integral image as one continuous path. Leader precursors have been observed to develop starting at the boundary of the corona region [10] and have been registered as discharge activity in the inter-electrode space [15].

Finally, it is noted that the obtained streamer lengths are within the expected range, if the maximum streamer length $l_{s,max}$ according to (3) is considered. It represents the maximum corona extension assuming the (cold) critical field $E_{cr,0}$ as the average channel field.

### 9.6 Conclusions

The radius of streamers and the extension of first streamer corona in SF$_6$ for strongly and weakly non-uniform field arrangements at
50 kPa and 100 kPa were experimentally investigated at ambient temperature.

The results demonstrate the general validity of $C_s^- = 3 \text{ m}\cdot\text{Pa}$ and $C_s^+ = 2 \text{ m}\cdot\text{Pa}$ and the $1/p$ pressure dependence of the streamer radius, cf. (1). For negative polarity, experimentally obtained streamer radii are presented for the first time and confirm indirectly determined values from breakdown measurements for weakly non-uniform background fields and disprove the indirectly determined values for strongly non-uniform background fields. As a consequence, the results indicate that the leader propagation model [5] cannot be fully applied for cases with strongly non-uniform background fields and negative polarity without adaptations. Possible improvements are mentioned and should be addressed in future.

Different results are obtained for strongly and weakly non-uniform field arrangements regarding the initial streamer corona extension. For the strongly non-uniform field arrangement the first streamers extend into the gap until the potential drop across the streamer equals the potential drop resulting from the background field. The average streamer channel field is equal to the critical field in cold conditions. For the weakly non-uniform field arrangement a significant deviation from the expected corona extension was found in agreement with [36]. Possible reasons for the deviation have been discussed. The full clarification of this discrepancy remains open for future research.
9.7 References


[9] Niemeyer, L., “Leader breakdown in compressed SF6: recent concepts and understanding”. Gaseous Dielectrics VI, edi-


9 Streamer radius and length


10 Summary and Outlook

This thesis focused on a contribution to a comprehensive picture of the discharge and breakdown processes in SF\(_6\) for technically relevant electric field configurations. It aimed to enable through an improved understanding the reliable prediction of the breakdown voltage and the partial discharge inception voltage. This is required for efficient development and operation of gas insulated high voltage equipment and thus is of interest for practical applications.

For the first time experimental investigations have been performed for small protrusions in uniform and weakly non-uniform background fields for a variety of pressures, different protrusion sizes and at both polarities. Such conditions are representative for particulate contamination and surface roughness in practical applications. It was shown that first a theoretical leader inception model, which is based on a critical charge criterion and which was derived from earlier models for strongly non-uniform gaps, can satisfactory describe the measured corona charges and the measured leader inception background fields. The importance of arrested leaders, which have been reported for the first time in uniform background fields, on the formative time lag and the breakdown has been demonstrated. Later a simple leader propagation criterion was formulated, also based on a critical charge criterion, and enabled the derivation of a breakdown criterion. It was shown that for small protrusions the parameter controlling the discharge is not the applied voltage but the background field in which the protrusion is embedded. Finally, based on the previous investigations, a physical leader propagation model that consistently described the observed phenomena in uniform background fields in SF\(_6\) was established. The author of the
present thesis contributed to these achievements, as described in chapter 1, which represent the basis for further research that was performed in course of the presented work.

The leader propagation model was applied and extended to weakly and strongly non-uniform fields and validated with additional experimental data. For a protrusion length of 410 µm placed in a weakly nonuniform background the leader inception and propagation model could describe well the measured minimum breakdown fields and immediate (after the statistical time lag) breakdown fields indicating that the model is also valid for very small protrusions and surface roughness in weakly non-uniform background fields. It was shown that in agreement with the model the measured leader breakdown fields were lowest at positive polarity, although the negative polarity is often decisive for the breakdown with very short voltage application times, e.g. LI applications. Thus, the importance of the consideration of the statistical times lags, which is not considered in the leader propagation model, was demonstrated. For the strongly non-uniform background fields a reasonable agreement of the modified model with the experimentally observable quantities was found although some discrepancies remained. These have been discussed in the context of physical effects, e.g. the variation of the streamer radius with field non-uniformity and considered as indication that the model helps to identify the importance of such effects.

Finally, models for first electron production, streamer inception and leader propagation have been systematically combined to evaluate the partial discharge inception and breakdown fields in compressed SF$_6$. The dependence of the three criteria (first electron, streamer inception, leader propagation) on parameters like pressure, geometry, voltage wave shape and polarity was presented and decisive criteria for breakdown and partial discharge inception were identified for a given configuration. The results show that only by taking into account all these physical mechanisms the known parameter dependencies of gaseous SF$_6$ insulation can be quantitatively explained. It is shown that the model can be used to predict critical
particle lengths, inception and breakdown fields for AC and LI voltage wave shapes. The largest uncertainty was identified in the first electron production rates, which depend not only sensitively on the polarity and field enhancement, but also on the details of the test conditions. Consequences for practical applications based on predictions from the model have been discussed. For technical equivalent roughness partial discharges (PD) occur only above 0.4 MPa. The operating or test voltage has to be relatively high for PD onset and the PD level is small, therefore not easily detectable. Thus, PD is not relevant for technical equivalent surface roughness. Protrusions and particles show always PD activity with onset levels at typical test (protrusion) and operating voltages (particles). The onset voltages and polarity depend on pressure and are typically 20%–40% below the breakdown voltage. The LI test is always more critical to pass compared to the power frequency withstand voltage test. The decisive voltage polarity is negative for most of the relevant cases and pressures above 0.4 MPa.

Additionally, details of the streamer dimensions have been investigated. The streamer radius is an important input parameter for the breakdown prediction models and no direct experimental information was available so far for negative polarity. Optical measurements of the streamer and leader channel dimensions were presented and compared to theoretical predictions and data from literature. The results demonstrate the general validity of the numbers used for the constant ($C_s$) in the leader propagation model and the $1/p$ pressure dependence of the streamer radius. For negative polarity, experimentally obtained streamer radii are presented for the first time and confirm indirectly determined values from breakdown measurements for weakly non-uniform background fields and disprove the indirectly determined values for strongly non-uniform background fields. As a consequence, the results indicate that the leader propagation model cannot be fully applied for cases with strongly non-uniform background fields and negative polarity without adaptions. Different results are obtained for strongly and weakly nonuniform
field arrangements regarding the initial streamer corona extension. For the strongly non-uniform field arrangement the first streamers extend into the gap until the potential drop across the streamer equals the potential drop resulting from the background field. The average streamer channel field is equal to the critical field in cold conditions. For the weakly non-uniform field arrangement a significant deviation from the expected corona extension was found.

The use of modern diagnostics, especially of an image intensifier and high speed video in combination with photo multipliers and fast current measurements, facilitated the presented results and enabled a detailed insight into the discharge processes. The above described investigations have led to an improved understanding of the pre-breakdown partial discharges and breakdown development in compressed SF$_6$ for technically relevant electric field configurations. Nevertheless, some open questions remain or have been initiated by the presented research. These are interesting topics for future research and are listed in the following.

- The leader propagation model is a one-dimensional model and it assumes rectilinear propagation of the leader along the background field line. Further, it is strictly deterministic and does not include any branching phenomena, so that it cannot predict the random aspects of leader propagation. It also does not account for ionic space charges. Further extensions of the model are of interest to address these points.

- The description of the first electron production, i.e. the modelling of the statistical time lag, has by far the largest uncertainties in the prediction of partial discharge inception and breakdown voltages. This first electron production depends on many details like gas purity, background ionisation from radiation, surface properties (chemical composition and structure), etc. It is of relevance especially for the breakdown and withstand prediction in impulse voltage applications and therefore of practical relevance. For example, the determination
of the distribution of negative SF$_6$ ions in technical relevant geometries and conditions or an investigation on which are the dominating surface and gas properties for first electron production would be of interest.

- The streamer radius measurements indicated that the leader propagation model cannot be fully applied for cases with strongly non-uniform background fields and negative polarity without adaptions. Possible improvements, like for example the consideration of space charges or a dependence of the corona charge approximation on field uniformity, have been mentioned and should be addressed in future. Also, in the initial streamer corona extension for the weakly non-uniform field arrangement a significant deviation from the expected corona extension was found. Possible reasons for the deviation have been discussed. The full clarification of this discrepancy remains open for future research.

- Application of the leader propagation model and the methodology for prediction of partial discharge inception and breakdown voltage to SF$_6$ alternatives.
Acknowledgments

First of all, I would like to thank my academic supervisor Prof. Dr. Christian M. Franck for giving me the opportunity to work on this research project and to write this thesis. I thank him for his advices, his patience, and for the continuous support.

Further, I thank Prof. Dr. -Ing. Stefan Tenbohlen for co-examining and reviewing this Ph.D. thesis.

I am grateful to ABB and the ABB Corporate Research Center for providing me with the excellent research facility and necessary infrastructure as well as for giving me the opportunity to conduct the research work. I want to thank my colleagues for the pleasant and inspiring atmosphere. My special thanks go to Dr. Martin Seeger, who was my mentor and supervisor at the ABB Corporate Research Center and (co)-author of all of the presented publications. From my earliest days at the research center, as a student intern under his supervision, he has inspired me for the topic of gaseous dielectrics. I thank him for all the interesting discussions, his manifold advises, and for the co-examination of this thesis.

I also want to thank the students who have contributed to the success of this thesis during their internships at the ABB Corporate Research Center. They are all named in the corresponding publications.

Finally, I would like to thank my family and my friends who encouraged me during the course of my thesis and helped me to go this long path.
Curriculum Vitae

2010 – 2015  External PhD student at the High Voltage Laboratory, ETH Zurich, Switzerland

since 2013  Group Leader “Gas Circuit Breakers”, ABB Switzerland Ltd, Corporate Research, Baden-Daettwil, Switzerland

since 2006  Scientist at ABB Switzerland Ltd, Corporate Research, Baden-Daettwil, Switzerland

2004/2005  Studies in Electrical Engineering at the University of Bath, England

2000 – 2006  Diploma studies in Electrical Engineering and Information Technology at RWTH Aachen University, Germany

1992 – 1999  Max-Planck-Gymnasium Gelsenkirchen, Germany