Doctoral Thesis

Prediction of Breakdown Voltages in Novel Gases for High Voltage Insulation

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Prediction of Breakdown Voltages in Novel Gases for High Voltage Insulation

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by

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2015
Abstract

Sulphur hexafluoride (SF$_6$) is an important insulation medium for high voltage equipment due to its superior insulation properties. SF$_6$ is widely used in gas insulated switchgear. However, the gas also has a very high global warming potential and the content of SF$_6$ in the atmosphere is constantly increasing. Further, due to the worldwide increasing demand for electric power the number of installations containing SF$_6$ as insulation medium is expected to grow. Therefore, an alternative insulation gas with similar electric properties but substantially less environmental impact would be preferable to substitute SF$_6$.

The traditional search for new insulation gases is done with classical breakdown experiments. They have to be carefully executed for different field configurations over a wide pressure range and for all standard voltage waveforms. This is a time consuming procedure. As an alternative for the investigation of a large group of candidate gases within a reasonable time horizon, recently a three step approach was developed. This approach comprises a quantum-chemical screening of interesting molecules, an investigation of the swarm parameters of selected gases and the prediction of the breakdown behaviour for technical relevant geometries of the best candidates. The aim of the thesis at hand is to provide a prediction method for the latter step.

In the literature a model for SF$_6$ is described to calculate the breakdown voltages in arbitrary electrode configurations and under standard voltage waveforms based on the stepped leader model. As input parameters, results from swarm experiments, i.e. the critical field strength and the effective ionization coefficient, thermodynamic properties and results from time lag measurements in a principal setup are sufficient. Those parameters can be accessed more easily than e.g. a full set of collisional cross sections which is required for most of the other available simulation models.

Before the investigation of different gases the model was crosschecked with own measurements in SF$_6$. For the application to other electron attaching gases than SF$_6$, it was necessary to develop a method to calculate the thermodynamic parameters of the gases and to derive the temperature dependence
Abstract

of those parameters. Experiments in a principal setup provide an estimation of the initial streamer radius and parameters for the description of the lower limit of the statistical time lags. Furthermore, a new method for the exact determination of the partial discharge inception voltage, providing start electrons by short X-ray pulses, was developed.

The strongly attaching gas octafluoropropane (C\textsubscript{3}F\textsubscript{8}) and the less attaching gas tetrafluoromethane (CF\textsubscript{4}) were chosen for the validation of the prediction method. Both gases are well investigated and therefore in the literature many contributions are available for comparison. The investigations of C\textsubscript{3}F\textsubscript{8} show that with the model it is possible to describe the partial discharge behaviour, the lowest breakdown voltages and the upper voltage limit for delayed breakdowns of the gas. For CF\textsubscript{4} additionally the breakdown voltages for homogeneous, weakly inhomogeneous and strongly inhomogeneous field configurations were calculated which showed good agreement with literature data. These results give strong evidence that the model can be used for the prediction of the breakdown behaviour of attaching gases.

Based on these findings the hydrofluoroolefin HFO1234ze was investigated which is only very recently discussed for high voltage insulation purposes. From swarm parameter measurements it is known that the gas is strongly attaching but exhibits a very pronounced pressure dependence of the critical field strength. Nevertheless, the partial discharge behaviour and the breakdown limits of the measurements in the principal setup can be well modelled. The breakdown voltages were predicted for a homogeneous field with substantial surface roughness and for a strongly inhomogeneous field for alternating and lightning impulse voltages. Classical breakdown measurements were performed for comparison. For this novel gas a very good agreement was achieved as well.

Thus, the thesis provides a method for the prediction of breakdown voltages of arbitrary field configurations under standard voltage waveforms for gases with electron attaching properties. With this further gases can be characterized for the usage as high voltage insulation media.
Kurzfassung


In der Literatur wird eine Methode beschrieben, mit der, aufbauend auf dem Modell des schrittweise vorwachsenden Leaders, die Durchschlagspannungen für SF$_6$ in beliebigen Elektrodenanordnungen unter Standardspannungsformen berechnet werden können. Als Eingangsparameter sind lediglich Schwarm-Parameter, d.h. die kritische Feldstärke und der effektive Ionisationskoeffizient, thermodynamische Größen und Ergebnisse einer Zeitverzugsmessung in einer Prinzip-Anordnung notwendig. Diese Parameter können einfacher beschafft werden als z.B. ein vollständiges Set an Wirkungsquerschnitten, wie es für die meisten anderen Simulationsmodelle benötigt wird.

Bevor andere Gase untersucht wurden, wurde das Modell mittels eigener Messungen in SF$_6$ erprobt. Für die Anwendung des Modells auf andere an-


Damit stellt diese Arbeit eine Methode zur Verfügung mit der die Durchschlagsspannungen von beliebigen Anordnungen bei Belastung mit Standardspannungen für anlagernde Gase berechnet werden können. Mit dieser Methode können weitere Gase für die Verwendung als Hochspannungsisolierungen charakterisiert werden.
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List of own Publications

During the work on this thesis several publications for conferences and journals emerged. Some chapters of this thesis are based on the following contributions:


The descriptions of the setup and the methods to gain the modelling parameters in chapter 4 are based on the respective parts of the publications [1], [2], [3] and [4]. The findings on the elimination of the statistical time lags (chapter 5) are based on publication [1]. The results on the octafluoropropane gas (chapter 6) are published in [2], those on the tetrafluoromethane (chapter 7) in [3] and the chapter 8 on the findings of the hydrofluoroolefin HFO1234ze is based on [4].

Further, some students worked on the project: Marcel Baumeler implemented the control of the experimental setup for the measurements in the principal setup. Tobias Wellerdieck extended the control to enable a fully automated execution of the experiments. He also performed measurements in SF$_6$ to validate the setup. Viktor Lenz measured and evaluated the partial discharge and breakdown behaviour of C$_3$F$_8$ and improved the evaluation tools. Jolanda Hell performed simulations and measurements concerning the statistical independence of breakdown experiments.
Additional publications, which are related to the project but which are not contained in this thesis:


List of Abbreviations and Symbols

Abbreviations

GIL | gas insulated line
GIS | gas insulated switchgear
GWP | global warming potential
IP | ion pair
ODP | ozone depletion potential
PFC | perfluorocarbon
VFT | very fast transient
positive protrusion | protrusion with positive applied voltage
negative protrusion | protrusion with negative applied voltage
critical volume | volume, where the field strength exceeds the critical field strength
## Symbols

<table>
<thead>
<tr>
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<th>unit</th>
<th>description</th>
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<tr>
<td>$\alpha$</td>
<td>1/m</td>
<td>ionization coefficient</td>
</tr>
<tr>
<td>$\alpha/N$</td>
<td>m(^2)</td>
<td>density reduced ionization coefficient</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td></td>
<td>fraction of corona charge $Q_c$ modelling the stem mechanism</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td></td>
<td>fraction of corona charge $Q_c$ modelling the precursor mechanism</td>
</tr>
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<td>$\alpha_{\text{eff}}$</td>
<td>1/m</td>
<td>effective ionization coefficient</td>
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<td>$\alpha_{\text{eff}}/N$</td>
<td>m(^2)</td>
<td>density reduced effective ionization coefficient</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td>enhancement factor (field emission)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>1/s</td>
<td>detachment rate coefficient</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>A s/(V m)</td>
<td>vacuum permittivity</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>m(^2)/Td</td>
<td>slope of $\alpha_{\text{eff}}/N$ at the critical field strength $(E/N)_{\text{crit}}$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1/m</td>
<td>attachment coefficient</td>
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<td>m(^2)</td>
<td>density reduced attachment coefficient</td>
</tr>
<tr>
<td>$\rho/p$</td>
<td>kg/(Pa m(^3))</td>
<td>normalized density</td>
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<tr>
<td>$\tau$</td>
<td>s</td>
<td>characteristic attachment time</td>
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<tr>
<td>$\Phi$</td>
<td>eV</td>
<td>work function</td>
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<tr>
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<td>opening angle</td>
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<tr>
<td>$c_0$</td>
<td>m/s</td>
<td>velocity of sound</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>distance of the plane electrodes</td>
</tr>
<tr>
<td>symbol</td>
<td>unit</td>
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<td>--------</td>
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<tr>
<td>$e$</td>
<td>C</td>
<td>elementary charge</td>
</tr>
<tr>
<td>$f(T,p)$</td>
<td></td>
<td>normalized function of the temperature and pressure dependence of the critical field strength</td>
</tr>
<tr>
<td>$h$</td>
<td>kg m$^2$/s$^2$</td>
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</tr>
<tr>
<td>$i$</td>
<td>A</td>
<td>current</td>
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<tr>
<td>$k_B$</td>
<td>J/K</td>
<td>Boltzmann constant</td>
</tr>
<tr>
<td>$l$</td>
<td>m</td>
<td>length of the corona</td>
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<tr>
<td>$n^-$</td>
<td>1/m$^3$</td>
<td>negative ion density</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>pressure</td>
</tr>
<tr>
<td>$s$</td>
<td></td>
<td>standard deviation</td>
</tr>
<tr>
<td>$t_{bd}$</td>
<td>s</td>
<td>total time to breakdown</td>
</tr>
<tr>
<td>$t_f$</td>
<td>s</td>
<td>formative time lag</td>
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<tr>
<td>$t_p$</td>
<td>s</td>
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<tr>
<td>$t_{pd}$</td>
<td>s</td>
<td>pre-breakdown partial discharge time</td>
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<tr>
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<td>s</td>
<td>statistical time lag</td>
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<tr>
<td>$u_s$</td>
<td>V</td>
<td>voltage drop across streamer corona</td>
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<tr>
<td>$v_d$</td>
<td>m/s</td>
<td>electron drift velocity</td>
</tr>
<tr>
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<td></td>
<td>reduced background field strength: $E_{hom}/E_{crit}$</td>
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<td></td>
<td>reduced partial discharge inception field strength</td>
</tr>
<tr>
<td>$x_{inc}^{calc}$</td>
<td></td>
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</tr>
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<td>unit</td>
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<tr>
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<td></td>
<td>experimentally determined reduced partial discharge inception field strength for the negative protrusion</td>
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<tr>
<td>$x_{\min}$</td>
<td>m</td>
<td>lower limit of breakdowns</td>
</tr>
<tr>
<td>$x_{\max}$</td>
<td>m</td>
<td>upper limit of delayed breakdowns</td>
</tr>
<tr>
<td>$z_s$</td>
<td>m</td>
<td>extension of the streamer corona</td>
</tr>
<tr>
<td>$z_{\text{crit}}$</td>
<td>m</td>
<td>extension of the critical volume</td>
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<tr>
<td>$z_{\text{drift}}$</td>
<td>m</td>
<td>electron drift length before attachment</td>
</tr>
<tr>
<td>$z_L$</td>
<td>m</td>
<td>total length of the leader sections</td>
</tr>
<tr>
<td>$z_{\min}$</td>
<td>m</td>
<td>minimal distance to the electrode to allow for streamer formation for positive protrusions</td>
</tr>
<tr>
<td>$z_+$</td>
<td>m</td>
<td>radial extension of $V_e$ for a positive protrusion</td>
</tr>
<tr>
<td>$z_-$</td>
<td>m</td>
<td>radial extension of $V_e$ for a negative protrusion</td>
</tr>
<tr>
<td>$A_{\text{eff}}$</td>
<td>$m^2$</td>
<td>effective electron emitting area</td>
</tr>
<tr>
<td>$C_{\text{ex}}$</td>
<td></td>
<td>expansion scaling factor</td>
</tr>
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<td>$C_{s,\text{pos}}$</td>
<td>Pa m</td>
<td>scaling factor for positive streamer radius</td>
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<tr>
<td>$C_{s,\text{neg}}$</td>
<td>Pa m</td>
<td>scaling factor for negative streamer radius</td>
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<tr>
<td>$D_s$</td>
<td>m</td>
<td>diameter of streamer corona</td>
</tr>
<tr>
<td>$E$</td>
<td>V/(m Pa)</td>
<td>electric field strength</td>
</tr>
<tr>
<td>symbol</td>
<td>unit</td>
<td>description</td>
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<td>electric field strength of the discharge channel</td>
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<td>$E_{crit}$</td>
<td>V/(m Pa)</td>
<td>critical electric field strength:</td>
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<tr>
<td></td>
<td></td>
<td>$(E/N)_{crit} \cdot N$</td>
</tr>
<tr>
<td>$E_{crit,0}$</td>
<td>V/(m Pa)</td>
<td>critical electric field strength at ambient temperature and pressure</td>
</tr>
<tr>
<td>$E_{hom}$</td>
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<td>electric field strength of a homogeneous field configuration: $U_{appl}/d$</td>
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<td>Td</td>
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</tr>
<tr>
<td>$(E/N)_{crit}$</td>
<td>Td</td>
<td>critical field strength, density reduced</td>
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<tr>
<td>$(E/N)_{crit,T}$</td>
<td>Td</td>
<td>temperature dependent critical field strength, density reduced</td>
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<td></td>
<td>streamer constant</td>
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<td>m</td>
<td>protrusion height</td>
</tr>
<tr>
<td>$L'$</td>
<td>m</td>
<td>total protrusion length: $L + z_L$</td>
</tr>
<tr>
<td>$M$</td>
<td></td>
<td>Mach number</td>
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<td>$N$</td>
<td>1/m$^3$</td>
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<td>$\dot{N}_e$</td>
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<td>corona charge</td>
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<td>$R$</td>
<td>m</td>
<td>protrusion radius</td>
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<tr>
<td>$R_{str}$</td>
<td>m</td>
<td>streamer radius</td>
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<tr>
<td>$T$</td>
<td>K</td>
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<td>------</td>
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<td>$T_i$</td>
<td>K</td>
<td>initial temperature</td>
</tr>
<tr>
<td>$U_{appl}$</td>
<td>V</td>
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<tr>
<td>$U_d$</td>
<td>V</td>
<td>breakdown voltage</td>
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<tr>
<td>$U_{d50}$</td>
<td>V</td>
<td>50% breakdown voltage</td>
</tr>
<tr>
<td>$V_e$</td>
<td>m$^3$</td>
<td>volume needed to generate at least one free electron with short X-ray pulse</td>
</tr>
<tr>
<td>$V_{int}$</td>
<td>m$^3$</td>
<td>integration volume</td>
</tr>
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</table>
1. Introduction

The world’s demand on electric power is increasing. At the same time traditional power generation based on fossil fuels has to be reduced to lower the environmental impact due to the emission of CO$_2$ from coal and gas plants. Additionally, some countries decided to force the nuclear power phase-out [Bun13, Bun59]. To cover the energy demand, huge amounts of new renewable energies such as wind and solar power are installed. In Europe, most of the wind turbines are installed along the coasts of the Atlantic and the North Sea. The best places for solar power are in the southern European countries or even in the Sahara Desert. This requires a substantial improvement of the power grid to bring the electricity to the load centres which are mostly far away from the production sites.

Because of the long distances, a European DC supergrid as backbone of the power grid is considered, [vHer10] and references therein and [Fri14]. But the limited possibilities of constructing new transmission lines are the main challenge. Thus, existing corridors will be used and upgraded, for instance by hybrid AC/DC transmission lines [Cha81, Gui14]. Further, the installation of gas insulated lines (GIL), which provide higher current transport capacities due to the convective cooling of the conductor, is a good option. For the insulation in GILs typically a mixture of 80% nitrogen (N$_2$) and 20% sulphur hexafluoride (SF$_6$) is used [Koc12a, p. 94]. Although SF$_6$ is an excellent insulation medium it has the disadvantage of a very high global warming potential (GWP) [For07]. But even when using mixtures for GIL, the equivalent CO$_2$ content for typical 400 kV lines [Koc12a] will be around 114 t per metre of installed line of three phases. Thus, for the broad installation of GILs and additional gas insulated substations it is desired to replace the SF$_6$ and SF$_6$–N$_2$ mixtures with different insulation media with substantially lower environmental impact.

But the question on replacing SF$_6$ is not only a question for future installations alone. Already today’s installations in the high and medium voltage grids involve many devices filled with SF$_6$ as insulation and arc quenching medium. The usage of SF$_6$ was rigorously restricted in the last years
Manufacturers of gas insulated switchgear (GIS) reduced the compartments size and improved their devices to reduce the leakage of SF$_6$ [Cig14]. Nevertheless, measurements of the atmospheric gas content, figure 1.1, show a still increasing trend with an even increasing growth rate in the last years. Maiss and Brenninkmeijer [Mai98] state a worldwide annual emission of about 6500 t/yr which has an equivalent of about 155 Mio t CO$_2$ per year. This seems to be a quite small amount (approximately 1% of the global annual CO$_2$ emissions), but anyhow it is in the range of the annual emissions of countries such as Belgium [eia14]. Due to the long atmospheric lifetime of SF$_6$ (approximately 3200 years [For07]) the gas will accumulate in the atmosphere.

**Figure 1.1.** The development of the global mean atmospheric content of SF$_6$. The linear fit shows an annual growth of 0.26 ppt [US 14].

The question of alternatives to SF$_6$ is already quite old. In the 1970s and 1980s intense research aimed to identify gases with insulation properties “superior” to those of SF$_6$ [Chr97]. In 1997 SF$_6$ was listed in the Kyoto protocol [Uni97]. Therefore, today’s research focuses on alternatives which are not necessarily better than SF$_6$ but have at least similar insulation capability and substantially less environmental impact [Oku11]. The SF$_6$ in gas insulated switchgear (GIS) has two substantially distinct tasks [Chr97]:
1. insulation of the high voltage,
2. arc quenching and current interruption in circuit breaker.

Therefore, a replacement candidate should meet the following basic and practical requirements among others [Als14, Chr97]:

- **physical and chemical:**
  - high electric strength,
  - good arc quenching capability (high thermal conductivity, fast gas recovery, self healing)
  - low boiling point and high vapour pressure at operating and ambient temperature
  - high heat dissipation
  - compatibility with existing switchgear materials
  - easy handling

- **health and safety:**
  - low toxicity
  - no flash point
  - no harmful decomposition products

- **environmental:**
  - low GWP
  - no ozone depletion potential (ODP)
  - minimal environmental impact

Some of the prerequisites are mutually exclusive at the first glance: the high electric strength requires a strongly attaching gas, but most of the strongly attaching gases are “toxic, chemically reactive, and environmentally damaging, with low vapour pressure, and decomposition products from gas discharges that are extensive and unknown.” [Chr97]. On the other hand, gases such as nitrogen (N\(_2\)) or carbon dioxide (CO\(_2\)), which are benign, have low attaching capability and thus low electric strength [Chr97]. Christophorou et al. [Chr97] give a good compilation on the requirements on SF\(_6\) alternatives.

Early research on the general behaviour of gaseous insulations in the mid of the 20th century, e.g. [Wil50, Cam55], and later investigations of potential replacements, which was especially intense in the 1980s, e.g. [Bia85], mainly focused on pure gases. Some candidates from these investigations show interesting electric properties, e.g. perfluorocarbons (PFC) such as CF\(_4\), C\(_3\)F\(_8\), C\(_3\)F\(_6\), c-C\(_4\)F\(_8\) [Bia85], but are toxic, have a high boiling point.
or still a substantial GWP. Therefore, gas mixtures are in the focus of most of today’s research. Recently, global players of gas insulated switchgear presented SF$_6$-free GIS. For this purpose many new “low GWP” molecules and related techniques are investigated [Kie14a] and patented [Cla10, Hyr10, Man12, Ing12, Pau14, War11, Tum12, Cos13, Lul11, Kie12a, Kie12b, Kie12c, Kie13b, Kie13a, Kie14b]. As most of the replacement candidates have high boiling points they have to be mixed with so called buffer gases. Best solutions for buffer gases would be nitrogen (N$_2$), carbon dioxide (CO$_2$), oxygen (O$_2$) or some of the noble gases [Fra14]. Further, for some mixtures, such as SF$_6$–N$_2$ mixtures, it is known that they exhibit a synergistic effect [Asc84]: with an admixture of 20% SF$_6$ into N$_2$ the critical field strength rises already to about 75% of that of pure SF$_6$. Such synergistic effects would be desirable.

The “traditional” way to identify and characterize gases as insulation medium is to perform breakdown measurements in typical electrode configurations (homogeneous, weakly inhomogeneous, and strongly inhomogeneous fields) with standard voltage waveforms (DC, AC, and lightning or switching impulses). For the complete characterization of a gas many breakdown experiments have to be carried out because it is not merely possible to deduce the breakdown behaviour from one specific measurement but rather a whole set of experiments is necessary. As the electrodes are damaged by the spark during breakdown this involves a repeated change of the electrode system [Bia85]. Thus, this is a very time and resource intensive process, especially if mixtures are considered as well. Additionally, an investigation of a continuous spectrum of mixing ratios is not achievable.

Hence, in the question of the search of potential replacements, new avenues have to be explored. At the High Voltage Laboratory of ETH Zurich such a new procedure to identify and quantify novel high-voltage insulation gases has been implemented. It consists of three steps [Fra14]:

1. A quantum-chemical screening of molecules. As already established for drug development or economic statistics, numerically calculated predictors are correlated with phenomenological quantities [Rab13]. With this method, molecules with high electric strength and low boiling points could be identified from a large database of promising chemical groups [Rab15].

2. Swarm parameter measurements of suitable gases from the screening process. In a Pulsed Townsend experiment basic quantities of electron
swarms in a gas or gas mixture can be determined such as the effective ionization coefficient [Dah12]. From this the critical electric field strength can be deduced. A characterization of the gas in different buffer gases will reveal synergistic effects [Fra14].

3. Prediction of the breakdown behaviour of the most promising candidates. As the swarm parameters are determined at low pressures and the characterization only holds for homogeneous fields, it is necessary to investigate the high pressure breakdown behaviour of the gases in inhomogeneous fields. As pointed out above, the investigation via breakdown experiments is resource intensive and not very flexible. Therefore, in the current approach measurements in a principal setup shall be performed. With those results and together with the swarm parameters it should be possible to predict the breakdown behaviour in various electrode configurations and under different voltage waveforms [Fra14].

The feasibility of the third and last step of this procedure is the topic of this thesis with the focus on the insulation properties. The proposed procedure should enable to “tailor” the gas mixtures for the different applications in high voltage technology.

The discharge development and breakdown processes in the strongly attaching SF₆ are still the subject of research. With the stepped leader model proposed in the late 1980s, many phenomena can be well described [Nie89]. Chapter 3 gives an overview over the processes leading to a stepped leader breakdown. Seeger and co-workers proposed a model based on the stepped leader breakdown [See09] and Bujotzek et al. extended this model to predict the breakdown voltages for arbitrary field configurations and different voltage waveforms [Buj13]. As this model only needs a few input parameters, it is chosen for the current investigations. The details of the model are given in chapter 3 as well.

Some of the parameters are deduced from measurements in a principal configuration. Chapter 4 provides explanations of the experimental setup of this principal configurations and the techniques for the parameter extraction. The breakdown experiments to validate the prediction of breakdown voltages are described there as well.

In chapter 5 a new experimental method is presented to eliminate the statistical time lags and thus, to precisely determine the discharge inception level of a certain arrangement. The chapters 6 to 8 present the results for
three different attaching gases and the application of the models according to [See09] and [Buj13] on these gases as well as literature data and own experimental data for the validation of the simulations.
2. Aim of this Work

The aim of the thesis at hand is to establish a method to predict the breakdown voltage of novel insulation gases for all technical relevant geometries and all voltage waveforms. The focus shall be on strongly attaching gases only and the prediction shall be possible with a minimum number of required measurements.

The prediction is based on the models of Seeger et al. [See09] and Bujotzek and Seeger [Buj13] which have been developed and successfully applied to SF₆. To achieve the above stated goal the following steps are taken:

- Construction of an experimental setup to perform discharge and breakdown measurements in a principal field configuration and execution of the measurements in different gases.
- Implementation of the models according to [See09] and [Buj13] and extensions for the prediction of breakdown voltages of other gases. This includes:
  - Implementation of a calculation method for thermodynamic parameters and temperature depending properties of the investigated gases.
  - Derivation of the experimental input parameter for the modelling from measurements in the principal configuration.
  - Extraction of parameters for the modelling of the statistical time lags for both polarities.
- Crosschecking of the literature data for SF₆ in [See09, Buj13] with own measurements and simulations.
- Validation of the predicted breakdown voltages for a set of well-known, but also for novel gases.

Experimental results for known gases are taken form literature. To compare the predicted values for novel gases, setups were constructed to perform classical breakdown voltage measurements with AC and lightning impulse waveforms in homogeneous, inhomogeneous and strongly inhomogeneous field configurations.
3. Theory

3.1. Sulphur Hexafluoride

Sulphur hexafluoride (SF$_6$) was first synthesized by Moissan and Lebeau and described in 1900 [Moi00]. In the 1940s and 1950s SF$_6$ was investigated as insulation gas, mainly compared to fluorocarbon gases and transformer oil [Cam47, Wil50, Cam53, McC54, Ber55, Cam55, How57, Sch49]. Starting in the end of the 1950s SF$_6$ was used as quenching medium in circuit breaker [Mos79]. The first encapsulated and SF$_6$ isolated switchgear was presented in 1965 [Mos79]. In the 1970s the research on the main mechanisms of partial discharges and breakdowns was started [Tak72, Bor79, Far79]. The major contributions arose from the work of the Franco-British Discharge Group [Cha84, Cha87] and of an international research group sponsored by the Canadian Energy Association [Wie88].

![3D ball-and-stick model and structural formula of the SF$_6$ molecule.](image)

The properties of the non-polar SF$_6$ gas are unique. It is a colourless, odourless, non-flammable and inert gas with a comparable low boiling point (−63.8 °C) [Ins14]. Thus, during normal handling of the gas no harm for humans or the environment arises. The low boiling point allows to use the gas at pressures up to 0.6 MPa even in relatively cold climates without the danger of liquefaction. SF$_6$ has very good dielectric and arc quenching
properties [Chr97]. Unfortunately, SF$_6$ has a lifetime of 3200 years in the atmosphere and a global warming potential (GWP) on a 100 year horizon of 23,900 compared to CO$_2$ with a GWP of 1 [For07]. With this it is one of the most potent known greenhouse gases. The use is restricted by the Kyoto Protocol [Uni97]. While SF$_6$ was widely used also outside the electric power industry up to the beginning of the first decade of the 21st century, the European so called F-Gas directive (the European regulation 842/2006 on certain fluorinated greenhouse gases [Eur06], which will be replaced by the European regulation 517/2014 on fluorinated greenhouse gases [Eur14]) bans SF$_6$ in all applications except in high voltage technology.

3.2. Breakdown in SF$_6$ Insulations

The mechanisms leading to breakdown in SF$_6$ are well investigated [Kuf00] but nevertheless it is still an ongoing topic in research [Sha14, Ren14, See14, Buj15]. In general, breakdowns in homogeneous and inhomogeneous fields are distinguished. The main concepts will be described in this section.

3.2.1. Homogeneous Fields

Biasiutti gives a good overview over the relevant relations of the breakdown in homogeneous field configurations [Bia85]. To predict the breakdown voltage of a homogeneous arrangement, it is necessary to know the effective ionization coefficient $\alpha_{\text{eff}}/N$ in dependence of the electric field strength $E/N$. Both are reduced by the number density $N$ of the insulating gas. The number density $N$ depends on the pressure $p$ and the absolute temperature $T$ of the gas:

$$N = \frac{p}{k_B \cdot T},$$

(3.1)

where $k_B$ is the Boltzmann constant. The effective ionization coefficient $\alpha_{\text{eff}}/N$ is equal to the difference between the ionization coefficient $\alpha/N$ and the attachment coefficient $\eta/N$:

$$\frac{\alpha_{\text{eff}}}{N} = \frac{\alpha}{N} - \frac{\eta}{N}.$$  

(3.2)
3.2. Breakdown in SF₆ Insulations

Both are functions of the applied field strength $E/N$. The effective ionization coefficient $\alpha_{\text{eff}}/N$ can be determined in so-called swarm parameter experiments. The electric field strength where $\alpha_{\text{eff}}/N$ equals zero is called critical electric field strength $(E/N)_{\text{crit}}$ and is a characteristic of the gas. The slope of $\alpha_{\text{eff}}/N$ at this point is $\gamma$. For strongly attaching gases, such as SF₆, the effective ionization coefficient can be approximated by a linear function for electric fields in the range of the critical electric field strength:

$$
\frac{\alpha_{\text{eff}}}{N} = \gamma \left[ \frac{E}{N} - \left( \frac{E}{N} \right)_{\text{crit}} \right].
$$

(3.3)

In general, the streamer criterion

$$
\int_{0}^{z_{\text{crit}}} \alpha_{\text{eff}} \, dz \geq K
$$

(3.4)

gives a first condition for the breakdown of a gas gap. $K$ is the streamer constant. The integration region is the region with $\alpha_{\text{eff}}/N > 0$. This typically starts at the surface of the high field electrode and extends up to the distance $z_{\text{crit}}$ ahead of the surface where the field strength drops below the critical field strength $(E/N)_{\text{crit}}$. In the case of homogeneous fields the fulfilled streamer criterion is sufficient for the breakdown and can be simplified to

$$
\alpha_{\text{eff}} \cdot d \geq K,
$$

(3.5)

where $d$ is the gap distance. If equation (3.3) is inserted into equation (3.5), the breakdown voltage $U_d$ results:

$$
U_d = \left( \frac{E}{N} \right)_{\text{crit}} \cdot N \cdot d + \frac{K}{\gamma}.
$$

(3.6)

This means, that as soon as the applied voltage exceeds the sum of the voltage necessary to establish an electric field equal to the critical field strength $(E/N)_{\text{crit}}$ plus the additional voltage $K/\gamma$, the breakdown of the homogeneous gas gap occurs. The additional voltage $K/\gamma$ is in the range of some 100 V to approximately 5 kV, depending on the gas [Bia85], and thus, relatively small compared to most breakdown voltages in gas gaps.

The breakdown can be strongly influenced by surface roughness. Biasiutti
Table 3.1.: Critical field strength and figure of merit for the sensitivity to surface roughness of SF$_6$.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(E/N)_{\text{crit}}$</td>
<td>360 Td</td>
<td>[Raj12b]</td>
</tr>
<tr>
<td>$(p \cdot L)_{\text{crit}}$</td>
<td>6 MPa $\mu$m (1bar, 20°C)</td>
<td>[Bia82]</td>
</tr>
</tbody>
</table>

derives a figure of merit which is inverse to the sensitivity of a gas to the surface roughness. For the reason of interpretation the quantity is given as a pressure dependent value which is related to the number density $N$ by equation (3.1). For a certain pressure $p$ and the protrusion height $L$ the critical value is ([Bia85] and references therein):

$$(p \cdot L)_{\text{crit}} = \frac{K/\gamma}{(E/p)_{\text{crit}}}.$$  \hspace{1cm} (3.7)

The smaller this figure of merit the more sensitive is the gas to small protrusions. Table 3.1 gives the critical field strength and the figure of merit for SF$_6$. The effective ionization coefficient $\alpha_{\text{eff}}/N$ can be found in e.g. [Raj12b]. The streamer constant in SF$_6$ has a value of $K = 10.5$ according to [Pet95].

### 3.2.2. Inhomogeneous Fields

Research related to breakdown mechanisms in SF$_6$ mainly focused on strongly inhomogeneous field configurations with point-plane or rod-plane electrodes. During the application of AC voltages those strongly inhomogeneous fields mostly break down in the positive half cycle [Gal86, Wie88, Oku98, Hay06]. Therefore, most contributions can be found concerning only positive strong inhomogeneities as the severest case. Only recently also homogeneous background fields with small protrusions are studied [See08, Buj13, Ren14].

Niemeyer and co-workers [Nie89] give a good review of the so called stepped leader breakdown in strongly inhomogeneous field configurations. They also show that it is possible to explain the breakdown of nearly homogeneous fields with small disturbances by these findings. In the following it is assumed, that the inhomogeneity is embedded in a homogeneous background field $E_{\text{hom}}$. The protrusion causes a (local) enhancement of the field. This
depends on the protrusion geometry. With a simplifying approach this geometry can be described by the protrusion height $L$ and the protrusion tip radius $R$. Bujotzek and Seeger give a formula for the calculation of the electric field $E(z)$ ahead of the protrusion [Buj13]:

$$\frac{E(z)}{E_{\text{hom}}} = 1 + \frac{L/R - 1}{(z/R + 1)^2} + \frac{2}{(z/R + 1)^3}. \quad (3.8)$$

This equation holds for strongly inhomogeneous fields with long protrusions in a homogeneous background field $E_{\text{hom}}$ as well as for small protrusions causing only a small disturbance of the background field $E_{\text{hom}}$. To the protrusion either positive or negative voltage can be applied. Throughout this thesis the terms “positive protrusion” or “negative protrusion” are used as abbreviation for protrusions with applied positive or negative voltage, respectively.

**Figure 3.2.**: Schematic of the stepped leader breakdown [See08, Fig. 5(a)]. Besides the discharge development in the bottom part, characteristic times and charge levels are indicated in the upper part together with the applied voltage.
Seeger et al. [See08] provide a schematic of the individual steps occurring during the stepped leader breakdown (see figure 3.2). They consider a step voltage with a very steep front and a sufficiently long duration to allow for breakdown development (dashed line). This voltage is applied to a test gap with a homogeneous field configuration with a small disturbance, as explained above. The applied voltage has to be high enough to establish a critical volume at the protrusion. A critical volume, which first develops in front of the electrode with the smallest curvature, is the volume where the electric field strength exceeds the critical field strength. Only if this volume is large enough a streamer can develop. After the application of the voltage step a certain time passes until the first discharge can be observed. As the processes providing a first electron are statistical processes, this time is denoted as statistical time lag $t_s$. The statistical time lag is polarity and pressure dependent, details are explained in section 3.2.2.1.

Due to the enhanced electric field at the small protrusion, a streamer corona will develop into the gap. At the end of the corona development the free electrons of the avalanches are attached to neutral molecules forming negative ions. The movement of the charged particles in the electric field leads to heating of the gas forming a conductive channel. The pressure increases due to the heating and the associated dissociation of the molecules. This increased pressure drives a channel expansion lowering the particle density until ambient pressure is reached. With the lower density, the critical field strength inside the channel is reduced and the voltage drop along the channel is lowered. A first leader section is developed. The field at the tip of the conductive channel is enhanced forming a new starting point for streamer corona. This can further heat the existing channel and introduce a prolongation by a new corona. If the applied voltage is high enough, the discharge propagates stepwise through the whole gap. Upon reaching the counter electrode the discharge channel is transformed to a spark. Otherwise a so-called arrested leader appears. This means that the steps bridge only parts of the gap. After removing of the space charge, a new discharge can develop starting at the tip. For leader forming the stem and the precursor mechanisms [Nie89] as well as the high frequency or energy mechanism [Hie91, Buc95, Ten97] are known. The high frequency or energy mechanism is only relevant for voltages with very high frequency components (VFT: very fast transient). The three mechanisms are described in detail in section 3.2.2.3.

Between the first discharge and the breakdown a substantial time can pass and several corona steps or arrested leaders can occur (see figure 3.2 (a) to
3.2. Breakdown in \( SF_6 \) Insulations

(d)). Depending on the time between successive arrested leader developments the new leader either restrikes in the same channel or propagates into a completely new channel (figure 3.2 (b) to (d)) [See08]. Streamer corona and leader steps can be distinguished by optical observation of the discharges or due to different pulse forms of the light emission and the discharge currents [Oku96, Hay06].

The sequence of the stepped leader breakdown can be described with characteristic times. They are also marked in figure 3.2. The statistical time lag \( t_s \) is the time between the voltage application and the first streamer corona. The time between the first corona and the initiation of the breakdown, where partial discharges and arrested leaders can occur, is the pre-breakdown partial discharge time \( t_{pd} \). The propagation time \( t_p \) is the time the stepped leader propagation needs to bridge the complete gas gap and transform to a spark. The pre-breakdown partial discharge time \( t_{pd} \) together with the propagation time \( t_p \) are also denoted as formative time lag \( t_f \). The total time to breakdown \( t_{bd} \) is the sum of the statistical time lag \( t_s \) and the formative time lag \( t_f \) [See08].

In general a breakdown can occur, if the following three requirements are fulfilled simultaneously:

1. a critical volume is needed, i.e. a volume where the field strength exceeds the critical field strength,
2. a free electron within this critical volume, which initiates the first avalanche, has to be provided, and
3. the magnitude of the applied voltage has to be high enough and the duration as to be long enough to allow for the stepped leader to reach the opposite electrode.

3.2.2.1. Statistical Time Lag

In strongly attaching gases (without any applied electric field) virtually no free electrons are present due to the large attachment coefficients. For the development of a discharge a free electron within the critical volume is necessary. At low voltages the critical volume at a protrusion is small. Thus, the probability of a free electron within this small critical volume is small as well.

The gas is constantly ionized by radioactive radiation from the outer earth shell and by cosmic radiation with high energies [Mos79]. Due to the high attachment coefficient of strongly attaching gases negative ions are formed.
within pico seconds [Mor96]. Ion production rates depend on the gas pressure and the location of the gas vessel. For SF\textsubscript{6} they typically vary between 30 IP/(cm\textsuperscript{3}s) and 50 IP/(cm\textsuperscript{3}s) for 0.4 MPa to 0.6 MPa [Wie88, Koc12b]. The steady state ion concentration in SF\textsubscript{6} is approximately $2.2 \cdot 10^4$ m\textsuperscript{-3} Pa\textsuperscript{-1} [Wie88, Chr90, Buj13]. Because of the very low probability of ionizing molecules directly within the critical volume, free electrons are mainly provided by two processes: the cold field emission of electrons from the electrode [Fow28, Lat95] or detachment from negative ions within the critical volume [Chr90, Xu96]. The field emission is dominating at negative protrusions, the detachment at positive protrusions.

It was found that field emission, basically a tunnelling process, requires an electric field at the electrode surface of $10^9$ V/m or higher [Lat95, Kuf00]. These high electric fields can only be produced by small curved electrodes such as fine wires, sharp points or surface roughness. For the above discussed small protrusion in a homogeneous background field an additional microscopic surface roughness is assumed. The resulting field enhancement is approximated by only one factor combining both effects [Buj13]. The cold field emission of a protrusion embedded in a homogeneous background field $E_{\text{hom}}$ is described by the Fowler-Nordheim equation and provides the electron emission rate $\dot{N}_e$ [Fow28, Lat95, Buj13]:

$$\dot{N}_e = \frac{A_{\text{eff}}}{e} \cdot 1.54 \cdot 10^{-6} \cdot \frac{10^{4.52/\sqrt{\Phi}}}{\Phi} \cdot (\beta \cdot E_{\text{hom}})^2 \cdot \exp \left( -\frac{2.84 \cdot 10^9 \cdot \Phi^{1.5}}{\beta \cdot E_{\text{hom}}} \right). \tag{3.9}$$

The value for the work function $\Phi = 4.5$ eV is a suitable choice for most of the metals used as electrode material. $e$ is the elementary charge. The homogeneous background field $E_{\text{hom}}$ is enhanced in front of the protrusion by the field enhancement factor $\beta$. The electrons are emitted from the effective area $A_{\text{eff}}$. A variation of the emitting area is quite insensitive to the electron emission rate. Thus, the field enhancement factor $\beta$ is the only remaining influence. The factor is depending on the geometry $L/R$ of the field disturbing protrusion. Bujotzek and Seeger [Buj13] list field enhancement factors for different protrusion geometries $L/R$ relevant for gas insulated switchgear from smooth surfaces (20 µm protrusions with $\beta = 15$) to particle size (3 mm protrusions with $\beta = 180$).

In the case of a positive protrusion no electrons can be provided by field
emission. Thus, the free electrons have to come “from the gas phase”, i.e. detachment from negative ions which are created by natural ionization and which are drifting into the critical field. Mainly four detachment processes are discussed in literature ([Han83, Chr00] and references therein): autodetachment, field-induced detachment, collisional detachment and photodetachment. In SF$_6$ collisional detachment of F$^-$ with neutral SF$_6$ molecules has the highest detachment rate [Chr90]. At electric fields above the critical field strength the probability of detachment is strongly increasing [Wie85, Xu96] and therefore detachment occurs mainly at the positively stressed high field electrode ([Chr90] and references therein). Thus, if a positive voltage is applied to a protrusion, the negative ions in the gas phase will drift towards the tip and electrons will detach there.

The volume-time-law, first described by Boeck [Boc75], gives the probability of a free electron to form an avalanche and lead to breakdown. Seeger et al. extended the volume-time-law with the detachment rate coefficient $\delta = \delta(E(z))$, where $E(z)$ describes the electric field ahead of the protrusion, and give an approximation of the rate of detached electrons within the critical volume [See08]:

$$\dot{N}_e = n^- \int_{V_{int}} \delta \, dV \approx \Omega \cdot 4\pi \cdot n^- \int_{z_{min}}^{z_{crit}} \delta(E(z)) \cdot (z + R)^2 \, dz. \quad (3.10)$$

The integration volume $V_{int}$ is that part of the critical volume in front of the protrusion where the distance to the electrode is at least $z_{min}$ (see figure 3.3). An electron will need at least this distance to form a streamer. The distance can be calculated by the streamer integral, equation (3.4). The outer boundary of the critical volume is given by $z_{crit}$, the position at which the critical field strength is reached. In [See08] the solid angle $\Omega = 0.1$ sr is determined as equivalent lateral limit for the critical volume.

The mean time to a first available electron for each polarity, which is equivalent to the statistical time lag, is then calculated by:

$$t_s = \frac{1}{\dot{N}_e}. \quad (3.11)$$

As both, the extension of the critical volume and the field enhancement due
3. Theory

The volume $V_{\text{int}}$ relevant for detachment from negative ions in the case of a positive protrusion. The minimum distance $z_{\text{min}}$ is needed for avalanche formation. The critical volume extents to $z_{\text{crit}}$. Based on [See08].

![Diagram of protrusion with volume and distances](image)

**Figure 3.3.**

The volume $V_{\text{int}}$ relevant for detachment from negative ions in the case of a positive protrusion. The minimum distance $z_{\text{min}}$ is needed for avalanche formation. The critical volume extents to $z_{\text{crit}}$. Based on [See08].

To the protrusion, the rate of detached or emitted electrons increase with increasing voltage, too, and thus, the statistical time lag decreases. This also implies that the statistical time lag decreases with increasing field distortion by increasing the protrusion length.

3.2.2.2. Elementary Streamers and Streamer Corona

If the electric field strength $E(z)$ in front of a protrusion is high enough and the streamer criterion (equation (3.4)) is fulfilled, a streamer can develop into a gas gap (which is space charge free in the case of a first streamer) [Nie89]. In the streamer head electrons are produced due to ionization processes. The attaching property of gases determine the rate of change of the electron density $N_e$ [Mor96]:

$$\frac{\partial N_e}{\partial t} = -N_e \eta v_e$$  \hspace{1cm} (3.12)

with the electron drift velocity $v_e$ and the attachment coefficient $\eta$. The solution is:

$$N_e(t) = N_e(0) \cdot \exp \left( -\frac{t}{\tau} \right), \quad \text{with } \tau = \frac{1}{\eta v_e}.$$  \hspace{1cm} (3.13)
The characteristic attachment time $\tau$ at atmospheric pressure and critical field strength is [Mor96]:

$$\tau(\text{SF}_6) = 62 \text{ ps}.$$  \hspace{1cm} (3.14)

It is known that streamers in SF$_6$ need approximately 10 ns to travel 1 cm [Mor95]. Thus, the typical attachment time is much smaller than the streamer travel time or in other words, the attachment free mean path is in the order of the streamer head size. Therefore, the field in the streamer channel $E_c$ has to be near the critical field $E_{\text{crit}}$ to maintain the conductivity of the streamer channel [Gal85, Nie89, Mor96].

The radius of a streamer $R_{\text{str}}$ is different for the two polarities. In case of a positive protrusion the avalanches develop in direction towards the tip forming a narrower channel. Avalanches starting at a negative protrusion develop into the gas gap and thus, tend to result in a broader discharge channel [Nie89]. Further, the radius is influenced by the radial diffusion of electrons and the emission of photons from the streamer head [Nie89]. Both quantities are controlled by the inverse of the number density of the particles or, at known temperature, of the gas pressure $p$ [Nie89]:

$$R_{\text{str}} = \frac{C_s}{p},$$  \hspace{1cm} (3.15)

with the streamer scaling constant $C_s$. Recently, the streamer radius was systematically investigated [Buj15], confirming the values for SF$_6$ previously inferred from Schlieren records and time lag measurements:

$$C_{s,\text{pos}} = 2 \text{ Pa m},$$  \hspace{1cm} (3.16)
$$C_{s,\text{neg}} = 3 \text{ Pa m}.$$  \hspace{1cm} (3.17)

A streamer corona consists of several tens to around 100 streamers [Gal86, Buj15]. As explained by Gallimbert and Wiegert [Gal86], the extension of the streamer corona is predominantly determined by the electric field strength in front of the protrusion. The solid line in figure 3.4 represents the distribution of the potential $\varphi$ ahead of the protrusion without a corona. When the corona starts to develop into the gas gap it produces a discharge channel with an electric field equal to the critical electric field strength, as discussed above. This is indicated by the broken line which has the slope of the critical field
Figure 3.4.: Extention of the streamer length $z_s$ according to [Gal86, Fig. 9] with the maximum of the potential $\varphi_0$ at the tip of the protrusion and the extension of the critical volume $z_{\text{crit}}$.

strength. At the distance $z_{\text{crit}}$ in front of the protrusion the undisturbed field equals the critical field strength (same slope as the broken line). This marks the outer boundary of the critical volume. Disregarding space charges created by the streamers, the potential drop $\Delta U$ between the undisturbed field and the streamer field causes the streamer to develop further into the gap beyond the boundary of the critical volume. The streamer propagation terminates at the distance $z_s$ where the voltage drop $\Delta U$ becomes zero. At this point the average field of the undisturbed field along the streamer equals the critical field strength [Gal86, Buj15]:

$$\int_0^{z_s} \left( E(z) - N \cdot \left( \frac{E}{N} \right)_{\text{crit}} \right) \, dz = 0. \quad (3.18)$$

Gallimberti and Wiegart [Gal86] interfered from their Schlieren records that, due to a small energy input per molecule, ionization and dissociation in the streamer corona are small.

3.2.2.3. Leader Development

Up to a certain threshold, denoted as leader inception voltage, the only discharges observed are streamer coronas [Gal86]. A streamer to leader tran-
transition requires an ohmic heating of the gas [Nie89]. The substantial energy input results in heating and, above a certain temperature, in dissociation of the gas molecules. This leads to a pressure increase and subsequently to expansion and density reduction [Nie89]. The electric field strength is directly depending on the particle density $N$ and reduces with increasing temperature. The reduction with the temperature is even stronger than can only be expected from the pure temperature effect as the dissociation products are, in general, less attaching. Cliteur and co-workers calculated the temperature dependence of $(E/N)_{\text{crit}}$ in SF$_6$ based on the Boltzmann transport equation and the local thermal equilibrium composition of the dissociated gas [Cli98]. Robin-Jouan and Yousfi [Rob07, You08] used a multi-term electron Boltzmann equation and improved cross sections to calculate the critical field strength with increasing temperature. If $f(T)$ is the normalized temperature dependence of the critical field strength it can be expressed by:

$$
\left( \frac{E}{N} \right)_{\text{crit,T}} = \left( \frac{E}{N} \right)_{\text{crit}} \cdot f(T).
$$

(3.19)

Figure 3.5 shows the normalized function $f(T)$ for SF$_6$ based on the calculations of [You08]. The heating is due to the corona charge which is fed through the discharge channel [Nie89]. Section 3.3 provides more information about the calculation of the heat input due to the charge.

For SF$_6$ three leader inception mechanisms are described: the stem mechanism and the precursor mechanism [Gal87, Nie89] and the high frequency or energy mechanism [Hie91, Buc95]. The stem mechanism in SF$_6$ was first observed by Gallimberti and co-workers in 1987 [Gal87] under negative polarity and occurs less frequently than the precursor mechanism. A schematic of the stem mechanism is provided in figure 3.6 (a). Due to the branching of the streamers there exists a common stem of a certain fraction of the streamers. All currents from the single branches flow through the common stem after the corona growing terminated. This heats the stem and leads to a leader section [Nie89, See09].

The precursor mechanism is only known for strongly attaching gases and is the inception mechanism under positive voltage stress [Nie89]. It starts at the boundary of the corona as shown in figure 3.6 (b). Figure 3.7 gives an overview over the details of the precursor mechanism. When the streamer corona stops traveling, the free electrons are attached to SF$_6$ molecules.
Thus, positive and negative ions are remaining in the channel (figure 3.7 (a)). They start drifting in opposite directions due to the electric field (figure 3.7 (b)) creating a new electric field in between the drifting parts (figure 3.7 (c)). Eventually, this additional field $\Delta E$ superimposed on the background field reaches the level of the critical field strength leading to a resumption of the ionization in this zone between the separated charges (figure 3.7 (d)). The resulting current $i$ heats the separation zone causing a pressure increase and, due to the subsequent expansion, a density decrease and a decrease of the critical field strength in this part allowing for further discharges at the ends of the filament. This process can lead to a propagation of the precursor which can reach the electrode (figure 3.7 (e)) and form a highly conductive channel. As a consequence the potential is brought to the former corona boundary. A new streamer corona can develop at the tip of the channel (figure 3.7 (e)) [Nie89].

With the energy mechanism [Buc95] and the high frequency mechanism [Hie91] the leader propagation processes for the breakdown under very fast transients (VFTs) can be explained. The underlying physical picture is similar for both mechanisms. Figure 3.8 gives a schematic of the process [Buc95]:

---

**Figure 3.5.** Normalized temperature dependence of the critical field strength $E_{\text{crit}}$ of $\text{SF}_6$ for 1 atm (solid), 2 atm (dashed), 4 atm (dotted) and 8 atm (dashed-dotted). Based on [You08].
3.2. Breakdown in $SF_6$ Insulations

Figure 3.6.: Leader inception mechanisms [See09, Fig. 2].

Figure 3.7.: Drift of positive and negative ions forming a precursor [Nie89, Fig. 9].
a transient voltage $u(t)$ is applied to the tip electrode. If the voltage rises above the streamer inception voltage a corona is formed which can be approximated by a sphere. The streamer diameter $D_s(t)$ is time dependent and thus also the voltage drop $u_s(t)$ across the streamer and the capacity $C(t)$ between the streamer volume and the counter electrode. Due to the strong time dependence of $u_s(t)$ and $C(t)$ a substantial and high frequency displacement current is flowing from the tip electrode across the streamer volume to the streamer surface yielding ohmic heating of the streamer volume. The heated volume leads to a leader section by subsequent expansion, reduction in density and thus, reduction in the electric field strength.

The fastest voltage waveforms which are considered in this thesis are lightning impulses. Thus, it is assumed that the first step of the leader development can either be formed by the stem or by the precursor process [See09]. At the end of the leader section a new streamer corona develops which may lead to a new leader section. While the first leader step can be formed by either mechanism the following steps are most likely formed by the stem mechanism [See09]. Each leader section can be regarded as a resistive elongation of the protrusion [Nie89].

In a certain voltage range, the applied voltage is not sufficient to allow the stepped leader process to fully bridge the gas gap. In this case the leader will stop its propagation and the remaining charge will recombine or drift to the electrodes. This leader is called an arrested leader [See08].
3.3. Discharge and Breakdown Modelling

Many models exist in literature describing (aspects of) the discharge and breakdown behaviour of SF$_6$, e.g. [Duj13, Sta14]. This thesis focuses on the model proposed by Seeger and co-workers [See09] which is based on the stepped leader model (section 3.2.2, [Nie89]). The first attempts for these calculations can be found in contributions from the 1980s [Gal86, Nie89].

The aim of this thesis is to provide a calculation tool to predict the breakdown behaviour of rather unknown molecules in different field configurations and under standard voltage applications without time consuming breakdown measurements for all relevant cases. For this purpose the model of Seeger et al. [See09] and the extension from Bujotzek et al. [Buj13] suit very well: as input parameters, results from swarm experiments – the critical field strength ($E/N_{\text{crit}}$) and the effective ionization coefficient $\alpha_{\text{eff}}/N$ – and thermodynamic properties are sufficient. No detailed cross sections, as for some other models, are needed.

It is assumed that the model is applicable to other gases as long as the stepped leader mechanism explains the process leading to the breakdown of the gas gap (section 3.2.2). This includes that the electric field strength of a discharge channel $E_c$ is equal to the critical field strength $E_{\text{crit}}$ (section 3.2.2.2) or in other words, that the attachment properties of the molecule is sufficiently high.

In this section first the details of the simulations according to [See09] are provided. In a second part the extension by [Buj13] to other relevant geometries and to standard voltage waveforms are presented.

3.3.1. Breakdown Parameters

The prediction of the breakdown voltages according to [Buj13] requires some breakdown parameters which can be extracted from time lag measurements by the model of Seeger and co-workers [See09]. The model from [See09] is based on the above described configuration of a homogeneous background field with a small protrusion on one electrode providing a field enhancement and thus, serving as starting point for discharges. The values are represented as a function of the reduced background field strength $x$ which is calculated with the homogeneous electric field strength $E_{\text{hom}}$ (applied voltage divided by the distance of the plane electrodes) and the critical electric field strength
\[ E_{\text{crit}} = N \cdot (E/N)_{\text{crit}} \] for the respective pressure:

\[ x = \frac{E_{\text{hom}}}{E_{\text{crit}}}. \quad (3.20) \]

The value \( x = 1 \) gives an upper limit as at this reduced field strength the electric field in the whole gap equals the critical field strength and thus, the upper limit of the insulation is reached [See08]. Further, this representation is useful to compare different filling pressures, as \( E_{\text{crit}} \) scales with the number density \( N \) or, at known temperature, with the pressure \( p \), and field configurations. From equation (3.8) describing the electric field ahead of a protrusion, it can be seen that the electric field strength of the homogeneous background field \( E_{\text{hom}} \) and thus the reduced field strength \( x \) controls the enhancement due to the protrusion. In an electrode configuration, four regions of discharges can be identified over an increasing applied electric field:

1. no discharge activities (between zero field and the streamer inception field \( x_{\text{inc}} \)),
2. partial discharges and arrested leaders (between \( x_{\text{inc}} \) and the minimum breakdown field \( x_{\min} \)),
3. arrested leaders and delayed breakdowns (between \( x_{\min} \) and the upper limit for delayed breakdowns \( x_{\max} \)),
4. only undelayed breakdowns (above \( x_{\max} \)).

The simulation calculates the three characteristic pressure dependent values which are input parameters for the later breakdown voltage prediction:

- the streamer inception field \( x_{\text{inc}} \),
- the minimum breakdown field \( x_{\min} \),
- the upper limit of delayed breakdowns \( x_{\max} \).

The model relies on two main assumptions: i) the gas is strongly attaching and ii) the breakdown occurs via a stepped leader processes. In strongly attaching gases the attaching length of electrons is much smaller than the streamer head dimensions [Nie89, Gal85, Gal86] or in other words, the characteristic attachment time has to be in the pico second range [Mor96], see also section 3.2.2.2. This requires a streamer channel field approximately equal to the critical field strength [Nie89]. Leader breakdown processes need gap distances substantially larger than the respective streamer corona size and not too low gas pressures [Nie89]. Further it is assumed that a new corona develops into a space charge free gap [See08].
### 3.3. Discharge and Breakdown Modelling

3.3.1.1. Streamer Corona

The streamer corona development starts at the tip of the protrusion. The protrusion consists of the metallic tip with length $L$ and already existing further leader sections with a total length $z_L$. Figure 3.9 presents a schematic of the redistribution of the electric field due to the overall protrusion length $L' = L + z_L$. The field enhancement can be characterized by a potential

According to [See09] the model presumes some simplifications which make the calculations deterministic: For the leader propagation a growth along the field lines and a leader without branching is assumed. Further, the electric field is taken as a Laplacian field, space charge effects are neglected and the parameters for the determination of the limits for delayed breakdowns ($\alpha_1$ and $\alpha_2$, for explanations see section 3.3.1.2) are fixed.

Figure 3.9.: Redistribution of the electric field due to a protrusion consisting of a metallic tip with the length $L$ and leader sections with the total length $z_L$ [See09, Fig. 2]. The field $E_0$ equals the homogeneous background field $E_{\text{hom}}$ and $E(z)$ the channel field $E_c(z)$. 

![Image of electric field redistribution](image-url)
difference $\Delta U$

$$\Delta U = E_{\text{hom}} \cdot L' - \int_{0}^{L'} E_c(z) \, dz. \quad (3.21)$$

$E_c(z)$ is the field in the already developed (leader) channel ahead of the metallic protrusion. As seen above, the channel field has to be equal to the critical field strength. But due to the heating and expansion processes the critical field strength in the channel is lower than the critical field strength at ambient temperature and pressure $E_{\text{crit},0}$. Inside the metallic protrusion the field reduces to zero.

The length $l$ of the corona developing at the protrusion tip is determined by the potential drop $\Delta U$. The streamer corona redistributes $\Delta U$ such that the electric field inside the corona equals the critical field strength $E_{\text{crit},0}$:

$$\Delta U = l \cdot (E_{\text{crit},0} - E_{\text{hom}}) + \Delta u. \quad (3.22)$$

The potential drop $\Delta u$ remaining ahead of the corona is small and thus will be neglected in the following [See09]. Inserting equation (3.20) into (3.22), the length of the streamer corona can be calculated

$$l = \left( \frac{\Delta U}{E_{\text{crit},0}} \right) \cdot \frac{1}{1 - x}. \quad (3.23)$$

As derived in [See09], the charge $Q_c$ of a streamer corona with the length $l$ can be calculated with the potential drop $\Delta U$ and the vacuum permittivity $\varepsilon_0$ approximately to

$$Q_c \approx 0.5 \cdot \varepsilon_0 \cdot \frac{\Delta U^2}{E_{\text{crit},0}} \cdot \frac{1}{1 - x}. \quad (3.24)$$

### 3.3.1.2. Leader Channel Development

As discussed in section 3.2.2.3 two mechanisms are considered to initiate a leader step: the stem and the precursor mechanism. For the stem mechanism a substantial part of the corona feeds their charge into the stem. In the limiting case the whole corona charge is fed into one common stem. The precursor starts at the boundary of the corona in the longest streamer (figure 3.6). Thus, only a small fraction of the corona charge $\alpha \cdot Q_c$ contributes
3.3. Discharge and Breakdown Modelling

to the channel heating. Although in reality both mechanisms can occur at the same time [Gal87], Seeger et al. discuss two limiting cases [See09]:

- stem mechanism: \( \alpha_1 = 1 \)
- precursor mechanism: \( \alpha_2 = 0.02 \)

This distinction is only made in the first discharge step. Starting with the second step always the stem mechanism with \( \alpha = 1 \) is assumed.

The initial channel temperature shall be \( T_i \). The charge \( \alpha \cdot Q_c \) causes a channel heating and a consecutive overpressure in the channel. The channel expands until it reaches the ambient pressure \( p \). The related change in the enthalpy \( \Delta h \) can be calculated by [See09]

\[
\Delta h = \frac{1}{\pi} \cdot \left( \frac{E}{p} \right)_{\text{crit},0} \cdot f(T, p) \cdot \left( \frac{p}{\rho} \right)_0 \cdot \frac{T_0}{T_i} \cdot \frac{p^2}{C_s^2} \cdot \alpha \cdot Q_c. \tag{3.25}
\]

The initial critical field strength in the channel is calculated according to the function \( f(T, p) \) as discussed in equation (3.19) and figure 3.5. The constant \( C_s \) scales the streamer channel radius as defined in equation (3.15). \( \rho/p \) is the normalized gas density and \( T_0 \) the ambient temperature. From the enthalpy increase \( \Delta h \) the temperature increase \( \Delta T \) of the channel to \( T_i + \Delta T \) due to the charge pulse can be calculated from the known temperature dependence of the enthalpy \( h(T) \).

The channel heated to the temperature \( T_i + \Delta T \) by the charge pulse \( \alpha \cdot Q_c \) expands to equilibrium pressure \( p \) resulting in a channel radius increase \( \Delta R \)

\[
\Delta R = \frac{C_s}{p} \cdot \sqrt{\frac{T_i}{T_0}} \cdot \left( \sqrt{1 + \frac{\Delta T}{T_i}} - 1 \right). \tag{3.26}
\]

From the expansion time needed to equilibrate the overpressure, a lower limit for the propagation time \( t_p \) can be estimated. Seeger et al. [See09] showed, that the expansion velocity scales with the velocity of sound \( c_0 \) and the average expansion Mach number \( C_{ex}(\Delta p/p)^M \). The leader develops into ambient gas, thus \( T_i = T_0 \) gives the lower limit

\[
t_p > \frac{C_s}{p} \cdot \left( \sqrt{1 + \frac{\Delta T}{T_0}} - 1 \right) \cdot \frac{1}{c_0 \cdot C_{ex}(\Delta p/p)^M}. \tag{3.27}
\]
For SF$_6$ $C_{ex} \approx 0.6$ and $M \approx 0.1$ are given. As it was not possible to conduct own CFD-simulations to determine these parameters for other gases, the same values are taken for further calculations (see appendix A).

The calculation of the streamer corona length and charge and the consecutive leader development is repeated with a renewed length $L'$ until the counter electrode is reached or the propagation conditions are not fulfilled anymore causing the propagation to stop.

### 3.3.1.3. Characteristic Reduced Field Strengths

As mentioned at the beginning of the section, three characteristic reduced field strengths can be calculated with the model according to [See09]. They are related to the calculations above:

- $x_{inc}$ is the lowest reduced field strength $x$ where the streamer criterion is fulfilled (equation (3.4)).

- $x_{min}$ is the lowest reduced field strength $x$ where the stepped leader can propagate to the counter electrode, when the first step is initiated by the stem mechanism, i.e. $\alpha = \alpha_1 = 1$.

- $x_{max}$ is the lowest reduced field strength $x$ where the stepped leader can propagate to the counter electrode, when the first step is initiated by the precursor mechanism, i.e. $\alpha = \alpha_2$.

Figure 3.10 shows the results of the calculation of these three characteristic reduced field strengths for a positive and a negative protrusion in SF$_6$. The geometries are taken from [See09]: 1 mm tip height, 250 $\mu$m tip radius and 20 mm distance of the plane electrodes. The inception field strength $x_{inc}$ is identical for both polarities as the streamer integral does not contain any information on the polarity. The results for $x_{min}$ and $x_{max}$ are different for the two polarities as the streamer radius is smaller for the positive case.

### 3.3.2. Breakdown Prediction

Bujotzek and Seeger [Buj13] proposed an extension of the model presented in section 3.3.1. With this extension the prediction of breakdown voltages for different field configurations and voltage waveforms is possible. They examined the behaviour of homogeneous electric fields with protrusions from 20 $\mu$m (for an excellent smooth surface) to 3 mm (large particles) for AC
3.3. Discharge and Breakdown Modelling

and DC voltages and positive and negative lightning impulses. The model is restricted to protrusions embedded in a homogeneous background field. For such protrusions the electric field distribution ahead of the tip can be calculated according to equation (3.8). The model distinguishes between short voltage applications, namely lightning impulses (LI), and long duration voltage applications such as AC and DC voltages. For the duration of a LI stress a reasonable characteristic time is $1 \mu s$, for AC and DC $1 \text{s}$ is used. This correlates with common times for withstand testing: the LI application takes only several microseconds, the withstand test for AC applications usually in the range of some $10 \text{s}$. Note, that for AC the peak voltages are considered.

For each geometry the following quantities have to be calculated:

- **statistical time lag:** This can be calculated according to the Fowler-Nordheim equation for the negative protrusion and based on the detachment processes for the positive protrusion, see section 3.2.2.1. For the detachment two ion densities are used: the steady state ion concentration of $2.2 \cdot 10^4 \text{ m}^{-3} \text{ Pa}^{-1}$ for LI and a reduced ion concentration of $0.1 \text{ m}^{-3} \text{ Pa}^{-1}$ for the AC and DC cases. This reduced concentration is

---

**Figure 3.10.** Simulated curves for SF$_6$ of $x_{\text{inc}}$ (dotted), $x_{\text{min}}$ (solid) and $x_{\text{max}}$ (dashed) for a positive (grey) and a negative (black) protrusion with $1 \text{ mm}$ tip height and $250 \mu \text{m}$ tip radius in a $20 \text{ mm}$ separation of the plane electrodes according to [See09].
due to the long duration of the voltage application. It can be assumed, that the initial ions are swept out of the gap and the ion concentration is only maintained by the ionization due to the background radiation. For both polarities and each pressure the reduced field strength necessary for the availability of one start electron was determined as this reduced field strength where the statistical time lag drops below the characteristic times of 1 s and 1 µs for AC/DC and LI, respectively.

- *reduced streamer inception field strength*: Discharges are only possible if the streamer criterion is fulfilled. This is independent from the polarity. The streamer inception field strength is equal to $x_{\text{inc}}$.

- *reduced breakdown field strength*: This is the minimal reduced background field strength where a discharge can propagate to the opposite electrode. As AC and DC voltages are applied for a rather long time, delayed breakdowns can occur. In this case $x_{\text{min}}$ gives the lowest breakdown field strength. The duration of a lightning impulse is so short that it only allows for immediate breakdowns. This is described by $x_{\text{max}}$.

This results in three parameters for each polarity and each voltage waveform. The figure 3.11 to 3.13 show an example calculated for a 1 mm protrusion in a homogeneous background field of 20 mm distance in SF$_6$ (see also [Buj13]).

The curves for the AC (and DC) case are shown in figure 3.11 together for both polarities. For the LI case the relevant quantities are plotted in figure 3.12 for both polarities. For the AC voltage application, breakdown can occur at both polarities. Reaching the breakdown field strength implies that the streamer integral is fulfilled. Hence, two factors can limit the breakdown voltage: (i) the breakdown field strength. For AC (and DC) voltages partial discharges are possible in the field range between the streamer inception field strength and the breakdown field strength. (ii) the availability of the first electron. In this case, the breakdown condition described by $x_{\text{min}}$ or $x_{\text{max}}$ is fulfilled but no electron starting an avalanche is available. For the example in figure 3.11, the breakdown is determined by the first electron in the pressure range from 0.25 MPa to 0.35 MPa. Above 0.35 MPa the AC breakdown will take place in the negative half wave. Thus, the positive breakdown is not crucial for all relevant geometries and pressures. The resulting curves for the breakdown voltages over pressure for AC and positive and negative lightning impulses are shown in figure 3.13.
3.3. Discharge and Breakdown Modelling

Figure 3.11.: Calculation of the breakdown field strength for AC and DC (1 mm protrusion, 20 mm electrode distance) in SF$_6$ according to [Buj13] (positive: grey, negative: black): statistical time lag (dashed-dotted), $x_{\text{inc}}$ (dotted) and breakdown field ($\approx x_{\text{min}}$) (solid). The thicker line indicates the resulting breakdown values.

Figure 3.12.: Calculation of the breakdown field strength for positive (grey) and negative (black) LI (1 mm protrusion, 20 mm electrode distance) in SF$_6$ according to [Buj13]: statistical time lag (dashed-dotted), $x_{\text{inc}}$ (dotted) and breakdown field ($\approx x_{\text{max}}$) (dashed). The thicker lines indicate the resulting breakdown values.
Figure 3.13.: Resulting breakdown field strengths (1 mm protrusion, 20 mm electrode distance) in SF$_6$ according to [Buj13]: AC (solid), positive LI (dashed) and negative LI (dotted).
4. Experimental Setups and Modelling Parameters

The first part of this chapter provides the description of the experimental setup of a principal field configuration used for the investigations of time lags. The measurements of the statistical and formative time lags are the basis for all following calculations. For the exact determination of partial discharge inception levels and the lower limit of breakdown voltages (not in all gases necessary), additionally a X-ray pulse source was installed. From the time lag experiments, unknown parameters for the models can be deduced. This is presented in the second part. The last part describes the setups for classical AC and lightning impulse (LI) breakdown voltage measurements. These results are used for verification purpose. In total four gases were investigated:

- sulphur hexafluoride (SF$_6$)
- octafluoropropane (C$_3$F$_8$)
- tetrafluoromethane (CF$_4$)
- hydrofluoroolefin HFO1234ze (C$_3$H$_2$F$_4$)

The experimental and simulative results of the investigations of the SF$_6$ gas are only partly presented in this thesis. They were mainly used to test the setup and the implementation of the model and to crosscheck the data published in [See08, See09, Buj13].

4.1. Time Lag Measurements

4.1.1. General Setup

The experimental setup provides a homogeneous electric field with a small protrusion to examine partial discharges and breakdowns in gases. Figure 4.1 depicts a schematic of the setup, figure 4.2 shows a photo of the setup in the laboratory.
Figure 4.1.: Test circuit for time lag measurements. The capacitances are $C_2 = 6 \text{nF}$ and $C_3 = 150 \text{pF}$. The ratio of the voltage divider is calibrated to $V_{HV}/V_{LV} = 2170$. The pressure vessel is not shown. For some measurements an additional X-ray source is installed outside of the vessel. See figure 4.2 for a photo of the laboratory.

The voltage circuit consists of a high voltage step-up transformer and a two-stage Grainacher cascade for doubling and rectifying the voltage. This source charges the capacitor $C_2$ with up to 200 kV. Depending on the polarity of the diodes, the applied voltage is positive or negative. As abbreviation the protrusions are denoted as positive or negative tips instead of protrusion with positive or negative voltage applied. With a pneumatic switch the voltage can be applied to the test vessel. The result is a step voltage without any overshoot (figure 4.4a). This is achieved by critical damping with the series resistor of $800 \Omega$. The rise time of the voltage is 500 ns. The voltage is applied for 10 s.

The capacitances of the circuit are chosen such that, in case of breakdown in the test gap, the energy transferred to the electrodes is kept to a minimum. This ensures that the damage of the electrodes is small and the tip does not have to be changed during the experiments.

Inside the test vessel, two plane aluminium electrodes (Ø 200 mm) are installed. In the bottom electrode a needle (Ogura, X-253-13) is placed, isolated from the plane electrode to enable the measurement of the discharge current. Two similar geometries are used:

(A) 15 mm distance between the plane electrodes with a protrusion of 1 mm length and 200 µm tip radius,
Figure 4.2.: Photo of the experimental setup for the time lag measurements in the laboratory.

(B) 20 mm distance between the plane electrodes with a protrusion of 3 mm length and 200 µm tip radius.

The test vessel can be filled with gas with pressures up to 0.60 MPa. Table 4.1 gives an overview of the experimental conditions used for the different gases. The upper pressure limit of the setup was not reached during the experiments either due to the upper voltage limit of the voltage source or due to the boiling point which caused liquefaction of the gas above a certain pressure level.

The discharge current is measured with a current probe (Pearson Model 2877: the usable rise time is 2 ns and the 3 dB-frequencies are \( f_{\text{low}} = 300 \text{ Hz} \),
4. Experimental Setups and Modelling Parameters

Table 4.1.: Experimental conditions for the time lag experiments.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Geometry</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF&lt;sub&gt;6&lt;/sub&gt;</td>
<td>(A)</td>
<td>0.20 MPa</td>
</tr>
<tr>
<td>C&lt;sub&gt;3&lt;/sub&gt;F&lt;sub&gt;8&lt;/sub&gt;</td>
<td>(A)</td>
<td>0.10 MPa</td>
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<tr>
<td></td>
<td></td>
<td>0.15 MPa</td>
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<tr>
<td></td>
<td></td>
<td>0.20 MPa</td>
</tr>
<tr>
<td>CF&lt;sub&gt;4&lt;/sub&gt;</td>
<td>(A)</td>
<td>0.10 MPa</td>
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<td></td>
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<td>0.20 MPa</td>
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<td></td>
<td></td>
<td>0.30 MPa</td>
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<tr>
<td></td>
<td></td>
<td>0.40 MPa</td>
</tr>
<tr>
<td></td>
<td>(B)</td>
<td>0.10 MPa</td>
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<td></td>
<td></td>
<td>0.20 MPa</td>
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<td></td>
<td>0.30 MPa</td>
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<tr>
<td></td>
<td></td>
<td>0.40 MPa</td>
</tr>
<tr>
<td>HFO1234ze</td>
<td>(A)</td>
<td>0.10 MPa</td>
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<td></td>
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</tbody>
</table>

\(f_{\text{high}} = 200 \text{ MHz}\). Additionally, the light emission is detected with a photomultiplier (Hamamatsu H10721-110, spectral response: 230–700 nm, \(t_{\text{rise}} = 0.57 \text{ ns}\)), equipped with a converging lens, through a window (fused quartz) in the compartment. The capacitive voltage divider, consisting of the capacitances \(C_3\) and \(C_4\), monitors the applied voltage. All signals are recorded with a wideband oscilloscope (RTO1024, 2 GHz, 10 GS/s) running in sequence trigger mode. The frame length is set to 20 µs. The maximal dead time between two frames is 300 ns. A maximum number of 80 frames per experiment run can be stored.

Between two experiments, a low AC voltage of about 10 kV is applied for 10 s to remove remaining ions from the gas gap. An additional waiting time of twelve minutes is kept to ensure statistical independence of subsequent experiments. The setup runs fully automatic.
The setup was checked with experiments in SF$_6$ with a pressure of 0.20 MPa and geometry (A). The results are shown in figure 4.3 for both polarities. The comparison with literature data [See08] reveals a good agreement. Seeger et al. [See08] provide data for 0.40 MPa which will be used for comparison in later chapters. As indicated in figure 4.3, the lower breakdown limit $x_{\text{min}}$ is identified as the lowest reduced field strength $x$ where a breakdown occurred, i.e. the left-most triangle. The upper limit of delayed breakdowns $x_{\text{max}}$ is given by the right-most triangle with a time lag above 1 µs.

4.1.2. X-Ray Experiments

As will be discussed later, it is of interest to determine the exact inception level of partial discharges in a given electrode configuration (section 5.1). As the production of first electrons due to detachment and field emission gives long statistical time lags in the voltage ranges of inception (section 3.2.2.1, [Mos79, Lat95, See08]), it is necessary to provide them artificially.

For artificial inception often illumination with ultraviolet light, e.g. mercury-vapour lamps, or $\gamma$-radiation is used [vBru81, Cha87]. The method with the UV light source has two disadvantages: the high energetic radiation in the low UV-range cannot pass fused quartz and therefore adequate ionization inside the gas compartment is not possible. The effect of radiation by UV light is normally caused by the release of electrons from the electrode material. Secondly, those lamps provide a permanent irradiation. This influences the composition of the charge carrier density in the gas continuously during the experiment. Additionally, the bright light prohibits the use of a photomultiplier which would result in less information about the discharges.

Therefore a pulsed X-ray source (XRS-3T, Golden Engineering, pulse width: 50 ns, dose/pulse: 2.8 mR at 30 cm distance) is used. The source produces very short X-ray pulses in the range of 50 ns. With this method free electrons are provided directly within the critical volume [Adi12]. Due to the short duration of the pulses the further development of discharges is not influenced. In addition, the radiation penetrates the aluminium shielding of the test vessel quite good [Adi12]. Thus, no additional quartz window is needed and the photomultiplier can be used for the detection of partial discharges.

The short pulse X-ray source is installed outside of the test vessel on the same level as the gas gap and as close as possible, as shown in figure 4.1. The X-ray tube is triggered by the rising edge of the applied voltage with a
4. Experimental Setups and Modelling Parameters

Figure 4.3.: Experimental results for the proof of the setup with SF$_6$ at 0.20 MPa for negative and positive protrusion (geometry (A)): statistical time lags $t_s$ (□) and formative time lags $t_f$ (▲). The horizontal dotted line gives the upper limit to the maximum of the step voltage. The solid lines indicate the experimental limits of $x^{\exp}_{\min}$ and $x^{\exp}_{\max}$. The dashed line marks the calculated inception field strength $x^{\text{calc}}_{\text{inc}}$. 

delay of approximately 20 µs. For these experiments the additional waiting time is reduced to five to six minutes, which is sufficient to ensure statistical independence of subsequent experiments. Due to the trigger delay of 20 µs, the length of the recorded frames is adjusted to 50 to 100 µs.

Figure 4.4 shows the voltage, current and light emission signals of two experiments with an applied voltage of 104 kV. The X-ray tube pulsed close to 22 µs. In the current channel ((b) and (d)) closing transients arise until 9 µs and between 11 and 15 µs in the displayed experiments. In the upper example (figure 4.4 (b) and (c)) the first partial discharge occurs together with the X-ray pulse (dotted vertical line). Figure 4.4 (d) and (e) show the signals with a naturally incepted discharge at 5 µs and an artificial (but small) peak in the photomultiplier signal due to the X-rays at the triggering instant.

Especially partial discharges during the closing transients can often hardly be identified in the current signal. In this case the photomultiplier is used for recognition (figure 4.4 (e)) and additionally for better discrimination of the temporal evolution of the discharges. Unfortunately the X-rays cause also an artificial pulse in the photomultiplier signal, as can be seen in figure 4.4 (e). If no natural pulse occurred before the X-ray application, the decision whether a discharge incepted due to the X-rays has to be done by the current signal (figure 4.4 (b) and (c)). Therefore the trigger instant of the X-ray tube was adjusted to a point without transients in the current signal. The lowest voltage a current peak is recognized, determines the inception level.

### 4.2. Modelling Parameters

The results of the time lag measurements, e.g. as depicted in figure 4.3, are the basis for the simulations. The simulations cover the determination of the breakdown parameters $x_{\text{inc}}$, $x_{\text{min}}$ and $x_{\text{max}}$ and the prediction of the breakdown voltages for arbitrary field configurations and standard voltage waveforms. The theoretical background of the simulations is summarized in section 3.2.2 and the equations for the calculation of the breakdown parameters are given in section 3.3.1. Four groups of input parameter are involved in the simulations according to [See09]:

1. swarm parameters such as the effective ionization coefficient $\alpha_{\text{eff}}/N$ and the critical field strength $(E/N)_{\text{crit}}$,
Figure 4.4.: First 25 µs of the signals of two measurements at 104 kV, negative tip, geometry (A), 0.20 MPa SF₆. (a): applied voltage, (b) and (d): current signals, (c) and (e): photomultiplier signal. The broken line indicates the trigger instant of the X-ray tube. In the first experiment ((b) and (c)) the discharge is induced by X-rays, in the second experiment ((d) and (e)) the discharge naturally incepts at 5 µs.
2. parameters of the gas, e.g. speed of sound \( c_0 \) and normalized gas density \( \rho / p \),
3. temperature dependence of \( (E/N)_{\text{crit}} \), normalized gas density \( \rho / p \) or enthalpy \( h \),
4. parameters from time lag measurements: streamer radius scaling factors \( C_{s,\text{pos}} \) and \( C_{s,\text{neg}} \) and the charge fraction \( \alpha_2 \) for the precursor mechanism.

### 4.2.1. Swarm Parameters

The swarm parameters can be measured, e.g. in Pulsed Townsend experiments. For most gases commonly used in high voltage technology, e.g. \( \text{SF}_6 \) and \( \text{CF}_4 \), one specific effective ionization coefficient \( \alpha_{\text{eff}} / N \) and thus, one specific critical field strength \( (E/N)_{\text{crit}} \) can be given. Nevertheless, some gases show a strong pressure dependence of the attachment coefficient \( \eta / N \) resulting in a pressure dependent \( \alpha_{\text{eff}} / N \). This is known for \( \text{C}_3\text{F}_8 \). For increasing pressure the attachment coefficient approaches a “high pressure” value as stated e.g. in [Hun87]. Another example is HFO1234ze. For quite new gases, such as HFO1234ze, no data can be found in literature and the swarm parameters have to be measured [Cha14]. The pressures, which can be investigated in a Pulsed Townsend experiment, are limited and mostly well below atmospheric.

In the case of HFO1234ze the swarm parameters could only be determined for pressures up to 40 kPa. Due to the strong pressure dependence in the range investigated and as no “high pressure” critical field strength could be deduced from the measurements in the swarm experiment (see figure 4.5), the AC breakdown field strengths of a homogeneous field for pressures up to 0.25 MPa are measured. For these measurements polished electrode with Rogowski profiles (similar to geometry (I) in section 4.3, see there for more details on the experimental setup) are used. With the additional results the critical field strength \( (E/N)_{\text{crit}} \) (in Townsend) in dependence on the pressure \( p \) (in Pascal) can be described as

\[
\left( \frac{E}{N} \right)_{\text{crit, HFO}} = 305 \text{Td} \cdot \left( 1 - \exp\left( -\frac{p + 55 \text{kPa}}{55 \text{kPa}} \right) \right). \tag{4.1}
\]

The critical field strength at 0.10 MPa results in 287 Td. Above 0.15 MPa deviations from the stationary value of 305 Td are small. The result of
4. Experimental Setups and Modelling Parameters

Figure 4.5.: Pressure dependence of the critical field strength of HFO1234ze. The ▲ mark the values obtained in the Pulsed Townsend experiment [Cha14], the ● mark the values determined in the AC breakdown experiments. The error bars indicate the standard deviation. The results of equation (4.1) are shown by the solid line.

On the basis of the breakdown experiments, the pressure independent value of the critical field strength of HFO1234ze is determined to 305 Td. This is 85% of the critical field strength of SF$_6$ ($E_{\text{crit, SF}6} = 360$ Td [Chr04]), which is within the standard deviation of the value calculated in [Rab14] and slightly higher than the results of [Kie14a].

The (high pressure) values of the critical field strengths for all investigated gases are summarized in the appendix A together with the gas parameters and scaling factors.

4.2.2. Temperature Depending Parameters

Besides these parameters characterizing the gas at ambient temperature, some parameters are needed at elevated temperatures, too. For the calculation of these quantities the software Cantera is used [Goo13].

All temperature depending parameters are only used to describe the leader
channel expansion due to the heating as explained in section 3.3.1.2. For this purpose it is sufficient to take only thermal dissociation into account and to neglect further dissociation mechanisms. Knowing the thermal dissociation, the temperature dependence of the enthalpy $h$, the normalized density $\rho/p$ and the critical field strength $(E/N)_{\text{crit}}$ can be calculated.

With the Cantera software the dissociation of gases with increasing temperature can be determined assuming thermodynamic equilibrium. An example of C$_3$F$_8$ can be found in figure 4.6. The results agree with literature data presented by Wang and co-workers [Wan12]. A comparison of the data obtained with the software to literature data of CF$_4$ [Wan13, Wu14] and SF$_6$ [You08, Wan13] shows a satisfying agreement as well. Knowing the fraction of each species at a certain temperature allows the software to calculate the normalized density $\rho/p$ and the enthalpy $h$ of the specific mixture of the species at this temperature.

Not as straightforward is the determination of the temperature dependence of the critical field strength (figure 3.5). Numerical calculations of the critical field strength depending on the temperature are published for SF$_6$ and CF$_4$ [Rob07, Wan13, Wu14]. But for most other gases, such as C$_3$F$_8$ and especially for novel and (for high voltage insulation purpose) unknown gases such as HFO1234ze, no data can be found. Therefore the temperature dependence of the critical field strength has to be estimated. For SF$_6$ and CF$_4$, the main influence on the critical field strength is the dissociation of the gas into less attaching components. Hence the estimation is also based on the thermal dissociation of the gas. Simply speaking, the temperature dependent critical field strength is the sum of the critical field strength of the molecules created by the dissociation weighted by their partial pressures. As an example for this procedure the temperature dependent critical field strength $(E/N)_{\text{crit,T}}$ for C$_3$F$_8$ is derived in the following.

Wang et al. [Wan12] presented computations of the thermal dissociation of C$_3$F$_8$. The results obtained with the Cantera software, shown in figure 4.6, are in sufficient accordance with these findings. If C$_3$F$_8$ molecules dissociate, first C$_2$F$_6$ and at higher temperatures CF$_4$ molecules appear [Wan12] which have reasonable critical field strengths ($E_{\text{crit,CF}_4} = 146 \text{Td}$, $E_{\text{crit,C}_2\text{F}_6} = 275 \text{Td}$ [Raj12a]). Thus, the critical field strength over temperature is approximated by superimposing the fraction of the different species multiplied by their critical field strength. This method has shown sufficient agreement between estimated and published curves for SF$_6$ and CF$_4$ (for both gases only the main molecule and the fluorine had to be taken into
4. Experimental Setups and Modelling Parameters

**Figure 4.6.** Thermal dissociation of C$_3$F$_8$ at 0.20 MPa obtained with the *Cantera* software. The dashed line indicates the total particle density.

**Figure 4.7.** Simulated temperature dependence of the critical electric field strength of C$_3$F$_8$ normalized to the value at room temperature for 0.10 MPa (solid line) and 0.40 MPa (dashed line).
4.2. Modelling Parameters

Further, the Wieland approximation [vBru87] for calculating the critical field strength shows no difference to the linear interpolation of the critical field strengths for the mixtures of C₃F₈ with C₂F₆ and C₂F₆ with CF₄. For C₃F₈–CF₄ mixtures, the deviation from the linear interpolation is 3% at its maximum and never exceeds the critical field strength of C₃F₈. Hence, the direct linear interpolation of the critical field strengths is applied to approximate the pressure and temperature dependence of the critical electric field strength of C₃F₈. As the C₃F₈ molecule dissociates already near room temperature, the critical field strength at elevated temperatures drops quickly to the value of CF₄. Figure 4.7 shows the results of the simulated critical electric field strength normalized to the value at room temperature for 0.10 MPa and 0.40 MPa.

4.2.3. Streamer Radius and Leader Inception Parameters

The parameters for scaling the streamer radius Cₛ,ₚₒₛ and Cₛ,ₙₑグル and the fraction α₂ of the charge contributing to the precursor mechanism are a priori unknown. With the model the inception field strength of partial discharges \(x_{\text{inc}}\), the minimum breakdown field strength \(x_{\text{min}}\) and the upper limit of delayed breakdowns, \(x_{\text{max}}\), can be computed (see figure 3.10 as example). While \(x_{\text{inc}}\) does not depend on any of the three unknown parameters, it is possible to vary the curves of \(x_{\text{min}}\) and \(x_{\text{max}}\) by adjusting \(C_{s,\text{pos}}\), \(C_{s,\text{neg}}\) and \(\alpha_2\) such that they agree with the experimentally obtained values. With an appropriate selection of the streamer radius scaling parameters \(C_{s,\text{pos}}\) and \(C_{s,\text{neg}}\), the level of the simulated curves of \(x_{\text{min, pos}}\) and \(x_{\text{min, neg}}\) can be individually adjusted to the experimental results. With the a priori unknown parameter \(\alpha_2\), representing the precursor inception mechanism, the level of the curves for \(x_{\text{max}}\) can be adopted. This step cannot be individually done for the two polarities as the model relates them both to the same charge fraction \(\alpha_2\). An overview over the adjusted parameters can be found in appendix A for all gases.

With this simulation the pressure dependence of the reduced inception field strength \(x_{\text{inc}}\) and the characteristics of the breakdown field strengths \(x_{\text{min}}\) and \(x_{\text{max}}\) can be calculated. For later comparisons figure 3.10 shows the results for SF₆ for a 1 mm protrusion over a pressure range up to 0.60 MPa. In this case values for \(C_{s,\text{pos}}\), \(C_{s,\text{neg}}\) and \(\alpha_2\) are taken from [See09].
4.2.4. Statistical Time Lags

The prediction of the breakdown field strength in arbitrary field configurations requires the determination of the mean time to the first available electron (statistical time lag \( t_s \)) additionally to the calculated values of \( x_{\text{inc}} \), \( x_{\text{min}} \), and \( x_{\text{max}} \). For negative protrusions the first electron is mainly provided by cold field emission and can be modelled by the Fowler-Nordheim equation (section 3.2.2.1). For the positive statistical time lag detachment processes from negative ions are the main source for free electrons which can be described by a modified volume-time-law as introduced in section 3.2.2.1. The resulting curves should approximate the lower left boundary of the statistical time lags \( t_s \) of the time lag measurements in the principal geometries (e.g. figure 4.3).

4.2.4.1. Negative Polarity

For negative polarity, field emission from the electrode is assumed to be responsible for provision of a first electron. As the field emission depends only on the electrode material but not on the gas itself, it applies independent from the gas examined. The pressure depending curves describing the mean time to an available free electron are provided by the Fowler-Nordheim equation (section 3.2.2.1). As discussed, a variation of the effective emitting area \( A_{\text{eff}} \) is not very sensitive and thus, is kept constant throughout this thesis with a value of \( A_{\text{eff}} = 10^{-12} \) m\(^2\). Bujotzek and Seeger [Buj13] varied the field enhancement factor \( \beta \) with different tip geometries \( L/R \) and kept it independent from the pressure. But the experimental results have shown that a certain pressure dependence of the factor \( \beta \) is necessary to yield a good correlation to the experimental data.

The values for \( \beta \) depending on \( L/R \) given by [Buj13] are considered to describe the values for SF\(_6\) at a pressure of 0.20 MPa. Fitting an exponential function to the values of \( \beta \) taken from [Buj13] with respect to the tip geometry \( L/R \) gives an empirical formula:

\[
\beta_{L/R} = a_1 \cdot \exp \left( a_2 \cdot \frac{L}{R} \right) + a_3 \cdot \exp \left( a_4 \cdot \frac{L}{R} \right) \tag{4.2}
\]

with the parameters \( a_1 = 170 \), \( a_2 = 0.01 \), \( a_3 = -235 \), and \( a_4 = -0.4 \).

To obtain the pressure dependence of the field enhancement factor, a power function is fitted to the entire pressure range investigated for the results of
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$C_3F_8$, $CF_4$ and HFO1234ze. The results for different pressures $p$ in Pascal and a certain electrode geometry $L/R$ are represented by

$$
\beta_{C3F8} = \beta_{L/R} \cdot 1.282 \cdot \left( \frac{p}{10^5 \text{ Pa}} \right)^{-0.612}
$$

(4.3)

$$
\beta_{CF4} = \beta_{L/R} \cdot 1.897 \cdot \left( \frac{p}{10^5 \text{ Pa}} \right)^{-0.462}
$$

(4.4)

$$
\beta_{HFO} = \beta_{L/R} \cdot 1.540 \cdot \left( \frac{p}{10^5 \text{ Pa}} \right)^{-0.862}.
$$

(4.5)

4.2.4.2. Positive Polarity

Free electrons for positive protrusions are provided by detachment from negative ions for attaching gases (section 3.2.2.1). As all investigated gases show attaching properties the same mechanism is assumed. In this case the statistical time lag $t_s$ can be calculated by the modified volume-time-law (equation (3.10)). For $C_3F_8$ and HFO1234ze the literature does not provide detachment coefficients. Calculations assuming that ions are directly created within the critical volume by cosmic particles resulted in far too high time lags [Koc14]. A second approach with the original volume-time-law proposed by Boeck [Boe75] did not give a satisfying result as well [Koc14]. Both theoretical approaches for the statistical time lag support the above stated assumption of additional electron production mechanisms. Thus, the detachment coefficients have to be estimated from the time lag measurements if not available. Data for $SF_6$ and $CF_4$ was found in [Xu96] and [Pet07].

For the estimation an inverse method was applied: as input parameter the lower left boundary of the statistical time lags for each pressure was fitted by a power function. The inverse of the statistical time lag $t_s$ is the rate of detached electrons $\dot{N}_e$ as stated in section 3.2.2.1. The rate of detached electrons $\dot{N}_e$ can be calculated by equation (3.10). The equilibrium density of negative ions $n^-$ is assumed to be equal to the number density in $SF_6$ with

$$
n^- = p \cdot 2.2 \cdot 10^4 \text{ m}^{-3} \text{ Pa}^{-1}.
$$

(4.6)

The detachment coefficient $\delta$ is depending on the field strength at a given point. Thus, no direct solution of the problem is possible. Therefore an inverse regression method is applied. This approach was tested with the detachment coefficient of $CF_4$ and yielded good agreement to literature data.
Figure 4.8.: Detachment rate coefficient $\delta$ depending on the ratio of the electric field $E$ to the critical electric field $E_{\text{crit}}$ for $\text{C}_3\text{F}_8$ (solid line, equation (4.7)), $\text{CF}_4$ (dashed-dotted line, [Pet07]), $\text{HFO1234ze}$ (dashed line, equation (4.7)), and $\text{SF}_6$ (dotted line, [Xu96]).

The general form of the detachment coefficient was determined to

$$\delta \left( \frac{E}{E_{\text{crit}}} \right) = c \cdot 10^{a \cdot \left( \frac{E}{E_{\text{crit}}} \right)^b}. \quad (4.7)$$

Coefficients for $\text{C}_3\text{F}_8$ are determined to $a = -5.672$, $b = -1.426$ and $c = 4.205 \cdot 10^{11}$ s$^{-1}$ and to $a = -6.947$, $b = -1.101$ and $c = 2.626 \cdot 10^{10}$ s$^{-1}$ for $\text{HFO1234ze}$. The curves are shown in figure 4.8 together with literature data for $\text{CF}_4$ and $\text{SF}_6$. With these results the statistical time lags $t_s$ can be calculated in forward direction with equation (3.10).

The number density of negative ions in the gas volume at the beginning of the voltage application is equal to the steady state ion concentration $n_1^- = n^-$. For electrode arrangements with less than four centimetres gap distance the equilibrium density is reduced due to the proximity of the electrodes [Wie88]. If an electric field is applied to the gas gap, the electrons start drifting to the anode and are neutralized when reaching the electrode. The subsequent ion density $n_2^-$ is determined by the natural ionization due to
4.3. Breakdown Experiments

The transition between the two ion densities is given by the drift time of the negative ions at the applied electric field. For the calculations the transition between $n_1^-$ and $n_2^-$ is defined by the time an ion needs for crossing half of the gap, because the maximum ion density is located in the middle of the gap due to the influence of the electrodes. If both ion densities are taken into account, it is possible to model the steep increase in statistical time lags which is observed for the positive polarity (e.g. appendix B and C).

The calculation of the drift time is only possible if drift velocities are reported. For other gases the assumption that 5 µs after the voltage application the negative ion density lowers to $n_2^-$ gives good results. The transition occurs mainly at voltages in the range of $x = 0.5$, i.e. at about half of the critical field strength. For the distances of the electrodes used in the experiments a drift velocity of around 1.5 mm/µs results. This value is higher than typical literature data (e.g. $v_{d,CF_4,70Td} = 0.45$ mm/µs [Pet07]). But on the other hand, the ions are drifting in direction of increasing electric field strength. As stated in section 3.3.2 a value of $n_2^- = p \cdot 0.1$ m$^{-3}$ Pa$^{-1}$ is assumed for the ion concentration maintained by cosmic radiation.

4.3. Breakdown Experiments

The example gas HFO1234ze is not well investigated at all. Therefore, classical breakdown experiments were performed for the validation of the prediction of breakdown voltages according to section 3.3.2. Alternating (AC) and lightning impulse (LI) breakdown voltages for two geometries (figure 4.9) were determined:

(I) Rogowski-profile electrodes with a substantial surface roughness. Due to an improved manufacturing process during the experiment series, the electrodes for the AC measurements had a surface roughness of approximately 400 µm and those for the LI experiments of approximately 300 µm. The roughness was manufactured as helical cut (similar to a thread but planar) at the high voltage side (figure 4.9 (a)). The electrode distance was adjusted to 15 mm.

(II) A 20 mm protrusion with 200 µm tip radius and distance of 20 mm between the tip and the counter electrode in a homogeneous background field (figure 4.9 (b)), i.e. the distance of the plane electrodes was adjusted to 40 mm.
4. Experimental Setups and Modelling Parameters

Figure 4.9.: Electrodes used as test object for AC and LI breakdown experiments.

Figure 4.10.: Schematic of the experimental setup for AC breakdown voltage determination with fast switch-off device (FSO) and test object (TO). The high voltage capacity of the voltage divider was $C_a = 50 \text{pF}$.

4.3.1. AC Breakdown Voltage

The AC breakdown voltages are determined with a progressive stress test. A schematic of the experimental setup is provided in figure 4.10. The voltage source was a cascade of two MWB transformers with a maximum rms voltage of 200 kV. A total series resistance of 100 kΩ between the transformer and the test vessel and a fast switch-off device (FSO) is used for the protection of the electrodes in case of breakdown. The FSO detects the breakdown by a current measurement in the earthing path of the test object. After the detection the transformer is short-circuited on the primary site and the supply
voltage is switched off. The total reaction time is around 1 μs. Thus, the energy input into the fault is kept small and the damages on the electrodes are reduced to a minimum. The breakdown voltage is measured with a 50 pF capacitive voltage divider and a peak voltmeter (MU15, High Volt). The voltage of some experiment series was also monitored with an oscilloscope (RTO1024, 2 GHz, 10 GS/s).

In a preliminary test the gradient of the voltage rise was varied between 5 kV/s and 40 kV/s. As no substantial deviation in the mean breakdown voltage was detected, the gradient was set to 20 kV/s for all experiments. The total number of breakdowns per experiment series was set to \( n = 41 \). According to [Hau84], this ensures sufficient data points for a statistical analysis. Preceding experiments showing conditioning occurred in the measurements of the homogeneous field configuration (I) and are not taken into account for the breakdown voltage calculation. Figure 4.11 shows the resulting individual breakdown voltages of an experiment series in HFO1234ze at 0.20 MPa with the strongly inhomogeneous configuration (II).

A pause time of 1 min was kept in between each individual experiment and additionally during the voltage rise the voltage was kept constant at 10 kV (rms) for 10 s before rising to breakdown. This should ensure that the actual experiment is not affected by the previous one and that the conditions are the same for every experiment.

The evaluation of the experiment series was done according to Hauschild and Mosch [Hau84]. The mean breakdown voltage \( U_{d50} \) is calculated as the average of the individual breakdown voltages. The standard deviation \( s \) is obtained according to the formula [Hau84]

\[
s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (U_{BD,i} - U_{d50})^2},
\]

with the breakdown voltage \( U_{BD,i} \) of the individual experiment with the experiment number \( i \). The mean breakdown voltage \( U_{d50} \) and twice the standard deviation \( s \) are plotted in figure 4.11.

The measurement series were tested for independence. A first indication gives the optical investigation of the distribution of the breakdown voltages in figure 4.11. For this example, the individual breakdown voltages seem to fluctuate randomly around \( U_{d50} \) in between twice the standard deviation. For a more precise evaluation the first and the last ten data points are compared.
with the F-test and the t-test for independence. The run-test for randomness is applied to the whole experiment series.

The F-test compares the variances $s^2$ of two samples $x$ and $y$ with $s^2_x \geq s^2_y$ and gives the test statistic $t_F$:

$$t_F = \frac{s^2_x}{s^2_y}.$$  \hspace{1cm} (4.9)

For a significance level of $\alpha = 0.05$ and a sample sizes of ten experiments each, the critical value is $F = 4.03$. If $t_F > F$ the variances $s^2_x$ and $s^2_y$ are not identical and the test failed. If the F-test is passed then the mean values $\bar{x}$ and $\bar{y}$ of the two samples can be compared by the t-test:

$$t_t = \frac{(\bar{x} - \bar{y})\sqrt{\frac{n_x n_y}{n_x + n_y}}}{\sqrt{\frac{(n_x-1)s^2_x + (n_y-1)s^2_y}{n_x + n_y - 2}}}.$$  \hspace{1cm} (4.10)

with the sample sizes $n_x$ and $n_y$. For identical sample sizes of $n_x = n_y = 10$
4.3. Breakdown Experiments

and a significance level of $\alpha = 0.05$ the critical value is $t = 2.101$. The test passes if $|t_F| < t$. For the example series in figure 4.11 the F-test results in $t_F = 1.66$ and the t-test in $t_t = 0.24$. Thus, both tests are passed and a common population and independent sample can be assumed.

In a second step the number of iterations is tested to ensure the randomness of the experiment series. Therefore the run-test is applied to the whole experiment series. The run-test tests a two-valued data sequence. In the case of the AC experiments the two states are: $U_{\text{BD},i} > U_{\text{d50}}$ or $U_{\text{BD},i} < U_{\text{d50}}$. Every group of identical state is one iteration. The total number of iterations is denoted with $r$, the total number of events with $U_{\text{BD},i} > U_{\text{d50}}$ with $k$. The sample size is $n = 41$. The test statistic $t_z$ can be calculated with:

$$t_z = \frac{r - \frac{2(n-k)k}{n}}{\sqrt{\frac{(n-k)k}{n^2}}} \cdot \left(\frac{2}{n\sqrt{n}}\right).$$

(4.11)

The critical value for a significance level of $\alpha = 0.05$ is $\lambda = 1.960$. If $|t_z| < \lambda$ the population contains sufficient iterations to be regarded as an independent population. For the example shown in figure 4.11 equation (4.11) results in $t_z = -0.015$.

4.3.2. LI Breakdown Voltage

The lightning impulse breakdown voltages are measured with two to four stages of an eight stage 1.6 MV Marx generator (Haefely/High Volt). The values of the resistors are adjusted to obtain a waveform close to the standard lightning impulse with a rise time $T_1 = 1.27 \mu s$...1.37 $\mu s$ and a time to half of the maximum $T_2 = 54 \mu s$. The up-and-down method is used with around 40 experiments per data point and voltage steps $\Delta u$ of 5 kV. The start voltage was chosen well below the lowest expected breakdown level. Then the voltage is raised in steps of $\Delta u$ until the first breakdown occurred. After a breakdown the voltage is lowered by $\Delta u$. If the gap withstood the voltage application the voltage is again raised by $\Delta u$. Between every voltage application a waiting time of 5 min or 10 min was kept to get independent individual experiments. Figure 4.12 shows the experiment series for the positive LI breakdown measurement in HFO1234ze at 0.20 MPa in geometry (II). The experiments before the first breakdown are not taken into account for the evaluation.
Figure 4.12.: Prospective voltages of an experiment series with positive lightning impulse at 0.20 MPa in HFO1234ze. Geometry (II) was used. The crosses indicate experiments with breakdowns, the circles mark the “holds”. The first six experiments show the ramping up of the voltage and are not taken for the breakdown voltage calculation. The dashed line indicates the mean breakdown voltage $U_{d50}$, the dotted line twice the standard deviation.

Table 4.2.: Evaluation of the mean breakdown voltage $U_{d50}$ and the standard deviation $s$ of the experiment shown in figure 4.12. The total number of experiments is $n = 39$. The breakdowns are less frequent ($k = 19$) than the holds ($q = 20$), thus the calculations are based on the breakdowns.

<table>
<thead>
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<th>Breakdown</th>
<th>Hold</th>
<th>Index</th>
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</thead>
<tbody>
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<td>$u_i$</td>
<td>$k_i$</td>
<td>$q_i$</td>
<td>$i$</td>
</tr>
<tr>
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<td>5</td>
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</tr>
<tr>
<td>145</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>
4.3. Breakdown Experiments

For a sufficiently large number of experiments $n$ the mean of the breakdown voltages gives a good approximation of the mean breakdown voltage [Hau84]. But it has been shown, that the height of the voltage step $\Delta u$ strongly influences the result. Therefore an estimation of the mean breakdown voltage $U_{d50}$ and the standard deviation $s$ according to Dixon and Mood is recommended (referenced in [Hau84]). For this evaluation the experiments are classified according to table 4.2 for the example in figure 4.12. The number of “breakdowns” and “holds” per voltage level are counted. Those with the less frequent events have a total number of $k$. The complementary events are counted $q$ times ($n = k + q$). The voltage $u_i$, where the less frequent event is counted the first time, is labeled with the index $i = 0$. The following voltage levels receive the indices $i = 1, 2, \ldots, r$.

With the abbreviations

$$A = \sum_{i=1}^{r} i \cdot k_i$$

$$B = \sum_{i=1}^{r} i^2 \cdot k_i$$

the mean breakdown voltage $U_{d50}$ and the standard deviation $s$ can be estimated by

$$U_{d50} = u_0 + \Delta u \cdot \left( \frac{A}{k} \pm \frac{1}{2} \right)$$

$$s = 1.62 \cdot \Delta u \cdot \left( \frac{k B - A^2}{k^2} + 0.029 \right).$$

For a calculation based on breakdowns the negative sign has to be taken in equation (4.14), otherwise the positive sign. The voltage $u_0$ is the one of the group with index $i = 0$.

In [Hau84] it is further outlined that the total number of experiments $n$ and the height of the voltage step $\Delta u$ can have a strong influence on the estimations. They propose additional correction factors. The evaluation for the experiment series resulted for all cases in negligible small correction factors.

As for the AC breakdown experiments, the experiment series were checked with a run-test for statistical independence. The method is identical to the
one explained above. The two values are in this case “breakdown” and “hold”. For the example the run-test passes with a test statistic of $t_x = 0.021$. 
5. Elimination of Statistical Time Lags

5.1. Introduction

Gases are widely used as insulation material in high voltage technology because of their excellent properties such as low loss factors and fast recovery after breakdown. Today, mainly sulphur hexafluoride (SF$_6$) is used in high voltage applications because of its good insulation properties compared to other gases.

As described in section 3.2.2, two necessary conditions must be fulfilled for discharge inception: i) the field strength must exceed the critical field strength in some part of the volume and ii) a free electron within this critical volume must exist. The provision of free electrons is a statistical process described by the Fowler-Nordheim equation and the modified volume-time-law (see section 3.2.2.1). Both relations predict an exponentially increasing time to availability towards lower voltages. This means that the statistical time lag can be long [Mos79]. A lower boundary for discharge inception voltage is given by the dimension of the critical volume. This must be sufficiently large to allow a free electron to develop to a streamer according to the streamer criterion (see figure 3.3) [Mos79].

For certain combinations of electric field configuration and applied voltage waveform the availability of the first electron is determining the occurrence of a discharge, as seen in figure 3.11. In the case presented there, the appearance of an electron decides about a discharge for the technical relevant pressures between 0.25 MPa and 0.35 MPa.

The electric fields in gas insulated switchgear (GIS) are nearly homogeneous. Nevertheless, the surface has a certain roughness and during the installation process the surface of the compartments can be damaged or small conducting particles can remain. This causes local field enhancements and can lead to partial discharges.
First generation gas insulated switchgear were constructed with large safety margin. Today’s gas insulated switchgear are more compact and the dimensions will further decrease in the future [Cig14]. With increased field strength due to reduced dimensions as well as increased pressure in the compartments, the influence of surface roughness, surface damages and conducting particles is increasing. Therefore, it is of practical interest to know the exact inception level for such small protrusions. An experimental approach to study the minimum inception levels by extrapolation to infinite waiting times would be insufficiently accurate. The main goal of this chapter is to present a method to precisely determine the minimum inception fields for technical relevant geometries.

5.2. Results

For the experiments the principal setup with additional X-ray source according to the sections 4.1.1 and 4.1.2 is used. Experiments were run in 0.20 MPa SF₆ and with geometry (A), i.e. 1 mm protrusion and 15 mm distance of the plane electrodes.

Figure 5.1 shows the experimental results together with the results obtained from an experiment without X-ray application, see figure 4.3. The applied voltage during the X-ray experiments ranged from 40 kV to 140 kV and from 40 kV to 110 kV for positive and negative tip, respectively.

The results without X-ray radiation are depicted with open squares and open diamonds. Towards higher applied voltages they show the expected decreasing statistical time lag. Especially for the positive tip, the times to the first discharge are long for the lower voltage range. For both voltages the first observed discharges occur above the calculated inception level. For negative tip the results of two sets of measurements in macroscopic identical setups are shown. The statistical time lags of the second setup (open diamonds) are systematically shifted towards higher applied voltages. The experiments with positive tip and with X-rays for both polarities are performed with the first setup.

The results of the X-ray experiments are shown with circles and dots. The circles indicate partial discharges which appear at the instant of the X-ray pulses. The scattering of these points during the experiment with positive tip is caused by the transients due to the voltage rise which influenced the triggering unit of the X-ray tube. First discharges are recognized at 79.9 kV.
Figure 5.1.: Statistical time lags at 0.20 MPa SF₆ with (○ and ⋄) and without (□ and ◆) X-ray application (geometry (A)). The dashed line indicates the theoretical, the solid line the observed inception voltage. The dashed and dashed-dotted lines show the results of the Fowler-Nordheim equation for different effective areas and a field enhancement factor $\beta = 125$. Further explanations in the text.
and 78.6 kV for positive and negative tip, respectively. The dots denote first partial discharges which appeared before the X-ray tube has been triggered (as shown in figure 4.4 (d) and (e)). This means that the discharges incepted naturally. The inception voltage was determined by three individual experiments for each polarity with only small voltage steps in the expected region of inception.

The vertical line marks the theoretical inception level of partial discharges calculated with the streamer criterion (equation (3.4), \( (E/N)_{\text{crit}} = 360 \text{Td} \) [Chr04], \( K = 10.5 \) [Pet95], \( \alpha_{\text{eff}}/N \) according to [Chr04]). The evaluation gives 70.8 kV for a protrusion of 1 mm and a tip radius of 200 µm in a homogeneous background field with a separation of the plane electrodes of 15 mm.

5.3. Discussion

For the positive and negative tip the X-ray induced partial discharges start at voltage levels of 79.9 kV and 78.6 kV, respectively. The theoretical inception level for the ideal geometry is with a value of 70.8 kV below those voltages.

Small deviations in the exact geometry of the protrusion (length and tip radius) strongly affect the local electrical field in a small range ahead of the protrusion. The variation of the tip radius (175–250 µm) and the protrusion length (0.9–1.1 mm) gives a voltage level for streamer inception in the range of 61.8 kV (175 µm radius, 1.1 mm length) to 83.9 kV (250 µm radius, 0.9 mm length). The adjustment of the protrusion length can only be ensured within the range of ±100 µm. Due to partial discharges and breakdowns the geometry of the tip is influenced as well. The optical investigation of the tip after completion of the experiments suggests a flattened tip curvature and thus a small decrease in the protrusion length which in turn would give rise to a higher streamer inception voltage.

Further, the resolution of the measurement setup could also influence the results. As discussed in section 4.1.2, the inception voltage is determined by the occurrence of a peak in the current signal. These pulses can only be detected if the magnitude is above the noise level. This uncertainty is assumed to be in the range of 3 to 6 kV.

The number of electrons set free by the X-ray tube can be calculated as shown in [Adi12]. The release of one electron by a pulse of 8.91 µSv (22 mm aluminum shielding and 350 mm distance due to the pressure vessel)
5.3. Discussion

requires a volume of \( V_e = 7.55 \cdot 10^{-14} \text{ m}^3 \). The radial extension of the critical volume at the inception voltage is \( z_{\text{crit}} = 66.5 \mu\text{m} \) (figure 5.2). A lateral limitation of the critical volume is modelled by a spherical sector with a solid angle of \( \Omega = 0.1 \text{ sr} \) [See08]. For the positive polarity, the electrons have to be generated at a distance to the electrode larger than the critical length (figure 5.2). The additional distance required to form \( V_e \) beyond the critical length results to \( z_+ = 10.2 \mu\text{m} \). Calculated with the lowest local field strength in the volume \( V_e \) the drift length before attachment is \( z_{\text{drift}} = 1/\eta \approx 5.3 \mu\text{m} \) [Mor96]. Thus there is a probability less than 1 that the electron reaches the critical volume before attachment. At a voltage 2 kV above the inception level of 70.8 kV, the increased dimensions of the critical volume ensure an electron produced by the X-rays to fulfil the requirements for avalanche production. For the negative polarity there are two possibilities for generating a start electron: i) by ionization of the gas ahead of the electrode (figure 5.2) which requires a distance \( z_- = 17.3 \mu\text{m} \) to form \( V_e \) (additional 10.4 kV would be needed to generate a streamer with an electron released at \( z_- \)) or ii) by surface interaction, of which the second one is assumed to be the dominating one. For both polarities the experimentally found levels for X-ray induced discharges are nearly the same. This, together with the calculations above, suggests that the X-ray pulses release sufficient start electrons. Overall, the influence of small variations of the protrusion geometry gives the strongest uncertainty and explains the deviation between the measured and calculated inception voltage.

The results for the positive tip show a clear effect of the artificial supply of free electrons. For natural discharges the electrons have to be provided by detachment from negative ions in the gas volume which results in long time lags in the lower voltage range. By introducing the X-ray source the experimental inception limits can be tested within reasonable time.

At the negative tip electrons are mainly provided by field emission from the electrode. This gives a lower statistical time lag than in the positive case for this geometry and pressure. Therefore the threshold for natural inception is already in the range of the theoretical inception level and the X-ray induced discharges start at roughly the same voltage. Three experiments without artificial start electrons show partial discharges below the threshold examined with X-ray application. For both polarities the upper limit of the discharge time is determined by triggering the X-ray tube which is 5 to 20 \( \mu\text{s} \) after the voltage rise of the applied voltage. For the positive tip above 135 kV and for the negative tip above 100 kV the X-ray triggering instant is
5. Elimination of Statistical Time Lags

Figure 5.2.: Geometrical considerations of the volumes necessary for the calculations of electrons released by X-rays at streamer inception level. Left: positive tip, right: negative tip.

in the range or above the statistical time lag of naturally incepted partial discharges. For these voltages naturally incepted discharges occur before X-ray application.

Figure 5.1 shows two different sets of measurements for the negative polarity acquired with two macroscopically identical setups. The systematic shift could probably be explained with a variation in the effective area due to differences in the exact geometry of the protrusion (tip radius and length) or surface variations of the tip (oxide layers, micro protrusions). The results of the Fowler-Nordheim equation (section 3.2.2.1), plotted for a field enhancement factor of $\beta = 125$ and effective areas of $10^{-12}$ m$^2$ to $10^{-19}$ m$^2$ (figure 5.1), support these assumptions.

5.4. Conclusion

With the described experiment the discharge inception voltages were investigated. A limit of 79.9 kV and 78.6 kV for positive and negative protrusions are found, respectively, if the start electrons are provided artificially. The values are within the expected range and the differences to the theoretical inception voltage are discussed. Thus, with the method introduced in this chapter the inception level for partial discharges in a certain electrode con-
figuration can be determined with high accuracy. Further, providing the start electron artificially by a short X-ray pulse is an efficient method as it is not necessary to maintain the experiment conditions until a first electron is available and the investigation of the inception voltage can be completed within reasonable time.
6. Breakdown Parameters of a Strongly Attaching Gas

6.1. Introduction

The thesis aims to examine if it is possible to apply the existing models of partial discharges and breakdown levels developed for SF$_6$ ([See09], see section 3.3) to other gases. For a first evaluation a gas is selected which exhibits properties similar to those of SF$_6$.

As test gas the perfluorocarbon gas (PFC) octafluoropropane (C$_3$F$_8$) is chosen because PFCs are electronegative gases and C$_3$F$_8$ is the simplest PFC which exhibits similar critical field strength as SF$_6$ [Bia82] and similar attachment times, section 3.2.2.2. The structure of the molecule is depicted in figure 6.1.

Intense research on PFCs started in the early 1980s. Thus, many contributions can be found concerning the characteristics of C$_3$F$_8$ (and other PFCs) on the molecular level [Hun84, Spy85, Hun87, Hun88, Chr88, Chr98, Chr99, Lar07, Wan12, Dah13] and on the phenomenological level [Bia82, Oku02, Hik08, Hik09]. Although C$_3$F$_8$ was proposed as replacement candidate in several contributions, it still has a high global warming potential compared to CO$_2$. But it suits as test candidate as its properties are well-known.

![Figure 6.1: Structure of C$_3$F$_8$ molecule [Bol08].](image)
6. Breakdown Parameters of a Strongly Attaching Gas

6.2. Characteristics of C\textsubscript{3}F\textsubscript{8}

The critical field strength of C\textsubscript{3}F\textsubscript{8} is pressure dependent [Bia82] due to the pressure-dependent attachment coefficient $\eta$ [Chr04]. For this thesis, the suggested, density-independent values for the effective ionization coefficient $\alpha_{\text{eff}} / N$ from Christophorou and Olthoff are used [Chr04, Raj12a]. For consistency over the experiments and the simulative investigation, the value of the critical field strength of 330 Td resulting from the $\alpha_{\text{eff}}$-values is taken, although high pressure breakdown measurements give higher values [Bia82]. Exceeding the critical field strength in a gas gap with a homogeneous field is only a necessary condition for breakdown and typically not sufficient for small gaps and low pressures. The measured breakdown field strength of a homogeneous field configuration can only serve as an approximation of the critical field strength. This might lead to further deviations from the above value. Temperature dependencies of $\alpha_{\text{eff}}$ are not taken into account as it is assumed that the streamer always develops into an unaffected gas volume with a temperature according to the ambient temperature.

C\textsubscript{3}F\textsubscript{8} is known as a strongly attaching gas. The attachment coefficient [Raj12a] and the characteristic attachment time [Mor96] (section 3.2.2.2) are comparable to the values of SF\textsubscript{6}. Further the corona extension is assumed to be in the same range as for SF\textsubscript{6}. Thus, the chosen setup should allow for leader development.

6.3. Discharge Phenomena

The experimental setup as described in section 4.1.1 was used. Experiments were executed for 0.10 MPa, 0.15 MPa, and 0.20 MPa and both polarities. Figure 6.2 gives an example of the current measurement of an experiment with 0.20 MPa and a negative voltage step of 170 kV. During this experiment five events were recorded. At 0\,\mu s the voltage is applied. After a statistical delay time $t_s$ of around 260 ns a first discharge appeared. This pulse is overlaid by the voltage switching transients in the shown current channel. Thus, this very early discharge can only be observed in the additional light emission signal (similar to figure 4.4). Consecutive discharges are detected at around 47\,\mu s, 122\,\mu s, 161\,\mu s, and 185\,\mu s, of which the last one leads to breakdown. The delay between the first discharge and the breakdown at 186\,\mu s is denoted as the formative time lag $t_f$. 
Figure 6.2.: Discharge currents in $\text{C}_3\text{F}_8$ at 0.20 MPa pressure and negative tip (geometry (A)). The applied voltage was $U_{\text{appl}} = 170$ kV. The small insets depict zooms of the discharges.
Figure 6.3.: Discharge current and light emission records in C₃F₈ at 0.20 MPa for a negative tip (geometry (A)) from different measurements. Note the different current and light intensity scales.
Figure 6.3 shows the predominantly observed patterns of discharges at negative polarity. Note the different scales for current and light emission for the different cases. The upper pictures display the current signals, the lower ones the curves detected by the photomultiplier. In figure 6.3 (a) an example for the first corona is depicted. The first corona is characterized by a single pulse with increasing height upon increasing applied voltage. Subsequent corona discharges either have the form as in figure 6.3 (a) or as in figure 6.3 (b). The latter pattern consists of multiple discharge pulses with first increasing and then decreasing magnitude. Arrested leader discharges could only be observed starting at 0.15 MPa. Their characteristics are similar to leader discharges in SF$_6$ and C$_2$F$_6$, as described by Hayakawa [Hay06]. Figure 6.3 (c) shows a typical arrested leader discharge. It starts with a few small corona discharges followed by a large pulse corresponding to the formation of a leader step. This large pulse is followed by further smaller corona pulses. A leader step right before breakdown is depicted in figure 6.3 (d). Especially for the discharges with leader steps, the very bright light emission and the long duration of this emission have to be highlighted in contrast to observations made in SF$_6$.

Further characteristic of the arrested leader discharge pattern are the lead time – between the first (corona) pulse and the main (leader step) pulse – on the one hand, and the lag time – between the main (leader step) pulse and the last (corona) pulse – on the other hand. For the example of a leader discharge in figure 6.3 (d) the lead time is 480 ns, the lag time 4000 ns. For the experiments at 0.20 MPa the maximum lead time varies between 50 ns and 1800 ns. Most of the discharges have a lead time below 500 ns and the total average is approximately 120 ns. The maximum lag time takes between 1000 ns and 8200 ns and most leader discharges terminate within 3000 ns. The average lag time is around 1100 ns. These times are much larger than observed in SF$_6$, where times of 50 ns before and 100 ns after the largest pulse are reported [See08].

6.4. Results

6.4.1. Time Lags

The measurements show partial discharges (see figures 6.2 and 6.3) for both polarities although there are considerably less for the positive tip. These
results are in good agreement with those of [Hik09]. Arrested leader steps are only detected at 0.15 MPa and 0.20 MPa. For the negative tip towards lower applied voltages only corona discharges could be observed, at higher voltages arrested leader discharges could be recognized as well. As the discharges of the positive tip incept at higher voltages, in this case mostly arrested leader steps can be observed as long as the first discharge does not lead directly to breakdown.

For each polarity and pressure the statistical and formative time lags are evaluated for the experiments. The results for 0.10 MPa, 0.15 MPa, and 0.20 MPa are shown in figure 6.4 to 6.6. The statistical time lags $t_s$ are marked with open squares, the formative time lags $t_f$ with triangles. Further, the maximum time to reach the plateau of the applied step voltage is indicated by the horizontal dotted line. On the abscissa, the reduced background field $x$ is plotted for a better comparison of different pressures and with other gases. For the scaling of the reduced field strength $x$, the value of the critical field strength of 330 Td is used. This is lower than the values obtained by breakdown experiments and does not take into account the pressure dependence of the critical field strength [Bia82]. Thus, the resulting reduced field strengths $x$ are slightly higher. This is done for a better comparison with the simulation results. Further, the results of the calculation of the statistical time lags according to section 4.2.4 are included with dashed-dotted lines.

For negative polarity the first partial discharges are detected around $x = 0.42$ for 0.10 MPa, $x = 0.43$ for 0.15 MPa and around $x = 0.38$ for 0.20 MPa. The statistical time lag $t_s$ decreases with increasing voltage. At electric fields higher than $x = 0.72$, $x = 0.65$, and $x = 0.61$ for 0.10 MPa, 0.15 MPa, and 0.20 MPa, respectively, breakdowns occur ($x_{\min}$). The formative time lag $t_f$ decreases with increasing applied electric field strength as well. Above $x = 0.89$, $x = 0.81$, and $x = 0.71$, respectively, the first discharge leads immediately to breakdown ($x_{\max}$). Those experimentally obtained values for $x_{\min}$ and $x_{\max}$ are indicated by solid lines in the figures 6.4 to 6.6.

The first discharges for the positive tip were observed at $x = 0.70$ for 0.10 MPa, $x = 0.55$ for 0.15 MPa, and at $x = 0.52$ for 0.20 MPa. In contrast to the negative results, the statistical time lags $t_s$ of the positive tip can be divided into two groups, in particular at 0.20 MPa. One group with very fast first discharges with constant $t_s$ at around 1 µs. A second group starts with delays around 1 s to 10 s and decreases linearly on the logarithmic time scale to 1 µs. Unlike the experiments with negative protrusion, nearly
6.4. Results

Figure 6.4: Statistical (□) and formative (▲) time lags for negative and positive tip (geometry (A)) at 0.10 MPa in C$_3$F$_8$. The lines indicate $x_{\text{min}}$ and $x_{\text{max}}$ from experiment (solid line), $x_{\text{inc}}$, $x_{\text{calc}}$, and $x_{\text{calc}}^{\text{max}}$ from calculations (dashed lines), theoretical limits for the statistical time lag (dashed-dotted line) and the maximum time needed to reach the maximum of the applied step voltage (dotted line). $x_{\text{max}}$ and $x_{\text{calc}}^{\text{max}}$ are identical for the positive tip.
Figure 6.5.: Statistical (□) and formative (▲) time lags for negative and positive tip (geometry (A)) at 0.15 MPa in C$_3$F$_8$. The lines indicate $x_{\text{min}}$ and $x_{\text{max}}$ from experiment (solid line), $x_{\text{inc}}^{\text{calc}}$, $x_{\text{min}}^{\text{calc}}$, and $x_{\text{max}}^{\text{calc}}$ from calculations (dashed lines), theoretical limits for the statistical time lag (dashed-dotted line) and the maximum time needed to reach the maximum of the applied step voltage (dotted line). $x_{\text{min}}$ and $x_{\text{min}}^{\text{calc}}$ as well as $x_{\text{max}}$ and $x_{\text{max}}^{\text{calc}}$ are identical for the positive tip.
6.4. Results

Figure 6.6.: Statistical (□) and formative (▲) time lags for negative and positive tip (geometry (A)) at 0.20 MPa in C₃F₈. The lines indicate $x_{\text{min}}$ and $x_{\text{max}}$ from experiment (solid line), $x_{\text{inc}}^{\text{calc}}$, $x_{\text{min}}^{\text{calc}}$, and $x_{\text{max}}^{\text{calc}}$ from calculations (dashed lines), theoretical limits for the statistical time lag (dashed-dotted line) and the maximum time needed to reach the maximum of the applied step voltage (dotted line). $x_{\text{min}}$ and $x_{\text{min}}^{\text{calc}}$ are identical for the positive tip.
no experiments with exclusively partial discharges were observed. For the positive tip most experiments with partial discharges also show breakdowns. The lower breakdown limit $x_{\text{min}}$ is at $x = 0.70$, $x = 0.61$, and $x = 0.52$ for 0.10 MPa, 0.15 MPa, and 0.20 MPa, respectively. The breakdowns occur with formative time lags up to a few seconds. The delays reduce steeply within a small field range. The majority of the breakdowns follows within less than 1 µs after the first discharge. In these cases, the determination of propagation steps until breakdown was rather difficult. Above $x = 0.85$ (0.10 MPa), $x = 0.74$ (0.15 MPa), and $x = 0.64$ (0.20 MPa) all breakdowns evolve from the first discharge ($x_{\text{max}}$).

For the statistical time lags $t_s$ the theoretical limits are calculated according to the Fowler-Nordheim equation and the modified volume-time-law (section 3.2.2.1). The values for the field enhancement factors are determined to $\beta_{0.10 \text{MPa}} = 190$, $\beta_{0.15 \text{MPa}} = 145$ and $\beta_{0.20 \text{MPa}} = 125$ (section 4.2.4.1. The detachment coefficient according to section 4.2.4.2 are used. The results are included in figures 6.4 to 6.6 with dashed-dotted lines.

### 6.4.2. First Corona Charge

Figure 6.7 shows the first corona charges for both polarities and all investigated pressures. The charges are scaled with the pressure $p$ and the square of the protrusion length $L$. This results in charges of $10^{-11}$ C/(Pa m$^2$) to $10^{-8}$ C/(Pa m$^2$). The main part of the experiments has charges around several nano coulombs per Pa m$^2$. The corona charges are slightly increasing with increasing field strength. The measured points for positive tip start at higher reduced field strength with respect to the negative protrusion as already seen in the time lag measurements (figures 6.4 to 6.6).

In section 3.3.1.1 a formula for the calculation of the charge $Q_c$ of the streamer corona is given with equation (3.24). By rewriting this equation with the corona length $l$ (equation (3.23)) and taking into account that for the first corona the protrusion length is determined by the metallic tip length $L$ only, the charge of the first corona can be expressed by

$$Q_c = 0.5 \cdot \epsilon_0 \cdot \left( \frac{E}{p} \right)_{\text{crit,0}} \cdot p \cdot L^2 \cdot \frac{x^2}{1 - x}, \quad (6.1)$$

with the vacuum permittivity $\epsilon_0$, the pressure reduced critical field strength $(E/p)_{\text{crit,0}}$, the pressure $p$, the protrusion length $L$ and the reduced field
6.4. Results

Figure 6.7: Charge of the first corona in $\text{C}_3\text{F}_8$ (geometry (A)): ○ 0.10 MPa negative tip, ● 0.10 MPa positive tip, □ 0.15 MPa negative tip, ■ 0.15 MPa positive tip, △ 0.20 MPa negative tip, ▲ 0.20 MPa positive tip and computational results according to equation (6.1) (solid line).

strength $x$. This equation also gives the scaling law with the pressure $p$ and the square of the protrusion length $L$. The relation is also shown in figure 6.7 with the solid line.

6.4.3. Simulation

Figure 6.8 presents the simulation of the reduced inception field strength $x_{\text{inc}}^{\text{calc}}$, the reduced positive and negative minimal breakdown field strength $x_{\text{min}}^{\text{calc}}$ and the upper limit of the reduced field strength for delayed breakdown $x_{\text{max}}^{\text{calc}}$ depending on the gas pressure together with the experimental results. The curves show a decreasing behaviour with the pressure. The inception field strength $x_{\text{inc}}$, calculated with the streamer criterion, varies only little between $x = 0.23$ at 0.10 MPa and $x = 0.19$ at 0.40 MPa. The pressure dependence of the experimental results for $x_{\text{min}}$ and $x_{\text{max}}$ can be reproduced quite well by the simulation, except for the results for the negative minimal breakdown field strength. The pressure dependence of these measurements is less than predicted by the model. The results of the simulation are depicted...
6. Breakdown Parameters of a Strongly Attaching Gas

**Figure 6.8:** Simulation of the pressure dependence of the reduced inception field strength $x_{\text{inc}}$ (dotted line), the reduced positive (grey solid line) and negative (black solid line) minimal breakdown field strength $x_{\text{min}}$ and the positive (grey dashed line) and negative (black dashed line) limit of delayed breakdowns $x_{\text{max}}$ together with experimental results ($\bullet x_{\text{min,pos}}$, $\bigcirc x_{\text{min,neg}}$, $\blacksquare x_{\text{max,pos}}$, $\square x_{\text{max,neg}}$) for $\text{C}_3\text{F}_8$ and geometry (A).

Starting with the simulation, the radii of the streamer were a priori unknown. No publication was found concerning the geometric dimensions of the discharges in $\text{C}_3\text{F}_8$. Thus, the scaling parameters $C_{s,\text{pos}}$ and $C_{s,\text{neg}}$ for the radius (see equation (3.15)) are adjusted such that the curves for $x_{\text{min}}^{\text{calc}}$ fit the experimental results. The parameters are with $C_{s,\text{pos}} = 1.9\ \text{Pa m}$ and $C_{s,\text{neg}} = 2.7\ \text{Pa m}$ in the range of the factors used for simulations of SF$_6$ (see section A.2). Similarly the scaling factor $\alpha_2$ – determining the amount of charge contributing to the precursor mechanism and leading to immediate breakdown – is chosen such that the behaviour of $x_{\text{max}}^{\text{calc}}$ for both polarities matches the experimental results. With $\alpha_2 = 0.1$ it is higher than for SF$_6$ ($\alpha_{2,\text{SF}_6} = 0.02$).

The implemented model also gives the possibility to examine the steps leading to breakdown. Characteristics such as leader step length, channel fields and channel temperature can be investigated [See09]. As an example
Figure 6.9.: Simulation of the step charges of the last leader discharge which leads to breakdown in C\textsubscript{3}F\textsubscript{8} over the propagation time \( t_p \) (solid line, negative: \( x = 0.643 \), positive: \( x = 0.56 \)) and measurements at the same reduced field strength (negative: \( \triangle x = 0.643 \), \( \bullet x = 0.645 \), \( \square x = 0.641 \), positive: \( \triangle x = 0.561 \), \( \bullet x = 0.572 \), \( \square x = 0.572 \), \( \▲ x = 0.568 \), \( \circ x = 0.568 \)), \( p = 0.20 \text{ MPa} \), geometry (A).
6. Breakdown Parameters of a Strongly Attaching Gas

Figure 6.9 shows the simulation of the charges of the individual steps of the last leader discharge which leads to breakdown (cf. the discharge at around 186 µs in figure 6.2). The voltages used for the measurements in figure 6.9 were slightly above $x_{\text{min}}$ at a pressure of 0.20 MPa. The charges determined from several experiments are plotted for comparison. For both polarities the charges increase from several tens of pico coulombs to several nano coulombs, both, in the experiments and in the simulation. The time needed for the breakdown development (i.e. the propagation time $t_p$, starting with the first pulse of the leader discharge leading to breakdown) varies substantially in the experiments with negative protrusion from 130 ns to more than 1 µs. In the experiment with positive polarity, the development times vary between 70 ns and 200 ns. The simulated times to breakdown are 350 ns and 380 ns for the negative and positive breakdown, respectively.

6.5. Discussion

6.5.1. Time Lags

The comparison of the results of the time lag measurements for negative and positive tip reveals that negative partial discharges incept at lower voltages. Further the reduced inception level decreases with increasing pressure for both polarities. The reduced breakdown level $x_{\text{min}}$ is lower for the positive protrusion and decreases with pressure as well. The lower inception of partial discharges for the negative tip for $\text{C}_3\text{F}_8$ is also reported by Hikita and co-workers [Hik09]. For SF$_6$, the general behaviour of the statistical and formative time lags for both polarities and for several pressure levels is reported in [See08], see also figure 4.3 for results at 0.20 MPa. Overall the results for C$_3$F$_8$ are analogous.

The main difference between the results for the positive protrusion obtained for C$_3$F$_8$ and the results for SF$_6$ from literature [See08] is the absence of the region with only partial discharges. The time of voltage application in the experimental setup is limited to 10 s as then the voltage decreases too much due to self-discharge of the capacitors. This determines the upper limit of observed statistical time lags. For all pressures at the indicated $x_{\text{min}}$ (figures 6.4 to 6.6) this upper limit for observable time lags is reached. It is assumed that towards lower electric fields, discharges with higher time lags could be observed. Whether breakdowns also occur at lower field strength
6.5. Discussion

is not clear. But the presence of delayed breakdown with formative time lags also reaching the upper limit and the comparison to experiments in SF$_6$ suggest that the breakdown limit observed in the experiments agree well with the “real” level. The behaviour below the limits for $x_{\text{min}}$ determined in these experiments can only be examined by providing the first electron artificially, e.g. by X-rays ([Adi12] and chapter 5). However, providing the start electrons would eliminate the information about the time lags.

Christophorou et al. [Chr81] report that for perfluorocarbons electron detachment from negative ions should be taken into account. To the author’s knowledge, for C$_3$F$_8$ autodetachment from metastable parent anions is reported [Hun84, Spy85] with lifetimes in the range of $10^{-11}$ s to $10^{-8}$ s [Hun87], but no detachment rates are available. Therefore a detachment coefficient was estimated according to the method presented in section 4.2.4. The resulting curves, which are included in figures 6.4 to 6.6 (positive protrusion), model the steep increase in the statistical time lags very well. With the pressure dependent enhancement factor (equation (4.3)) good results for the negative statistical time lag were achieved, too.

6.5.2. First Corona Charge

The theoretical equation (6.1), describing the first corona charge, is in good agreement with the majority of the experimental results. Nevertheless there are some first coronas in the negative 0.15 MPa and the positive 0.20 MPa experiments with quite low charges.

The general behaviour and the range of charges agree well with own charge measurements in SF$_6$. The comparison with data for SF$_6$ from literature [See09] shows good general agreement although the majority of these results is about a factor of 10 smaller than the measurements for C$_3$F$_8$. This can have several reasons such as measurement errors of the setup or slight differences in the method of finding the integration limits for the charge calculation.

6.5.3. Simulation

The simulation of the pressure dependence of the breakdown field strength can be adapted well to the results obtained in the experiments. Only the experimental results for $x_{\text{min, neg}}$ show a very flat behaviour in the pressure
range investigated compared to the other experimental and to the simulative results. Especially at 0.10 MPa the measured breakdown field $x_{\text{min,neg}}$ is significantly lower than the simulated values. For this pressure the approximation of the statistical time lags with the Fowler-Nordheim equation requires a high field enhancement factor. Further, regarding the discharge patterns of these experiments, no arrested leader have been observed. Probably this can be explained by a change in the discharge mechanism.

Some of the experiments at 0.15 MPa and negative protrusion exhibit quite small first corona charges compared to the majority of experiments (figure 6.7). This correlates with the value of $x_{\text{min,neg}} = 0.65$ for this pressure, which is slightly lower than expected. But on the other hand, the upper limit of delayed breakdowns $x_{\text{max,neg}}$ can be modelled in good agreement with the experimental results for all pressures.

The simulative results for $x_{\text{min,\text{pos}}}$ and $x_{\text{max,\text{pos}}}$ align very well with the experimental findings. Especially for $x_{\text{min,\text{pos}}}$ this is interesting as nearly no partial discharges without breakdown were observed for the positive polarity. This supports the assumption that the observed limits for $x_{\text{min,\text{pos}}}$ are in the range of the “real” limits.

The scaling factors for the streamer radius $C_{\text{s,pos}}$ and $C_{\text{s,neg}}$ found during the simulation are in the range of the factors for SF$_6$. Probably the dimensions of the molecules have influence on this property. The SF$_6$ molecule is slightly lighter than the C$_3$F$_8$ molecule (146 u vs. 188 u) and thus, slightly smaller (69 Å$^3$ vs. 109 Å$^3$ [Zha03]). On the other hand, the characteristics determining the electrical behaviour in general, such as critical field strength, characteristic attachment times and gradient of $\alpha_{\text{eff}}/N$ at the critical field strength, are comparable for both gases. If the simulation is performed with the scaling factors $C_{\text{s,pos}}$ and $C_{\text{s,neg}}$ for SF$_6$, this results in slightly too high values for $x_{\text{min,\text{pos}}}$ compared to the experiments. The negative curve matches only the measurement point at 0.20 MPa. Thus, within the measurement uncertainty the higher factors of SF$_6$ could be applied although the adaption made for the simulation gives better correlation.

The fraction of the corona charge leading to direct breakdown is with $\alpha_2 = 0.1$ higher than the value for SF$_6$ ($\alpha_{2,\text{SF}_6} = 0.02$). Thus, the range where delayed breakdowns occur is smaller for C$_3$F$_8$ compared to SF$_6$. Simulations performed with $\alpha_{2,\text{SF}_6}$ give results for $x_{\text{max}}$ which are far above the experimentally obtained ones.

Overall the simulation can be applied to the experimental results for C$_3$F$_8$
with very good agreement. Only minor changes in the a priori unknown pa-
rameters were necessary. A comparison to the results obtained for SF₆ (sec-
tion A.2) reveals that both gases have similar partial discharge and break-
down characteristics which was expected in advance as they have shown
similar characteristics relevant for the breakdown description. Thus, it can
be assumed that the model also predicts the behaviour of C₃F₈ at higher
pressures which could not be examined in this setup due to the limited volt-
age range.

A further indication that the model is suitable for the prediction of the
breakdown in C₃F₈ is the simulation of the charges of the steps leading to
breakdown (figure 6.9). Although the model does not involve the statisti-
cal variations appearing in real experiments, the range of the charges, the
tendency of the charge development and the rough time range are in good
agreement.

6.6. Conclusion

Measurements of the partial discharge and breakdown behaviour of C₃F₈
in a homogeneous field with a small disturbance (geometry (A)) were per-
formed. The results show that the general behaviour of this gas is similar
to the widely used SF₆, which was expected on the basis of the quite sim-
lar critical field strength and effective ionization coefficient. But on the
other hand, the pressure dependence of the attachment coefficient and the
substantially different behaviour of the critical field strength with the tem-
perature required an examination. With the experimental results it could be
shown that the model developed for SF₆ by Seeger and co-workers [See09]
(section 3.3.1) can be applied to C₃F₈. Only small changes to the a priori
unknown parameters of the streamer corona radius and the charge fraction
needed for the precursor mechanism were necessary. All other parameters
were taken from literature or were calculated.
7. Breakdown Prediction of a Low Attaching Gas

7.1. Introduction

Tetrafluoromethane (CF$_4$) is the simplest compound of the perfluorocarbon gases (PFC). The structure of the molecule is depicted in figure 7.1. The gas is used in many technical applications e.g. as refrigerant [Aro10], as plasma etchant, and in particle detectors [Chr96]. In high voltage technology CF$_4$ is used as admixture for circuit breakers in cold climate regions to prevent liquefaction of the gaseous isolation [Cig00, Mid00, Nie00, Pee06].

![Structure of CF$_4$ molecule][1]

Figure 7.1.: Structure of CF$_4$ molecule [Bol08].

Since the late 1940s, CF$_4$ has been in the focus of research investigating its dielectric properties. Thus, many contributions can be found investigating the breakdown behaviour in pure gas, e.g. [Cam47, Cam53, McC54, Ber55, Cam55, How57, Jam80, Woo80, Bia82, Hik08], and in gas mixtures with sulphur hexafluoride (SF$_6$), e.g. [Ber95, Yam98, Sun08, Hwa09], as well as concerning the properties on the molecular level, e.g. [Chr96, Hum87, Pek99, Pet07, dUrq07, Raj12c, Wan13, Wu14]. Thus, the properties of CF$_4$ are well-known. During the early research the gas was one of the candidates as an insulating gas better than air, later it was considered as replacement candidate for SF$_6$. Although the ozone depletion potential is zero, the global
warming potential over a period of one hundred years is with 7390 quite high compared to CO$_2$ [For07]. Hence, CF$_4$ will not serve as an alternative without any admixture.

The characteristics of C$_3$F$_8$ (section 6.2), which was examined in the previous chapter, are similar to those of SF$_6$, in particular the critical field strength and the sensitivity to surface defects. Therefore it is necessary to further examine the applicability of the model according to [See09] (section 3.3.1), to other gases. For this purpose the well-known and widely used CF$_4$ gas was chosen as second test gas.

The aim of this chapter is to show if it is possible to model a less attaching gas according to the simulations presented by Seeger and co-workers (section 3.3.1) as it was possible for the strongly attaching gas C$_3$F$_8$ (chapter 6). Beyond this, the extension to other electrode geometries – from smooth to highly disturbed – will be examined. Finally breakdown voltages are calculated. A comparison to literature data will give evidence if this can be done successfully with the model proposed by Bujotzek ([Buj13], section 3.3.2).

### 7.2. Characteristics of CF$_4$

The critical field strength of CF$_4$ is 146 Td [Raj12c], about half of the value of SF$_6$. The slope of the effective ionization coefficient $\alpha_{\text{eff}}/N$ at the critical field does not differ much between CF$_4$ and SF$_6$ [Bia82]. The resulting figure of merit, which is inversely related to the sensitivity to surface defects (section 3.2.1), is considerably higher than for SF$_6$: $(p \cdot L)_{\text{crit,CF}_4} = 26 \text{ MPa} \cdot \mu\text{m}$ vs. $(p \cdot L)_{\text{crit,SF}_6} = 6 \text{ MPa} \cdot \mu\text{m}$, with the pressure $p$ and the protrusion height $L$ [Bia82]. At the same pressure, protrusions in CF$_4$ can be more than four times as high as in SF$_6$ until their influence on the field distribution is pronounced enough to lower the breakdown voltage. Thus, the sensitivity to surface roughness is less pronounced in CF$_4$. Further, large electron drift velocities are reported [Hun87]. In contrary to SF$_6$, which mainly attaches thermal electrons, the main attachment in CF$_4$ occurs in the range of 6 eV to 10 eV [Nak91] via dissociative attachment processes [Chr96, Hun87]. The characteristic attachment time according to Morrow [Mor96] (section 3.2.2.2) is still short with about 700 ps. Therefore, the streamer channel field will be equal to the critical field strength and a discharge propagation via the stepped leader process is possible [Nie89].
7.3. Determination of Model Parameters

7.3.1. Results of Time Lag Measurements

Time lag measurements with the setup described in section 4.1.1 are performed. According to table 4.1 both geometries (A) and (B) are used. For both geometries experiments at pressures of 0.10 MPa, 0.20 MPa, 0.30 MPa and 0.40 MPa are conducted. Additionally, at 0.20 MPa experiments with X-ray application are performed.

The artificial protrusions of 1 mm and 3 mm height serve as starting point for the discharge processes. In the experiments the statistical time lag \( t_s \) and the formative time lag \( t_f \) are evaluated. The figures 7.2 to 7.4 give representative results for positive and negative protrusion for both geometries. The complete results can be found in appendix B. The experiments without X-ray application are coloured in grey, the ones with radiation in black. The small dots indicate the instant of X-ray application at the voltages investigated. This is the upper limit for statistical time lags during X-ray experiments.

The statistical time lags \( t_s \) behave similarly in all cases. They start with delays of several seconds and decrease towards time lags in the range of 1 µs to 0.1 µs with increasing voltage. The formative time lags \( t_f \) show the same pattern for negative protrusions. They first occur in the range of seconds at voltages higher than the partial discharge inception. Then they fall steeply to time lags below 1 µs. These short formative time lags mean direct breakdowns, i.e. the first discharge leads to immediate breakdown. The experimental bounds for the delayed breakdown \( x_{\text{min}} \) and \( x_{\text{max}} \) can be well defined. \( x_{\text{min}} \) is the lowest reduced field where breakdowns occur, \( x_{\text{max}} \) is the field strength above which only immediate breakdowns occur, i.e. breakdowns with formative time lags \( t_f \) less than 1 µs.

The formative time lags for positive tips without X-ray are always shorter than 1 µs and hence, breakdowns occur together with the first observed partial discharge. No delayed breakdowns and nearly no experiments without breakdown are observed. The determination of the values of \( x_{\text{min}} \) and \( x_{\text{max}} \) is not possible. During the experiments with geometry (A) breakdowns at the spherically rounded edges of the plates occurred above reduced fields of \( x = 0.8 \) for all pressures investigated.

For further investigations very short X-ray pulses were applied 20 µs after the voltage rise for a pressure of 0.20 MPa and both geometries (see section 4.1.2). The source provides start electrons for the development of
Figure 7.2.: Statistical (□) and formative (▲) time lags for negative and positive tip (with X-ray: ○ $t_s$, ▲ $t_f$) at 0.20 MPa and geometry (A) in CF$_4$. The small dots mark the application time of the X-rays. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the maximum time needed to reach the plateau of the applied voltage step (······).
7.3. Determination of Model Parameters

Figure 7.3.: Statistical (□) and formative (▲) time lags for negative and positive tip (with X-ray: ◦ $t_s$, ▲ $t_f$) at 0.20 MPa and geometry (B) in CF$_4$. The small dots mark the application time of the X-rays. The lines indicate the experimentally determined boundaries (——) and the calculated ones (—–—), theoretical limits for the statistical time lag (— · —) and the maximum time needed to reach the plateau of the applied voltage step (······).
Figure 7.4.: Statistical (□) and formative (▲) time lags for negative and positive tip at 0.40 MPa and geometry (B) in CF₄. The lines indicate the experimentally determined boundaries (——) and the calculated ones (−−−), theoretical limits for the statistical time lag (—·—) and the maximum time needed to reach the plateau of the applied voltage step (······).
Table 7.1.: Measured reduced inception fields $x_{\text{inc},\text{neg/pos}}$ for both geometries at 0.20 MPa in CF$_4$ and corresponding calculated value $x_{\text{inc},\text{calc}}$.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>$x_{\text{inc,neg}}$</th>
<th>$x_{\text{inc,pos}}$</th>
<th>$x_{\text{inc,calc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.40</td>
<td>0.39</td>
<td>0.33</td>
</tr>
<tr>
<td>B</td>
<td>0.20</td>
<td>0.20</td>
<td>0.13</td>
</tr>
</tbody>
</table>

(partial) discharges and thus, eliminates the statistical time lag. With this setup, for the positive tip delayed breakdowns are observed in a small extent of electric field strength (figures 7.2 and 7.3). For both protrusion lengths the delayed breakdowns occur in the same range as the first detected events in the experiments without X-rays. With these additional experiments the limits of $x_{\text{min,pos}}$ and $x_{\text{max,pos}}$ can be determined for 0.20 MPa. Regarding the negative tips, no changes in the limits for delayed breakdown were expected. Thus, only some exploratory measurements at higher voltages are performed.

With X-ray radiation it is possible to precisely determine the discharge inception voltage $x_{\text{inc}}$ (see chapter 5). The values calculated with the streamer criterion and the experimental inception levels are summarized in table 7.1. Both limits are also depicted in the figures 7.2 and 7.3. The calculated inception fields are slightly smaller than the experimentally determined boundaries. In geometry (A) the difference corresponds to about 7 kV, in geometry (B) it is approximately 10 kV. This was already observed in the experiments with SF$_6$ (figure 5.1). The main reasons for the deviation between experimental and calculated results are small discrepancies of the real geometry in the setup versus the idealized computational geometry of tip height and radius, as discussed in section 5.3.

Beside the experimental results the figures 7.2 to 7.4 also show the curves resulting from the calculation of the statistical time lags according to section 4.2.4. The field enhancement factors obtained from equation (4.4) are $\beta_{(A),0.20\text{MPa}} = 203$, $\beta_{(B),0.20\text{MPa}} = 273$, and $\beta_{(B),0.40\text{MPa}} = 198$. The curves predict the lower boundary for the negative $t_s$ very well.

The statistical time lag $t_s$ for positive protrusions is determined by detachment from negative ions in the critical volume (i.e. the volume where the electric field strength exceeds the critical field strength) for attaching
gases (section 3.2.2.1). Electron attachment in CF$_4$ is a dissociative process [Chr96, Hun87] and electron detachment cross sections are given for collisions of F$^-$ with neutral CF$_4$ molecules in [Pek99, Pet07]. For the calculations, the detachment rate coefficients published by Petrović and co-workers were used [Pet07]. As explained in section 4.2.4 two different number densities are used for the calculations due to the drift processes. For the calculations in CF$_4$ values of $n_1 = 220$ m$^{-3}$ Pa$^{-1}$ and $n_2 = 0.1$ m$^{-3}$ Pa$^{-1}$ are used. These are one to two orders of magnitude smaller than considered for SF$_6$ in [Buj13]. This adaption was necessary to achieve sufficient agreement with the experimental results. For the transition between the two ion densities the drift time of the negative ions at the applied electric field was taken into account. The drift velocities as a function of the field strength are taken from [Pet07]. Figures 7.2 to 7.4 show the results together with experimental data. If both ion densities are taken into account, it is possible to model the steep increase in statistical time lags for the positive polarity. The curves presented in the figures 7.2 to 7.4 do not exactly fit the time lag profile. A more detailed investigation of the density distribution at every time step will be needed if even more precise data is required.

7.3.2. Partial Discharge and Breakdown Fields

The results of time lag measurements in geometry (A) give limited information concerning $x_{\text{min}}$ and $x_{\text{max}}$. Thus, the adaption of the simulation of $x_{\text{min}}$ and $x_{\text{max}}$ is based on the measurements with geometry (B). With an appropriate selection of the streamer radius scaling parameters $C_{s,\text{pos}}$ and $C_{s,\text{neg}}$, the level of the simulated curves of $x_{\text{min, pos}}$ and $x_{\text{min, neg}}$ can be individually adjusted to the experimental results. With the a priori unknown parameter $\alpha_2$, representing the precursor inception mechanism, the level of the curves for $x_{\text{max}}$ can be adopted. This step cannot be individually done for the two polarities as the model relates them both to the same charge fraction $\alpha_2$. The result is shown in figure 7.5 together with the experimental data points taken for the adaption. The final parameters are summarized in section A.4. The same values are used for the simulation of geometry (A).

The simulated behaviour of the lower and upper limit for delayed positive breakdowns $x_{\text{min, pos}}$ and $x_{\text{max, pos}}$ in geometry (B) follow the experimental data. The only experimental data point for $x_{\text{min, pos}}$ is achieved by the measurement with X-rays. This is used for the determination of the positive streamer radius parameter which results in $C_{s,\text{pos}} = 1.7$ Pa m. With this
value the data point $x_{\text{min, pos}}$ for geometry (A), achieved with X-rays as well, can be well described, too. The negative streamer radius parameter $C_{s, \text{neg}}$ is adapted to a value of $4.5 \text{ Pa m}$. The fraction of first corona charge $\alpha_2$ describing the upper limit of the delayed breakdowns $x_{\text{max}}$ is set to a value of $\alpha_2 = 0.05$ according to both, the negative and positive experimental results.

With this parameter set, the curves for $x_{\text{min, pos}}$ and $x_{\text{max, pos}}$ are at lower voltages than the corresponding ones of the negative protrusion. The slopes of the positive curves are steeper in the lower pressure range than the slope of the negative curves. In the higher pressure range the distance between the lower and upper limit for positive delayed breakdowns is less than for the negative tip.

### 7.3.3. Discussion

**Time Lags.** The general behaviour of the statistical and formative time lags in CF$_4$ (figures 7.2 to 7.4) is similar to those in SF$_6$ ([See08] and figure 4.3) and C$_3$F$_8$ (figures 6.4 to 6.6). But the results show the limitations
of the geometries used. As CF$_4$ is more than four times less sensitive to surface roughness [Bia82] the results acquired with geometry (A) give little information about the breakdown behaviour in the presence of an inhomogeneity. This was also seen in the breakdowns that occurred at the edges of the plates. Thus, additional measurements with a more pronounced tip (geometry (B)) were performed.

From the experiments without X-ray radiation it is not possible to extract the limits of $x_{\text{min,pos}}$ and $x_{\text{max,pos}}$ of delayed breakdowns. Without radiation, the first observed event at the lowest applied electric field still results in an immediate breakdown. Sung and co-workers [Sun08] also reported identical values for partial discharge inception and breakdown voltages. Bibby et al. [Bib65] and Sung et al. [Sun08] suggest that the electron attachment which occurs mainly at energies between 6 eV and 10 eV [Nak91] is a reason for this behaviour. The peak of the attachment cross section is quite small (roughly $2 \cdot 10^{-22}$ m$^2$ [Nak91]). Ionization starts above 16 eV [Nak91]. Unlike in e.g. SF$_6$, the gap in the energies between attachment and ionization cross sections is small. In avalanches in SF$_6$ the low energetic electrons are affected by strong attachment and ionization requires an elevated electric field producing electrons with energies in the ionization regime. In contrary, in CF$_4$ a certain electric field is necessary that electrons gain energies in the range of the attachment cross section. At the same time, assuming a Maxwellian distribution of the electron energy, a growing number of electrons reach energies where ionization can take place. As the two cross sections are located beside each other and as the ionization cross section is substantially larger the discharge development is not effectively prevented by the attachment process.

The experiments with additional X-ray radiation revealed a small field region of delayed breakdowns in the range of the longest observed statistical time lags. But the formative time lags are still quite short and delayed breakdowns are the minority of the events.

A calculation of the step length of the first corona reveals that in geometry (A) the first discharge extends to about 1.5 mm at $x_{\text{min}}$ and for geometry (B) to around 2 mm. Thus, the first step already crosses about 10% of the total gas gap. Further, the shapes of the recorded current pulses show that the breakdown development needs less leader steps than e.g. in C$_3$F$_8$ for similar conditions. Both facilitate the breakdown with the first occurring discharge.
**Partial Discharges and Breakdown Fields.** With the experimental data points restricted to the ones shown in figure 7.5 the simulation parameters can be well adapted. The experiments with X-ray application are a good verification as these values and the results of the simulation coincide.

If all results are taken into account, the decrease of the negative experimental limits with increasing pressure is less pronounced than the simulated trend. The same holds for the experimental results of geometry (A) for negative and positive experiments except for the results with X-ray application. The reason is most probably that – as mentioned already – the gas is much less sensitive to protrusions than e.g. SF$_6$. The behaviour of the negative boundaries for the delayed breakdowns is flatter than for the positive limits. This as well indicates a reduced sensitivity towards protrusions [Bia85].

A comparison of the a priori unknown factors $\alpha_2$, $C_{s,pos}$ and $C_{s,neg}$ to the values used for SF$_6$ (section A.2) and C$_3$F$_8$ (section A.3) show an interesting trend: $C_{s,pos}$ for CF$_4$ is smaller than in both strongly attaching gases. This quantity is determined by one data point only. Thus, the possible variations of the value due to the uncertainty could also result in a slightly higher value. The fraction of corona charge $\alpha_2$ determining the upper limit of delayed breakdowns $x_{max}$ for both polarities is higher than for SF$_6$ ($\alpha_{2,SF6} = 0.02$) but lower than for C$_3$F$_8$ ($\alpha_{2,C3F8} = 0.1$). In contrary, the parameter for the negative streamer radius $C_{s,neg}$ is substantially higher than for the strongly attaching gases ($C_{s,neg,SF6} = 3$ Pa m, $C_{s,neg,C3F8} = 2.7$ Pa m). The main reason is the difficulty in interpreting the results of the time lag measurements with the negative protrusions.

### 7.4. Prediction of Breakdown Voltages for Technical Relevant Geometries

With the measurements presented in the previous section, all parameters which are necessary for the prediction of breakdown voltages for arbitrary electrode geometries are known. The geometries are selected from experiments reported in literature. Table 7.2 summarizes the parameters of the geometries and the corresponding references. For some of the geometries not all of the parameters needed are reported. For these setups reasonable assumptions are made.
Table 7.2.: Values of the protrusion length $L$, the protrusion radius $R$, and the distance $D$ of the plane electrodes of the geometries used in the simulation of AC and LI breakdown fields in CF$_4$. The gap length $D$ includes the protrusion length $L$. The last column gives the references from literature.

<table>
<thead>
<tr>
<th>$L$ (mm)</th>
<th>$R$ ($\mu$m)</th>
<th>$D$ (mm)</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>50</td>
<td>5</td>
<td>[Cam53, How57, Woo80, Ber95]</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>10</td>
<td>[How57, Jam80]</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>15</td>
<td>this chapter</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>20</td>
<td>this chapter</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>13</td>
<td>[Sun08]</td>
</tr>
<tr>
<td>20</td>
<td>500</td>
<td>30</td>
<td>[Hik08, Yam98]</td>
</tr>
</tbody>
</table>

7.4.1. Simulation

Figures 7.6 to 7.8 depict the simulated reduced breakdown field strengths according to section 3.3.2 for the geometries shown in table 7.2. The breakdown fields are computed for alternating (AC), positive (LI$^+$), and negative (LI$^-$) lightning impulse voltage application. For AC, peak voltages are considered. Direct voltage (DC) stress results in the same curves as for alternating voltages and is not marked separately.

The geometry with 100 $\mu$m tip is simulated for electrode distances of 5 mm and 10 mm. The resulting curves for the different voltage stresses are the same. Nevertheless they are both shown for better visibility of the difference in the experimental results. The curve for AC breakdown decreases nearly linearly from $x = 1$ at 0.10 MPa to about $x = 0.8$ at 0.60 MPa. The reduction is less pronounced for the negative LI curve. The positive LI breakdown field does not differ from $x = 1$ for the investigated pressure range. Reference data for AC, negative DC and negative LI breakdown were found in literature for pressures up to 0.40 MPa. Howard conducted his experiments with and without a radium source [How57]. In figure 7.6 the results with radiation are plotted. The deviations to results without radium source are given to 0.5% for power frequency, 0.1% for negative DC and 4.3% for negative lightning impulse. A small pressure dependence can be seen in the experiments as well.

The simulation of the larger protrusions reveals a more pronounced pres-
7.4. Prediction of Breakdown Voltages

**Figure 7.6.** Simulated breakdown voltages in CF$_4$ for AC (——), positive lightning impulse (— — —), and negative lightning impulse (······) for the homogeneous fields with surface roughness.
Figure 7.7.: Simulated breakdown voltages in CF$_4$ for AC (---), positive lightning impulse (– – –), and negative lightning impulse (· · · · · ·) for the geometries (A) and (B).
Figure 7.8.: Simulated breakdown voltages in CF$_4$ for AC (——), positive lightning impulse (– – –), and negative lightning impulse (· · · · ·) for the strongly inhomogeneous field configurations.
sure dependence. Except for the 1 mm protrusion at pressures less than 0.30 MPa the breakdown field for positive lightning impulse is smaller than for negative voltages. With increasing protrusion length the LI$^+$ curve approaches the trend of the AC curve.

The results of the simulation of the 1 mm and 3 mm protrusion are compared to the measurements of the statistical and formative time lags (see figures 7.2 to 7.4). For this purpose for every pressure the reduced field strength $x$ was evaluated where the first breakdown occurred within less than 1 s for the AC case and within less than 1 µs for the LI cases (i.e. statistical plus formative time lags). The literature data found for the 10 mm and 20 mm protrusion correlates qualitatively and quantitatively well with the simulated results.

7.4.2. Discussion

Although problems occurred while interpreting the experimental results of the time lag measurements the results of the simulations of AC and LI breakdown field strength correlate quite well to literature data. Bujotzek denoted the small protrusion of 100 µm as “technical equivalent surface roughness” [Buj13] as it can be found e.g. in gas insulated switchgear. Thus, the literature data found for homogeneous fields is compared to those simulations even though electrodes for breakdown experiments normally have very smooth surfaces with roughness less than 1 µm.

Breakdown in homogeneous gas gaps is considered to occur at the instant when the electric field strength reaches the critical field strength of the gap [Kuf00], i.e. at reduced fields of $x = 1$. Especially the results for the lightning impulse voltage are slightly above $x = 1$. Most probably this is due to the short duration of the voltage application where the availability of the breakdown initiating electron is crucial. This is also seen by the large impact of a radioactive source on the results of [How57] compared to the results of AC and DC voltage.

The simulations of the protrusions of 1 mm and 3 mm show that in this region the transition of the “worst case” for lightning impulse stress from negative – for very small defects – to positive polarity – for pronounced disturbances – occurs. This coincides with the experimental breakdown limits for the negative tips which are lower or in the same range as for positive polarity for those two geometries. First electrons for positive tips are mostly provided via detachment from negative ions in the gas phase. Detachment is
strongly field dependent [Wie88, Xu96]. Thus, if the defect produces only a small field enhancement, the detachment process is not efficient. The analysis of the simulative results in view of the limiting factor of the breakdown shows that up to a defect height of 1 mm the positive LI breakdown is exclusively determined by the statistical time lag. For very small defects over the entire pressure ranges and for protrusions of 1 mm up to at least 0.30 MPa, the negative statistical time lag is considerably lower. Hence, the negative LI breakdown occurs at voltages lower than in the positive case and negative is the critical polarity. For the geometry with the 3 mm protrusion the limit of the positive statistical time lag is in the same field range as for the negative tip. Further the boundary for breakdown development is found in the same field range as well. Thus, the statistical time lag is not the limiting factor over the entire pressure domain.

The correlation of the values extracted from time lag experiments to the simulations (1 mm and 3 mm protrusions) is not as good as for the other cases, but they are within the tolerances. Although CF$_4$ is used in some applications of today’s switchgear, no data was found for small protrusions for additional comparison. Breakdown voltages from literature are averaged over a certain amount of measurements or given as 50% probability of breakdown. The data extracted from the time lag measurements gives the lowest electric field strength observed during the experiments. Thus, there was no averaging and the statistical behaviour of breakdown events is not taken into account.

In literature the simulations can be found for SF$_6$ [Buj13] (see also figures 3.13). The general trend is quite similar for both gases. Especially the critical polarity for lightning impulses is negative for small defects and switches to positive for higher protrusions, too. But for SF$_6$ this transition is nearly completed already for the 1 mm tip whereas in CF$_4$ it takes place above 1 mm. Further, the results in SF$_6$ show the higher sensitivity towards surface defects in the more pronounced curvature of the curves.

7.5. Conclusion

In this chapter experimental results of time lag measurements for CF$_4$ are presented. Starting from these experiments simulation parameters of the lowest positive and negative breakdown voltage and the upper boundaries for delayed breakdowns were determined. Although the interpretation of
the experimental results had to take into account the (from SF$_6$) different attaching property of CF$_4$, it was possible to achieve satisfactory results from the simulation. Thus, it can be concluded, that the proposed method is also applicable to gases less attaching than SF$_6$ or C$_3$F$_8$.

Starting from the simulation of the discharge inception voltage and the boundaries of delayed breakdowns, an extrapolation towards breakdown voltages of direct, alternating and lightning impulse voltages of both polarities is presented for different electrode geometries. The comparison to literature data showed that a good match between simulations and experiments is achieved. Hence, the tools given by Seeger et al. and Bujotzek et al. seem to be useful for the prediction of the behaviour of gases in the range from weakly to strongly attaching as long as the streamer channel field is equal to the critical field strength of the gas, bearing in mind the simplifications assumed for the simulations.
8. Breakdown Prediction of a Quite Unknown Gas

8.1. Introduction

In the previous chapters it was shown that it is possible to adapt the models according to sections 3.3.1 and 3.3.2 to other attaching gases such as octafluoropropane (C₃F₈, chapter 6) and tetrafluoromethane (CF₄, chapter 7). Those gases were chosen because they are well-known from literature and thus, the calculations could be compared to literature values.

The aim of this chapter is to investigate, if it is also possible to assess the high voltage insulation capability of a quite unknown gas only by using the models. For this purpose the hydrofluoroolefin HFO1234ze is chosen. To prove the modelling classical breakdown experiments are executed and the results are compared.

8.2. Characteristics of HFO1234ze

The hydrofluoroolefin HFO1234ze (trans-1,3,3,3-tetrafluoroprop-1-ene, chemical formula: C₃H₂F₄) is a relatively new gas. Figure 8.1 shows the structure of the molecule. The HFO1234ze was tested and patented [Lul11, Kie13b, Kie14a] for use in high voltage equipment. But no details are known about the electric properties. The gas showed good performance in the quantum-chemical analysis [Rab15], is not harmful [Hon14] and can be easily purchased. In [Kie14a] a critical field strength of 0.8 that of SF₆ was determined, which is in approximate accordance with calculations according to [Rab15] which resulted in 1 ± 0.35 times the critical field strength of SF₆ [Rab14]. The effective ionization coefficient and the critical field strength determined in a swarm experiment showed a pronounced pressure dependence without saturation in the range up to 40 kPa [Cha14] and the molecule shows strong attaching properties. The pressure dependence of the critical field strength
\((E/N)_{\text{crit}}\) was further investigated with AC breakdown experiments as described in section 4.2.2. The resulting “high pressure” critical field strength is 305 Td. The boiling point of HFO1234ze is \(-19^\circ\text{C}\) and causes liquefaction at room temperature at 0.42 MPa [Hon14]. The global warming potential is 6 on a 100 year time horizon [WMO14], and the ozone depletion potential is zero [Kie13b].

![Figure 8.1: Structure of HFO1234ze molecule (upper part) and of the isomer HFO1234yf (lower part) [Bol08].](image)

The isomer HFO1234yf is better investigated regarding thermodynamic properties and is proposed to suit as substitute for air conditioning and heat pump devices. But this is controversial [Pea13]. The thermophysical properties of both derivates are very similar [Hig10, Lin14] but HFO1234yf is extremely flammable (risk phrase R12, GHS hazard statement H220) [Hon08]. Both molecules decompose to trifluoroacetic acid (TFA) in the atmosphere, which cannot be further degraded and thus, will accumulate in the atmosphere when released extensively [Jav08, Hen12, WMO14]. For this investigation HFO1234ze is chosen because it is less flammable.
8.3. Determination of Model Parameters

8.3.1. Time Lag Measurements

Time lag measurements were carried out with the setup described in section 4.1.1. For the electrodes configuration (A) was used and pressures of 0.10 MPa, 0.15 MPa, 0.20 MPa, 0.25 MPa and 0.30 MPa of HFO1234ze are investigated. At 0.20 MPa additional experiments with X-ray application are performed. As examples, figure 8.2 shows the results of the investigations with 0.20 MPa pressure and positive and negative tip. The complete set of results can be found in appendix C.

The evaluation of the pulses was difficult because the light emission of HFO1234ze in the range of the spectral response of the photomultiplier was poor. The distributions of time lags without X-ray application follow the trend already seen for other gases. The statistical time lags $t_s$ start in the range of seconds and decay to micro seconds. This time range of micro seconds is a lower boundary due to the voltage rise. Time lags above some seconds cannot be detected with the setup. The partial discharges start at lower voltages for the negative protrusion.

Breakdowns are observed with delays for both polarities, but disruptions at positive tips start at lower field strength. For the positive case, breakdowns start at fields only slightly above the first observed partial discharges. For negative protrusions, a substantial field range is in between the lowest voltage where only partial discharges are detected and the lowest breakdown voltage. Looking at the whole pressure range investigated, the lowest reduced field strength for only partial discharges and the lowest reduced field strength for breakdowns (which denotes $x_{\text{min,exp}}$) decrease with increasing pressure for both polarities.

With the application of X-rays shortly after the voltage reached its maximum, electrons for starting an avalanche are provided. In HFO1234ze the lowest breakdown field strengths for positive protrusions are in general higher than the fields of the first observed partial discharge without breakdown (in contrary to e.g. C$_3$F$_8$ and CF$_4$). Thus, the focus of the experiments with X-rays is on the partial discharge inception field strengths, which are determined for $x_{\text{inc, pos}} = 0.36$ and $x_{\text{inc, neg}} = 0.32$, respectively.

The statistical time lags occurring with the positive tip and X-rays are limited to the delay of the X-ray pulse after the voltage application (about 20 µs). The inception field strength $x_{\text{inc, pos}}$ could be reproduced in indepen-
Figure 8.2.: Statistical (□ without and ○ with X-rays) and formative (▲ without and ▲ with X-rays) time lags (geometry (A)) at 0.20 MPa in HFO1234ze. The small dots mark the time of the X-ray application. The vertical solid lines indicate the experimental limits of \( x_{\text{inc}} \), \( x_{\text{min}} \) and \( x_{\text{max}} \), the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for \( t_s \) is marked by the dashed-dotted line.
dent experiment runs. Above this field strength all experiments showed a discharge pulse if X-rays were applied. The behaviour in the negative case is clearly different. Although start electrons were provided, not every X-ray pulse led to a discharge above $x_{\text{inc,neg}}$. Further, about half of the partial discharges showed statistical time lags substantially longer than the 20$\mu$s delay of the X-ray application. The distribution of those delayed discharges is similar to the ones without X-ray, but they are shifted towards lower reduced field strengths. In a second experiment run no discharge was observed until $x = 0.36$ was reached.

8.3.2. Simulation Parameters

Figure 8.3 presents the results of the simulation according to section 3.3.1 together with the values determined from the time lag experiments. The a priori unknown parameters are adapted, as explained in sections 6.4.3 and 7.3.2, to $C_{s,\text{pos}} = 1.5 \text{ Pa m}$, $C_{s,\text{neg}} = 2.7 \text{ Pa m}$ and $\alpha_2 = 0.03$. As figure 8.3 shows, the experimental values for the positive tip can be well modelled with these parameters. The measured results for the negative polarity at 0.10 MPa and 0.15 MPa are substantially lower than the calculated curves. For a pressure of 0.30 MPa the experimental point for $x_{\text{max,neg}}$ could not be obtained due to the upper limit of the voltage source.

The reduced inception field strength $x_{\text{inc}}^{\text{calc}}$ has very pronounced pressure dependence. The experimental data points for the streamer inception fields at 0.20 MPa gained with the investigations with X-rays are inserted into the graphic. They are slightly higher than the calculated inception field.

8.3.3. Discussion

Qualitatively, the results of the measured time lags in HFO1234ze (figure 8.2) show the same behaviour as known for SF$_6$ (figure 4.3 and [See08]), C$_3$F$_8$ (figures 6.4 to 6.6) and CF$_4$ (figures 7.2 to 7.4). The pressure dependence of $x_{\text{min}}$ and $x_{\text{max}}$ can be traced exactly by the simulation.

The results of the time lag measurements for the negative tip show a substantial range between the field of the first observed discharge and $x_{\text{min}}$ for all pressures investigated. This is identical to the other gases. The results for the positive protrusion in HFO1234ze are very similar to the experiments in
C\textsubscript{3}F\textsubscript{8} (figures 6.4 to 6.6) and in SF\textsubscript{6} (figure 4.3 and [See08]). In HFO1234ze for most pressures a small field range between the first occurrence of discharges without breakdown and the first delayed breakdown exist. This was slightly different in C\textsubscript{3}F\textsubscript{8} where the first observed discharge lead to breakdown. In SF\textsubscript{6} this range was slightly larger than in HFO1234ze. The lower boundary of the statistical time lags could be well modelled for both polarities with the parameters given in section 4.2.4.

Regarding the X-ray experiments with positive tip, the statistical time lags are limited to the delay of the X-ray pulses of about 20 µs. The measurements in SF\textsubscript{6} (figure 5.1) and CF\textsubscript{4} (figures 7.2 and 7.3) show the same behaviour. Hence, the X-rays seem to provide sufficient electrons to start an avalanche. The discharge pattern observed in the negative case in HFO1234ze seems to be random. The inception field strength obtained in the second experiment run gives the same value as for the positive protrusion. But still delayed discharges occurred also if free electrons are provided. As these delayed discharges are shifted towards lower field strengths compared to the measurements without X-rays, a certain influence of the artificially provided...
electrons cannot be excluded. This pattern was not seen in measurements with other gases.

The parameters $C_{s,\text{pos}}$, $C_{s,\text{neg}}$ and $\alpha_2$ determined from the time lag measurements in HFO1234ze are very similar to the ones obtained for SF$_6$ (section A.2) and C$_3$F$_8$ (section A.3). With those values the experimental results of $x_{\text{min}}$ and $x_{\text{max}}$, particularly the positive ones, can be well modelled.

The simulated trends of $x_{\text{min}}$ and $x_{\text{max}}$ in HFO1234ze for the negative polarity do not fit as well to the experimental limits as for the positive tip (figure 8.3), especially for the pressures below 0.20 MPa. In C$_3$F$_8$ only the measured values of $x_{\text{min},\text{neg}}$ deviate from the calculation, the $x_{\text{max}}$ values in C$_3$F$_8$ could be well reproduced (figure 6.8). Therefore, a different discharge mechanism for 0.10 MPa in C$_3$F$_8$ was assumed to be responsible. In CF$_4$ both, $x_{\text{min},\text{neg}}$ and $x_{\text{max},\text{neg}}$ revealed a weak pressure dependence compared to the simulation (figure 7.5). In this gas most probably the reduced sensitivity to surface roughness causes this characteristic. For HFO1234ze the figure of merit for the sensitivity to surface roughness according to [Bia82] is with a value of approximately 7 MPa µm for 0.20 MPa similar to SF$_6$ and C$_3$F$_8$. The value for 0.10 MPa is with approximately 13 MPa µm nearly twice as high, but still well below the figure of merit of CF$_4$ (26 MPa µm, section 7.2). The sensitivity to surface roughness is inversely proportional to the figure of merit. These values are consistent with the experiments in HFO1234ze, where good results were achieved with the 1 mm protrusion. Hence, the sensitivity of the gas was sufficient so that discharge development always started at the inhomogeneity. The behaviour of the breakdown limits in HFO1234ze corresponds better to the results in C$_3$F$_8$, as the experimental trend of $x_{\text{max}}$ can be modelled quite well at 0.20 MPa and higher. Only the flat behaviour of $x_{\text{min}}$ is not represented adequately.

The calculated reduced inception field strength $x_{\text{inc}}$ has very pronounced pressure dependence compared to SF$_6$, C$_3$F$_8$ and CF$_4$ (figure 3.10 and [See08], figure 6.8 and figure 7.5). This can be explained by the still substantial pressure dependence of the critical field strength and the effective ionization coefficient in the pressure range up to 0.15 MPa. The experimentally determined inception points are roughly 10 kV and 20 kV higher than the result of the streamer criterion. The main reason is due to small tolerances in the experimental setup as discussed in section 5.3.
8.4. Prediction of Breakdown Voltages for Technical Relevant Geometries

8.4.1. Results

The results provided in section 8.3 form the basis for the prediction of the breakdown voltages in arbitrary field configurations. The breakdown voltages are calculated according to the model described in section 3.3.2. The figures 8.4 to 8.6 show the results for the geometries summarized in table 8.1, which represent typical field configurations of real high voltage equipment. The protrusion height of 300 µm to 400 µm gives an upper limit for arrangements with very rough surfaces. Small particles or surface damages are in the range of the 1 mm protrusion. Very long particles can reach 20 mm. These conditions result in very different field distributions covering many interesting cases.

Table 8.1.: Geometries used for the calculation of the breakdown field strengths in HFO1234ze. The distance of the plane electrodes includes the length of the protrusion.

<table>
<thead>
<tr>
<th>Type</th>
<th>Protrusion height</th>
<th>Protrusion radius</th>
<th>electrode distance</th>
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<tr>
<td>roughness</td>
<td>400 µm</td>
<td>200 µm</td>
<td>15 mm</td>
</tr>
<tr>
<td>roughness</td>
<td>300 µm</td>
<td>200 µm</td>
<td>15 mm</td>
</tr>
<tr>
<td>needle</td>
<td>1 mm</td>
<td>200 µm</td>
<td>15 mm</td>
</tr>
<tr>
<td>needle</td>
<td>20 mm</td>
<td>200 µm</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

For all geometries the simulated reduced breakdown fields for positive and negative lightning impulse are higher than for AC voltages. The positive lightning impulse breakdowns have lower breakdown field strengths than the negative impulses, except for the configuration with the smallest protrusion height where both breakdown fields are quite similar over the calculated pressure range. An increasing protrusion length reduces the breakdown withstand of the gap.

To verify the simulation results, classical breakdown experiments are performed as described in section 4.3. The mean breakdown voltage and twice the standard deviation are depicted in the figures 8.4 and 8.6 for the con-
8.4. Prediction of Breakdown Voltages

**Figure 8.4.** Results of the simulation for HFO1234ze (AC (solid), LI$^+$ (dashed), LI$^-$ (dotted)) and the measurements of breakdown voltages of the homogeneous field configuration with substantial surface roughness. The experimental results are plotted with plus/minus twice the standard deviation.

**Figure 8.5.** Results of the simulation for HFO1234ze (AC (solid), LI$^+$ (dashed), LI$^-$ (dotted)) of the breakdown voltages in geometry (A). The “experimental results” are derived from the time lag measurements.
**Figure 8.6.**: Results of the simulation for HFO1234ze (AC (solid), LI$^+$ (dashed), LI$^-$ (dotted)) and the measurements of breakdown voltages of the strongly inhomogeneous field. The experimental results are plotted with plus/minus twice the standard deviation.

Figurations with a high surface roughness (400 µm for AC and 300 µm for LI breakdown experiments) and with a 20 mm protrusion. For AC the peak values are plotted. Additionally, for the 1 mm protrusion the reduced field strength of the first breakdown occurring less than 1 s (relevant for AC breakdown) or less than 1 µs (relevant for lightning impulse breakdown), respectively, after voltage rise are taken from the time lag measurements and included in figure 8.5 with the simulated breakdown voltages (similar to CF$_4$, figure 7.7).

The experimental results for the AC breakdown in the homogeneous field configuration with the 400 µm protrusion are slightly below the calculated ones, but the simulated curve is within twice the standard deviation. For the breakdown measurements with lightning impulses the roughness of the electrodes was less than for AC. For both pressures and both polarities the experimental mean LI breakdown voltages are identical. The measurements of the positive LI correspond to the simulated data. The deviation for the negative case is higher.

Regarding the experimental results for the very inhomogeneous field with
the 20 mm protrusion, the lightning impulse breakdown voltages agree very well with the prediction, except for the negative points at 0.20 MPa and 0.25 MPa which are slightly too high. The pressure dependence of the results of the AC breakdown measurement is as expected, but the breakdown field strengths are too high. The values are in between the results for positive and negative lightning impulse breakdown.

For the 1 mm protrusion no additional breakdown measurements are performed. For a first estimation, values from the time lag measurements are depicted as described above. For the AC breakdown, values for both polarities are included. The simulation predicts that the positive polarity is determining the breakdown. This corresponds to the experimental data as the positive values agree well with the simulated curve. The negative values are similar or higher than the positive ones. Regarding the lightning impulse breakdown voltages, the simulated data represents an upper boundary of the experimental data.

8.4.2. Discussion

The overall comparison between the prediction of the breakdown voltages of the quite different field configurations and the experimentally obtained mean breakdown voltages reveals a good agreement. The level of the simulated curves is mostly within twice the standard deviation of the measured values.

During the AC experiments with the rough electrodes, breakdowns occurred in the positive and in the negative half cycle of the voltage. The fraction of breakdowns in the positive half of the AC voltage (i.e. positive polarity at the rough surface) increases from 7.3% to 19.5% and 48.8% with increasing pressure. This coincides with the simulation which predicts that the negative half would be decisive up to 0.14 MPa, then changing to the positive half. For the LI case the simulations show that a small change in the protrusion height results in substantial changes of the breakdown field strengths. Thus, for a matching of the predicted and measured breakdown fields an exact knowledge of the protrusion geometry or the surface roughness, respectively, is essential.

The simulation of the 1 mm protrusion predicts that the positive half of the AC voltage is decisive for the breakdown. Although the inserted experimental data represent the lowest breakdown voltage, they agree very well with the simulation. For the lightning impulse breakdown voltages the calculations represent an upper boundary. The determination of a mean breakdown
voltage from the time lag measurements is not possible. Nevertheless, the mean voltage would be higher than the shown values. An indicative measurement of the mean lightning breakdown voltages at 0.30 MPa give evidence to this assumption.

The discrepancy between the calculated and the measured AC breakdown voltages for the 20 mm protrusion is substantial. The results are higher than the positive but lower than the negative lightning impulse breakdowns. A revision of the electrodes and a second determination of the AC breakdown voltages were done to exclude experimental problems and to confirm the results. It is not possible to predict such behaviour with the model, but most probably it could be explained by corona stabilization. On the one hand, the breakdown field strength for lightning impulse voltage application was predicted very well for both polarities. On the other hand, the model does not take into account the influence of space charges. As the AC voltage is increased during the experiment, first the discharge inception limit is reached and space charge can be created. This space charge may lead to an increased breakdown voltage [Bia85, S. 199][Kuf00].

Due to the breakdowns, black deposit was found on the electrodes after the experiments. For HFOs it is known that carbon dust precipitation occurs due to the spark-overs [Kie14a]. This is a drawback for the use in high voltage insulation as carbon is a good conductor and therefore, insulating surfaces could be short-circuited. But in literature several approaches are described to prevent carbonization [Eis65, Chr82].

HFO1234ze cannot be used as pure insulation gas for high voltage equipment due to the high boiling point. But it could serve as insulation in the medium voltage range, for example in ring main units on the secondary distribution level. Simulations with representative geometries suggest that it will not be necessary to increase the pressure (normally about 0.14 MPa) when replacing the SF$_6$ by HFO1234ze to maintain the same insulation performance. Only the operation temperature would have to be limited to $-10^\circ$C to $-15^\circ$C to avoid liquefaction [Hon11].

8.5. Conclusion

In chapter 7 the model for the prediction of breakdown field strengths in arbitrary field configurations under AC and lightning impulse voltage stress (section 3.3.2) was applied to the attaching gas CF$_4$. In the present chap-
ter, the prediction method was successfully applied to a mostly unknown molecule for the first time. All parameters necessary for the calculations are derived from swarm parameters, the thermodynamic quantities are calculated and the remaining ones can be extracted from the time lag measurements. The results obtained by classical breakdown experiments agree well with the calculations, except for the AC breakdown in the very inhomogeneous configuration, as discussed. Thus, it seems that the model can be applied to predict the breakdown behaviour of unknown gases in a wide range of applications. Still, it is necessary to bear in mind the limitations of the model.

The value of the critical field strength of HFO1234ze is in an interesting range. But unfortunately, the boiling point is quite high and the gas liquefies already at around 0.42 MPa at room temperature. Therefore, it will not suit as pure insulation gas but could be used as an admixture in high voltage gaseous insulations. For the use of HFO1234ze as part of a mixture, a synergistic effect with other gases, especially with commonly used buffer gases such as N$_2$, CO$_2$ or synthetic air, would be of great interest and has to be investigated. On the other hand, HFO1234ze can most probably be used as replacement for SF$_6$ in medium voltage applications. The disadvantage of carbon dust precipitation has to be prevented by appropriate measures.
9. Conclusion and Outlook

For the research towards new insulation gases a crucial point is to find a way to replace the time consuming investigation via classical breakdown measurements. As shown in [Fra14] a new three step approach for this research could be to screen large groups of potential molecules, to investigate the swarm parameters of promising candidates and to predict the breakdown field strength of the best gases. Models are described in literature [See09, Buj13] for the prediction of breakdown voltages of the widely used SF$_6$ in arbitrary field configurations under standard voltage waveforms.

This thesis focused on the last step of the proposed three step approach. The aim was to establish a method to predict the breakdown voltage of novel gases based on the models for SF$_6$. To achieve this goal new techniques had to be establish to obtain the temperature dependent critical field strength of unknown gases and to extract parameters for the description of the statistical time lag from time lag measurements, e.g. the pressure dependent field enhancement factor and an estimation of the detachment coefficient.

Experiments in the well-known gases C$_3$F$_8$ and CF$_4$ have shown that it is possible to apply the model for SF$_6$ to a wide range of low to strongly attaching gases. The investigation of the relatively new hydrofluoroolefin HFO1234ze confirmed first estimations of the critical field strength found in literature. Further, the prediction of the breakdown voltages for a wide range of geometries showed a very good agreement with classical breakdown experiments. These findings give very strong evidence that the models are suitable for the third step of the proposed approach in the research of new insulation gases.

Two points should be considered for further research in the modelling of attaching gases: For all gases investigated the simulation of the negative minimal breakdown field strength $x_{\text{min}, \text{neg}}$ deviated from the experimental investigations for the lower pressure range. Probably because the streamer radius for small pressures and negative voltages is smaller than expected. Findings in [Buj15] give suggestions towards this direction. Further, the influence of space charges is not taken into account for the breakdown predic-
Conclusion and Outlook

The AC breakdown voltages for the very long protrusion in HFO1234ze showed higher breakdown voltages than expected which potentially could be explained by space charge creation.

The modelling of statistical time lags for the negative protrusion gave good results with the pressure dependent field enhancement factors. For the positive protrusion it was possible to approach the steep increase of the time lags towards lower voltages by two different negative ion densities. But the approach is not as exact as for the negative protrusions. The statistical time lag mainly influences the prediction of the breakdown voltages for very small protrusions and surface roughness. Thus, depending on the focus of the geometries for further research a better modelling of positive statistical time lags would be desirable.

At the moment the realized model is restricted to protrusions in homogeneous background fields. Especially in real geometries of gas insulated switchgear and gas insulated lines, slightly inhomogeneous background fields, e.g. coaxial fields, occur very often. An implementation of such configurations would further extend the applicability of the model. With a suitable implementation of the high frequency/energy mechanism it would be possible to study not only standard voltage waveforms but also very fast transients (VFTs).

Most candidate gases for the replacement of SF$_6$ show a quite high boiling point which limits the usable pressure range. In addition it is known that certain gas mixtures, e.g. SF$_6$–N$_2$ mixtures, exhibit very pronounced synergistic effects. These synergistic effects can be detected in swarm parameter measurements. For both reasons the model, which is now validated for pure gases, should be extended and adapted for mixtures of two and more gases to enable the prediction for potential gas mixtures as well.
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A. Parameters and Scaling Factors for the Simulations

The scaling factors for the expansion of the streamer channel is not varied during the simulations as for this the computation of the gas-dynamics would have been necessary. They are therefore summarized in section A.1. The other scaling factors and gas parameters are given for each gas individually in the following sections.

A.1. General Scaling Factors

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A.2. Sulphur Hexafluoride

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A. Parameters and Scaling Factors for the Simulations

A.3. Octafluoropropane

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<td>$\left(\frac{\rho}{p}\right)_0$</td>
<td>$7.7 \cdot 10^{-5}$ kg/Pa m$^3$</td>
</tr>
<tr>
<td>critical field strength</td>
<td>$(E/N)_{crit}$</td>
<td>330 Td</td>
</tr>
<tr>
<td>velocity of sound</td>
<td>$c_0$</td>
<td>116 m/s</td>
</tr>
</tbody>
</table>

scaling factor

| precursor mechanism    | $\alpha_2$   | 0.1   |
| positive streamer radius| $C_{s,pos}$ | 1.9 Pa m |
| negative streamer radius| $C_{s,neg}$| 2.7 Pa m |

A.4. Tetrafluoromethane

<table>
<thead>
<tr>
<th>gas parameter</th>
<th>value</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalized density</td>
<td>$\left(\frac{\rho}{p}\right)_0$</td>
<td>$3.5 \cdot 10^{-5}$ kg/Pa m$^3$</td>
</tr>
<tr>
<td>critical field strength</td>
<td>$(E/N)_{crit}$</td>
<td>146 Td</td>
</tr>
<tr>
<td>velocity of sound</td>
<td>$c_0$</td>
<td>180 m/s</td>
</tr>
</tbody>
</table>

scaling factor

| precursor mechanism    | $\alpha_2$   | 0.05  |
| positive streamer radius| $C_{s,pos}$ | 1.7 Pa m |
| negative streamer radius| $C_{s,neg}$| 4.5 Pa m |

A.5. HFO1234ze

<table>
<thead>
<tr>
<th>gas parameter</th>
<th>value</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalized density</td>
<td>$\left(\frac{\rho}{p}\right)_0$</td>
<td>$4.7 \cdot 10^{-5}$ kg/Pa m$^3$</td>
</tr>
<tr>
<td>critical field strength</td>
<td>$(E/N)_{crit,lim}$</td>
<td>305 Td</td>
</tr>
<tr>
<td>velocity of sound</td>
<td>$c_0$</td>
<td>151.6 m/s</td>
</tr>
</tbody>
</table>

scaling factor

| precursor mechanism    | $\alpha_2$   | 0.03  |
| positive streamer radius| $C_{s,pos}$ | 1.5 Pa m |
| negative streamer radius| $C_{s,neg}$| 2.7 Pa m |
B. Time Lag Measurements in CF$_4$

This chapter provides all experimental results of the time lag measurements in CF$_4$. In total four pressures (0.10 MPa to 0.40 MPa) are investigated for both principal electrode configurations, i.e. for 1 mm protrusion length (geometry (A)) and for 3 mm protrusion length (geometry (B)). The statistical and formative time lags without X-ray application are marked with grey open squares (□) and grey-coloured triangles (▲), respectively. With X-ray application (only at 0.20 MPa) the statistical time lags are indicated with circles (⊙), the formative time lags with black triangles (▲). The small dots mark the application time of the X-rays.

From the time lag measurements the experimental boundaries of $x_{\text{min}}$ and $x_{\text{max}}$ can be deduced. If applying X-rays also $x_{\text{inc}}$ can be determined. These experimental boundaries are marked with solid lines (——). The corresponding calculated limits are indicated by dashed lines (–––). Theoretical limits for the statistical time lag are computed either by the Fowler-Nordheim equation or by the modified volume-time-law (section 3.2.2.1) and the results are plotted with dashed-dotted lines (—·—). The dotted line (······) gives the maximum time needed to reach the maximum of the applied voltage step.

The results show for both polarities and both geometries only a small amount of delayed breakdowns, especially at low pressures. While for a positive tip nearly all of the lowest observed discharges led to immediate breakdown, for the negative tip only partial discharges are detected for a substantial field range, except for the two investigations at 0.10 MPa. For geometry (A) above $x = 0.8$ a substantial part of the breakdowns at the positive tip occurred at the outer edges of the plate electrodes and did not start at the protrusion as expected. Reasons are discussed in section 7.3.3. For the negative tip and pressures of 0.30 MPa and 0.40 MPa in geometry (A) the formative time lags seem to show a “gap” between 1 µs and 100 µs. Its origin is not clear. The experimental results of the positive statistical time lags are not as well approached by the theoretical curves as for C$_3$F$_8$ and HFO1234ze, especially for geometry (B).
Figure B.1.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (A)) in CF₄ at 0.10 MPa. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (· · · · · ·).
Figure B.2.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (A), with X-ray: ⬜ \( t_s \), ▲ \( t_t \)) in CF\(_4\) at 0.20 MPa. The small dots mark the application time of the X-rays. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (· · · · · · · · · ·).
Figure B.3.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (A)) in CF$_4$ at 0.30 MPa. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— – —) and the upper limit to reach the maximum of the applied voltage step (·······).
Figure B.4.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (A)) in CF₄ at 0.40 MPa. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (—·—) and the upper limit to reach the maximum of the applied voltage step (· · · · · ·).
Figure B.5.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (B)) in CF₄ at 0.10 MPa. The lines indicate the experimentally determined boundaries (—) and the calculated ones (–––), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (········).
Figure B.6.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (B), with X-ray: ○ $t_s$, ▲ $t_t$) in CF$_4$ at 0.20 MPa. The small dots mark the application time of the X-rays. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (· · · · · ·).
Figure B.7.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (B)) in CF$_4$ at 0.30 MPa. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (· · · · ·).
Figure B.8.: Statistical (□) and formative (▲) time lag for negative and positive tip (geometry (B)) in CF₄ at 0.40 MPa. The lines indicate the experimentally determined boundaries (——) and the calculated ones (– – –), theoretical limits for the statistical time lag (— · —) and the upper limit to reach the maximum of the applied voltage step (· · · · · ·).
C. Time Lag Measurements in HFO1234ze

In HFO1234ze the investigations were limited to 0.30 MPa due to the low boiling point and due to the limited voltage range of the high voltage source (see negative polarity in figure C.5). This chapter provides all experimental results of the time lag measurements in the principal configuration. The experiments in HFO1234ze were executed with geometry (A), i.e. with a protrusion length of 1 mm.

The statistical time lags are marked with open squares (□), the formative time lags with grey triangles (▲). At 0.20 MPa additional investigations with X-rays were executed. The field strength of the application and the corresponding application time are marked with small dots. The statistical time lags are indicated by circles (○) and the formative time lags by black triangles (▲). The experimental limits of $x_{\text{inc}}$, $x_{\text{min}}$ and $x_{\text{max}}$, deduced from the time lag measurements, are marked with solid lines, the calculated inception field $x_{\text{inc}}^{\text{calc}}$ with dashed lines. The calculations of the mean time to a first available electron, i.e. the statistical time lag, is given by the dashed-dotted lines. The dotted line indicates the maximum time to full voltage.

In contrary to the results in C$_3$F$_8$ and CF$_4$ for nearly all pressures a small range of only partial discharges could be observed at positive voltage application. The conspicuity of the statistical time lags at the negative protrusion under X-ray application was discussed in section 8.3.3. Even more pronounced than for CF$_4$ is the “gap” in the formative time lags between 1 µs and 100 µs which can be observed for all pressures and both polarities. No explanation was found for this phenomenon.

The calculated inception field strength $x_{\text{inc}}^{\text{calc}}$ has a very pronounced pressure dependence (figure 8.3). For 0.10 MPa and 0.15 MPa the calculated inception is well above the experimentally observed inception field strength. As the fitted and experimental values for those pressures are similar (figure 4.5) an underestimation of the slope of the effective ionization coefficient $\alpha_{\text{eff}}/N$ in the range of $(E/N)_{\text{crit}}$ for those two pressures is reasonable.
Figure C.1.: Statistical (□) and formative (▲) time lags (geometry (A)) in HFO1234ze at 0.10 MPa. The vertical solid lines indicate the experimental limits of $x_{\text{min}}$ and $x_{\text{max}}$, the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for $t_s$ is marked by the dashed-dotted line.
Figure C.2.: Statistical (□) and formative (▲) time lags (geometry (A)) in HFO1234ze at 0.15 MPa. The vertical solid lines indicate the experimental limits of $x_{\text{min}}$ and $x_{\text{max}}$, the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for $t_s$ is marked by the dashed-dotted line.
Figure C.3.: Statistical (□) and formative (▲) time lags (geometry (A), with X-ray; ○ $t_s$, ▲ $t_f$) in HFO1234ze at 0.20 MPa. The small dots mark time of the X-ray application. The vertical solid lines indicate the experimental limits of $x_{inc}$, $x_{min}$ and $x_{max}$, the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for $t_s$ is marked by the dashed-dotted line.
Figure C.4.: Statistical (□) and formative (▲) time lags (geometry (A)) in HFO1234ze at 0.25 MPa. The vertical solid lines indicate the experimental limits of $x_{\text{min}}$ and $x_{\text{max}}$, the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for $t_s$ is marked by the dashed-dotted line.
C. Time Lag Measurements in HFO1234ze

Figure C.5.: Statistical (□) and formative (▲) time lags (geometry (A)) in HFO1234ze at 0.30 MPa. The vertical solid lines indicate the experimental limits of $x_{\text{min}}$ and $x_{\text{max}}$, the broken line the calculated inception field. The dotted line gives the upper limit of the time to the maximum of the applied voltage. The calculated boundary for $t_s$ is marked by the dashed-dotted line.
D. Acknowledgments

When I started my work at the High Voltage Laboratory I was very curious about what is expecting me in the next years. I would like to thank Prof. Christian Franck for giving me the opportunity of the research project and for his continuous support and encouragement whenever problems arose, be it with the experimental or the modelling part of the work. This made the time at the HVL a time full of valuable experiences.

Further I want to thank Prof. J. Kindersberger, the co-examiner, for carefully reading and evaluating my thesis, and for his helpful remarks.

My project would not have been possible nor successful without the help and support of many people: Hans-Jürg, Henry and Dave who helped me with the construction in the lab and the setup of the measuring devices. Claudia, who assisted when the computers or the network refused working. Karin, who always knew what to do if there was trouble with invoices and other administrative things. My office mates Dominik, Sedat, Mo, Malte and Raphael, for a good working atmosphere and many interesting discussions about flying fishes and other animals in the plots. And all others, who took time to discuss difficulties in the setup or in the programming or with the support hotline of some company or just to talk about anything and everything. And finally the Friday barbecue whenever the weather was good enough. All this made the life at HVL so pleasant.

In the end, I want to express special thanks to my parents, who supported me all the years even when I came up with a new crazy idea and to David.