COMPARATIVE STUDIES OF HIGH-GRADIENT RF AND DC BREAKDOWNS

Von der Fakultät für Mathematik, Informatik und Naturwissenschaften der RWTH Aachen University zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften genehmigte Dissertation

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# Nomenclature

## Acronyms

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<th>Description</th>
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<tr>
<td>ADC</td>
<td>Analog-to-digital converter</td>
</tr>
<tr>
<td>ASTA</td>
<td>Accelerator Structure Test Area</td>
</tr>
<tr>
<td>BDR</td>
<td>Breakdown rate</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-coupled Device</td>
</tr>
<tr>
<td>CLIC</td>
<td>Compact Linear Collider</td>
</tr>
<tr>
<td>CTF2</td>
<td>CLIC test facility 2</td>
</tr>
<tr>
<td>CTF3</td>
<td>CLIC test facility 3</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition system</td>
</tr>
<tr>
<td>FC</td>
<td>Faraday cup</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transformation</td>
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<tr>
<td>GE</td>
<td>Grating efficiency</td>
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<tr>
<td>GLC</td>
<td>Global Linear Collider</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>ILC</td>
<td>International Linear Collider</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>LEP</td>
<td>Large Electron-Positron Collider</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>LINAC</td>
<td>Linear accelerator</td>
</tr>
<tr>
<td>LTE</td>
<td>Local thermodynamic equilibrium</td>
</tr>
<tr>
<td>NEG</td>
<td>Non-evaporable getter</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>NLC</td>
<td>Next Linear Collider</td>
</tr>
<tr>
<td>NLCTA</td>
<td>Next Linear Collider Test Area</td>
</tr>
<tr>
<td>OTR</td>
<td>Optical transition radiation</td>
</tr>
<tr>
<td>PETS</td>
<td>Power extraction and transfer structure</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier</td>
</tr>
<tr>
<td>QE</td>
<td>Quantum efficiency</td>
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SEM Scanning electron microscope
SLAC Stanford Linear Accelerator Center
TLM Two line method
UHV Ultra-high vacuum
UV Ultraviolet

Constants

$\epsilon_0$ Vacuum permittivity, $8.854187 \cdot 10^{-12} \text{ As} / \text{Vm}$

$h$ Reduced Planck constant, $6.582118 \cdot 10^{-22} \text{ MeV s}$

c Speed of light, $299792458 \text{ m/s}$

e Electron charge, $1.602176 \cdot 10^{-19} \text{ C}$
Chapter 1

Introduction

“God made the bulk, surfaces were invented by the devil.”

Attributed to Wolfgang Pauli

The experimental work presented in this thesis was done in order to compare the physics of breakdowns occurring in high-power rf accelerating structures with a similar breakdown phenomenon observed in high-gradient dc spark gaps. What motivated this comparison was the need to benchmark different structure materials and surface treatments for their breakdown characteristics under equal electric field gradients. Since tests with dc spark gaps are less expensive in cost and time compared to rf tests, the relevance of the dc results towards their application in rf structure design was questioned and the comparison presented in this thesis was triggered.

The rf breakdown is a key issue in the CLIC project, a multi-TeV linear collider which is being designed for high-energy physics research at the energy frontier. A main component of CLIC are the high-gradient accelerating structures, with a 100 MV/m accelerating gradient in order to keep the overall site length below 50 km. 140000 of these structures will be needed to build CLIC, but a breakdown in only one of these structures is capable of deviating the beam and reducing the luminosity of the full complex. It is therefore a CLIC feasibility issue to develop rf structures running with the nominal accelerating gradient and at the same time with a very low breakdown probability. The experimental work done in this thesis will also help to get a better understanding of breakdown physics and will be used to benchmark breakdown models. Finally, the goal of the overall breakdown research is to understand the phenomenon in order to optimize high-power rf structure design and maximize performance.

1.1 The need for a linear collider in HEP

Since spring 2010, the LHC at CERN has been routinely colliding proton beams with a 7 TeV center-of-mass energy. This energy will be increased to 14 TeV with a nominal luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ in the coming years. At the same time the detectors have started taking data, the corresponding analysis results are following the amount of integrated luminosity. The LHC experiment aims at finding proof of the predicted standard model Higgs particle, and beyond this of the first signs of supersymmetry or other kinds of new physics.

The choice of building a hadron collider instead of a lepton machine was driven by the fact that the technology for a lepton linear collider with the desired beam energy was not available at the time of decision. In addition, heavy hadrons are expected to interact with the predicted Higgs particle with a much higher cross section than leptons due to strong coupling. Furthermore, a hadron collider at CERN had the advantage of reaching this center-of-mass energy at reduced costs by reusing the civil infrastructure of the LEP positron-electron collider.

LEP is the predecessor of LHC and reached a maximum of 105 GeV per beam, limited by the synchrotron radiation losses which could not be compensated in a technically feasible and economical way by the rf acceleration system.
Since the power $P_s$ radiated by synchrotron radiation due to transverse acceleration in the collider’s dipole bending magnets is proportional to the particles relativistic mass $\gamma$ to the power of four, the different rest mass when changing from electrons to protons results in a reduction of the radiated power by a factor of $10^{13}$ at equal particle energy $E$ and magnet bending radius $R$, see equation (1.1).

$$P_s = \frac{e^2c}{6\pi\epsilon_0} \left(\frac{E^4}{(m_e c^2)^4} \right) \frac{R^2}{\gamma^4}$$

(1.1)

An increase of beam energy from 0.2 TeV to 14 TeV like it was the case from $e^+e^-$-LEP to p-p-LHC results in a factor of $1.5 \cdot 10^6$ times more radiated power. This increase is still negligible compared to the decrease arising from the change of particle rest mass.

The effort to run a circular lepton machine of LEP size is immense. The LEP2 - the superconducting rf system upgrade of LEP necessary to reach 105 GeV of particle energy - finally consisted of 256 superconducting cavities distributed over four underground caverns, powered by 44 klystrons of 1.2 MW (peak) of continuous wave rf power at 352 MHz. This was necessary to compensate a particle energy loss of 3.5 GeV per turn, resulting in a radiated synchrotron radiation power of about 600 W per meter of dipole magnet.

Despite the fact that the physics results of the LHC are yet unknown, the particle physics community agrees on the necessity of a lepton collider as a complementary high energy physics instrument. This request is due to the downside of hadron physics: While leptons are still believed to be point-like particles without further substructure, protons consist of two up, one down quark and gluons mediating the strong force. This leads to the fact that when colliding two protons, the internal state energy of the two colliding protons is randomly distributed over the six constituents and therefore not predictable. The LHC is therefore well adapted to discover potentially existing new particles, but it is less able to do precision physics. Nevertheless, these precision measurements are vital for modern particle physics since they allow the discovery of potential deviations from theory based calculations, which often only show up in higher order corrective terms, but can point towards completely new physics.

The need for these precision measurements with lepton colliders and the limitations of circular lepton machines have triggered the development of linear colliders. Linear colliders are substantially different from circular colliders or storage rings in the following ways:

- Linear colliders do not need dipole magnets, since the acceleration takes place on a straight line up to the interaction region. Apart from the negligible synchrotron radiation losses from longitudinal acceleration and focusing magnetic fields, no synchrotron radiation losses take place in the main LINAC. The damping rings, transfer lines, bends etc. are operated at low particle energies.

- A linear collider consists of two opposed straight accelerators whose beams collide in the center of this facility, known as the crossing point or interaction region. This is where the physics detector will be placed. Since two detectors of different technologies are a minimum requirement for cross checking results, the collider will have to be equipped with a beam switchyard or a two-detector push-pull system. Circular machines on the other hand can have as many crossing points as foreseen by the beam optics lattice and are therefore more easy to implement and can furthermore have simultaneous collisions in these detectors.

- While a circular collider can store and collide the beams for many hours, a linear collider will be a one-pass machine. Besides, a reuse of the used beam is not technically feasible nor economical.

- A circular collider is practically always a synchrotron: The initial beam is injected at low energies and then accelerated in a central rf section while the magnetic field is synchronously ramped up to keep the beam on an orbit inside the vacuum chamber. A linear collider has an active rf acceleration over its full length, the beam is accelerated at all time from the injection to the final focusing system right before the interaction point. While in a proton synchrotron the rf system does not have to be particularly powerful in respect to particularly high gradient (e.g. several MV/m superconducting cw standing wave cavities in LHC) due to the multi-pass acceleration in a circular machine, the rf system in a linear collider has to provide very high peak accelerating fields to keep the overall length and therefore the total costs as low as possible, while still reaching the required center-of-mass energy and luminosity.

As of 2010, two linear collider concepts are under active development: The International Linear Collider (ILC) and the Compact Linear Collider (CLIC). Both projects share common concepts such as sources,
damping rings and detectors, but differ completely in the main beam acceleration concept. While the ILC developed superconducting, standing wave rf cavities running at 1.3 GHz and 35 MV/m maximum acceleration gradient close to the point of being industrialized, the CLIC main LINAC is based on room temperature, travelling wave 12 GHz cavities operating at a 100 MV/m gradient. Assuming that a total site length of 50 km is the upper limit for political acceptance of the project, the achievable center-of-mass energy with the existing technology is 0.8 TeV for the upgraded version of ILC and 3 TeV for CLIC in the final stage of expansion.

Furthermore, the generation of the rf power required for the main accelerating structures follows two different concepts in ILC and CLIC: while ILC plans to use klystrons to power the superconducting cavities, a new two beam based power generation system was developed for CLIC. This system will be explained in more detail in the following section. More details on both concepts can be found in [58] for ILC and in [21] for CLIC. The physics prospects for CLIC in comparison with ILC are summarized in [39].
1.2 The CLIC accelerator

The CLIC project is developing a 3 TeV center-of-mass electron-positron collider based on high-gradient, room-temperature accelerating structures and a novel two-beam based rf power generation scheme. While conventional accelerators use klystrons to power single or sets of structures, the rf power for the CLIC accelerating structures is provided by a two-beam scheme: the so-called drive beam is a low energy, high current beam produced in a high efficiency LINAC. It is then multiplied in frequency and current using a system of delay loops and combiner rings and sent down to sectors of accelerating structures in the main tunnel using transfer lines. After having passed a return turnaround, the drive beam is parallel to the main beam.

This main beam, the actual beam used for the physics experiments, is initially of low energy and low current, but of very high beam quality after having passed the damping rings and booster LINACs. To accelerate the main beam, rf power is extracted from the drive beam in the so called PETS structures and transferred to the main beam accelerating structures using waveguides. In principle, this resembles a beam-to-beam transformer [79]. This combination of PETS and accelerating structures is repeated many times along the main LINAC in modules of 2 m length. Each contains PETS, accelerating structures, rf distribution networks, focussing magnets, vacuum pumps and a variety of stabilization mechanisms and diagnostics. Two of these LINACS including drive beam plant and main beam source provide head-on collisions of electrons on positrons.

![Figure 1.1: CLIC 3 TeV linear collider complex layout](image)

Figure 1.1 shows the projected layout of the CLIC accelerator complex. This complex can be separated into two functional areas: The drive beam generation complex can be found above the main LINAC and can itself be split into two practically identical complexes, one to supply the electron main LINAC and one to supply the positron LINAC. The generation of a drive beam starts with a high-intensity electron source, injecting a 4.2 A beam bunched at 1 GHz into the drive beam LINAC. This klystron driven LINAC is designed to be fully loaded at the design beam current, providing an rf to beam power efficiency of nearly 98%, making it possible to keep the overall power consumption at the 400 MW level. At the end of this LINAC, the electrons exit with 2.4 GeV and are first injected into a delay loop and then into combiner rings. In these rings, the bunches from several bunch trains from the drive beam LINAC are combined to achieve a bunch frequency of 12 GHz and a peak beam current of 101 A. This beam is then transferred to the main
1.2. THE CLIC ACCELERATOR

LINAC tunnel where its power gets extracted in the PETS structure until the beam is decelerated down to 240 MeV. The power extraction is done within sections of 880 m. These are supplied with the drive beam using electromagnetic kickers and an elaborated timing scheme.

The main beam generation complex can be found in the lower half of figure 1.1. It comprises the sources for electrons and positrons, injector LINACs, damping rings and boosters. The assignment of this complex is to deliver 9 GeV electron and positron beams with 312 bunches of $3.72 \cdot 10^9$ particles each per train to the starting point of the main LINAC. The beam must have a transverse emittance below 600 nmrad (horizontal) and 10 nmrad (vertical), 44 µm bunch length and a 1.3% energy spread in order to be able to reach the design luminosity.

Shortly before the first main beam bunches arrive at the main LINAC, the drive beam starts producing 136 MW of rf power per PETS structure which are split to power two accelerating structures with 64 MW each. This power creates an accelerating field of 100 MV/m inside the structures. The total length of the rf pulse is 240 ns, covering the rf filling time of the structure and an accelerating field flat-top corresponding to the 156 ns main beam bunch train length.

Figure 1.2 shows a drawing of the basic rf network of CLIC with drive and main beam indicated. Furthermore, the rf system includes mechanisms to switch off the power production in the PETS, power splitters to feed two accelerating structures from one PETS, wakefield damping around each structure and rf diagnostics.

![Figure 1.2: Drawing of one half of the rf network of a basic CLIC module. A. Samoshkin, CERN.](image)

Both main LINACs will be assembled from these basic rf units into CLIC modules of 2 m length each. These modules will have equipment adapted to its role in the beam optics lattice, e.g. different strength quadrupole magnets, diagnostics and so on. After being accelerated to the nominal energy, the beam passes through the 2.5 km long final focus system to be focussed down to a beam size at the interaction point of 45 nm height and 0.9 nm width. This is necessary to achieve the projected luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ with the given bunch charge and average current. A stabilization of the final focus magnets to the sub-nm level is required to achieve this value, relaxed values of the bunch train parameters are excluded by the otherwise increased requirements for the beam optics and rf structure design.
1.3 CLIC accelerating structures: 100 MV/m as a feasibility issue

At a given center-of-mass energy, the overall length of the main LINAC and the total acceleration gives the average accelerating gradient and the achieved fill factor of the LINAC, which is defined as the average (including magnets, beam instrumentation, collimators etc.) by the peak accelerating gradient (inside the accelerating structures). The fill factor is about 0.78 in the CLIC 3 TeV scheme.

To get to the projected 3 TeV center-of-mass energy within the boundary of less than 50 km total site length, the main beam accelerating structures will have to provide an average of 100 MV/m loaded gradient. This must also be done with high efficiency in order to reduce the power consumption of the full CLIC complex to a feasible value. Structures with very high gradients have been developed in the last decades and reached up to 193 MV/m at 30 GHz with a pulse length of 15 ns [95]. These structures are largely limited by rf breakdown. An rf breakdown is defined as a sudden change in the electric parameters of the structure, resulting into heavy reflections back to the rf source and a cut-off of the transmitted power. This leads to a collapse of the accelerating field inside the structure and to the stimulation of tranverse fields which can give a tranverse kick to the passing beam [1]. Accompanying effects are light emission, the ejection of electrons and ions out of the structure, X-rays and surface damage. These effects are indications that the breakdown itself is a rf initiated surface plasma process.

In the 3 TeV CLIC, around 140000 accelerating structures and 70000 PETS structures will be in use at the same time with a 50 Hz rf repetition rate. Assuming that a breakdown in a single structure or PETS can cause a drastic loss in luminosity for that bunch train, the operational maximum breakdown rate has been calculated to be one breakdown in roughly $10^7$ rf pulses at 100 MV/m loaded gradient (or later on referred to as probability per rf pulse and structure, here $4 \cdot 10^{-7}$).

Furthermore, structures are damaged by breakdowns and potentially degrade in performance on long time-scales. Ideally, the rf structures and also the PETS should survive about 20 years of CLIC operation, adding up to about $2 \cdot 10^{10}$ rf pulses.

To achieve these low breakdown rates and high structure lifetimes, a systematic investigation of structure geometries, materials and production processes has been started in the recent years. In parallel, the physics of the breakdown and structure performance scaling laws became a growing field of research in the CLIC project.

1.4 State of the art in accelerator performance limitation

In 2008, the first high-gradient structure achieved the required CLIC rf structure parameters [34]. The high-power test conducted at SLAC showed that the T18_vg2.6 accelerating structure can run in excess of a 100 MV/m unloaded gradient at a breakdown rate of $4 \cdot 10^{-7}$ and the nominal CLIC pulse length of 230 ns.

The structure, however, does not include wakefield damping, an essential part of the CLIC structure design which is necessary to suppress higher-order-mode transverse rf fields caused by misalignments. This feature is implemented by modifying the structure geometry and introducing rf damping material inside wakefield damping slots.

In 2010, high-power tests of a full CLIC accelerating structure including wakefield damping are planned.

1.5 Study of the breakdown phenomena

Given the importance of the breakdown process to the CLIC project, several theoretical and experimental approaches towards understanding this phenomena have been started. These include theoretical modelling of surface processes under the influence of high-power rf fields, including the breakdown initiation, subsequent plasma processes and its impact on the rf.

On the experimental side, data from low- and high-power rf tests have been analyzed, looking for correlations of damage, particle ejection and breakdown rate with the energy dissipated by breakdowns and possible precursors. To extend the knowledge and especially to connect theoretical and experimental studies of the breakdown process, new diagnostic techniques like optical, time-resolved spectroscopy were applied to rf and dc breakdowns. They are the subject of this thesis. These results will help to define input parameters to the simulation codes and will help to benchmark these.

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1 Beam loading: The beam takes energy from the rf and therefore reduces the gradient. 100 MV/m loaded gradient corresponds to roughly 110 MV/m unloaded gradient, e.g. during a structure test without beam.


Chapter 2

Introduction to accelerating structures

Acelerating structures are a key part of all particle accelerators. Whereas early particle accelerators used purely electrostatic acceleration and were therefore limited by the maximum voltage which could be handled, the invention of the first rf linear accelerator by Rolf Wideröe in Aachen in 1928 opened the path to overcome this limitation. Nowadays, the highest achievable gradients in multicell structures are around 100 MV/m in normal conducting travelling wave structures at multi-GHz frequencies. At those high gradients, new limitations occur and are a matter of ongoing research, including this thesis. Understanding and overcoming these limitations is of fundamental importance for the feasibility of a high gradient accelerator such as CLIC.

The next sections will give an introduction to accelerating structures, especially travelling wave structures operating at room temperature. For more details and also a more general introduction, see [89] and [90].

2.1 Travelling wave accelerating structures and performance limiters

Accelerating structures are used to provide a rf field configuration in which it is possible to accelerate charged particles. To do so, a rf electric field in the direction of the particles trajectory has to be provided by the structures geometry which in addition is slowed down to a phase velocity equivalent to the speed of the particle. If the particle is now injected into the structure at the correct phase, it will “surf” on the electromagnetic wave and gain energy while it travels with it. It is then called synchronous. The maximum energy that the particle can gain is given by the average electric field (taking into account the phase) the particle is subjected to multiplied by the length of the path it travels in that field. The equation (2.1) connects the energy gain $\Delta W$ with the particles charge $q$, the amplitude of the accelerating field $V_0$ and $\phi$, the phase of the particle relative to the rf field.

$$\Delta W = qV_0 \cos \phi$$  

(2.1)

The accelerating field $V_0$ depends on which principle wave or mode is selected by design for operation. More details on this in section 2.1.2

2.1.1 Overview of a travelling wave accelerating structure

Travelling wave accelerating structures consist of three main part: Input/output coupler, matching cells and regular cells. Matching cells and regular cells form together what is called a disk stack. The couplers are used to couple the rf power coming from an external power source via a waveguide (in most cases a rectangular waveguide) into the disk stack. To do so, it has to convert the waveguide mode into a circular mode which is then matched by the matching irises to travel through the disk stack of the regular cells with a minimum of reflection. The wave is then coupled out by the output coupler and then dumped into a load.

Openings below cutoff of the operating frequency are foreseen on an axis on both sides of the structure in order to allow the beam to pass through. The structure is fully rotationally symmetric around that beam.
axis except for the coupler openings for the waveguide input and output. As already indicated in figure 2.1, the iris surfaces have to be rounded to avoid field enhancement of the electric field component and to avoid limitations explained later in this chapter.

### 2.1.2 Periodic loading and Floquet’s theorem

A travelling wave structure can be simplified to a circular waveguide with a periodic disk loading. In a circular waveguide with the lowest transverse-magnetic mode TM01, the electric field configuration of a travelling wave in $+z$ direction is given by equation (2.2):

$$
E_z(r, z, t) = E J_0(Kr) e^{j(\omega t - k_0 z)}
$$  \hspace{1cm} (2.2)

With $\omega$ being the angular frequency of that mode, $k_0 z$ the corresponding wavenumber and $J_0$ the Bessel function of zeroth order. The dispersion relation for this uniform waveguide (2.3) is:

$$
\omega^2 = (\omega_c)^2 + (k_c c)^2
$$  \hspace{1cm} (2.3)

Here, $\omega_c = K c$ is the cutoff angular frequency with $K$ being the cutoff wavenumber. The phase velocity can then be written as (2.4):

$$
v_p = \frac{\omega}{k_0} = \frac{c}{\sqrt{1 - (K c)^2/\omega^2}} > c
$$  \hspace{1cm} (2.4)

As a result, the phase velocity of the fundamental wave in this waveguide is above the speed of light $c$, indicated by the parabolic line in figure 2.2. If a particle - even though it might already be relativistic - enters such a waveguide, the average acceleration will be zero. To achieve synchronism between the particle and the fundamental wave, the phase velocity is slowed down by periodic disk loading with a distance $d$ between two disks. This results in a periodic modulation of the
null
and output couplers, coupling irises and regular cells. Even the regular cells are not necessarily periodic in geometry. In modern structures like the CLIC G structure (see section 4.3 for details), the irises are tapered by gradually decreasing the iris diameter towards the output, resulting in a constant accelerating field along the beam axis despite ohmic and beamloading losses. Numerical tools for structure design are either based in frequency domain like HFSS™ [12] and GdfidL [22] or in time domain like Microwave Studio™ [26].

2.1.4 Surface and volume field distribution

Using the above mentioned numerical software tools, the exact distribution of fields on the surface and in the inner volume of an accelerating structure can be calculated and areas of high electric and magnetic fields can be indentified. These areas are especially interesting since they are known to be those where performance limiting surface effects are taking place. An example for surface fields calculated for a modern CLIC travelling wave accelerating structure is shown in figure 2.3.

Figure 2.3: Surface magnetic (left) and surface electric field distribution in a quater cell of a CLIC waveguide damped structure (WDS). All values have to be multiplied by \(10^9\) to get nominal values. The full structure is made of longitudinally stacked disks, each of them shaped like four of the shown quadrants. By A. Grudiev, CERN.

It is evident from this figure that the maximum electric surface field can be found on the iris close to the beam axis and the maximum electric field in the walls of the cells. The knowledge of the field distribution is important for the post mortem analysis of high power tested
2.2 High power limits and scaling laws

Phenomenological and model based high power limits serve as scaling laws for the design of optimum performance structures. A better understanding of the physics of high power rf helps to define design parameters and even the phenomenological approach - that is the extrapolation of successfully implemented design parameters - will lead to a better accelerating structure performance. As already mentioned in section [1,5] the goal of this thesis and its underlying experimental work is to provide experimental support for existing and refined scaling laws. The following summary gives an overview of the scaling laws for high power accelerating structures developed so far. All models are based on the assumption, that Paschen’s law [78] is not relevant due to a very low pressure, typically below $10^{-3}$ Pa. In that region, the mean free path of the particles is longer than the gap distance between the electrodes. Therefore, gas-particle interactions are negligible.

2.2.1 The Fowler-Nordheim field emission law

All models have a common starting point: the main process leading to dark current and breakdown is field emission of electrons from microscopic emitters on the surface. These emitters are made of either the surface material itself (like machining marks, surface roughness or grain boundaries and whiskers) or of other materials such as impurities (dust, cleaning fluid remnants). In the latter case, cleanroom handling procedures can be crucial during the final assembly of the structure. The electron emission can be enhanced by the shape of the field emitter, expressed by the field enhancement factor $\beta$. Figure 2.4 shows examples of field emitter geometries and the corresponding $\beta$.

![Figure 2.4: Field enhancement factors $\beta$ for different geometries. The axis are aspect ratios of different geometries, see figures inside plot. From [78].](image)

The emitted current as a function of the field enhancement factor $\beta$, the work function $\phi [\text{eV}]$ and the local electric field $E [\text{V/m}]$ is given by the Fowler-Nordheim equation [42]. This field emission current originates from the increase of tunneling through the surface with increasing applied surface field. This
potential barrier - more specific than the difference between Fermi level and vacuum potential - is called work function and is a specific material parameter. With an increasing surface electric field gradient, the tunneling probability of electrons increases and field emissions starts. A simplified version \[87\] of the Fowler-Nordheim equation for practical calculations is equation (2.10).

\[
I_F[A/m^2] = \frac{1.54 \cdot 10^{-6} \cdot 10^{4.52\phi^{-0.5}}}{\phi \beta^2 E^2 \exp\left(-\frac{6.53 \cdot 10^9 \phi^{1.5}}{\beta E}\right)}
\]  

(2.10)

The work function $\phi$ changes with material and crystallographic orientation, values for selected materials are listed in tables A.1 and A.2 in appendix A.

Typical values for $\beta$ observed in experiments are in the order of 10 to 100, the corresponding field emission current as a function of the local electric field are plotted in figure 2.5.

![Figure 2.5: Field emission current in $[A/\mu m^2]$ for copper (100) and different $\beta$: Solid green line for $\beta=100$, dashed red line for $\beta=50$ and dotted blue line for $\beta=10$.](image)

The dynamic range of the emitted current is remarkable, a change from 50 MV/m to 100 MV/m in electric field translates into a current change of 8 orders of magnitude. This sensitivity makes measurements of the emitted current challenging since currents in the order of several $\mu A/\mu m^2$ can change the surface properties (see chapter 5) and result in a breakdown.
2.2. HIGH POWER LIMITS AND SCALING LAWS

2.2.2 The Kilpatrick criterion

Kilpatrick's criterion is the first attempt to create a phenomenological high power limit, published in 1957 [61]. This limit is valid for rf and pulsed dc. The basis for the criterion was data obtained empirically from experiments with spark gaps in vacuum applying either rf or dc voltage. The criterion describes a threshold gradient which defines the border between 'no vacuum sparking' and 'possible vacuum sparking' [61]. Kilpatrick formulated this criterion as equation (2.11) and indicated in figure 2.6 a line separating the areas of unperturbed operation of the gap (that is no breakdowns) and the area of operation possibly perturbed by breakdowns.

\[ WE^2 e^{-1.7 \times 10^5 E} = 1.8 \cdot 10^{14} \]  

(2.11)

\( W [eV] \) represents the maximum ion energy at the cathode which is equal to the applied voltage to the gap of the dc case. For rf, \( W \) has to be corrected using the frequency and gap size resulting in a transit-time like correction. \( E [V/cm] \) is the electric field gradient at the cathode surface.

![Figure 2.6: Kilpatrick’s original plot from [61]. See text for explanation. \( Me \equiv MHz ('\text{Megacycles}') \).](image)

Kilpatrick's criterion has been reformulated in [19] to include the frequency in the rf case. The results show a square-root dependency of the maximum electric field to the frequency (2.12).

\[ f[MHz] = 1.64 \cdot E[MV/m]^2 \cdot e^{\frac{8.5}{\sqrt{f[MHz]}}} \]  

(2.12)

Kilpatrick based his model on the impact of electrons and ions on the cathode and the following avalanche discharge initiated above a certain frequency and electric field threshold, resulting in ion and electron multiplication when the primaries hit the cathode surface. The quasi transit time factor for ion movement in a rf electric field was therefore calculated using the mass of a hydrogen atom [61]. Furthermore, no dependency on the electrode material was found. Only traces of surface contaminants such as oil from handling decreased the breakdown threshold. Besides his criterion, Kilpatrick pointed out that a conditioning process can increase this threshold both in rf and dc. Conditioning was afterwards established as a standard procedure for all accelerating structures as well as high voltage dc applications. In 1989, J.W. Wang...
revised Kilpatrick’s criterion driven by the fact that experiments already performed better than expected by
the criterion. He also proposed a new breakdown mechanism based on microscopic field emitters and the
Fowler-Nordheim emission law \[85\].

2.2.3 The P/C criterion

A more recent attempt to model the high-power performance of a travelling-wave structure is the phe-
nomenological P/C-criterion. Here, a structure is limited by a maximum power flow going through it. Since
a pure field-emission criterion - which is directly bound to a maximum surface electric field - has been
shown to be insufficient as a simple limiting factor after analysing data from different experiments
with varying rf parameters \[94, 93, 1\], this new criterion based on the power-flow has been proposed
by W.Wuensch in 2006 \[92\]. This results out of the observation that structures with larger aperture and a
higher group velocity tolerate higher power flows but at the same time lower surface electric fields. This is
quantified in equation (2.13).

\[
\frac{P t^{\alpha}}{C} < \text{const.}
\]  

(2.13)

P is the power flow through the structure, C the smallest circumference of the structures irises and t the
pulse length. The pulse length dependence $\alpha$ is a material dependent parameter and has been measured to
be $\approx \frac{1}{3}$ for copper structures and $\approx \frac{2}{3}$ for molybdenum structures \[97\].

This equation combines two models based partially on features observed at that time and basic physics:
Craters created by breakdowns are all similar in geometry, having a diameter of the order of 100 µm \[95\],
independent of frequency and structure parameters. They are very small compared to the structures’ fea-
tures, even at frequencies as high as 30 GHz. Thus, the power available to the breakdown can only be
proportional to the power above the breakdown, which is equal or lower than the total power flow through
the structure divided by the smallest iris circumference, resulting in comparable microscopic damage by
breakdowns independent of structure parameters. The constant value of equation (2.13) varies only in the
range between 10 and 20\(\frac{MWns}{mm^{1/3}}\) for copper, even with changes of one order of magnitude in group
velocity and pulse length and changes of factors of two to three in frequency, iris diameter, input power and
maximum surface field. In addition, the constant value becomes really constant after conditioning has been
finished, that is when all impurities, dirt and other sources of breakdowns have been removed by processing.
The value is then the proportional to the absolute maximum field level the surface can withstand before a
breakdown which is not caused by the before mentioned effects occurrences. A table summarizing values
obtained in different experiments can be found in \[92\].

The $P t^{\alpha}$ term is an extension of the $P t^{1/2}$ ablation limit described in \[37\] which bases the pulse-length
dependency scaling on one-dimensional heat diffusion into the bulk. This assumption seems to be too gene-
ral in case of copper and molybdenum, where more-dimensional heat diffusion, higher respectively lower
thermal conductivity and other radiative effects such as thermal radiation might play a role.

2.2.4 The modified Poynting vector $S_e$

Although the P/C scaling fit a large fraction of available data, deviation in some standing and travelling wave
structures was observed from geometries scaled to different frequencies. Some structures exceeded the P/C
limitation. In addition the criterion does not apply to standing wave structures since there is practically no
power flow. The observation that scaled structures achieve similar gradients at similar pulse lengths and
breakdown rates \[86, 176\] stands in contradiction to the P/C limitation where one expects a scaling of these
values inversely with to frequency \[47\]. The new model is like the P/C criterion based on the limited power
flow, but the new model considers now both a real and imaginary (reactive) part of it, making this criterion
applicable also to standing wave structures. The model describes the local fields around a field emitter tip
and quantifies how the field emission current influences the local rf field. This field is perturbed by the
emitted current taking energy out of the field i order to extract and accelerate electrons similar to the beam
loading in macroscopic structures. The available power flow therefore determines the power available for
the field emission which, in addition is dependent of the field enhancement factor and the material of the
emitter tip. Due to this emission current, the tip will be subjected to ohmic heating. An upper limit of the
possible temperature rise is the melting of the tip, resulting in a breakdown when exceeded. An equivalent
explanation is the increase in density of field evaporated neutral atoms supported by the heating of the
2.2. HIGH POWER LIMITS AND SCALING LAWS

In more detail, this scaling law is deduced using the field configuration around a field emitter of Fowler-Nordheim type of cylindrical shape with a hemispherical cap (see figure 2.7). For this tip, the pulsed ohmic heating is calculated from which the power necessary to heat up the tip to its melting point within a certain time (here 100 ns) can be extracted. The result when assuming a height of the tip of \( \approx 1 \mu m \) is a field emission current of \( \approx 36 \, A / \mu m^3 \) using the copper properties available in appendix A. Similar values have been found in experiments presented in [70].

A \( \beta \) factor of 40 to 60 can be estimated from this model using surface electric fields \( E \) of around 200 MV/m which are known to be the copper breakdown threshold from DC sparc experiments (see chapter 5), a tip diameter of 17-25 nm follows from these calculations. This is in agreement with a maximum local electric field of \( \beta \cdot E \approx 10 \, GV/m \) which is supposed to be sufficient to pull neutral copper atoms out of the copper crystal lattice into the vacuum [62], [31].

![Figure 2.7: E-field configuration (color-coded logarithmic intensity) around a cylindrical field emitter. The arrows indicate the field direction. From [47].](image)

As mentioned above, power necessary to heat up the tip is taken from the rf field, more precisely from the power flow along the surface which can be described by the Poynting vector. Field emission and current flow through the tip resulting in ohmic heating occurs and modifies the rf electromagnetic field in the vicinity of the tip, leading to power losses into the heating of the tip and into the field emission current. The residual power flow is therefore reduced by these losses as indicated in figure 2.8.

The corresponding loss equation as a function of time can be found in [47]. These expressions are then generalized to be valid for both travelling and standing wave structures. The expression for the time dependency of the Fowler-Nordheim power loss in a sinusoidal electric field is then given by equation (2.14).

\[
P_{FN}(t) = A E_0^3 \sin^3 \omega t \cdot exp\left(\frac{-62}{\beta E_0 \omega t}\right)
\]  

(2.14)

With \( A \) being the surface area of the field emitter and \( \omega = 2\pi f \) the angular frequency. For all other variables see equation (2.10). The rf power flow can be divided into a real and an imaginary part with a 90° phase shift between both. The real part is the energy propagation inside travelling structures only and the imaginary part energy oscillations between storage in electric and magnetic fields present in all resonant cavities. Resulting from the phase shift, the reactive power flow - out of phase with \( P_{FN} \) - is not as efficient in providing power for the field emission as the active power flow being in phase with \( P_{FN} \). The ratio between these two, each multiplied with the field emission power loss, is called weighting factor \( g_c \). This
factor depends on the local field $\beta E_0$, but is only weakly correlated to it. Using the complex pointing vector $\vec{S}$, which is available from numerical rf simulation programs for every point of the structure, the new local field quantity can be written as (2.15).

$$S_c = \Re\{\vec{S}\} + g_c \cdot \Im\{\vec{S}\}$$  \hspace{1cm} (2.15)

The unit of $S_c$ is $W/\mu m^2$. As design guideline for new RF structures, $S_c$ should not exceed $5W/\mu m^2$ if the structure is supposed to operate at a breakdown rate smaller than $1 \cdot 10^{-6}$ m and a 200 ns pulse length assuming a standard pulse length dependence. Since $S_c$ can be calculated for each point on the structure surface, possible zones with a high breakdown probability can be identified prior to machining and testing the structure.

The validity of the $S_c$ criterion and of other high gradient limits is under continuous experimental study right now, testing for example the CLIC_G structure which has been designed specifically with regard to this criterion. First results should be available by mid 2010 [47].

### 2.2.5 Fatigue related limitations

CLIC accelerating structures will have to be designed for a total lifetime of $\approx 2 \cdot 10^{10}$ rf pulses, corresponding to 20 years of operation with nine months of full time operation per year at a 50Hz repetition rate. Each rf pulse will stress the surface of the accelerating structure by electromagnetic forces and pulsed surface heating. The latter will heat up the surface of about 60 K during each pulse [55], inducing a thermal strain of $9.2 \cdot 10^{-2}$, corresponding to a macro stress of 110 MPa [6]. These cyclic stresses can lead to fatigue related damage roughening of the surface. This could result in a decrease of the Q-factor and possibly create field emitter tips. Material fatigue effects limit the lifetime of a structure by increasing the breakdown rate and also by decreasing the accelerating gradient by increased losses on the surface. Since such high stress cycle numbers with such short pulses of the order of 100 ns and the damage criterion given by the lowest acceptable rf performance have not yet been addressed by material researchers, a dedicated research program has been started at CERN in order to find materials which can withstand those numbers of cycles and have at the same time the necessary rf and machining parameters. To extend known lifetime data available up to $10^7$ cycles and to investigate pulse length and heat depth influence on fatigue, several high-cycle measurement setups have been developed. One uses ultrasound generators to apply cyclic stresses to cylindric material samples, another a UV laser to simulate pulsed surface heating and a third a specially designed cavity with interchangeable samples for material testing with rf. The ultrasound setup operates at 24000 compression/expansion cycles per second, thus simulating CLIC lifetime in ten days of continuous operation. The laser setup and the rf setup operate at 200Hz [23] 60Hz respectively and are predominantly used for surface studies such as roughness measurements during and after smaller amounts of stress cycles [64], [63]. The tests have been focussed on samples of high conductivity oxygen-free copper (OFC) and copper based alloys like GlidCop© or CuZr, all of them produced with different machining and surface
treatment techniques [13]. In addition, the dependence of the fatigue resistance from the grain orientation has been observed. First results show a difference in degree of damage patterns when looking at grains with different orientations on an evenly treated surface [5], [7]. The lifetime expectation determined here and the breakdown behaviour of the corresponding materials tested in the dc setup are used as preselection criterion for the material which will then be used for an accelerating structure and tested with rf [14].
2.3 CLIC high gradient studies

To approach the feasibility issue of the CLIC main linac accelerating structures of 100 MV/m at a BDR of $4 \cdot 10^{-7}$, the CLIC high-gradient rf program at CERN comprises research in the fields of material science, rf design and theoretical multiphysics modelling. The initial rf structure design program revealed several constraints on rf high-power performance and lifetime. This led to the need to do research beyond the scope of classical rf design. These programs include the search for the surface physics underlying the breakdown and fatigue phenomena both in theory and experiment. Results are then used to refine or newly establish scaling laws which will then be used in rf design in order to increase the high-gradient performance. This includes not only the geometrical design of the structures, but also the choice of materials, rf processing schemes, manufacturing techniques as well as cleaning and handling procedures.

The next two sections will introduce the experimental approaches of the CLIC high-gradient rf program. The theoretical work done in parallel with frequent exchange of experimental results and theoretical predictions in reach of the experiment is described in more detail in chapter 3.

2.3.1 Rf tests

CLIC rf structure tests aim at gaining a detailed performance analysis of a structure design by testing it with high power rf. Test facilities are available at SLAC, KEK and CERN. More details on the experimental setup can be found in chapter 4. These tests consist of two parts: the conditioning of the structure followed by the actual measurement of the BDR at different power levels and processing states. In this context, processing state refers to the amount of pulses a structure has been tested with at a certain point in time. The conditioning process is a stepwise increase of input power at a fixed pulse length which is defined as the conditioning target at a given processing state. When a breakdown occurs, the input power is stopped and then restarted at a lower input power and/or pulse length which are then gradually increased within several tens of rf pulses until they reach again the target values. After each increase in input power, which means changing the conditioning target, the BDR rises immediately at the beginning and then quiets down until a low steady state BDR at this conditioning target is reached. The input power is then increased again and this process is repeated until the nominal input power is reached or if the BDR does not quiet down anymore after one of these power increases, which indicate that the maximum achievable field at this pulse length has been reached. This ramping process is now repeated with stepwise increasing pulse length. If no further step in input power level at nominal pulse length is possible without permanently increasing the BDR rate, the structure is considered to be fully conditioned. Typically, structures keep conditioning during all the processing time, even during the later BDR measurements, but the increase in performance is negligible compared to the first hours of conditioning. If the BDR already saturates at lower input power and/or pulse length, a problem leading to increased BDR must be assumed to be present in this structure.

After the structure was successfully conditioned, the BDR is measured at different constant levels of input power and pulse length. In this mode, the input power and pulse length is not backed up if a breakdown occurs. An example of a processing history can be found in figure 2.9 with corresponding explanations in section 2.3.3.

Several other measurements are done in parallel, specialized on the detection of dark current and light emissions. These measurements are not directly relevant to the structures’ high gradient performance, but are dedicated to breakdown physics and breakdown onset research. A specialized kind of rf tests are the rf fatigue tests done at SLAC with a mushroom cavity and numerous tests of high power rf components such as waveguide flanges, valves, splitters and so on. More details on the rf fatigue tests can be found in section 2.2.5.

2.3.2 Dc tests

Since rf tests take more than a year from the design phase to the testing phase and because there is a limited availability of high power rf testing slots, only a small number of structures can be produced and tested per year. Therefore, a new structure design typically incorporates several new design features, or if a structure performs well, several identical structures have to be tested in order to gain information about the reproducibility of this performance. As a consequence, it is not possible to test single features each in a separate structure. An approach to overcome these limitations is the dc spark test stand. It is dedicated to study the influence of materials, machining, cleaning and handling techniques on breakdown rate and maximum sustainable field gradient. Over the years, several other tests and diagnostic methods were used
in combination with the dc setup in order to study breakdown plasma and surface physics and to support theoretical modelling of breakdowns as well as the process triggering breakdowns with experimental data. The description of some of these experiments is part of the scope of this thesis. A final goal of the dc setup is the application of the results to rf structure design and manufacturing, leading to better high power rf performances at a fraction of the time and cost an equivalent test in rf would have. One of the issues is the transferability of dc results to rf. This task is address in this thesis.

The dc spark test can be simplified to a spark gap in vacuum with a power supply that allows the creation of adjustable electric field gradients in that gap, which are in the same order of magnitude than the surface fields in rf structures. In addition, the power supply allows the pulsed application of these fields to the gap. More details on the setup can be found in section 4.3. The processing of the spark gap is similar to rf structures, a conditioning phase is followed by breakdown rate measurements. During the conditioning, the field is stepwise increased until a breakdown occurs. If this is the case, the voltage is set back to its initial, low value and the ramp starts again. If no breakdown occurs, a maximum voltage is defined where the system stops the conditioning mode if this value is reached. At that moment, the conditioning is finished and BDR measurements can start at constant electric field gradients.

The dc spark setup is in addition equipped with several other instrumentation for breakdown and surface physics investigation. Its capability to measure the field enhancement factor of the surface and the possibility to collect light emitted by processes happening in the gap will especially play a role in the later chapters of this thesis.

2.3.3 Breakdown rate test data analysis

The BDR of a structure is the number of breakdowns observed in a data set divided by the number of total pulses. It is measured per structure and sometimes converted in BDR per meter of active structure. Measuring this value therefore means measuring a probability which can only be quantified if a breakdown has been probed with a sufficient amount of test pulses with equal pulse energy, shape and duration. The BDR definition is equally valid for the dc test stand, except that the gap is the only place where a breakdown can occur, making the per unit length definition unapplicable.

The BDR is measured at different conditioning states of the structure and spark sample respectively. As an example, the measured BDRs at different processing times and gradients for the CERN T18 structure tested at SLAC are plotted in figure 2.9.

Already in NLC/GLC structure tests at SLAC in the early years of 2000, a remarkably strong exponential behaviour of the BDR with rising accelerating gradient has been observed [35]:

\[ E^x \cdot BDR = \text{const.} \]  

(2.16)

Here, E is the accelerating field gradient at fixed pulse length and x a free parameter. In structure tests, this parameter has been routinely fitted to a value between 30 and 35 and is independent of the used frequency [47]. Another correlation between pulse length and gradient has been found for data taken at a fixed BDR:

\[ E \cdot t^{1/6} = \text{const.} \]  

(2.17)

This sixth-root dependence of the pulse length t from the accelerating gradient E does also not show a correlation with the operating frequency [47] and is used for the comparison of data taken at different pulse lengths.

Both equations can be combined in one general formula connecting the accelerating gradient, the pulse lengths and the BDR:

\[ E^{30} \cdot t^5 \cdot BDR = \text{const.} \]  

(2.18)

In figure 2.9 fits of equation (2.18) to data points at different gradients and at fixed processing times are plotted. Similar plots are made for all structure tests and are standard for the presentation and comparison.
In dc, a similar behaviour has been observed [29], but the pulse length dependence does not apply here since the pulse length is fixed in the setup and in the range of seconds compared to a few 100 ns in rf. In a future upgrade of the dc setup with a more versatile power supply, the pulse length dependency can be addressed and studied.

The error on the breakdown rate decreases statistically with the square-root of the number of detected breakdowns, thus with the number of rf pulses at a constant breakdown rate and rf parameters respectively constant gradient dc pulses. Therefore, a limiting factor significantly influencing the ability to measure very low breakdown rates is the repetition rate of the rf or dc pulses and the available test time (see chapter 4 for details on the available repetition rates). In rf, a statistically significant BDR of $10^{-7}$ 1/pulse/m can be achieved in around 1000 h of test at a 60 Hz repetition rate. The repetition rate of the dc setup is very low due to its mechanical switches ($\approx 0.1$ Hz), but a planned change to solid state based switches will soon allow to reach repetition rates in the order of 1 kHz, thus getting the ability to measure BDRs of the order of $10^{-10}$ 1/pulse within a reasonable testing time.
Chapter 3

Theoretical description of breakdowns

The complexity of the breakdown phenomenon has meant that a complete and quantitative description has eluded researchers. Most models assume that field emission is an important part of the initiation of a breakdown. The process can be broken into three steps. In the following three subsections, the assumed physics of a breakdown will be described following these three steps. This division has been driven by the major effects which are happening at the cathode [15]. There will be no further consideration of the anode effects unless mentioned since the anode is not playing an important role in the onset phase of the breakdown in this model. Each step can also be found in figure 3.1 to which these subsections will refer to. As far as there are differences concerning rf or dc, these are mentioned there. All models describe statistical breakdown appearing in the statistical breakdown regime after the structure or sample has been fully conditioned.

3.1 Onset phase

The starting point of the breakdown model described here is field emission from a surface which rises above a certain electron current density, later on referred to as breakdown threshold. The source of this field emission are geometrical objects on the surface, the so called field emitters. A breakdown model has to explain what these field emitters look like and how they are changing under the influence of an electric field in order to eventually reach the breakdown threshold and trigger a breakdown. No effect is known which could otherwise explain an electron current emission from a flat surface.

The simplest model of a field emitter is an object sticking out of the otherwise flat material surface (see figure 3.1, box a). Ideas about the origin and material of this emitter tip can be very different and several scenarios are conceivable: Contamination of the surface by dust particles of various compositions of materials or traces of machining, handling, cleaning, material fatigue etc. that formed emitter tips on the surface by deformation of the bulk material.

The shape of these emitter tips defines the field enhancement factor $\beta$. Its size was estimated to less than 1 $\mu$m in height and less than a few tens of nm in diameter, resulting in an effective volume of a few thousand atoms above the ideally flat surface [57]. The current flowing through this tip heats it up when the electric field is applied. In addition, the electric force applies a tensile stress to the surface atoms, possibly leading to a shot-to-shot or even intra-pulse deformation of the tip which can progressively evolve in increasing the field enhancement factor of the tip. This self-amplifying effect will then eventually trigger a breakdown once the breakdown threshold is exceeded. Currently, this tip growth respectively formation is subject to investigations and simulations using molecular dynamics codes [44], [8]. However, there is not yet experimental proof of this effect.

Measurements of dark current$^1$ of rf structures suggest that multiple field emitters are present in accelerating structures. This results in the statistical behaviour of the breakdown rate due to successive changes of each of the emitters which leads to consecutive breakdowns. The measured dark current is too high

$^1$ Inside rf structures, the field emitted electrons can be captured by an electromagnetic field of correct phase which then ejects these out of the accelerating structure through the beam pipe. Here, the emission current can be measured using an external magnetic spectrometer in respect to the accelerating gradient together with the momentum versus current distribution at fixed gradient (see for example [85]). Field emission current ejected out of the structure is herein later referred to as dark current.
to be supportable by a single field emitter of the above mentioned size without breaking down. Even in
the dc setup one expects a number of field emitters in the order of 10 to 20 on the surface which is under
test (approximately $0.8 \text{mm}^2$), estimated by the measured field emission current and the assumptions of the
maximum current capacity of a single field emitter. Despite multiple emitters, only one emitter will domi-
nate, given the exponential behaviour of the emission current with $\beta$ and finally develop up to a breakdown

With ohmic heating of the field emitter caused by the emitted current flowing through the tip, field emission
of neutral atoms into the vacuum starts (see figure 3.1 box a)). This is expected to be the most important
effect for the creation of the copper gas around the tip. Other effects like field evaporation of positive ions
from the anode, negative ions from the cathode and neutral evaporation from outside the field emitter tip
might play a role in the breakdown process but are not yet completely integrated in a model [41], [84]. The
timescale of these processes was estimated to be below a ns.

The next step of the onset phase is ionization of the liberated neutrals by collisions with emitted and
accelerated electron current. Due to the composition of the until now still neutral gas above the field emitter,
Coulomb collisions, elastic collisions, charge and momentum exchange and impact ionisation between
electrons and neutrals and each species with themselves are possible. The surface impact ionisation and
the resulting increase in electron current will then lead to a fast increase in ionization density of the gas
above the field emitter (see figure 3.1 box b ). For a system with copper electrodes, ionizations levelling
up to $Cu^{5+}$ have been observed in the CERN dc spark setup (see chapter 6 for details on the results). The
ionization happens right after the neutral evaporation and lasts only a few ns before the burning phase starts.
3.1. ONSET PHASE

Figure 3.1: Breakdown stages in chronological order. See text for further explanations.
3.2 Burning phase

The rising ion density results in a sheath potential above the field emitter. As a consequence, the local field \( \beta \cdot E \) increases up to 10 GV/m and has a huge impact on the emission current density since it follows an exponential behaviour. When arriving at current densities of several \( A/\mu m^2 \), the tip melts and the liquid metal evaporates. This increases the ion and neutral density and creates a fast growing plasma sheath above the field emitter tip (see figure 3.1 box c)). This process continues with ion bombardment of the surface which induces sputtering of neutrals, ions and positively charged clusters of atoms from the surface into the plasma. At the same time, the plasma expands and the size of the surface affected by sputtering and cluster impact erosion increases to some tens of \( \mu m \) which is six orders of magnitude bigger in area than the initial breakdown spot. As plasma density and temperature is increased steadily, the Debye length of the plasma decreases, reducing the sheath potential to 1-2 \( \mu m \) thickness within less than 1 ns after the ionization cascade started. At this point, the plasma sheath thickness stabilizes, concentrating the full potential in it. The rest of the plasma column above consists of quasi-neutral plasma of constant density with ion-electron recombination, resulting in optical emission (see figure 3.1 box d)). The plasma density and temperature distribution shown in figure 3.2 have been simulated numerically using a dedicated particle-in-cell (PIC) code [82], [17], [54]. This simulation includes a one-dimensional plasma model of the CERN dc setup and will soon be upgraded to a two-dimensional model. This combination allows a direct comparison between simulation and experimental results.

![Figure 3.2: Plasma parameter situation at the beginning of the burning phase. From PIC simulation [82].](image)

3.3 Cratering phase

Additionally, copper ion sputtering on the surface is expected to create new field emitters on the surface which will then also melt and evaporate in an explosive manner, due to the high surface gradient created by the plasma sheath. This will result in the formation of further craters around the initial one (see chapter 5.6 for experimental results). The full arc is maintained as long as an external supply current is available from the capacitors in the dc case or as long as rf power is supplied to the structure. Next, the plasma is expected to disappear by expansion cooling and by recombination since no external potential is available anymore to confine the plasma. The expansion has been modeled as a Coulomb-explosion of ions in [59] and was measured in the 30 GHz setup at CERN. The results are shown in the same article. The recombination of ions to neutrals is expected to be mainly radiative recombination and was observed to last up to 3 \( \mu s \) after the end of the energy supply to the arc in the visible and near-UV range (see chapter 6 for experimental results). After that time, the surface is unaffected until the next build-up of the electric field. If the field emitters created by the previous breakdown have a sufficient \( \beta \), another breakdown will follow. This keeps on going until the created field emitters have a sufficiently low \( \beta \) not to fulfill the onset conditions or until the electric field gradient is reduced.
Chapter 4

Experimental facilities and instruments

The experiments described in this thesis have been carried out in three different facilities. Two of them are dedicated to rf structure tests (at CERN and at SLAC) and one of them to dc spark experiments (CERN).

4.1 The 30 GHz structure test facility at CERN

The CLIC 30 GHz structure test stand is part of CTF3 and has been operational since 2004. This test stand is able to supply up to 52 MW of rf power at 74 ns pulse length. The pulse length is adjustable from 10 ns to 1500 ns [96], however, the achievable rf power goes down with higher pulse lengths. The main elements of this setup are the power extraction and transfer structure - later on referred to as PETS [71] - , a high-power and a low-power waveguide network and the accelerating structure under test.

Figure 4.1: Layout of the CTF3-facility at CERN. The 30 GHz test-stand is encircled in red.

The electron beam necessary to create rf power in the PETS is delivered by the first part of the CTF3 LINAC which is capable of producing a 70 MeV beam with up to 6.4 A current. It has a 3 GHz bunch spacing and a 1 mm bunch length. The repetition rate can in principle go up to 50 Hz, but has been limited to 5 Hz in 2006 in order to limit radiation. Power is transferred to the accelerating structure test stand from the PETS by a 17 m long low-loss overmoded TE01 waveguide. It also includes a high power variable attenuator as well as a transition to standard WR34 rectangular waveguide at its end towards the accelerating structure. The full high-power part of the 30 GHz teststand is illustrated in fig. 4.2. All parts are evacuated to approximately $10^{-8}$ mbar. The transition to the air filled diagnostic waveguides of the low power network is made by ceramic windows on the low power sides of the directional couplers.

Figure 4.2 shows the setup of the full high-power and low-power rf system. During a structure test, three signals are measured for each rf pulse: Incident power, reflected power from the input and transmitted power at the exit of the structure. Two directional couplers of -50dB coupling are used to sample these signals which are captured in the low power DAQ system. These signals are then transmitted via standard rectangular WR34 waveguides to the klystron gallery directly above the CTF2 building. Here the signals are attenuated to keep the power level in the calibrated working range of the following rf DAQ system. The incoming signals are then mixed with a 31.5 GHz cw signal. The resulting 1.5 GHz down-mixed signal is filtered out by bandpass filters. These signals are split with one branch transmitted directly via coaxial
Figure 4.2: Layout of the CTF3 30 GHz test stand at CERN. In foreground: The CTF3 LINAC with beam- 
line dogleg to the PETS tank. In background: The accelerating structure test stand housed in 
the former CTF2 building.

cables to the control room and displayed online using an oscilloscope. The other part of the split signals are 
fed into I/Q demodulators in order to be separated into phase- and amplitude-correlated signals in baseband. 
These baseband signals are then digitized using Aquiris ADC boards with a bandwidth of 250 MHz and a 
sampling rate of 1GSa/s. Finally, each calibrated dataset consists of three I/Q pairs of waveforms with 1000 
data points which are stored together with additional machine parameters such as vacuum pressure and 
machine parameters by the conditioning software (see 4.1.1 for details on the software). This data allows 
the essential features of the high-power behaviour of the structure to be monitored shot by shot.
4.1. THE 30 GHz STRUCTURE TEST FACILITY AT CERN

Figure 4.3: Photograph of the test structure vacuum tank at the end of the low loss transmission line. Parts of the breakdown detection instrumentation is indicated by the arrows.

4.1.1 Test stand controls and operation

The 30 GHz structure test stand is controlled by a dedicated JAVA-based software \cite{38} which will be referred to as conditioning software. This software controls all relevant hardware involved in the structure test process except the CTF3 LINAC where it only has control over the gun status (on/off and start/stop timing signals). The LINAC has to be set up by the operator prior to each structure test run.

The conditioning software has two main operation modes: Structure conditioning mode and breakdown rate mode. The conditioning mode is used for automatic conditioning (see section 2.3.1 for a definition of this process) of new structures as well as reconditioning after venting of the structure vacuum vessel. The breakdown rate mode is used to measure the structure’s performance in terms of breakdown rate at defined power levels after the structure has been conditioned. Details of these modes are described in the following two paragraphs. For both modes, in case of a breakdown, the software stores all rf and detector waveforms, vacuum pressure values and machine parameters of the current pulse plus the corresponding data of the three previous pulses for data analysis.

**Conditioning mode** A new accelerating structure needs conditioning before it can reach its maximum gradient performance. In the CERN 30 GHz test stand, conditioning is done by increasing the structure input power at short pulse lengths (typically 40 ns at the beginning) until a breakdown is detected by dedicated breakdown detectors (see 4.5.1). In that case, the pulse length is shortened to the shortest available pulse length (defined by the LINAC, approximately 10 ns) and then increased again to the nominal value within a few pulses (pulse length steps are 2.5 ns which equals around twelve pulses to reach 40 ns again). The maximum input power has to be selected by the operator manually and is gradually increased over the conditioning period. When a conditioning process is finished, there is only a negligible increase in performance expected, which does not justify further time consuming conditioning. The operational mode is then switched to breakdown rate mode (see next paragraph for further details). The typical time for complete conditioning is of the order of 100 h of non-stop operation in 30 GHz and 1000 h in 12 GHz. This discrepancy results from the availability and pulse length of the different power sources. The repetition rate of the SLAC X-band power source is 12 times higher and the system is independent of other usages unlike the 30 GHz setup which has to share the LINAC with the CTF3 experiments.

After having measured the breakdown rate at a given pulse length, the conditioning process is started again
Figure 4.4: Layout of the CTF3 30 GHz test stand at CERN.
with longer pulses. This loop is repeated until the nominal gradient at nominal pulse length is reached or until the structure is declared to be underperforming when these parameters cannot be reached because of continuous breakdowns.

**Breakdown rate mode** When structure performance does not increase anymore significantly over time, the breakdown rate of that structure can be measured by running the structure at a fixed power level and by counting the number of breakdowns occurring in that mode of operation. The amount of breakdowns per unit time is the breakdown rate and is mainly expressed as a probability for a breakdown per rf pulse. For example, the desired breakdown rate for the CLIC structures is $4 \cdot 10^{-7}$ [breakdowns per pulse].

### 4.1.2 Calibration of the 30 GHz test stand

Calibration of the 30 GHz rf DAQ system must be done regularly because of temperature drift, ageing of components and after DAQ hardware modifications. The rf detection electronics system has to be calibrated to be able to get absolute power readings. Also, after the change of the structure under test, the system has to be calibrated and adjusted in order to keep the input power for the DAQ system at its operating power range since structures require different input powers for same gradients. To eliminate uncertainties and errors originating from temperature changes during the day and over longer time periods, an automatic calibration system was developed and implemented. This system synthesizes 30 GHz cw power at well defined power levels and feeds these into the main rf network using directional couplers. The synthesized signal is then changed in power level and the corresponding Acqiris ADC values are recorded using a specific LabView based software. An embedded MatLab routine then fits and calculates the necessary calibration parameters. A total calibration run takes less than one minute and can be started manually or automatically after user defined intervals and does not need any intervention since the system automatically sets the CTF3 accelerator in standby mode and switches it back to normal operation after the calibration has been finished. The new system replaces the old method of calibration which required manual interventions on the waveguide network and which took approximately one working day. As a result, it was therefore only done directly before each new structure test started.

The waveguide network is calibrated at low power using measurements done with a network analyzer (Agilent PNA E3864 network analyzer [4]). These measurements characterize all waveguide components from the structure itself up to the interfaces to the down-converter and cannot be redone without hardware access to the waveguide network. Therefore it was only done when the structure under test was changed. Table 4.1 summarizes the errors for each step of the calibration. Calibration checks were done regularly during high-power tests. The result of the check done during the TM02 structure test will be given in section 5.2.1.

<table>
<thead>
<tr>
<th>№</th>
<th>Component measured</th>
<th>Device used for measurement</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Structure under test</td>
<td>Agilent network analyzer</td>
<td>±0.01 dB</td>
</tr>
<tr>
<td>2</td>
<td>Directional coupler</td>
<td>Agilent network analyzer</td>
<td>±0.01 dB</td>
</tr>
<tr>
<td>3</td>
<td>Waveguide transmission lines</td>
<td>Agilent network analyzer</td>
<td>±0.01 dB</td>
</tr>
<tr>
<td>4</td>
<td>Variable attenuators</td>
<td>Agilent network analyzer, 1dB steps</td>
<td>±0.01 dB</td>
</tr>
<tr>
<td>5</td>
<td>CW rf Synthesizer power output</td>
<td>Internal reading</td>
<td>±0.1 dB</td>
</tr>
<tr>
<td>6</td>
<td>CW calibration power after attenuator and phase shifter</td>
<td>Agilent power meter</td>
<td>±0.05 dB</td>
</tr>
<tr>
<td>7</td>
<td>Calibration power distribution network</td>
<td>Agilent network analyzer</td>
<td>±0.01 dB</td>
</tr>
<tr>
<td>8</td>
<td>rf power to voltage waveform (downmixing and I/Q demodulation)</td>
<td>Acqiris cards [3]</td>
<td>$\leq \pm 2%$ at 100 mV fullscale</td>
</tr>
<tr>
<td></td>
<td>Total error</td>
<td>-</td>
<td>±0.2 dB ± 2%</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of calibration errors in the 30 GHz DAQ calibration chain.
4.2 The X-band structure test facility at SLAC

During a six week period, high-power rf experiments have also been carried out using the X-band structure test facility ASTA at the Stanford Linear Collider Center SLAC in California, USA. This facility delivers up to 500 MW of RF power at 200 ns pulse length and at American X-band frequency (11.424 GHz). In ASTA, the output power of two 50 MW klystrons with 1.5 μs pulse length is combined and compressed using a SLED-II type pulse compressor system [91]. The repetition rate used in the experiments was 60 Hz which leads to much shorter conditioning times and better statistics for the structure tests than the 5 Hz repetition rate achieved in the CERN 30 GHz structure test stand. Similar setups exist at SLAC with the NLCTA and at KEK with Nextef and are envisaged for CERN with the stand-alone 12 GHz power source which will run at a 50 Hz repetition rate.

![Figure 4.5: Schematic of the ASTA rf power generation system.](image)

The structure under test is housed in a dedicated concrete bunker which is next to the klystrons in order to keep the attenuation in the connecting waveguides low. The klystrons are connected by a power combiner and an overmoded low-loss transmission line to the structure inside the bunker, in line with the pulse compressor on top of the concrete bunker. Inside the bunker, an optical table is used as a support for the structure and accessories such as ion pumps, rf loads and rf diagnostics. The diagnostics used in that setup are similar to the ones used in the CERN 30 GHz setup. Two options are possible: Either two faraday cups (button-style electrodes integrated in a DF40 vacuum feedthrough) on each side of the structure or one faraday cup and one optical window for light analysis. The latter setup has been used for the experiments presented here.

Figure 4.6 shows a photograph of the setup inside the concrete shielding bunker and on top of the optical table. The structure with attached cooling blocks can be found in the center of the image. Connected to both sides of the structure are mode converters which convert the arriving rectangular waveguide mode to a circular mode matched to the structure. Still symmetrical on both sides, the mode converters are followed by a vacuum pipe T-piece in order to allow vacuum pumping through the beampipe of the structure using the attached ion pumps. On the left side behind that T-piece, a vacuum window was attached on the beam axis. This window allows a direct line-of-sight view into the structure and was used in the experiments described here to collect the light created by a breakdown. The T-piece on the left side is sealed with an electrical vacuum feedthrough. On the vacuum side of this feedthrough, a stainless steel disk of approximately 1 cm in diameter is welded to the central conductor and the air side is connected via a coaxial cable to an oscilloscope outside the bunker. This Faraday cup is used as a dark- and breakdown current pickup. The mode converter flanges perpendicular to the beam axis are the rf input (left side) and rf output (right side) ports. After a pumping T-piece for rectangular waveguides and directional couplers for power diagnostics, these waveguides are connected to the klystrons and to a high-power load, respectively.
Figure 4.6: Photograph of the SLAC structure test stand showing the structure and connected rf and vacuum equipment. The ruler is calibrated in inches.
4.3 Accelerating structures used in presented experiments

The accelerating structures used in the scope of this work can be classified depending on their electrical and mechanical properties. The following list covers the main parameters. For comparison, the parameters of the state of the art accelerating structure CLIC G are presented in addition. A detailed list of all structure parameters of the CLIC G structure can be found in [48]. Also structures of similar design have already been successfully tested at nominal CLIC rf parameters [2],[34].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TM02</th>
<th>C30 speedbump</th>
<th>C10</th>
<th>CLIC G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of regular cells¹</td>
<td>30</td>
<td>30</td>
<td>10</td>
<td>24</td>
</tr>
<tr>
<td>(&lt; a &gt; / \lambda )²</td>
<td>0.35</td>
<td>0.35</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Phase advance per cell [deg]</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Mode</td>
<td>TM02</td>
<td>TM03 (1st), TM01</td>
<td>TM01</td>
<td>TM01</td>
</tr>
<tr>
<td>Group velocity v_/c [%]</td>
<td>2</td>
<td>1.2 (1st), 4.8</td>
<td>1.35</td>
<td>1.66, 0.83⁴</td>
</tr>
<tr>
<td>Constant impedance</td>
<td>impedance</td>
<td>impedance</td>
<td>impedance</td>
<td>gradient³</td>
</tr>
<tr>
<td>Peak surf. field [MV/m]</td>
<td>220</td>
<td>220</td>
<td>195</td>
<td>225⁵</td>
</tr>
<tr>
<td>Rshunt/Q [kΩ/m]</td>
<td>12</td>
<td>29</td>
<td>16.2</td>
<td>14.6, 17.9²</td>
</tr>
<tr>
<td>Pinput 100 MV/m [MW]</td>
<td>24</td>
<td>24</td>
<td>48</td>
<td>63.8</td>
</tr>
<tr>
<td>Nominal t脉冲 [ns]</td>
<td>70</td>
<td>70</td>
<td>230</td>
<td>240.8</td>
</tr>
</tbody>
</table>

¹ Plus one coupling cell between couplers and first resp. last regular cell, two in total for each structure
² Tapered structure, first value for input, second value for output regular cell
³ Tapered, decreasing inner diameter towards output
⁴ Averaged iris diameter a to wavelength λ ratio
⁵ With beamloading, without beamloading max. surf field 245 MV/m on iris 20

Table 4.2: Structure parameters for the structures used in the presented experiments. All structures are of travelling wave type and made of OFE copper. The C10 structure is sealed, all other structures need a vacuum tank.

A more detailed overview of the design and the motivation of each structure can be found in [99], the results of the high-power tests of the TM02 and speedbump structures are summarized in [43].
4.4 The CERN dc spark setup

Similarities and differences between rf and dc breakdowns are one of the main subjects of this thesis. The CERN dc spark setup was initially conceived for testing the breakdown field strength of different kinds of materials in order to speed up the validation of different materials for rf structures. It has evolved to a setup which is used for basic breakdown experiments to illuminate the underlying physics. The setup enables experiments concerning the optical emission of breakdowns, imaging, surface investigations and tests, electrical characteristics of the breakdown plasma, vacuum behaviour and breakdown statistics. Since the beginning of 2008, a second dc spark setup has been operational. It is very similar to the original system, but offers higher voltages and can therefore be used to achieve higher electric field gradients.

4.4.1 The dc spark vacuum and mechanical system

![Figure 4.7: View into the dc spark setup main vacuum chamber. The sampler holder is on the left, the tip fine adjustment system on the right. In the center, the rectangular sample with the rounded tip is visible. In standard material tests, the sample holder is the cathode and the tip is anode.](image)

Figure 4.7: View into the dc spark setup main vacuum chamber. The sampler holder is on the left, the tip fine adjustment system on the right. In the center, the rectangular sample with the rounded tip is visible. In standard material tests, the sample holder is the cathode and the tip is anode.

The sample can be moved manually in three axis by external micrometer screws. Two axis are used to select the point of interest on the sample, keeping the distance between tip and sample roughly the same. The remaining axis is used for a coarse approach of the sample towards the tip, the fine adjustment of the gap distance is afterwards done by the tip’s moving system. This system translates the movement of an outside vacuum micrometer screw via a feedthrough and a lever arm based reduction system into a linear movement of the tip a hundred times smaller than the reading on the micrometer screw. The distance is zeroed by approaching the tip slowly to the sample until electrical contact is established and then retracting the tip using the reading on the micrometer screw. This reading has to be converted into real distance values by a lookup table which has been prepared previously by CERN’s metrology service.

The vacuum chamber is baked out typically for one day after each exposure of the inside components to the air and reaches typically a $5 \cdot 10^{-10}$ mbar residual pressure [29] after two days of pumping, measured with standard Penning and Pirani gauges. In addition, a residual gas analyzer (RGA) is attached to the vacuum system in order to analyze breakdown induced outgassing by its atomic weight.

Optical measurements are possible via a standard vacuum window used mainly for imaging and an optical fiber feedthrough for spectroscopy. This feedthrough is located on the opposite site of the vacuum window.
A vacuum compatible fiber pigtail can be placed at about 1 cm distance to the tip in order to ensure good light collection but still good insulation from the high voltage parts.

4.4.2 The dc spark electrical system

The electrical system of the dc spark setup is identifiable in figure 4.8. Both the sample holder and tip are insulated from the grounded vacuum chamber by ceramic insulators. The sample holder is tied to ground using a second feedthrough and a cable going to a central grounding point for the high voltage system. This was done to use the grounding cable in combination with a current transformer pickup coil in order to measure the current flowing through the spark on the low potential side of the spark, thus avoiding insulation problems. The current transformer used is a Bergoz CT type with a bandwidth of 500 MHz [16]. Figure 4.9 shows the circuit diagram of the new dc spark setup. The old setup is similar except for the switches S5 and S6 which have to be set manually by connectors here, whereas the new setup uses computer controlled relays. The two main operation modes are the $\beta$ measurement mode described in the next section and the breakdown mode which includes the previously mentioned conditioning and breakdown rate modes. These two differ only in the control command of the high voltage power supply, that is increasing the voltage before each breakdown attempt in conditioning mode and keeping the voltage constant as well as recharging the capacitors in breakdown rate modes.
4.4. THE CERN DC SPARK SETUP

Field emission measurement mode  In this mode, the field enhancement factor $\beta$ of the emission sites on the sample is measured by setting the switches in the circuit according to Table 4.3. In this configuration the high voltage power supply is directly connected to the tip via two current limiting resistors and the cathode is grounded via the electrometer (Q/I meter, Keithley 6517A Electrometer [60]). This electrometer measures the current - typically in the order of pA - as a function of the high voltage. The $\beta$ can be extracted from these two values by fitting the Fowler-Nordheim equation to these. The 50M$\Omega$ resistor before the electrometer is used to protect it in case of a breakdown which is not very likely at the voltages used for these measurements (typically 0.8 kV to 2 kV) but still a danger as it would destroy the sensitive electronics of the electrometer.

<table>
<thead>
<tr>
<th>$#$</th>
<th>Step</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\beta$-mode</td>
<td>O</td>
<td>O</td>
<td>C</td>
<td>O</td>
<td>C</td>
<td>O</td>
</tr>
</tbody>
</table>

Table 4.3: Switch settings for $\beta$ measurements. $O$ for open switch and $C$ for closed switch.

Conditioning and breakdown rate mode  In conditioning and breakdown rate modes, the main capacitors (the series of 0.47$\mu$F capacitors in Figure 4.9) are charged via switch S1 to a specified voltage which is either increased after each breakdown attempt in conditioning mode or kept constant in breakdown rate mode. Next, the power supply is disconnected from the capacitors and the main switch (S2, high voltage hammer switch) as well as the grounding switch S6 are closed for a period of time, typically 2 s. At the moment the switches are closed, an electric field is established between tip and sample. The three 1nF capacitors connected in series to the ground and to the anode are used to damp overshoots of the system when switching the main switch. After the main switch is opened again, S1 closes to recharge the main capacitors and the process starts from the beginning. After a series of breakdown attempts has been finished, for safety reasons, switch S4 closes to discharge the main capacitors. Table 4.4 summarizes the different switch settings and the corresponding functions. The main capacitors can be interchanged to vary the stored energy. This feature can be used to study energy dependence of breakdown craters created on the sample for example.

<table>
<thead>
<tr>
<th>$#$</th>
<th>Step</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Charging</td>
<td>C</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Breakdown attempt</td>
<td>O</td>
<td>C</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Discharge capacitor</td>
<td>O</td>
<td>O</td>
<td>C</td>
<td>O</td>
<td>O</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Switch settings for conditioning and breakdown rate measurements. $O$ for open switch and $C$ for closed switch.
Figure 4.9: Circuit diagram of the dc spark electrical system. Layout by S. Calatroni, CERN.
4.5 Instruments for breakdown detection and physics exploration

In this section, the instruments for breakdown detection and breakdown physics experiments are presented. While the rf test stand instrumentation applies exclusively to the experiments conducted in rf, the optical spectrometer setup including the setup for time-resolved spectroscopy has been used both for rf and dc experiments.

4.5.1 Rf test stand instrumentation

In addition to the rf power measurements described in section 4.1, the structure test stand is equipped with measurement and detection devices for breakdown detection and breakdown physics experiments. Since the conditioning software needs a trigger if a rf pulse caused a breakdown, at least one of the detectors listed in table 4.5 has to be connected to the DAQ system and configured in the conditioning software. This table succeeds table 1 in [20] from 2004.

<table>
<thead>
<tr>
<th>#</th>
<th>Detector type</th>
<th>Effect measured</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High power rf DAQ</td>
<td>Reflected power</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>High power rf DAQ</td>
<td>Missing energy</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Faraday cup (FC)</td>
<td>Charge of emitted currents</td>
<td>Beam axis, up- and downstream</td>
</tr>
<tr>
<td>4</td>
<td>Photomultiplier</td>
<td>Emitted light</td>
<td>Structure beam axis, FC as mirror</td>
</tr>
<tr>
<td>5</td>
<td>Rogowski coil</td>
<td>Induced voltage by emitted currents</td>
<td>Beam axis, up- and downstream</td>
</tr>
<tr>
<td>6</td>
<td>Scintillation detector</td>
<td>X-ray emission</td>
<td>Unshielded, outside vacuum</td>
</tr>
<tr>
<td>7</td>
<td>Accelerometer</td>
<td>Acoustic shockwaves</td>
<td>Directly touching the structure</td>
</tr>
<tr>
<td>8</td>
<td>Vacuum gauges</td>
<td>Released gas</td>
<td>Structure vessel</td>
</tr>
<tr>
<td>9</td>
<td>Rest gas analyser</td>
<td>Released gas composition</td>
<td>Structure vessel</td>
</tr>
</tbody>
</table>

Table 4.5: Basic detection methods for breakdown detection needed by the conditioning software, all effects occur from an rf breakdown.

All 30 GHz structure tests used faraday cups as standard breakdown detection devices. For breakdown physics test runs, other detectors have also been used for triggering the DAQ. Details of the detectors are as follows:

1. **RF DAQ, reflected power**  The reflected power signal can directly be used to detect a breakdown event, either with an analogue threshold detector using a spare rf signal from the rf network or by defining a digital threshold on the reflected waveform of the high power DAQ system. This signal is a clear indicator for a breakdown since the power level of the reflected signal can easily reach -3dB of the incident power whereas it is less than -20dB during non-breakdown pulses.

2. **RF DAQ, missing energy**  To detect a breakdown event, the power waveforms recorded by the 30 GHz rf DAQ (see 4.4) system are analyzed in real-time by the conditioning software. The waveforms are integrated over time and the missing energy is calculated as in equation (4.1):

\[
E_{\text{missing}} = \int_T P_{\text{incident}}(t) \, dt - \eta \int_T P_{\text{transmitted}}(t) \, dt - \theta \int_T P_{\text{reflected}}(t) \, dt
\]  

This integration is done in software by summing up all ADC values in a power waveform and correcting it according to its timebase. The operator can set a threshold in the software which indicates a breakdown. The missing energy corresponds to the amount of energy which has been converted to a form which is undetectable by the high power rf DAQ. To which forms it can be converted will be discussed in section 5.2. The factor \( \eta \) in the missing energy formula (4.1) takes this into account and is equal to the loss factor S12 of the structure as measured with the network analyzer. The factor \( \theta \) corrects the reflected energy for ohmic losses which are dependent on the position of the breakdown inside the structure. The losses depend on the path length the reflected pulse has to travel inside the lossy structure. Since the reflected power during a breakdown can be of equal power level than the transmitted power, these losses should be taken into account as soon as the rf DAQ allows a reasonable positioning of the breakdown which is not yet possible in the
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30 GHz system. It is however possible in the X-band DAQ at SLAC, but calibrated transmitted and reflected power data were not available at that time.

For breakdown physics investigations, the missing energy is an important value for correlations with other measurements as can be seen in the later chapters.

3. Faraday cups Each breakdown in an accelerating structure is accompanied by a burst of emitted electrons and ions along its beam axis [59]. This charge is collected by faraday cups on both sides (see figure 4.3) of the accelerating structure. These cups have been designed to fulfill two tasks: to collect the emitted charge with time resolution (therefore they have been designed to be matched to the 50Ω impedance of the DAQ-ADC) and to reflect light emitted on the beam axis towards a radially mounted vacuum window. To do this, the front of the inner aluminium cylinder of the faraday cup has been cut at a 45° angle and polished to be highly reflective and optically flat. This allows light collection using a PMT and imaging using a camera.

![Figure 4.10: Drawing of the faraday cup used for breakdown detection in the 30 GHz structure tests. Beam axis is horizontal, the emitted currents come from the right side. The upper flange is closed with a vacuum window to allow optical devices to be attached. Design by T. Lefèvre, CERN BE-BI.](image)

The structure vacuum vessel allows two farady cups to be mounted on each side of the structures beam axis, the distance from the exits of the structure to the surface of the faraday cups is approximately 15 cm (measured on rotational axis for TM02 structure).

4. Photomultiplier As mentioned before, the design of the faraday cups allows not only charge collection but also imaging of the inside of the structure and collection of the light emitted by breakdowns. The latter task is done by using a Hamamatsu R7400U series photomultiplier [52] mounted behind the vacuum window (as indicated in figure 4.3) of the faraday cup. The electrical connection to the the Acqiris ADC boards is made by 50Ω coaxial cable, properly terminated in the ADCs. The high-voltage is supplied from a power supply in the klystron gallery and is therefore accessible for voltage adjustments which are necessary to adapt the amplification factor of the photomultiplier to the occurring light levels. In past experiments, this photomultiplier has been used with a set of optical bandpass filters for coarse spectroscopy, but the resolution was insufficient for line identification.

5. Rogowski coil The currents emitted during a breakdown induce a voltage when passing through a Rogowski coil [77] mounted in front of the structure output. The emitted current is proportional to the integral of the measured induced voltage into a known load (here 50Ω for the standard Aquiris ADCs) since:

\[ U_{\text{induced}} = -L \frac{dI_{\text{emitted}}}{dT} \]

where \( L = \frac{AN\mu}{l} \)

with \( N \) is the number of turns, \( A \) the cross section of the small windings, \( l \) the circumference of the coil through the central points of the small windings and \( \mu \) the magnetic permeability of the coils central
toroid. A value proportional to the emitted current is calculated by integrating the measured voltage and dividing this by the impedance of the ADCs. Experiments were prepared to show the feasibility of this kind of breakdown detector and will be studied in detail in future structure test runs.

Figure 4.11: Photograph of a Rogowski coil used for the detection of electrons ejected out of a rf structure during a breakdown (30GHz speedbump structure in the background. The wire is wound around a toroid (can be air), the cross section of the toroid resembles $A = \pi \cdot a^2$, $l = 2\pi \cdot R$ is the circumference of the toroid at half its ring cross section. A very similar setup is used as a beam current monitor (beam transformer) in accelerators.

6. Scintillation detector During a breakdown, electrons are emitted from the structure surface and the breakdown plasma and afterwards accelerated by the rf field. These electrons then hit the surface and create bremsstrahlung which can be detected outside the structure and even outside the vacuum vessel. The pulse length of the bremsstrahlung flashes is approximately of the same length as the rf pulse. To detect these signals, a photomultiplier with a plastic scintillator attached was used. Plastic scintillators have very short light decay times of the order of 2ns, and are therefore ideal for fast triggering and intensity waveform measurements [65]. The photomultiplier used was a Hamamatsu R2238-01 [49] and the attached plastic scintillator was 5 mm thick. Both were integrated in a cylindrical aluminium housing with a black cardboard disk as an entry window. Such photomultiplier assemblies have formerly been used as beam loss detectors in the CTF2 experiment.

7. Acoustic sensors Acoustic sensors can be used to sense the shockwaves induced in the structure by a breakdown. Piezoceramic accelerometers were used in some tests and were directly attached to the structure. The accelerometers consist of an electrically contacted piezoceramic disk with a small weight mounted on top. When an acoustic shockwave travels through the material of the structure, the disk is compressed and expanded due to the inertia of the attached weight. In the 30 GHz structure tests, these detectors were attached to the high power waveguide and its bends in order to detect breakdowns there. KEK and SLAC used this technique regularly on sealed X-band structures [28]. The sealed structure design has the advantage of easy implementation of the accelerometers since they can be directly attached to the structure without dealing with vacuum compatibility and feedthroughs. This is due to the fact that the structure is designed in a way that it has no openings on its surface except rf flanges and beampipes which are used for pumping the structure. If multiple sensors are used on a structure, the position of the breakdown can be calculated using the travelling time of the acoustic waves in the material.
4.5.2 The optical spectrograph

The optical spectrograph used for the experiments described here is a f/4 Czerny-Turner type imaging spectrograph with a 303 mm focal length made by Andor Technology, model Shamrock SR-303i-B [11]. The spectrograph has two output ports selectable by an automatic flip-mirror. One of them is equipped with a motorised slit (10 µm to 3 mm), the other with a flange for a camera. This flip mirror is controlled by the spectrograph’s software. The input port features a similar motorised slit plus an electromechanic shutter as well as an f-number matching optic to couple light from an optical fiber to the spectrograph. The desired wavelength range can be selected by three different gratings mounted on a grating turret which is turned by a stepping motor with reduction gears. The spectrograph used here has been equipped with the following gratings:

<table>
<thead>
<tr>
<th>#</th>
<th>Lines/mm</th>
<th>Blaze(nm)</th>
<th>$Q \geq 20%$</th>
<th>Nom. dispersion (nm/mm)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>500</td>
<td>350-1200</td>
<td>21.5</td>
<td>1.68 at 546 nm</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>500</td>
<td>250-800</td>
<td>2.4</td>
<td>0.19 at 546 nm</td>
</tr>
<tr>
<td>3</td>
<td>2400</td>
<td>Holographic</td>
<td>250-600</td>
<td>0.96</td>
<td>0.08 at 435 nm</td>
</tr>
</tbody>
</table>

Table 4.6: Grating data for the gratings used with the optical spectrograph, data from [11]. Q is the spectral efficiency. Resolution valid for 10 µm slit and 26 µm pixel size.

The spectrograph’s camera output is equipped with an Andor Technologies iDus CCD camera, model DU420A with a front illuminated open-electrode CCD chip [10]. The CCD chip has thermoelectric cooling and can be cooled down to 90 K below ambient temperature with air cooling and to 105 K below ambient temperature with water cooling in order to reduce dark current collected in the pixels. The chip is a two dimensional CCD matrix with 1024 horizontal and 255 vertical pixels. Each pixel is 26 µm by 26 µm in size with a total active area of 26.6 mm by 6.7 mm. With the 2400l/mm grating, the maximum resolution is 0.025 nm. Quantum efficiency information of the CCD can be found in figure 4.12 and [10].

The auxiliary output equipped with a motorised slit is used for the time resolved spectroscopy described in detail in section 4.5.3.

The CCD camera acquisition can be triggered by either the user via a software button or via an external TTL signal. The exposure time is set either by the software or by the length of the external TTL signal. In a combined mode, the exposure time can be set by software, but the exposure is started by the rising edge of the triggering TTL signal. The readout is done over a USB2.0 connection by the dedicated Andor SOLIS software [9] which controls the spectrograph and the camera at the same time. The camera can be operated at different modes. The two most often used modes are imaging mode where the full picture is read out and 'full vertical binning' mode. In the latter mode, all pixels of a vertical column are integrated in a charge sensitive sample-and-hold circuit and then digitized by a 16 bit ADC. This mode effectively reduces readout noise and is the main mode used for spectroscopy. The imaging mode is basically only used for alignment purposes of the system. Seeing the image of the input slit by the CCD, the systems focussing and light throughput can be optimized. Effective light collection close to the breakdown was a difficult task and required solutions were adapted to each setup.

In the dc setup, the collection was done using vacuum compatible fiber pigtails with an open and polished side facing the breakdown site. All optical fibers and fiber pigtails used in the dc and rf setups are 1 mm diameter P1000 VIS-NIR low OH content (400 nm to 2100 nm) acrylate fibers [74]. In the CERN 30 GHz rf structure test setup, light collection was done using the faraday cups’ polished surface deflecting the light produced inside the structure towards the vacuum window. A biconvex lens on the atmospheric side of the window focussed that light into the open end of an optical fibre. This fibre then transported the light to the spectrometer (see figure 4.3 for the detailed setup). This method of light collection turned out to be ineffective because of losses due to the size of the reflective faraday cup which covered only one tenth of the possible emission angle. Another source of light loss was the varying position of the breakdown inside the structure. Despite precise alignment, the projection of the breakdown created by the lens onto the fiber input was bigger than the surface of the fiber input, itself leading to a complete loss of coupling when the breakdown light was focussed next to it, due to a breakdown position outside the acceptance area. After the analysis of these problems, a new kind of light collection technique was developed and implemented: the light collection cone (see figure 4.13).

The light collection cone was designed to guide the light produced by the breakdown into the optical fiber without additional optics. The angle of the cone was chosen to reflect all of the light into the fiber
at grazing incident angles without reflecting light back into the structure. The angle had to be adapted to the numerical aperture of the fiber (NA = 0.22), the space limitations inside the vacuum chamber and the machining capabilities. The front opening of the cone is of 10 mm in diameter in order to cover the full output aperture of the 30 GHz and even the X-band structures. The total length of the cone is 100 mm plus 25 mm for the fiber ferrule. It was mounted directly on the fiber feedthrough flange and inside a vacuum bellow to allow it to be aligned and adjusted as close as possible to the structure output, even when the structure vessel is already under vacuum in order to reach maximum light collection efficiency (see figure 4.14 for a photograph of the setup).
Figure 4.13: 3D drawing of the light collection cone designed and used for the 30 GHz structure test stand. The smaller side of the tapered cone ends into a bore hole which will accommodate the ferrule centering the optical fiber. The cone was made out of stainless steel and polished by hand.

Figure 4.14: Photograph of the light collection cone installed in the 30 GHz setup.
4.5.3 Setup for time-resolved spectroscopy

The auxiliary output of the spectrograph was attached to two different PMT detectors for time-resolved spectroscopy of light emission from dc and rf breakdowns. As mentioned before, the output of the spectrograph can be directed either on the CCD camera or on the PMT assembly by a flip-mirror built in the spectrograph.

Two modes of operation were used for taking time-resolved spectra: A single line setup with a high sensitivity PMT and a multi-line setup with a lower sensitivity multicolumn-PMT.

Figure 4.15 shows the setup for single line time-resolved spectroscopy. In this configuration, the output of the spectrograph is equipped with a variable motorised output slit similar to the one used as input slit. With the slit width and the rotatable grating, the wavelength interval of the spectrum produced by the grating in the spectrograph can be selected. A PMT is mounted after the slit on an x-y-table in a light tight box that is attached to the spectrograph. The x-y-table allows the optimisation of the alignment of the PMT without opening the light tight box in order to reach a maximum of detection efficiency.

For a maximum of detection efficiency, a Hamamatsu R6357 PMT was selected which is a PMT specially designed for spectroscopical applications. It features a high sensitivity of 105 mA/W at a 450 nm peak sensitivity wavelength, a wide spectral response from 185 nm to 900 nm and a fast rise time of 1.4 ns to achieve high temporal resolution [50]. The signal was read out with an oscilloscope digitizing at 1 GSa/s, triggered by the pulse itself when used in the dc setup as well as by a trigger from the CTF3 timing system when used in the 30 GHz setup.

Figure 4.16 shows the setup for multi-line time-resolved spectroscopy. To acquire multiple wavelength intervals at the same time, the multichannel PMT Hamamatsu H7260 was used [51]. This PMT offers 32 independent channels of 1 mm pitch (0.8 mm active area) and a spectral response between 300 nm and 600 nm as well as a rise time of 0.8 ns. It is directly mounted in the focal plane of the auxiliary output of the spectrograph as shown in figure 4.16. The size of the spectrum in the focal plane of this output is of 28 mm (the same size as for the camera output, but the camera has only 26.6 mm active CCD area). Thus, one channel corresponds to a wavelength interval of 17.2 nm if used with the 150 l/mm grating and of 1.8 nm if used with the 1200 l/mm grating. The input slit was set to 1 mm
during these measurements in order to allow a maximum of throughput without decreasing the resolution. The readout was also done with a fast digitizing oscilloscope at 1 GSa/s, triggered by either the signal itself or a machine trigger. The maximum number of signals that could be recorded at the same time was limited to four by the number of channels of the oscilloscope.

Figure 4.16: Setup for multi-line time-resolved spectroscopy. Multichannel PMT with connector box (left) and spectrograph with auxiliary port (right) are connected for that purpose.
Chapter 5

Power and energy measurements

In this chapter, power and energy balance measurements in the rf and dc setups are presented and the results are compared. These include high and low power rf measurements as well as current and voltage measurements in the dc setup. Additionally, measurements of emitted currents from rf structures are shown here. These measurements were motivated by the fact that precise measurements of the energy dissipated by breakdowns - and in which energy form it is converted - will help our understanding of the underlying physics. The measured energies can also be used to correlate with effects such as surface damage, light intensity and particle emissions. An extended circuit model for the dc spark setup was developed to cross check the measured current and voltage waveforms with the output of a simulation.

5.1 Low power rf measurements of structures

At a low enough power, the structure’s rf behaviour is purely defined by the geometry and the surface material. At higher power levels, surface effects affect the operational reliability of the structures. In this regime, the probability of rf breakdowns rises, leading to a dramatic change of rf properties within one shot once the breakdown is triggered. This results in a decreased acceleration or in the worst case in a total loss of the beam.

To initially check the design of an rf structure, low power S-parameter measurements are done with a network analyser prior to all high power rf tests. These measurements are used to check the matching of the structure at its operating frequency, to correct the phase advance and generally, to see if the machining and assembly procedures were successful. To adjust small deviations from the calculated low power rf behaviour, tuning mechanism are foreseen in all structure designs.

Figure 5.1 shows a low power frequency sweep measurement done on the 30 GHz TM02 with a network analyzer [4]. In the left plot, the reflection from the input port of the structure (S11) is showing a pattern typical for travelling wave structures with one dip for each regular and coupling iris in the structure. The minimum reflection is close to the nominal operating frequency of 29.985 GHz (in air). The reflection is -35 dB which is a good matching value and therefore no tuning of the structure was required. In the right plot, the transmission pattern (S12) is plotted. One can see that the transmission is -3.4 dB at the operation frequency and that the structure acts as a bandpass filter with approximately a 700 MHz bandwidth.

The measured S-parameters of the TM02 structure have been used to calculate transmitted and reflected pulses from the input pulse. This has been done online to check the calibration of the rf DAQ system and in later data analysis by comparing real and calculated waveforms. In case of a breakdown, this method was used to calculate the nominal transmitted and reflected pulses as they would have looked like without breakdown. This has been used also during offline rf data analysis. More on this can be found in chapter 5.2.1.
5.2 Rf waveforms and power balance during breakdowns

During normal testing of a 30 GHz rf accelerating structure, the incident, reflected and the transmitted power waveforms are recorded using the DAQ system described in section 4.1.

In the case of a rf pulse without breakdown, these waveforms have ratios similar to the low power measurements. Figure 5.2 shows an example of a non-breakdown pulse which has been recorded during the TM02 structure test at CERN. The transmitted power (green waveform) is attenuated by a factor of 0.45, corresponding to -3.4 dB. It has the same shape as the incident pulse due to the flat frequency response of the structure (compare to figure 5.1 right plot). It is shifted in time, which is mainly an effect of the electrical delay in the structure and of little differences in waveguide length (≈±3 ns). The reflected pulse (black line, multiplied by a factor of 100 for illustration) is attenuated by roughly a factor of 1000 (corresponding to -30 dB). The reflected pulse does not preserve the shape of the incident pulse due to the strong frequency dependency of the reflection S-matrix (compare to figure 5.1 left plot).

In case of a breakdown during the rf pulse, the transmitted and reflected waveforms do not follow the low power behaviour anymore. A typical breakdown pulse which was recorded in the same run is shown in figure 5.3. Here, the transmitted power does not reach the expected -3.4 dB power level but is cut off in its rising edge and decays back to very low power levels. At the same time, the reflected power signal starts rising to a reflection of power at levels of the order of magnitude of the incident pulse and keeps that level until the end of the pulse.

A breakdown significantly influences the rf behaviour of the structure, creating conditions inside the structure that lead to a substantial reflection of the input power and a complete loss of transmission. Measurements at SLAC with X-band structures routinely show that the position of the breakdown inside the structure can be determined by detecting phase and timing of the rf signals with a spatial resolution of the order of one disk length, indicating that the breakdown is a local phenomena with a size equal or less than the diameter of a disk iris. A similar measurement is not possible in the 30 GHz setup, due to the shorter length of the 30 GHz structures and the lower temporal resolution of the DAQ system.

Using the three waveforms recorded during each pulse, an energy balance calculation was done by integrating the power signals over time. The energy dissipated in the structure was calculated by subtracting the transmitted and reflected energy from the incident energy. This can be done for non-breakdown pulses where the power dissipation is purely due to structure resistance and for breakdown pulses where energy is dissipated by the breakdown and its accompanying effects later referred to as missing energy in addition to the ohmic losses. A formula for the missing energy can be found in equation (4.1) in section 4.5.1. It is obvious that in breakdown pulses the ratio of ohmic losses and missing energy is a function of the position x of the breakdown in the structure which is given by the factor \( \theta = \theta(x) \). It expresses the amount of attenuation by ohmic losses of the reflected power as function of the breakdown position. Since the position of the breakdown could not be resolved by the 30 GHz system, only the transmitted power could be corrected for ohmic losses. The result of these measurements is plotted in figure 5.4 on an absolute energy scale versus the integrated incident power and in figure 5.5 as distribution of the missing energy normalized to the input power for each single breakdown.

Typical pulsed rf input energies are between 0.1 J and 1 J. The missing energy is then obviously lower due...
5.2. RF WAVEFORMS AND POWER BALANCE DURING BREAKDOWNS

to energy conservation. This explains the diagonal structure of the distribution shown in figure 5.4 and indicates a good calibration of the rf DAQ system. The incident energy is never fully converted to missing energy as it can be seen by the gap between the dashed line and the beginning of the data points in figure 5.4. An explanation of this behaviour can be found in the energy content of the rising edge of the input pulse: A fraction of the incident energy will already be transmitted before the field inside the structure reaches the breakdown field threshold. Surprisingly, no correlation between the incident energy and the missing energy is visible.

The distribution of the missing energy (normalized to the integrated incident energy for each rf pulse) is flat over most of the input power range. Towards higher missing energies, the number of observed breakdowns tends towards zero. No breakdowns dissipating all input power have been observed. Since the reflected power in case of a breakdown is of the same order of magnitude than the transmitted power and sometimes even higher, the energies plotted in the histogram include a significant amount of power loss due to ohmic attenuation of the reflected signal. One can estimate that the real missing energy is therefore lower than shown here. These measurements have to be subjected to dedicated experiments with appropriate DAQ capabilities like for example the future 12 GHz high power structure test stand at CERN.

Further analysis of the 30 GHz rf data could not reveal any correlations of missing energy to rf power or timing which has to be attributed to the insufficient resolution of the 30 GHz DAQ system. In addition, rf data from X-band tests at ASTA were not available with calibrated transmitted and reflected channels. The forms of missing energy undetectable for the rf DAQ system are for example electromagnetic waves of frequencies other than 30 GHz including visible, infrared and ultraviolet light, X-rays of different energies, possibly harmonics of the fundamental 30 GHz and kinetic energy of accelerated electrons and ions. Finally, direct effects like ohmic heating of field emitter tips and indirect effects like surface ion and electron bombardment heat up the surface and with it the structure leading to a rf energy loss. Ohmic surface resistive losses are however not an indicator for a breakdown since they occur also in non-breakdown pulses and have to be corrected for in the missing energy calculation.
Figure 5.2: Typical pulse without breakdown. Data taken from the TM02 accelerating structure test at the 30 GHz structure test facility at CERN.

Figure 5.3: Example breakdown pulse, recorded with equivalent machine settings and parameters of the pulse in figure 5.2. Nota bene: The reflected power is not scaled as in figure 5.2.
Figure 5.4: Absolute missing energy versus absolute incident energy for TM02 test structure. Transmitted power is attenuation corrected (+3.4 dB). The black dashed line indicates the total transformation of incident energy to missing energy.

Figure 5.5: Missing energy distribution for TM02 test structure. Missing energy is given as ratio of missing energy to incident energy. Transmitted power is attenuation corrected (+3.4 dB).
5.2.1 Rf power waveform reconstruction and calibration check

Using the low power rf measurements mentioned in section 5.1 as transfer functions, transmitted and reflected power signals can be calculated from the measured incident power signal. This allows the calibration of transmitted and reflected power DAQ channels and to predict the nominally transmitted and reflected signals which would occur if the measured signals were perturbed by a breakdown.

The incident power signal was decomposed into its frequency components by a Fourier transformation (implemented as FFT algorithm) and folded with the above mentioned transfer functions. The transmitted and reflected waveforms were then obtained with an inverse FFT. In figure 5.7, a breakdown pulse (dotted lines) measured in the 30 GHz C30 speedbump structure has been plotted together with the calculated, unperturbed signals (solid lines).

This process has been implemented in software for real-time monitoring of the power waveforms in order to check the calibration during high power tests. Figure 5.8 shows an example of a measured and calculated non-breakdown pulse which was taken during the TM02 structure test, after a calibration run done with the automatic calibration system developed for that task and described in more detail in section 4.1.2. The left plot in figure 5.6 shows the correlation between incident energy and transmitted energy as a direct check for the DAQ calibration. The fit (red line) to the points in the principle arm of the distribution (all other points outside this arm are breakdown pulses) indicates a power loss in the structure of -3.6 dB which is -0.2 dB more than expected from the low power measurements. This is inside the expected error range (compare to table 4.1). In the right plot of figure 5.6 the correlation between measured and calculated transmitted energy is shown. The dashed, black line indicates a full match between energy sums, but the fit (red line) indicates that the transmission is overestimated by about 10%, which slightly varies with real transmitted energy. This agreement is sufficient to reconstruct the nominal transmitted power waveform if the measured one has been perturbed by a breakdown. For the reflected power signals, this agreement is in the order of 25% due to the high noise level of the very low power signal which could not be amplified without loosing dynamic range and therefore loosing the reflected signal during a breakdown by saturation of the ADCs.

Figure 5.6: Correlation of incident to transmitted energy (left plot) and of calculated transmitted to measured transmitted energy (right plot). Dashed, black lines indicate 100% conversion respectively overlap in energy sum. Red, solid lines are fits to the diagonal, non-breakdown data points. All other points not lying on the diagonal are pulses with breakdown.
5.2. RF WAVEFORMS AND POWER BALANCE DURING BREAKDOWNS

Figure 5.7: Example of a rf breakdown pulse in the C30 speedbump structure (second, reversed test) showing the use of the low power measurements to calculate the expected non-breakdown pulses.

Figure 5.8: Comparison between measured signals (solid lines) and calculated signals (dashed, orange lines). All calculated signals are derived from the measured incident signal (left plot). See text for more details.
5.3 Dc I-V waveforms and power balance during breakdowns

In analogy to the power waveforms in rf, voltage and current waveforms for non-breakdown and breakdown events were measured with the dc spark setup. The system is described in more detail in section 4.4.2. In a non-breakdown event, the gradient in the spark gap stays constant until it is disconnected from the power supply. A breakdown can occur either directly at the point in time when applying the voltage to the gap or with some delay. In figure 5.9, the voltage and current waveforms of a delayed breakdown are plotted. The distribution of the lengths of the delays has been analyzed in [31] and shows a dependency on the materials used for tip and sample. 500 ns after the breakdown starts, the peak current during the discharge reaches nearly 120 A at voltages of the order of several volts.

Figure 5.10 shows the current and voltage waveforms of an immediate breakdown. Here, the voltage rises steeply at the beginning, peaks at the nominal voltage after only 40 ns and then decays to zero within 500 ns. At that point, the current reaches its maximum, as it was the case in the delayed breakdown. The shape of the current waveform is determined by the frequency response of the power supply and the plasma parameters. A corresponding circuit model will be presented in section 5.4. The integrated power signal derived from the current and voltage waveforms is consistent with the systematic errors of the DAQ system, due to energy conservation when a complete discharge of stored energy in the power supply occurs. See chapter 8 for a more detailed analysis. This energy is both determined by the capacitors in the power supply and the initial voltage. For the configuration used to obtain the data plotted in figure 5.9 and 5.10, the total energy is given by equation (5.1):

\[
E = \frac{1}{2} CU^2 = \frac{1}{2} \cdot 15 \text{nF} \cdot (5.25 \text{kV})^2 \approx 0.21 \text{J} \tag{5.1}
\]

In order to compare the most directly rf and dc breakdowns, the capacitor was chosen to store an energy similar to the incident energy in high power rf structure tests. Because of the series resistance in the dc spark power supply, the question concerning the fraction of the energy which is actually dissipated in the arc was addressed with the help of a circuit simulation presented in the next section.

Figure 5.9: Example breakdown pulse with delay, copper sample and tip, 15 nF capacitor, 5.25 kV nominal voltage. Data taken with the dc spark setup at CERN. Voltage in blue (black), current in red (grey).
5.4 DC BREAKDOWN EQUIVALENT CIRCUIT MODEL

In order to understand the inherent response of the dc spark system’s electrical circuit, a circuit model based on the circuit diagram 4.8 was developed. This model was extended in order to fit to the real setup, since the old circuit diagram did not allow to predict the fast transient behaviour of the real setup. Motivated by the fact that the old model did not allow to reproduce the measured electrical behaviour, the new model now allows to estimate the influence of the electrical circuit on the measured waveforms. The results of the circuit extension, the corresponding simulations and supporting experiments are presented in the following sections.

5.4.1 Extension of the circuit model

The model is based on the dc spark circuit diagram in figure 4.9 to which equivalent circuits for transmission cables from the power supply to the spark gap and from this gap to ground were added. The new circuit diagram is shown in figure 5.11. All components in the red, dashed box are part of the circuit already known from the formerly presented dc spark setup. No additional components were added. The components inside the green, dashed box are components which model the spark gap and will be explained in more detail in section 5.4.2. Following components were added to get a more precise model of the real setup: transmission lines T1 and T2 including the resistors R3 and R4 to model the 50 $\Omega$ coaxial cables supplying the spark gap anode and the connection from cathode to ground. The resistors R5 and R6 are resistances found in the grounding scheme of the real setup.

The model now includes parasitic inductances, capacitances and resistances found in the transmission lines and in the grounding scheme. Not yet included are parasitic impedances of the cabling inside the high-voltage cabinet containing the parts in the red box of figure 5.11 the corresponding values for the UHV feedthroughs and in-vacuum cabling. An estimation of these values is difficult but are likely to be below the values which can be found for 0.5 m of the high-voltage cable used to supply the spark gap.
5.4.2 New circuit model validity check

In the new circuit model, the spark gap has been replaced by the switch S2 and a two terminal electrical circuit X of unknown properties, as placeholder. The switch is used to model the delay of the breakdown onset and the component X can be replaced with any two terminal electrical circuit. To check the validity of the new circuit model, the component X has been replaced by a short circuit (5 mΩ resistor) which corresponds to a short circuit in the spark gap. This eliminates all unknown parameters of the spark gap and allows a full simulation of this model. Afterwards, measurements with a shorted spark gap were done in the CERN dc spark setup number one, using the same initial voltage as in the simulation. For this experiment, the high-voltage cables supplying the spark gap were disconnected from their vacuum feedthroughs and were shorted. The two plots in figure 5.12 show the measured voltage (left plot) and current (right plot) for a spark and a short circuit, both taken at an 8 kV capacitor voltage.

![Figure 5.12: Measured voltage (left plot) and current (right plot) waveforms for a spark (red, dashed line) and for a shorted gap (black, solid line). All values taken at 8 kV capacitor voltage. 20 µm gap (400 MV/m) in the spark case.](image)

Remarkably, the waveforms taken with a normal and shorted gap are similar both for voltage and current waveforms. The only difference in the current waveforms is the - compared to the short-circuit current waveform - increased current in the falling edge of the waveform measured with spark, starting around 800 ns after the trigger (1400 ns absolute time in figure 5.12). In the voltage waveforms, the spark waveform shows slightly more negative voltages than the short-circuit waveform after the negative undershoot, starting around 500 ns after the trigger (800 ns absolute time). The waveforms contain also high-frequency components of several 10 MHz and higher, namely the increased noise on the signals taken with the shorted
5.4. DC BREAKDOWN EQUIVALENT CIRCUIT MODEL

gap and the ringing in the peak of the current waveforms in the spark case. From these results, one can conclude that the electrical properties of the spark only have minor influence on the measured waveforms. In particular during the first few 100 ns, no significant differences between spark and shorted waveforms are visible, if the high-frequency ringing is neglected. This is a valid assumption since it is likely that this noise is caused by the slightly changed grounding resistances of the shorted setup. The later differences in current and voltage must be caused by a changing resistivity of the spark plasma due to expansion into the surrounding vacuum and therefore, the loss of plasma conductivity respectively charge carriers in the - at that moment - already vanished electric field.

5.4.3 Simulation results of the new model

The results of the simulation of the model introduced above show the best fit for the measured data if the component X is replaced by an inductance of the order of 2 µH (that is in the place of the spark gap) with an internal series resistance of 1 mΩ. In these waveforms, the free parameters are the switching time of the switch SW2 and the value of the inductance X. This switch closes with an adjustable delay after the main switch SW1 in order to mimic the breakdown delay. The value of the inductance of around 2 µH is about a factor of two higher than what is expected to be present as additional parasitic inductances in the system. Furthermore, if this inductance would be located in the discharge current path inside the power supply before the transmission lines, the simulated voltage and current waveforms would be different. If the inductance is replaced by a short circuit in the simulation, the negative overshoot in voltage decays within 100 ns to zero, which has not been observed in the measured waveforms. Since the waveforms measured with a shorted spark gap are similar to the simulated ones with the 2 µH inductance, this inductance must be located somewhere in the current path of the power supply system. Since a dedicated device with these properties could not be found, it was probably distributed over the full system. The delay time of SW2 does not have an influence on the overall characteristics of the transient behaviour, except for a longer flat top voltage before SW2 turns on.

Figures 5.13 and 5.14 show the simulated current and voltage waveforms in comparison to experimental data at a 8 kV initial voltage and an 28.5 nF capacitance. This experimental data will be used in chapter 8 in order to compare the light intensity emitted by a breakdown to the current and voltage waveforms.

In figure 5.13, the discharge current limiting resistor R2 had a value of 25 Ω for the simulation, which equals the value of the resistor used in the real setup. Also the value of X was optimized to give the best fit to the measured data. Using the experimental conditions as initial parameters of the simulation, the reproducibility of the measured waveform is remarkable when taking into account the simple electrical model. A drawback is the simulated current which is about a factor of two higher than the measured current. Nevertheless, it reproduced the shape equally well. A reason for this behaviour could be an improper matching of the impedance of the power source to the impedance of the external cabling. The source impedance is given by 25 Ω, which has not been observed in the measured waveforms. Since the waveforms measured with a shorted spark gap are similar to the simulated ones with the 2 µH inductance, this inductance must be located somewhere in the current path of the power supply system. Since a dedicated device with these properties could not be found, it was probably distributed over the full system. The delay time of SW2 does not have an influence on the overall characteristics of the transient behaviour, except for a longer flat top voltage before SW2 turns on.

This effect has to be accounted to the fix value of the internal series resistance of X which most likely does not exactly represent the plasma resistance behaviour, as already indicated by the results of the precious section. Therefore, the model has to be refined as soon as better electrical data from PIC plasma simulations are available.

Even though this simulation model is not perfect yet, the representation of the measured waveforms is good enough to make statements about the power dissipating elements of this circuit. To do so, the power dissipation of all ohmic components of the circuit was simulated and then integrated for both configurations shown in figures 5.13 and 5.14. The results are presented in table 5.1.

As one can see from the table, practically all of the energy is dissipated in R2 and independent is of the configuration. Further simulations showed that putting additional resistors into the current path (e.g. a series resistor to X of several Ohms) led to a distortion of the waveform. Values of such a resistor of more than 1 Ω did not reproduce the voltage overshoot anymore, even when adapting the value of X. This is not totally inconsistent with the plasma model and the experimental results. Assuming that energy in the plasma can only be dissipated by accelerating charges, an order of magnitude calculation taking into account the experimental voltage waveform shown in 5.13 gives approximately a value of 20 mJ of energy dissipated....
Table 5.1: Energy dissipation in ohmic components. Conf.1: $R_2 = 25\Omega$ and $X = 1.8\,\mu\text{H}$. Conf.2: $R_2 = 50\Omega$ and $X = 2.8\,\mu\text{H}$. Total energy stored in $C_1$ at 8kV: 912 mJ. Values do not sum up to 912 mJ because of numerical rounding and finite simulation time (conf. 2 current decays longer than conf.1).

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_{\text{conf.1}}$ [mJ]</th>
<th>$E_{\text{conf.2}}$ [mJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2</td>
<td>908.9</td>
<td>909.1</td>
</tr>
<tr>
<td>Remaining R’s</td>
<td>3.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

by this process. All other plasma processes like ionization, sputtering etc. are secondary effects driven by the accelerated charges. This dissipation can well be hidden in the differences between the simulated and the measured electrical waveforms.

In total, the dissipated energy in the breakdown is about a factor of ten smaller than it was expected before and therefore up to a factor of a 100 smaller than the missing energy in rf structures. Whether this difference in dissipated energy is significantly affecting the breakdown properties will be discussed in the following chapter. A redesign of the dc spark setup electrical system should take into account these results. The system can not be treated anymore as a pure dc system if the transient behaviour should be addressed experimentally. A new design must follow rf design rules in order to achieve a system bandwidth of a minimum of 1 GHz and to be able to acquire ns-plasma effects.
5.4. DC BREAKDOWN EQUIVALENT CIRCUIT MODEL

Figure 5.13: Comparison of voltage and current signals measured and acquired. Simulation results are plotted in dashed lines. See text for details on the experimental conditions. Simulation with $R_2 = 25\,\Omega$ and $X = 1.8\,\mu\text{H}$.

Figure 5.14: Same experimental data as in figure 5.13 but simulation with $R_2 = 50\,\Omega$ and $X = 2.8\,\mu\text{H}$.
5.5 Emission currents in dc and in rf structures

There are two distinct current regimes which one has to differentiate: emission currents during stable operation and emission currents in the case of a breakdown which can be of higher orders of magnitude. The first regime refers to an electron emission from field emitters on surfaces being exposed to high electric fields. This emission follows the Fowler-Nordheim law introduced in section 2.2.1. In the case of a breakdown, electron currents are liberated from the surface by several effects. These include the already mentioned field emission which is of orders of magnitude higher due to an increased field enhancement factor and an increased surface potential due to the plasma sheath (compare with chapter 3). In addition, electrons extracted from the ionized plasma and secondary electrons extracted by surface bombardment of primary electrons contribute to the emission current.

Although occurring in rf and dc, a different experimental approach is necessary to measure these emission currents. These are explained in more detail in the next two sections.

5.5.1 Field emission current emission in dc

In the dc spark system, the anode is at the opposite and very close to the cathode sample. This results in emitted electron trajectories which run from the cathode to the anode. A constant voltage can be applied to the gap for a few seconds, resulting in a constant current (dark current) through the gap. This current can be directly measured by the dc spark DAQ system as long as no breakdown occurs. In field emission mode (see section 4.4.2), this voltage is varied and plotted against the resulting current in a Fowler-Nordheim plot. The field enhancement factor \( \beta \) can be extracted from the slope of the measured curve. Care has to be taken in order not to reach to gap voltages which could result in a breakdown. This may damage the electrometer through overcurrents.

These \( \beta \)-measurements are done routinely in the dc spark setup. More information on the results can be found in [31], [82], [30] and [29].

If the system is run in breakdown rate mode or conditioning mode, no field emission current measurement is possible. However in the case of a breakdown, the waveforms explained in detail in the previous section 5.3 are recorded. These currents are called breakdown currents and are not considered as dark current.

5.5.2 Electron and ion currents emitted by breakdowns

In rf structures, currents are emitted from the structure surface during the rf pulse. Some of the emitted electrons escape the structure through the beampipe and are detected by a faraday cup positioned on the virtual beam axis (see section 4.5.1 for details on the instrumentation). This is the case for both dark current emitted during each rf pulse without breakdowns and currents emitted from rf structures with breakdown. This has been observed for all 30 GHz and X-band structures. Typical values for 30 GHz and X-band structures are several µA dark current and around 100 mA for breakdown emission currents. The duration of the emission is generally shorter than the incident rf pulse length.

Figure 5.15 shows the dark current emission during a breakdown collected by the upstream faraday cup (power input side of the structure), together with the corresponding rf waveforms.

The dark current signal is of negative sign (inverted in the plot for illustration purposes), indicating that the collected charge carrying particles are electrons. The signal is delayed due to cable delays. The time of flight of the electrons is negligible because of the short distance of 20 to 30 cm from the breakdown spot to the faraday cup and the high velocity of the electrons even at the lowest expected energies. Timing corrections could not be applied since the total delay in the rf DAQ is unknown. Attempts were made to correlate the electron emission of a breakdown to the rf signal waveforms and the integrated power values as well as signal timings. However, no correlations were revealed. The reason for this is likely to be geometric: Breakdowns occur at different positions in the structure, and even if the breakowns emit the same amount of electrons per unit energy of input power radially isotropically, the current exiting the structure will be modified as a function of its position. In addition, the faraday cup covered only one third of the emission angles allowed by geometry. The current emitted towards the vacuum vessel walls surrounding the faraday cup is likely to create secondary electrons which are then collected by the cup, resulting in a lower and possibly dispersed signal. A faraday cup with better collection efficiency and bias voltage for secondary electron rejection should be foreseen for future experiments. Positive signals following the negative electron peak have been observed and identified as slow ions from the breakdown plasma. A detailed description of these events can be found in [59].
Dark current emission measurements of 30 GHz structures were not addressed experimentally for the scope of this work. An attempt to see dark currents emitted from the TM02 structure with the faraday cup failed due to the low sensitivity of the ADCs optimized to cover the dynamic range of the strong breakdown current emission. Measurements of dark currents were done at SLAC and KEK and can be found among others in [88].

Figure 5.15: Breakdown in the 30 GHz TM02 structure, power waveforms and dark current signal (inverted) from upstream faraday cup.
5.6 Surface damage by breakdowns

Rf breakdowns cause damage to the structure surface, the spot where the field emitter was located gets destroyed by melting and sputtering within microseconds. The diameter of the resulting crater is of the order of several micrometers which is orders of magnitude higher than the assumed nanometer-sized field emitter who started the breakdown. It is assumed that the sputtering of the surrounding area by metal ions and probably also clusters or droplets of the surface material creates new field emitters there. This can cause spreading of the breakdown sites radially from the initial one in a random-walk like pulse-to-pulse process. Finally, the results are macroscopic patches of breakdowns of a diameter of a few millimeters. In figure 5.16 a photograph of an iris with damage caused by breakdowns during the rf test is shown. No deterioration of the low power rf parameters due to this damage was observed.

In dc, the breakdown damage looks similar, but the breakdowns do not spread far due to the small size of the area influenced by the high electric field. Sample (cathode) and tip (anode) show surface melting. Material transport between both has been observed by using samples and tips of different materials. A summary of the crater morphology and the scaling of the crater's diameter with discharge energy can be found in [52] and [53]. In figure 5.17 a SEM picture of typical breakdown sites is shown. Well visible are the craters of a micrometer size with metal which solidified while it was radially ejected outwards. The displaced mass is typically of the order of some cubic micrometer (approx. nanograms). To melt one cubic micrometer of copper (starting at room temperature), approximately 4 nJ are necessary. This is only a tiny fraction of the measured missing energy as millions of craters per breakdown would be necessary if all the energy was dissipated by melting. In contrary, the observed number of craters is only of the order of several thousands per structure, which roughly corresponds to the counted number of breakdowns during the processing and the testing of the structure.
5.6. SURFACE DAMAGE BY BREAKDOWNS

Figure 5.16: Optical microscope photograph of the first regular cell of a high-power tested and cut CERN T18 structure. The central, matt spot is caused by several breakdowns which occurred during the test. The mesh-like features on the shiny surface are grain boundaries.

Figure 5.17: Scanning electron microscope image of the surface of the iris shown in figure 5.16. The typical craters created by breakdowns can be seen here. In addition, the grain boundaries can be seen in more detail as long trenches in the surface.
Chapter 6

Optical spectroscopy in rf and dc

Optical spectroscopy is a powerful diagnostic tool for investigating manifold plasma and surface processes in a breakdown. It is noninvasive which is the only possibility when dealing with high electromagnetic fields. Spectra can include a variety of features such as emission lines of various width from different elements and continuous emission of thermal or broadening effect sources. These features can be used to extract information about the involved elements, the temperatures and the densities of the breakdown plasma as well as possibly unpredicted effects.

6.1 Optical spectroscopy during breakdown

In the following two sections, the results of the time-integrated spectroscopy of breakdowns in the dc and rf setups are presented. For all measurements, the spectrometer and CCD-camera, together with the corresponding light collection system described in section 4.5.2 have been used. Sections 6.1.1 to 6.1.3 will focus on the identification of elements and ion species, whereas in 6.1.4 plasma parameters from the spectra will be examined. The reproducibility of the spectrum for breakdowns occuring with similar experimental conditions will be adressed in sections 6.1.5 and 6.1.6. Section 6.1.7 will summarize the observed differences and similarities between rf and dc spectra.

All spectra in this chapter have been integrated over the whole breakdown process. There is strong evidence that the breakdown plasma is not in local thermodynamic equilibrium (LTE) (see chapter 3), which complicates the extraction of the plasma parameters from the data. More details on the temporal behaviour of the breakdown process can be found in chapter 8.

6.1.1 Spectroscopy of dc breakdowns on copper samples

Using the dc setup number one, the spectra in figures 6.3 and in more detail the figures B.1 to B.11 have been measured with an OFE high-purity (7-9) large grain-size copper sample. To do so, the setup has been regulated to provide a breakdown at every pulse by setting the field to 400 MV/m. The spectrograph’s camera trigger input was connected to the trigger signal of the main hammer switch. The trigger delay was less than 1 µs for the integration and the hammer switch closing time was well above 1 ms. Therefore the full emission process of the breakdowns was captured. The camera integrated as long as the hammer switch was closed. The gap was conditioned to a constant breakdown field before the spectra have been taken. The pressure inside the vacuum chamber was \(5 \times 10^{-9}\) mbar.

The intensity of single shots for the normal resolution spectra in 6.3 and the high resolution spectra shown in appendix B were too low for line identification. Therefore, each spectrum was averaged over 20 breakdowns and then processed by background subtraction and QE correction.

The spectra obtained show the emission lines expected from ionized copper and a white light background. The observed ionization levels are CuI (neutral), CuII (single ionized \(Cu^{1+}\)) and CuIII (double ionized \(Cu^{2+}\)). All major lines in this wavelength interval are present. Their intensities above 500 nm are similar to the relative intensities obtained from NIST [73], even though the experimental conditions for obtaining the reference ones were different (see for example [81] as a source for the NIST database). Below 500 nm, the total intensity of the lines is lower than expected. This effect has to be attributed to the position of the breakdown relative to the light collection fiber. Indeed, light created in the spark is modified by the
reflectance of copper (figure A.1) as illustrated in figure 6.2. Multiple reflections can easily occur in the small (20 µm) but wide (2 mm tip diameter) gap, which leads to a strong attenuation. The geometry of the system seems to have favoured breakdowns on the far side of the tip in respect to the fiber input because of a possible electric field maximum caused by a misalignment. This lead to a constant attenuation of the light at shorter wavelengths. However, the system does not offer enough freedom of movement to readjust the gap on that small scale.

The existence of ionization levels up to CuIII indicate that peak plasma temperatures above 20.28 eV (7.72 eV for CuII) are reached during the breakdown. Higher ionization levels are not excluded but are outside the sensitivity range of the spectrograph, these lines being in the deep ultraviolet.

The white light background is present over the full wavelength range and is roughly flat between 400 nm to 800 nm, varying between 90 and 130 ADC counts. In the wavelength range below 400 nm and above 800 nm, the background is attenuated by the decreasing efficiency of the CCD camera and the grating used, even though the spectrum has been corrected for these efficiencies. This is caused by the fact that the efficiency values in this wavelength ranges are very small and therefore subject to increased errors. The efficiency values were obtained from the manufacturer and could not be validated at CERN.

There are at least three possible sources of the white light background: one is dense plasma effects such as Doppler and Stark broadening and collision effects above the plasma sheath (stage d) shown in figure 3.1). Secondly, during the onset phase of the breakdown (stage a) and b) in figure 3.1, space charge effects close to the field emitter create conditions leading to a continuous white light emission. Or third, the emission is caused by black body radiation. In this case, the black body emission peak would sweep through the visible and its emission would broaden according to the temperature of the copper surface which is probably changing over the full breakdown process. An argument in favour of the black body explanation is that the ratio of the emitted intensity above the background without lines and the line intensities without that background is approximately 1 to 1. Comparing these to the timescales of the above mentioned stages of the breakdown model and with the results of chapter 8 which imply around three orders of magnitude less background than line intensity, if this radiation is only caused by the effects appearing during the stages b) and c) of the breakdown model, the black body radiation or the dense plasma effects in stage d) or a combination of both are the most likely interpretation of this background.

Furthermore, a broadening of CuIII and CuII lines can be observed in the spectrum whereas no broadening was found for CuI lines. This broadening is clearly visible around 436 nm where seven CuIII lines are present. In addition, these lines broaden this conglomeration to one line of 5 nm pedestal FWHM (left plot in figure 6.1). The spectrograph’s resolution would have allowed to resolve these seven lines into two groups of each four and three lines with a separation down to the background level if no broadening was present. An example for the broadening of CuI lines can be found around 493 nm (left plot in figure 6.1). It is however less prominent then the CuIII broadening.

![Figure 6.1: Details of the dc Cu breakdown spectrum showing the broadening of CuIII (left plot, vertical bars indicate CuIII line positions) and CuII lines (right plot, vertical lines indicate CuII line positions).](image-url)
temperatures above the ionization level of CuIII are present twice during short moments in time when the plasma heats up and cools down. Each ionization cross section of Cu is therefore favoured at these moments and in the time integrated spectrum, the overlay of all the lines can be seen. Still, these lines have to be broadened by the processes mentioned for the white background explanation in order to create a distribution which has been found in figure 6.1. However, the plasma conditions necessary for the creation of double ionized copper are most likely to cause line broadening by thermal and impact pressure effects too. The spectra have also been examined for further elemental atomic lines caused by impurities (see [80]). These could be in the sample or tip and result from the absorption of gases and solvents used during handling and machining and cleaning else be present in the dc spark system itself. Even though several unidentifiable dim lines have been found, these do not fit to elements which are likely to be present in the material or system. These lines have been tested for consistency with line emissions from H,C,N,O,F,Cl,Ar and all metals listed as impurities for OFE copper. In particular, the bright lines with a strong broadening around 463 nm could not be clearly identified. Only argon, which is used for venting the dc spark system before opening the vacuum chamber, has bright emission lines of these wavelengths and a probability to be present in the system. However, most other ArI and ArII lines which are supposed to be up to a factor of a 1000 brighter (according to relative intensities from [73]) do not appear in the spectrum. If these lines are originated from argon, the excitation of these lines must be favoured by the plasma conditions during the breakdown, but the breakdown plasma model does not yet allow a quantitative approach to this phenomena. Identifiable lines in addition to the copper lines are the two second-order lines of the CuI at 324.75 nm and 327.40 nm which can be found in the spectrum at exactly twice their wavelength. In addition, a HI line at 656.27 nm (possibly mixed with a second HI line at 656.28 nm) could be identified, probably resulting from water absorbed during treatment and handling of the sample. Further hydrogen or oxygen lines could not be found. The conditioning of this spot before the spectra were taken seemed to be insufficient for removing all hydrogen from the spot surface.

Putting an upper limit on the level of impurities in the breakdown would require a breakdown model which includes the excitation of ions of different species and elements as well as the resulting photon emission which is not yet available. In addition, atomic excitation cross section data for most ionization states higher than neutral excitation is unavailable and would therefore need to be measured in advance. An empirical attempt to put an upper limit on the spectroscopically detectable quantity of oxygen in the sample surface will be made in section 6.2.

Figure 6.2: Illustration (not to scale) of light propagation for different breakdown (green ovals) positions relative to the collection fiber. For the breakdown on the right, major parts of the collected light will have been at least once reflected by the copper surface modulating the emitted light with the reflectance of the sample. The lens based collimator is used for total light intensity measurements, see chapter 8.
Figure 6.3: Full breakdown emission spectrum of a breakdown in the dc setup. 400 MV/m gradient, high purity OFE copper sample (huge grain) and tip, 28 nF main capacitor. Spectrometer set to 150 l/mm grating and 50 µm input slit width, integration when main switch was closed (1 s), 20 accumulated integrations with background subtraction and quantum- and grating-efficiency correction. The horizontal bars are wavelength intervals referring to detailed spectra in appendix B, the vertical bars correspond to relative intensities from [73]. Red (dotted) for CuI, green (dash-dotted) for CuII and orange (dashed) for CuIII.
6.1. OPTICAL SPECTROSCOPY DURING BREAKDOWN

6.1.2 Spectroscopy of dc breakdowns on molybdenum samples

The molybdenum spectra in figures 6.4 and B.12 to B.22 have been measured in the same way as the copper spectra. For this, the dc spark setup number two has been used. The optical setup and its parameters were the same as in the copper spectra experiments explained above, the vacuum feedthrough and the in-vacuum fiber being the only separate parts for each setup. Nevertheless, these parts are identical parts concerning all parameters.

The molybdenum sample and tip were made out of 99.95% purity Mo and cleaned using the same standard CERN procedure used for the copper samples. The gap was conditioned with 50 breakdowns to reach constant breakdown fields, before the spectra were taken to remove all possible surface treatment effects. The gradient was set to 550 MV/m in order to have a breakdown each time the field was applied. The pressure inside the vacuum chamber was \(3 \cdot 10^{-10}\) mbar after bakeout.

![Figure 6.4: Full breakdown emission spectrum of a breakdown in the dc setup. 550 MV/m, molybdenum sample and tip, 28 nF main capacitor. Spectrometer set to 150 l/mm grating and 50 µm input slit width, integration when main switch was closed (1 s), with background subtraction and quantum- and grating-efficiency correction applied. The horizontal bars are wavelength intervals referring to detailed spectra in appendix B, the vertical bars correspond to relative intensities from [73], red (dotted) for MoI and green (dash-dotted) for MoII.](image)

The molybdenum breakdown spectra show a very dense distribution of lines over the observed wavelength range and quasi-continuous white light background slightly falling in intensity towards the infrared. This is due to the efficiency modulation of the spectrometry system, as it was already the case for the copper spectra. The spectrum is plotted in figure 6.4 together with relative line intensities taken from [73]. The reflectivity of molybdenum is practically constant over this wavelength range (see figure A.1). Therefore, the attenuation observed at short wavelengths in the copper spectra does not appear here. The line spectrum shows the expected MoI and MoII lines and a strong HI line at 656.27 nm (possibly mixed with a 656.28 nm HI line expected here). MoIII lines could not be observed here since these emission lines are in the deep ultraviolet. The ionization energy necessary for creating MoII is of 16.22 eV. Therefore,
the plasma temperature has to have reached this value during the breakdown in order to make these lines appear in the spectrum.

Due to the lower purity of the molybdenum compared to the copper used for the spectrum in figure 6.3, more lines caused by impurifying elements were expected to contribute to the spectrum. The spectra were therefore examined for all possible signatures of elements besides molybdenum. However, the tremendous amount of MoI lines equally distributed over the full observed wavelength interval and the achieved spectral resolution made it impossible to distinguish between lines originating from molybdenum and those originated from other elements. Moreover, the lack of a breakdown model predicting the emission lines strengths of elements made it impossible to allocate unidentified lines to certain elements.

6.1.3 Spectroscopy of rf breakdowns in copper structures

In order to extend spectroscopic data to rf, the C10 accelerating structure has been measured at SLAC. These tests were made at SLAC in the ASTA facility (see 4.2 for details on the setup). The SLAC C10 structure is a ten-cell travelling wave structure operating at 11.424 GHz and is only 10 cm long with a 6 mm aperture. Therefore, a good emission light output was expected. The structure’s material was OFE copper and brazed in an atmospheric pressure hydrogen furnace and cleaned with a mild etching in addition to other cleaning procedures similar to those used at CERN. A peculiarity of this structure is the reusable in- and output coupler design. The couplers are connected to the disk stack via stainless steel vacuum waveguide flanges with an inner diameter adapted to the circular electromagnetic mode which couples them into the disk stack. In order to minimize losses inside these flanges, the walls were copper plated and a copper gasket was used for sealing. This gasket had to provide good electrical contact due to its position in a high current region.

The spectrum obtained with this setup and shown in figure 6.5 was taken at a structure input power of 40 MW and 200 ns pulse length. At this power level, the BDR of the already 200 h conditioned structure was of the order of $10^{-3}$, resulting to about one breakdown per two minutes. This interval was chosen to exceed the integration time of the spectrograph in order to avoid multiple breakdowns per integration as well as missing breakdowns during the dead time of the camera (between two integrations). The observed wavelength range and resolution is equal to the one used for the dc spark spectra. As expected, the recorded intensities are sufficient for time integrated spectroscopy. The saturation of the camera at one strong emission line was even observed.

The spectrum consists of a white light background and multiple lines from copper and other elements. Just like in the dc spark spectra, the rf breakdown spectrum is modified by the reflectance of copper which leads to lower intensities towards shorter wavelengths. Due to the fact that the background practically vanishes at the UV end of the spectrum and that the bright CuI emission lines at 324.75 nm and 327.40 nm are lower in intensity than the CuI lines around 515 nm, one can deduce that the attenuation of the emitted light is the result of multiple reflections in the complex geometry of the accelerating structure. The white light background is flat except for this modulation over the observed wavelength range.

In addition to this background, the line emission pattern is more complex and features more lines at first sight compared to the dc breakdown spectra on copper. These lines were assigned to the emission lines on FeI, CrI and NiI, the alloy metals of stainless steel of 316L type. An endoscopical inspection after the disassembly of the structure showed clear indications of a single breakdown spot between the stainless steel flanges and the copper gasket connecting input coupler and disk stack, probably caused by mechanical defects on the surface of the gasket and/or a misalignment during assembly. The defect was dominating the breakdown rate and its spatial distribution. Therefore, no breakdown spectrum without the additional lines originating from the stainless steel could be recorded.

Nevertheless, this experiment shows that spectroscopy can be a powerful tool for a noninvasive diagnostic of breakdowns and their source already in the early stage of an rf test. More details on that can be found in section 6.3.
Figure 6.5: Full breakdown emission spectrum of a breakdown in the SLAC C10 structure. 40 MW input power, 200 ns pulse length. Spectrograph set to 150 l/mm grating and 50 µm input slit width, 120 s integration time, 60 Hz repetition rate, approximately 40 breakdowns.
6.1.4 Estimation of plasma parameters for copper dc breakdowns

In a LTE plasma, the plasma temperature and the plasma density can be extracted from the spectrum. For estimating the plasma temperature, the two-line-method or a Boltzmann plot, which is the extension of the two-line-method to multiple lines can be used. The plasma density is correlated to the line width of a hydrogen line and can for that reason only be measured if this line is present in the spectrum with sufficient intensity to be measured with high resolution. Even though the breakdown spectra are expected to be non-LTE plasma from the current breakdown model, an attempt has been made to estimate the plasma temperature using a Boltzmann plot. The necessary lifetimes and transition probability parameters of the different CuI excitation levels have been extracted from [18] and [167]. From atomic structure theory, an equation (6.1) for relative line intensities can be deduced if a Boltzmann distribution is assumed for the population of the excitation levels [46].

\[ \ln \left( \frac{I_\lambda}{g_A} \right) = - \frac{E_u}{k_B T} + \text{const.} = -aE_u + b \]  

(6.1)

For each line, the wavelength \( \lambda \), the intensity I, the oscillator’s strength f, the statistical weight of the lower level g and the energy of the upper level \( E_u \) have each to be measured or be obtained from literature. \( k_B \) is Boltzmann’s constant and T the desired plasma temperature. For the estimation of the dc spark copper plasma, the lines listed in table 6.1 have been chosen because of the availability of precise level parameters from [18] and because these lines are close enough together in the spectrum to render possible errors in QE or GE negligible.

<table>
<thead>
<tr>
<th>( \lambda ) [nm]</th>
<th>Lower ([cm^{-1}])</th>
<th>Upper ([cm^{-1}],[eV])</th>
<th>( gA ) ([10^8/s])</th>
<th>( gf )</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>510.55</td>
<td>11202.6</td>
<td>30787.7 (2.65)</td>
<td>0.0503</td>
<td>0.0197</td>
<td>4s22D_{5/2} - 4p2P_{3/2}</td>
</tr>
<tr>
<td>515.32</td>
<td>30253.3</td>
<td>49935.2 (4.30)</td>
<td>4.6971</td>
<td>1.8710</td>
<td>4p2P_{1/2} - 4d2D_{5/2}</td>
</tr>
<tr>
<td>521.82</td>
<td>30783.7</td>
<td>49942.1 (4.30)</td>
<td>5.7331</td>
<td>2.3417</td>
<td>4p2P_{3/2} - 4d2D_{5/2}</td>
</tr>
<tr>
<td>529.25</td>
<td>43514.0</td>
<td>62403.3 (5.38)</td>
<td>3.3215</td>
<td>1.3955</td>
<td>4s4p4D_{7/2} - 4s5s4D_{7/2}</td>
</tr>
<tr>
<td>578.21</td>
<td>13245.4</td>
<td>30535.3 (2.63)</td>
<td>0.0511</td>
<td>0.0256</td>
<td>4s22D_{3/2} - 4p2P_{1/2}</td>
</tr>
</tbody>
</table>

Table 6.1: Transition probabilities, wavelength in air, oscillator strengths and lower and upper energy levels for selected CuI lines. From [18].

The line intensities have been determined by fitting a Gaussian profile with variable offsets to each of the emission peaks. The offset was added to comprise a vertical shift of the lines, due to the white light background. Figure 6.6 shows the fits done for the 510.55 nm and 515.32 nm line as examples. Assuming a plasma a with broad Maxwellian velocity distribution, the Gaussian profile was preferred to the Lorentzian profile resembling the natural line width caused by the decay times of the different levels and the uncertainty principle, since doppler broadening dominates the line width. The broad Maxwellian velocity distribution is a reasonable assumption in the current breakdown plasma model with temperatures up to 100 eV reached in simulations and above 20 eV verified by the existence of CuII emission lines. Each fitted Gaussian profile has then been integrated in order to obtain the total emission intensity and then plotted in the Boltzmann plot in figure 6.7. The obtained temperature is T=6110K with a wide confidence belt (1\( \sigma \)) ranging from T=3870K to T=14550K, mostly accounting to an error of ±70% on the intensity of the 529.25 nm line.
6.1. OPTICAL SPECTROSCOPY DURING BREAKDOWN

Figure 6.6: Example of lines fitted with gaussian profiles for obtaining the absolute intensity. More details in the text.

\[
\ln(\lambda I/gA) = -1.948^{-0.9029} \cdot E_u + 20.79^{24.78}_{16.79}
\]

Figure 6.7: Boltzmann plot for plasma temperature estimation from single spark breakdown spectrum. The slope translates into T=6110K (3870K - 14550K) with an SSE of 2.2 of the linear regression.
Reproducibility of rf and dc spectra

To check the reproducibility of the measured spectra, a series of breakdown spectra were taken in the dc and rf setup. In both setups, the experimental conditions were kept constant during the measurements. This was particularly difficult in the case of the rf spectra because of high background noise from radiation and a drifting input power caused by temperature variations in the pulse compressor which had to be adjusted manually over the whole data-taking process.

To get comparable spectra, the total intensity of each breakdown spectrum was calculated by summing up all CCD channels and used to normalize this intensity to one. After this, the mean value and standard deviation for a series of these normalized spectra was calculated. The result is plotted in figure 6.8 for 499 breakdown spectra in the dc setup and in figure 6.9 for 17 breakdown spectra obtained with the C10 structure in the ASTA facility at SLAC.

Both for rf and dc, the lines and background features of the spectra remain remarkably constant when the experimental conditions are unchanged, the shape only scales depending on the total emitted intensity. More details and interpretation on this are given in the next section, 6.1.6.

Figure 6.8: Dc breakdown spectrum on copper sample, 8.25 kV, 20 µm gap, 50 µm input slit width. Average of 499 spectra, normalized to total integrated intensity for each breakdown before averaging. Mean value plotted in blue (black), the symmetric standard deviation in red (grey) lines.
6.1.6 Reproducibility of line ratios in dc and rf

The ratio between selected emission lines were analyzed using the spectra which were obtained to see the reproducibility of the spectral features in the previous section. Ratios were extracted from the quantum efficiency corrected spectrum without an intensity normalization. Figure 6.10 shows the ratio between the CuI emission lines at 510.55 nm and 521.82 nm for dc (left plot) and rf breakdowns (right plot). A linear regression fit was applied to these values, the result is given in the plots. One can observe that the line ratio is constant over one order of magnitude in a single line intensity and that it can be well extrapolated at the origin for both plots. Nevertheless, the slope of both fits differs by a factor of 2.5, indicating a difference in plasma temperature of the breakdowns. Just like in section 6.1.4 the plasma temperature can be calculated using the ratio of line intensities (two-line-method, TLM). The equation (6.2) is the single line pair version of the Boltzmann plot used there, it is commonly used for LTE plasmas. More details on this method can be found in [18], [32], [57] and [40].

\[
\frac{I_a}{I_b} = \frac{g_a A_a \lambda_b}{g_b A_b \lambda_a} \exp \left[ - \left( \frac{E_a - E_b}{kT_e} \right) \right]
\]  

(6.2)

\(E_a\) and \(E_b\) are the upper level energies for the selected transitions and \(g_a A_a\) and \(g_b A_b\) the corresponding transition strengths and Einstein coefficients. Equation (6.2) can be transformed into (6.3) in order to obtain an expression for the electron temperature.

\[
T_e = - \left( \frac{E_a - E_b}{k} \right) \left[ \ln \frac{I_a g_a A_a \lambda_a}{I_b g_b A_b \lambda_b} \right]^{-1}
\]  

(6.3)
Using the values given in table 6.1, the temperatures for selected line ratios were calculated and listed in table 6.2. For further line ratios, either transition data is unavailable or the upper level energies $E_a$ and $E_b$ are similar or equal.

<table>
<thead>
<tr>
<th>$\lambda_a$ [nm]</th>
<th>$\lambda_b$ [nm]</th>
<th>$T_e$ [K] for dc</th>
<th>$T_e$ [K] for rf</th>
</tr>
</thead>
<tbody>
<tr>
<td>510.55</td>
<td>521.82</td>
<td>4280 K ± 9 K</td>
<td>5366 K ± 61 K</td>
</tr>
<tr>
<td>578.21</td>
<td>521.82</td>
<td>5271 K ± 7 K</td>
<td>6369 K ± 33 K</td>
</tr>
<tr>
<td>510.55</td>
<td>515.32</td>
<td>3976 K ± 3 K</td>
<td>4515 K ± 43 K</td>
</tr>
</tbody>
</table>

Table 6.2: Dc and rf breakdown plasma temperatures calculated with the two-line-method for different line ratios.

The energy dissipated by the breakdowns is of 0.93 J (29 nF, 8 kV) for dc and less than 7.4 J (37 MW, 200 ns, no missing energy value available, see section 5.2) for rf. Due to the low spread of the ratios and high statistics, the error on the temperature is lower than the error of the temperature estimation using the Boltzmann plot in section 6.1.4.

In figure 6.11, the ratio of the CuII peak intensity around 495 nm (496 nm to 499 nm) to the line intensity of the 521.82 nm CuI line is plotted for dc (left plot) and rf (right plot). The spread of ratios is higher compared to figure 6.10 because the intensity for CuII is composed of three CuII lines which are not resolvable in the spectra and because the position of the breakdown modulates the intensity by multireflection, an effect already introduced in section 6.1.1. Due to the multiline composition of the plotted CuII peak intensity, a temperature estimation using TLM is not possible. However, the relatively constant ratios show that the creation of CuII ions and their decay is also reproducible for breakdowns in similar experimental conditions. An equal statement can be made for CuIII ions in dc. On the other hand, rf no data for this peak is available due to the fact that these lines were overlaid by contaminant lines from stainless steel alloy materials. A plot underlying this can be found in figure 6.12 right plot. In the left plot of this figure, the ratio of the two transitions to ground state of copper (324.75 nm and 327.40 nm) are plotted using dc spectra. The ratio is again remarkably constant since all excitation states have to finally decay via these transitions. Therefore, only a dependency on the total dissipated energy is expected. These lines are also not available in rf due to multireflection attenuation. This effect becomes more important when the line intensities are compared to the total intensity obtained by integrating over the whole spectrum. Figure 6.13 presents these ratios for three lines, namely the 324.75 nm, 521.82 nm and 809.26 nm lines as examples for lines in the near UV, the central visible and the near IR parts of the breakdown spectra. One can see that the highest spread in ratios appears for the UV lines whereas there is little spread for the IR lines, the spread of the visible line being in between those. This behaviour is expected when assuming different positions of the breakdown and therefore different attenuations of the light caused by multireflection. Connecting the position dependent path lengths of the emitted light with the reflectivity curve of copper (figure A.1), the high spread in the low reflectivity region and the little spread in the high reflectivity region becomes obvious.
6.1. OPTICAL SPECTROSCOPY DURING BREAKDOWN

Figure 6.10: Ratio of CuI lines, from dc (left, 8 kV, 20 µm gap, 10 µm input slit width) and rf (right, 37 MW, 200 ns, 100 µm input slit width).

Figure 6.11: Ratio of CuII to CuI lines from dc (left) and rf (right). Same dataset as in figure 6.10.

Figure 6.12: Line ratio of 324.75 nm and 327.40 nm emission lines (left) and intensity of CuIII peaks at 437 nm relative to CuI line (right). Same dataset as in figure 6.10.
Figure 6.13: Ratio of line intensities of selected lines and the total integrated spectral intensity. There is an increase in spread of this ratio towards the UV side of the spectrum due to different positions of the breakdown.

Figure 6.14: Comparative plot of dc (solid blue line) and rf (dashed red line) spectra. Total integrated intensity of rf spectrum is adjusted in order to be congruent with dc continuum.
6.2. ESTIMATION OF SURFACE TREATMENT DURABILITY BY SPECTROSCOPY

6.1.7 Similarities and differences of dc and rf copper breakdown spectra

The dc and rf spectra obtained by integrating spectroscopy have several similarities and differences:

1. Rf and dc spectra show copper emission lines up to CuIII, higher excitation states are possible but not in the detectable wavelength range of the used setup. These copper lines dominate the spectrum. In the highly resolved dc spectra (appendix B), several low intensity lines could not be identified by comparison with atomic emission databases. These lines can probably be assigned to molecular emission lines since these appear mostly near the IR region where the emission lines of most molecules likely to be present in the vacuum system or even dissolved in the sample are located.

2. The continuous background of both spectra is responsible for approximately 70% of the total intensity whereas the remaining 30% are attributed to lines, neglecting those from the stainless steel alloy metals in the rf spectrum. Figure 6.14 shows a direct comparison of both spectra with adjusted intensities for achieving a congruent continuum background.

3. Both spectra are reproducible in shape and only differ in total integrated intensity for breakdowns with equal experimental conditions. Line ratios of copper emission lines are also constant then.

4. Line ratios of different line pairs give different results in electron temperature although the line ratios are stable and reproducible. The plasma can therefore not be a LTE plasma. Nevertheless, the plasma parameters during the breakdown must be equal from breakdown to breakdown.

5. The near UV parts of the breakdown spectra are modified due to a breakdown position dependent attenuation resulting from the low reflectivity of copper in that wavelength range.

6.2 Estimation of surface treatment durability by spectroscopy

Besides the dc spark experiments with high purity copper samples, experiments with oxidized copper samples have been carried out in order to either measure the breakdown field strengths of the unconditioned gap or to estimate the breakdown-resistance of this oxide layer. This layer was created by baking a cleaned OFE copper sample for 48 h in an oven at 425 K in ambient air, until the surface showed first signs of discoloration from which the size of the oxide layer thickness was estimated to be around 15 nm. Details on the preparation and results of the corresponding BDR measurements can be found in [30]. The conditioning process of this sample has been followed with the spectrograph by taking a spectrum each time and as long as the voltage was applied to the gap. The spectra for the first, th 15th, the 53rd and 80th breakdown are plotted in figure 6.15. These spectra have been chosen because of their similarity in intensity compared to the very first breakdown, which allows a good comparison.

In addition to the expected CuI, CuII and CuIII lines, the first breakdown shows lines originating from OI and CII which already are not present anymore in breakdown 15 and never appear again for the following breakdowns. One can conclude from this behaviour that surface treatments of several 10 nm are destroyed by the first breakdowns and do not influence the achieved breakdown field after the conditioning, in comparison to an uncoated surface. This is in agreement with the field development measured during conditioning: for the very first breakdowns, the breakdown field is significantly higher (up to 400 MV/m compared to 150 MV/m after conditioning) but decreases afterwards and stabilizes at the breakdown field of uncoated copper samples (see [30] for details). This result is valid only for the dc case since the breakdowns always take place at the same spot. In rf, the overall behaviour of a structure with an oxidized surface might show different results because the surface exposed to high electric and magnetic fields is several orders of magnitude higher. If the structure does not show any hot spots (that is a fixed breakdown position resulting from impurities, machining marks, misalignment etc.), the breakdowns will supposedly be distributed over that surface and therefore only a few breakdowns will happen at exactly the same place and the surface coating could show an overall increase in breakdown field. In fact, a breakdown can create new breakdown spots from ejected metal hitting the surrounding surface and creating new field emitter tips. In the dc case, these would not play a role anymore when they are out of the high electric field region which is less than 0.3 mm², but in rf, that area is still affected by the electromagnetic fields and can therefore lead to a spreading of breakdown spots over a larger area.
Figure 6.15: Development of the breakdown emission spectrum during conditioning of a surface oxidized copper sample. The thickness of the oxide layer was estimated to be around 15 nm (first signs of discoloration). First breakdown spectrum in red, breakdown 15 in blue, breakdown 53 in green and breakdown 80 in black (missing OI peaks after the first breakdown).
6.3 Optical spectroscopy for structure failure analysis

As accelerating structure technology advances, more and more materials will be used inside the structure in high-field regions. In a final CLIC structure, damping material and possibly NEG-coatings for vacuum pumping will be used. However nowadays, the prototype structures already contain brazing alloys and flanges made out of materials different than the disk material. If breakdowns occur on these materials due to defects or alignment errors, the corresponding elemental lines will be visible in the spectrum of that breakdown. Line identification will then distinguish the involved elements and conclusions about where the breakdown takes place and why, like silicon and carbon lines pointing to a problem with the silicon-carbide damping material will be able to be made. A good example for a breakdown on a stainless steel flange of the C10 structure can be seen in figure 6.5. Post-mortem analysis of this structure initially showed copper surfaces which have been coated with stainless steel that has been evaporated by breakdowns (see figure 6.16). This optical diagnostic method can be helpful for a fast failure analysis during an unsuccessful structure test. If the breakdown spectrum shows lines other than the ones expected from the disk material, the rf test can be stopped early and the structure can be replaced. This helps to save expensive structure testing time since BDR results obtained with a defect structure are not representative for that design.

Figure 6.16: Flange connecting input coupler and disk stack of the CERN C10 structure tested at SLAC. Material evaporation by breakdowns coated the upper, left part of the inner copper part of the flange with stainless steel. Stainless steel alloy metal lines could already be seen during the structure test in the breakdown emission spectra. Photo by SLAC.
Chapter 7

OTR emission from rf structures and dc spark gap

During the conditioning of copper samples in the dc spark setup, a continuous dim light emission from the spark gap was observable by eye. A similar emission was also detectable after a breakdown when the voltage was still applied to the gap, images of this emission can be found in section 7.6. This led to an effort to identify the origin of the light and its spectral composition.

7.1 OTR from low energy electrons

The source of this light emission was identified as being an optical transition radiation caused by electrons which have been accelerated by the electric field in the gap and their impact on the anode. These reach energies corresponded to the applied voltages of 1 keV to 10 keV. The light emission is present as long as the voltage is applied to the gap and current is flowing. Other possible sources of this light emission which were considered were the excitation of rest gases and and glow from ionizing vacuum gauges. All of these could be excluded because the light emission is originating from the gap and not from other parts of the system and because gas excitation would cause a line dominated spectrum. In addition, a background spectrum taken with no voltage applied to the gap has been subtracted from all spectra shown here.

Visible OTR emission from electrons in the low keV range was first observed in 1919 by J.E.Lilienfeld \[69\] in X-ray tubes. The explanation and theoretical description of this phenomena which followed in 1946 by Ginsburg and Frank \[45\] advanced that this radiation is produced by charged particles crossing at constant velocity the interface of two media with different dielectric constants. The changing dipole field of the particle - and in the conducting case its image charge - causes the emission of this visible transition radiation. The emitted intensity of this transition is linearly proportional to the current for non-relativistic particles which is a valid assumption for the electron energies achieved in the dc spark setup.

\[
I_{OTR} = \frac{\int_0^\infty dI}{d\lambda} d\lambda = \frac{(ze)^2 \gamma \omega_p}{3c} = \frac{\alpha z^2}{3} \gamma \hbar \omega_p
\]

In this equation, \(dI\) is the intensity per wavelength interval \(d\lambda\), \(ze\) the particle charge, \(\gamma\) the relativistic Lorentz factor and \(\omega_p\) the plasma frequency, which is a material dependent parameter \[98\]. The spectral intensity distribution is expected to be continuous with a decrease around the plasma frequency of the emitting metal. At this frequency, the dielectric constant \(\epsilon(\omega)\) becomes zero. For copper, the plasma frequency is \(1.6 \cdot 10^{16}\) Hz, a value which corresponds to a wavelength of 0.12 µm. In addition, the spectrum can be intensity modulated by interband transitions. This effect is clearly visible for copper, where an interband transition from the d-level to the Fermi-level creates a steep increase in reflectivity around 2.1 eV (590 nm). No other interband transition contributes at this wavelength. This effect produces the reddish color of copper. The imaginary part of the dielectric constant of copper is temperature dependent, thus resulting in a linear change of position of this shoulder by -0.007 eV per 100 K (2.115 eV at 295 K). However, the imaginary part of the dielectric constant has to be measured with very good precision in order to be able to extract temperature information from the spectrum. The optical system used here is not able to resolve this, but in future setups, this effect might offer a possibility for an indirect temperature estimation of the involved
surfaces. More details on the temperature dependency and its derivation can be found in [25]. The transition radiation is polarized in the incident electron plane [27], but the optical system used for the dc spark experiments was not equipped for polarization measurements.

### 7.2 OTR emission spectra from copper in the dc spark setup

After the OTR light was observed by eye, the light emission was measured using the optical spectrograph. These measurements have been done in parallel with the aquisition of the breakdown spectra in the dc spark setup number one so that the setup is the same as described in chapter 6. An example of a dc spark copper OTR spectrum is plotted in figure 7.1. Here, obvious, single bin wide noise peaks derived from cosmic rays and environmental radioactivity have been removed manually by interpolating the affected area with random numbers of average and variance equivalent to the surrounding signal. Noise peaks of more than two bins width were left in the spectrum.

![OTR light spectrum emitted by a copper spark gap in the dc setup.](image)

**Figure 7.1:** OTR light spectrum emitted by a copper spark gap in the dc setup. 20 µm gap, 4.25 kV, 10 accumulated spectra of 60 s integration time, 150 l/mm grating, 250 µm input slit width, CCD QE corrected. Huge grain (cm range) copper.

The spectrum shows a well developed shoulder at 2.1 eV, as expected from the interband transition. The wavelength at 50% of the shoulder is 588.2 nm ± 2 nm. A current of 9 µA to 12 µA was measured with the power supply current meter during the integration of the spectrum. Further details of the spectrum are three emission peaks at 1.51 eV, 1.61 eV and 1.72 eV, which are better visible in figure 7.1 (4.25 kV spectrum). These features are not regularly found during OTR emission spectroscopy. In addition, several different spectra have been observed with sometimes stronger accentuated emission at these wavelengths and sometimes without. There was no correlation detectable between the appearance of these features and the conditioning state of the gap. Similar emissions have been observed in a room temperature copper rf cavity [72] and were explained with electroluminescence of surface semiconducting impurities, especially
copper oxide and alumina. Both impurities are expected to be present on the sample and tip surface since these have been stored under air wrapped in aluminum foil. A relation between electroluminescence and electron emission from oxides was derived qualitatively in [56] with the conclusion that these impurities are an instrumental cause of breakdowns. The results of the emission spectroscopy done here can neither confirm nor falsify this statement. Breakdowns have been observed after OTR spectra with and without these emission features. There was no detectable decrease in breakdown field or other correlations in relation with these emission lines. The measured current corresponds to a dissipated power of 45 mW, which is used for accelerating the electrons to 4.25 keV in the gap. The penetration depth is of the order of 80 nm [83] at the point where the electrons will create bremsstrahlung in the wavelength range around 0.3 nm. These will then be directly absorbed in a layer of several 10 nm after creation. The thermal conductivity of copper is then sufficient to transport the heat to the tip holder. Thermal calculations predict a heating of the order of 1 K for copper which seems plausible in regards to the good thermal conductivity of copper. For surface oxidized samples, no OTR light emission was observed even at very high gradients which were up to twice as high as the ones reached with pure copper samples. The explanation from [31] is that Cu$_2$O has a higher work function than pure copper. This reduces the Fowler-Nordheim emission current which was observed in the setup and can therefore also change the emitted OTR light intensity.

7.3 Line emission of neutral molybdenum in the OTR spectrum

OTR light was also found in the dc spark setup number two with a molybdenum sample and tip. As expected, the emission spectrum is a flat continuum over the full observed wavelength range. This is due to the fact that no interband transitions or other effects exist which considerably modify the spectral characteristics of molybdenum in the visible range.

Besides the continuous OTR spectrum, two lines at 693.4 nm and 694.7 nm were unexpectedly present in all spectra taken during OTR measurements with this molybdenum sample and tip. A systematic search and testing excluded any other source in the dc spark setup and the spectrography system than the gap as source of these lines. The strongest evidence for this is the absence of these lines and the OTR without voltage applied to the gap: Ionizing Pirani vacuum gauges could be excluded by being switched off during the measurements. This showed no change in the measured spectrum, nor was this dc spark system equipped with an ion pump.

The two emission lines are blended in their pedestals due to the resolution limit of the spectrograph of $\Delta \lambda = 0.0029$. Higher resolution was not possible due to the low intensity of these lines. Different gap voltages did not affect the position of the lines. However, the intensity of the lines changed randomly after each breakdown for identic voltages, keeping the intensity ratio of both lines. The current flowing through the gap during the integration was 110 µA, leading to a temperature increase of about 50 K, as simulated by thermal simulation programs. Because of missing transition parameters for these lines, the selection mechanism of them is unclear. Other lines might be emitting as well, but are a minimum of three orders of magnitude more faint, or else they would have been detected in the low resolution OTR overview spectrum, which had already lead to the discovery of the two molybdenum lines. In the current breakdown model, these lines might be an affirmation of the build-up neutrals before the breakdown starts (see figure 5.1 stage a). Compared to the copper OTR spectra, the current was a factor of ten higher, resulting in higher surface temperatures on molybdenum caused by the three times lower thermal conductivity (see appendix A). It is conceivable from the model that only transitions of a precisely defined cross-section and excitation energy are excited, causing an emission such as the one in figure 7.2. These effects are under further theoretical study which uses the breakdown PIC code which is currently under development. No signs of electroluminescence were found in the molybdenum OTR spectrum, even though thicker surface oxidation layers were expected from the handling in the air and even though the content of impurities from other metals is higher than in the high-purity OFE copper used for the copper OTR spectra.
7.4 OTR emission spectra from rf structures

After observing OTR in the dc system, an attempt was made to see if it is also produced in rf structures. This OTR light emission was expected to be created by dark current hitting the structure walls. The spectrograph was installed in CTF2 close to the structure in order to minimize transmission losses by minimizing the length of the optical fiber to 1 m. To shield the CCD camera from radiation produced by the structure and the CTF3 LINAC close by, the spectrograph was installed in a lead box of 10 cm wall thickness made out of unused lead bricks (to avoid any radiation from radioactive contamination or activation). The spectrograph was then remotely controlled from the klystron gallery after the initial calibration with an HeAr-light source. The structure installed for these experiments was the CERN built 30 GHz speedbump structure [33]. To take the OTR spectrum, the gradient in the structure was chosen to to create a maximum of dark current. This implies running the structure very close to the breakdown limit, but at the same time, lower than one breakdown within 600 s which has been chosen as the optimal integration time, taking into account the pile-up of noise in the CCD camera due to radiation and the time needed for the LINAC to be operated in stable conditions. All spectra containing a breakdown or a machine interlock, like a klystron reset, have been removed from the data. The sum of 60 accumulated and background subtracted spectra taken at 66 MV/m, 70 ns pulse length, 5 Hz repetition rate in the 30 GHz speedbump structure is plotted in figure 7.1. This corresponds to a total OTR light emission time of 12.6 ms which is four orders of magnitude shorter than the integration time used in the dc setup, which explains the low intensity of the signal.

Although quite low in intensity, the spectrum from the rf cavity shows the same shoulder around 2.1 eV as the copper OTR spectrum from the dc setup. The center of the shoulder at 50% height is at 2.04 eV ±0.1 eV. With surface fields of three times the accelerating gradient, the electrons can gain up to 200 keV/mm on the first few micrometers above the surface, but the gradient drops to the operational gradient of 66 MV/m when approaching the structure axis. The mean free path length to the next iris is
3.3 mm, the total active length of the speedbump structure is 12 cm (28 regular and two coupling cells), but the gradient is not sufficient to reach the dark current capture limit at around 170 MV/m. Therefore, the maximum energy the electrons can reach is approximately 220 keV. With which energy the electrons finally hit the surface is strongly dependent on the position of their emission, the fields at that point and the rf phase at the time of emission. The increase in the relativistic Lorentz factor up to $\gamma = 1.2$ is supposed to slightly increase the emitted photon intensity as predicted by equation (7.1).

The OTR measurement has been repeated at SLAC with the C10 as described in the rf breakdown spectra section. To avoid scintillation light created by dark current electrons in the vacuum window, a permanent dipole magnet was attached with its magnetic axis perpendicular to the beam axis to deflect dark current electrons away from the beam axis and on to the beam pipe (see figure 4.6). The OTR light created there is outside the acceptance cone of the light collection optics. This eliminated the initially observed scintillation light. No effects from the magnetic field induced in the structure by the permanent magnet are expected. The spectrograph was installed inside ASTA under the optical table which supports the C10 structure and the attached rf diagnostic equipment. To protect the CCD camera and the spectrograph from X-rays created by the structure, a 2.54 cm thick lead sheet has been placed between both. Additional shielding in form of several thin lead sheets and some lead blocks were directly put around the structure. A maximum of 600 s of integration time was used. This value is equal to the time used for the 30 GHz structure OTR spectroscopy, however, the spectra taken in ASTA are significantly more noisy, leading to many more spectra which had to be discarded after readout since less shielding compared to the setup in CTF2 could be applied. At a 60 Hz rf pulse repetition rate and pulses of 45 MW and 200 ns pulse length, the effective integration time was 7.2 ms and therefore of the same order of magnitude than the effective time achieved in the CTF2 OTR spectroscopy with the accumulation of 60 spectra. From the breakdown spectroscopy with the same setup, it was known that the light collection efficiency is higher than the one achieved in CTF2. But being even more sensitive to OTR light than before, no OTR light could be detected.

Three possible explanations are: the geometry of the structure causes the collection efficiency to be lower for OTR light than for light emitted by breakdowns. Multiple reflections might occur, resulting in an attenuation of the emitted signal as a function of the place of electron impact. The second argument involves the electromagnetic field configuration inside the structure. Since the C10 structure is shorter and has a bigger aperture, the majority of the captured dark current is ejected out of the structure where the created OTR light is not collected by the spectrograph, no calibrated dark current measurement was available to compare these values to the 30 GHz structure data and the method of comparison is unclear at this point too. Also, the overall emitted dark current could be lower due to a different surface processing state of the structure. At the time the spectra were taken with the 30 GHz speedbump structure, it had approximately one tenth of the conditioning time compared to when these were taken with the C10 structure (5 days at 1 Hz for the speedbump structure compared to 24 h at 60 Hz for the C10). The reduction of field emitters and consequently the decrease in dark current is a possible cause for the missing OTR light.
7.5 \( \beta \) measurements using OTR

The linear dependency of emitted OTR light intensity on current (see equation (7.1)) in the dc spark setup was used to determine the field enhancement factor of field emitters on the sample surface. This method proved to be a suitable technique for the high electric field regime where the usual gap current based technique could not be applied due to the risk of destruction of the electrometer by a breakdown. It therefore allows \( \beta \) measurement close to the breakdown limit.

To do so, OTR spectra at different gap voltages have been taken and are plotted in figure 7.4. A 5 kV gap voltage, corresponding to a gradient of 250 MV/m, could not be sustained and induced a breakdown. The spectra show an intensity rise with voltage increase in the part of the spectrum above the interband transition shoulder at 590 nm. In addition, the peaks in the near infrared possibly arising from semiconducting impurities (compare to section 7.2) are clearer and higher in intensity as the voltage increases.

During the conditioning of a new OFE copper sample, a spectrum has been taken for each breakdown attempt until a breakdown occurred. The integrated emitted intensity is plotted in figure 7.5 for several of these conditioning ramps. The intensity rise is roughly exponential as expected from the Fowler-Nordheim emission law with derivations towards the low voltages arising from too little integrated intensity. In general, ramps reaching high voltages are more clearly following this exponential behaviour. Ramps already breaking down at low voltages will apparently have a higher \( \beta \) than those breaking down at high voltages. Between each ramp, the \( \beta \) is very likely to be modified by the induced breakdown. The spread of breakdown gradients was at that moment with \( \pm 35\% \) higher than the \( \pm 10\% \) around 170 MV/m which can be found when the gap is fully conditioned [31].

For a ramp reaching high breakdown fields, the field enhancement factor \( \beta \) was calculated using the Fowler-Nordheim plot in figure 7.6. From the slope of the linear fit, \( \beta \) could be determined to \( \beta = 90 \pm 20\% \). This
is similar to the field enhancement factors measured using the field emission current in the dc spark setup [31]. The intensity data has a rather huge error for low fields. However at higher fields the linear fit is a good approximation, although non-linear space-charge effects are considered to change the behaviour at fields close to the breakdown but do not seem to play a role at these field levels.

A simultaneous measurement of field emission currents and OTR light intensity measurements was not possible because the voltage used for emission current measurements has to be kept low enough to avoid breakdowns which would immediately destroy the electrometer used for these measurements.

Although the OTR light emission increases proportionally to the applied voltage and an average breakdown field with low spread was found for copper, an OTR light intensity threshold could not be used as a precursor for predicting a breakdown when the field is applied for the next time.
Figure 7.5: Integrated OTR light intensity for ramped gap voltage during conditioning of a copper sample. Gap size 20 µm, exposure time per spectrum 5 s, input slit width 100 µm, 150 l/mm grating. Integrated from 403 nm to 974 nm.

\[ S = -760 \pm 89 \]
\[ \Rightarrow \beta = 90^{102} \]

Figure 7.6: Fowler-Nordheim plot to extract the field enhancement factor \( \beta \) using data from a ramp plotted in figure 7.5.
7.6 Images of light emission after breakdowns in the dc setup

Optical imaging of breakdown emission sites in the dc spark setup was made to get an order of magnitude estimation of the size and of the diameter of the breakdown plasma. The dc setup is well adapted for imaging due to its simple geometry and easy optical access to the breakdown site. For this measurement, a long working distance microscope has been set up outside the dc spark setup in front of the vacuum window and focussed on the gap between tip and sample (comparable view to the one shown in image 4.7 but with higher magnification). The microscope was connected to a color TV camera and a PC based USB video framegrabber.

Breakdown imaging runs were made in a mode which gives a breakdown on each pulse. This is typically fulfilled for copper samples at 600 MV/m (12 kV, 20 µm gap). The field is applied for 60s.

The light emission from the breakdown itself could not be captured because of saturation of the TV camera by the emitted light and heavy electromagnetic disturbances caused by the discharge itself. This electromagnetic pulse perturbed the synchronization of the video image and made that frame unusable. After the breakdown, the frame synchronization was reestablished and a red afterglow could be observed at some points of the sample. These kept emitting until the field was switched off (see figure 7.7).

The powering of the after-glow may have been caused by details of the powering scheme: the main capacitor is discharged by the breakdown, but immediately starts to recharge because the HV power supply is connected to it via a $40 \, \text{M} \, \Omega$ resistor. The voltage to which it recharges is smaller than the voltage it achieves without the spark gap being connected because the current flowing through the spark gap forms a voltage divider together with the above mentioned $40 \, \text{M} \, \Omega$ series resistor. The current reading of the HV power supply was of the order of 100 µA, resulting in a field 300 MV/m being approximately 50% lower than the field applied at the beginning. This explains why there were no further breakdowns observed after the initial one in the time the field was still applied.

7.6.1 Source of the observed after-glow

The observed after-gloows were deep red and of varying intensity over parts of the image. From areas of low to high intensity, the color changes towards orange, yellow and finally white. The colors are consistent with the spectrum expected from OTR radiation, which is explained in the section above. The OTR emission could be caused by field emission continuing after the breakdown occurred and an electric field is still present. Due to the reflectivity of the copper sample, it was not possible to distinguish the source of the light because the mirror image is as bright as its source, but in the cathode-dominated breakdown model (see chapter 3) and from the electrical polarization of the gap, it is likely that the sample (cathode, corresponding to the lower part of the spots in figure 7.7) is the source of the electrons and the tip (anode,
corresponding to the upper part of the spots in figure 7.7 is the source of the OTR light. As one can see in the images in figure 7.7, the number and distribution of emission sites changes after a breakdown. In the left image, one strong emission site can be recognized in comparison to three smaller emission sites in the right image. A possible explanation is a surface modification by the breakdown and therefore the destruction of an old emission site and the creation of a new one, being well in accordance with the breakdown model presented in chapter 3.
Chapter 8

Time-resolved optical spectroscopy of rf and dc breakdowns

The breakdown model used in the scope of this work predicts a start-up of the breakdown processes in only a few ns, but it is supposed to last as long as energy is available to keep the plasma processes running. During that time, the model predicts that the breakdown plasma is created, heats up and cools down again, changing its plasma parameters over orders of magnitude from ultra high vacuum to dense and hot plasmas and back to vacuum. As an effect of these changes, the optical emission of the breakdown is supposed to have a change in its intensity.

To approach this change in intensity and to see a possible change in the spectral distribution of the emitted light, experiments using a time-resolved spectrometry setup have been carried out. This setup consists of the spectrograph already used for the integrated spectroscopy and OTR experiments which was equipped with a fast photomultiplier tube in addition to the CCD camera.

In this chapter, the correlation between the measured power waveforms and the emitted light waveforms and their reproducibility will be analysed at first for dc and rf. This is necessary to be able to normalize the heraftser shown time-resolved light intensity measurements. These are then analysed for spectral composition, time behaviour and reproducibility.

8.1 Power and light intensity in rf and dc

Figures 8.1 and 8.2 show typical light intensity waveforms of breakdowns recorded at SLAC in the C10 structure at 42 MW input power and 200 ns pulse length. The acquisition had to be triggered on the light intensity signal itself because recording all waveforms at a 60 Hz repetition rate was not possible with the available DAQ (Agilent digital storage oscilloscope). For this reason, the intensity waveform timing is not synchronized to the rf pulses. In figure 8.1, the breakdown light emission was therefore assumed to start with the rf power.

Two major features can be identified in the light emission waveform: A sharp peak at the beginning which is not present in all breakdown waveforms, and a longer, broader and less intense peak right after which is always present in the recorded waveforms. The first, sharp peak rises in intensity with a risetime of about 2 ns and then decays within 50 ns to practically no light emission. Following this, the light emission starts again slowly and reaches its maximum within 0.5 µs with a maximum intensity which is about half the one of the first peak. It decays afterwards within 2 µs to zero. The total emission period lasts about 3 µs, which is much longer than the rf pulse. As indicated by the power waveform, the input power has ended when the second light peak reaches its maximum intensity.

The first, sharp peak is yet unexplained. To exclude systematic effects which are likely to occur in the high electric noise environment of ASTA, the PMT has been covered with opaque paper for some breakdowns. In this configuration, the DAQ no longer triggered during breakdowns. The first peak must therefore be a light signal produced by the breakdown. Similar peaks have been observed during the onset of arc plasmas and the origin has been explained by excited hydrogen outgassing from the field emitter site. If this is the case, a breakdown event with such a peak could be indicative for a breakdown on a yet unaffected surface and without peak a breakdown on a spot which has already been subjected to breakdowns and cleaned
of hydrogen. Hydrogen is known to diffuse up from the bulk so the peak could also indicate a site on which a breakdown has not occurred for a certain time. Even though several breakdowns at different power levels have been observed, a quantitative statement about the statistical distribution of breakdowns with and without this first, sharp light peak cannot be given. Qualitatively, the ratio between both types were not reproducible for equal power levels, although the statistics are limited.

In the case of dc breakdowns, voltage, current and light intensity were simultaneously time recorded. Figure 8.3 shows the full waveforms. In figure 8.4 the first 700 ns are plotted as detailed zoom into figure 8.3. The power waveform was calculated using the available voltage and current waveforms. At first sight, the power waveform is similar to the rf waveforms. It consists of a pulse of about 100 ns width which is approximately of gaussian shape with deformations caused by noise and system-related oscillations. The power waveform is based on voltage and current waveforms and is qualitatively different from the rf case since power is non-zero during the whole light emission process. Looking at the current waveform, one can identify a fast rise to maximum within 150 ns and then a decay to zero within 3 µs, as expected from a capacitor discharge. However, the voltage waveform behaves unexpectedly. It shows the same peak behaviour at the beginning as the power waveforms, becomes negative afterwards and then decays from there to zero as long as current is flowing. A result of further investigations on the dc spark electric circuit showed that the waveforms are dominated by the transient response of the system. A detailed explanation of this behaviour based on further measurements and a new circuit model is given in section 5.4.

The emitted light waveform is nevertheless similar to the waveforms recorded in rf except for the higher intensity caused by the better light collection efficiency of the dc optical system. It starts with an initial sharp rise in intensity, peaks after a few ns and decays to half its intensity within 30 ns. This intermediate minimum is not zero like in the rf waveforms. If this difference can be attributed to a better separation of the effects causing the first peak and the later long light emission in rf, or just to the higher available intensity, is unclear. After this minimum, the light emission increases again for about 300 to 400 ns and then decays within 3.7 µs with a shallow bump 1 µs after the maximum. The light emission is present as long as the voltage and current is non-zero. The first peak is always present and scales roughly linearly with the total intensity of the second peak. No decrease with increasing number of breakdowns on the same spot have been found.
8.1. POWER AND LIGHT INTENSITY IN RF AND DC

Figure 8.1: Light emission from rf breakdown in SLAC C10 structure at 515 nm ± 2 nm (blue waveform). Generalized rf power waveform (red, rectangular pulse) created using the corresponding power and pulse-length values.

Figure 8.2: Rf breakdown light intensity waveform, equal conditions as in figure 8.1.
Figure 8.3: Light (total, unfiltered intensity seen by Hamamatsu R7400U-01 PMT [52]), voltage, current and calculated power waveforms for a dc breakdown. Waveforms have been low-pass filtered by software to eliminate high-frequency noise.

Figure 8.4: Detailed view of the initial peak from figure 8.3.
8.2 Time-resolved spectroscopy of breakdowns in the dc setup

After the examination of the total light emission of a breakdown in rf and dc, the time-resolved spectral composition was addressed by further experiments. For these experiments, the spectrograph was used as a monochromator to filter wavelength intervals out of the total emission. This filtered light was then detected by a Hamamatsu R6357 PMT with a 1.4 ns rise time and a 15 ns signal transit time at the operating voltage of 1100 V. Details of this setup can be found in section 4.5.3. In addition to this setup, a collimation lens was attached to the vacuum window of the dc setup as indicated in figure 6.2. This collimation lens is located on the opposite side of the tip. The light collected there is sent through an optical fiber to a Hamamatsu R7400U-01 PMT whos signal output is recorded using another channel of the digital storage oscilloscope which is already recording the voltage, current signals and the signal from the PMT attached to the spectrograph.

To get a spectrum from the time resolved signals, the desired wavelength range has to be scanned by recording the light emission waveforms at different wavelengths. A constraint of this method is that only one wavelength interval can be recorded per breakdown, complicating assembling the full spectrum due to shot-to-shot overall intensity variations. This makes it difficult to differentiate between a simple breakdown position dependent intensity modification and other physical processes. To overcome that problem, the above mentioned lens based light collection system was installed to acquire the total intensity which was then used as normalization factor for the wavelength-filtered waveforms. A more detailed explanation on this can be found in section 8.2.3.

8.2.1 Consistency between integrated and time-resolved spectroscopy

Due to the fact that each time-resolved spectrum has to be scanned using at least one breakdown per wavelength interval, the consistency between this spectrum and the time-integrated spectrum acquired with the CCD camera using only one breakdown had to be checked. To do so, the input and output slit of the spectrograph was set to 200 μm, corresponding to a 1 nm wavelength FWHM interval when using the 1200 l/mm grating. The operating voltage of the spectroscopy PMT was adjusted to 1100 V and the one of the total intensity PMT to 650 V while observing several breakdowns to ensure that the total output voltage of the PMTs does not exceed 1 V and therefore avoid saturation effects of the PMT. To increase the signal to noise ratio of the spectroscopy PMT signal, it was terminated electrically into a 500Ω instead of using the oscilloscope 50Ω input termination (the remaining input impedance of the oscilloscope of 1MΩ is negligible compared to other errors, e.g. the tolerance of the 500Ω resistor of 1%). The accompanying decrease of bandwidth by a factor of 3 was not affecting the overall signal shape.

Figure 8.5 shows the result of a numerically post-processed time-resolved scan between 500 nm and 530 nm in 1 nm steps in comparison to a single breakdown spectrum taken with the CCD detector under the same conditions. In a first processing step, the 20 acquired waveforms were each integrated in time and then averaged for both the spectroscopy and the total intensity PMT. In the second step, the calculated total intensity values for all 30 wavelength settings were normalized to one and the resulting normalization factors were applied to the corresponding intensities acquired with the spectroscopy PMT. The obtained spectrum should now be independent of the breakdown light intensity.

Both spectra show peaks at the expected line positions of the CuI transitions 510.55 nm, 515.32 nm and 521.82 nm. The intensities of these peaks in the integrated time-resolved spectrum have similar relative heights than the integrated spectrum. All three peaks are at least a factor of two above the background intensity which is itself rather unstable and does not reproduce the other spectrum. To see the reason for this discrepancy, the shape reproducibility of the acquired waveforms has to be examined. This will be done in the following section.

The total emitted light intensity of a dc breakdown varies from breakdown to breakdown as can be seen in the left plot of figure 8.6. Sometimes, groups of consecutive breakdowns show altogether a high or low intensity, but single high intensity peaks were also detected. The correlation of intensity to the energy measured by integrating the power waveforms is weak (right plot in figure 8.6). Ultimately, the total dissipated energy was found to be a value which can not be used to normalize the waveforms acquired with the spectroscopy PMT.
Figure 8.5: Comparison of time integrated spectroscopy by CCD (red line, one breakdown) and numerically integrated time-resolved spectroscopy by PMT (blue stairs, 20 breakdowns averaged for each step). Copper sample, equal gradient and energy for all breakdowns.

Figure 8.6: Integrated intensity of consecutive dc copper breakdowns, 8 kV, 20 µm gap (left). Energy from integrated power waveforms versus integrated intensity, same dataset (right).
As pointed out before, the normalization of the waveform coming from the spectroscopy PMT to the total emitted intensity is crucial to eliminate intensity fluctuations due to the movement of the breakdown. It is not possible to separate emission lines from continuous background emission if this is not done correctly. In fact, the use of the total light intensity PMT readout as normalization factor is difficult as can be seen in figure 8.7. Here, the total intensity PMT readout and the wavelength interval intensity are plotted against each other for three different wavelength intervals which are in the continuous background region of the spectrum. Each point in the plot corresponds to one breakdown. The spread of points does not show a direct correlation, only after averaging over several breakdowns with constant wavelength and power settings. The intensity distribution converges towards the spectrum seen in figure 8.5. The reason of this discrepancy is supposed to be a geometry effect from pulse to pulse movement of the breakdown and the resulting change in intensity seen by the two detectors opposite of each other. In future experiments, the measured total light intensity should be extracted from the same light path as the one going to the spectrometer, e.g. a fiber splitter with 99/1% splitting ratio. Such a device was not commercially available for the fibers used in this experiment and will have to be developed for that purpose.

8.2.2 Shape reproducibility of time-resolved signals in dc

The reproducibility of the full spectrum light emission waveform shape was checked next. For this task, 600 total light intensity waveforms were averaged and the corresponding standard deviation was calculated. The result is plotted in figure 8.8 where one can see that the overall shape is preserved after the initial rise in intensity is over. The high spread during the first 100 ns risetime is caused by the above mentioned first sharp peak which is not always present in this configuration. The explanation for this is the change in termination impedance described in 8.2.1 and the accompanying loss in bandwidth which then smooths out the first peak or lets it disappear if it is too high in frequency, respectively too short in time due to the peak’s own length and intensity fluctuation.

The shape conservation of the wavelength filtered light waveforms was tested too. Several plots of time-resolved emissions of CuI lines and continuum lines with average and standard deviation plots can be found in section 8.2.4. Even though less data was available for each wavelength interval due to the scanning method of the time-resolved spectroscopy, the waveform shape turned out to show similar, reproducible features for consecutive breakdowns.
Figure 8.7: Total light intensity plotted against wavelength interval intensity of three different wavelength settings in the continuum of the copper emission spectrum. Single breakdown event per point.

Figure 8.8: Mean value and standard deviation of the total intensity waveforms. Dataset of 600 breakdowns on copper.
8.2.3 Time-resolved spectrum of dc copper breakdowns

The wavelength range from 500 nm to 530 nm was scanned in 1 nm intervals and processed by averaging and normalizing in the dc setup with copper sample and tip and a 400 MV/m gradient. Figure 8.9 shows the result of this scan. Each horizontal line in this plot corresponds to the average of 20 breakdown waveforms at a fixed wavelength setting, normalized to the average of the 20 total intensity waveforms taken in parallel. The voltage applied to the 20 μm gap was 7 kV, resulting in a breakdown for each attempt. Three waveforms stand out from the others in this plot, namely the ones at 511 nm, 516 nm and 522 nm central wavelength corresponding to the CuI emission lines at 510.55 nm, 515.32 nm and 521.82 nm. They are higher in intensity and the emission is about 500 ns longer than the continuum emission.

Figure 8.9: Time-resolved spectrum from 500 nm to 530 nm sampled in 1 nm intervals. Horizontal axis is time, vertical axis wavelength. The intensity is color coded, higher intensity towards red (white to dark grey). Taken in the dc setup with a copper sample at 7 kV, 20 μm gap.

The continuum background is not constant in intensity as already shown in 8.5 and about a 500 ns shorter emission time is visible compared to the CuI line emission length. Already in this plot, there is a slight hint towards the double peak structure of the 521.82 nm line hidden in the intensity modulation of the strong emission lines. This will become more obvious when these lines are examined in more detail in the following section.
8.2.4 Time-resolved waveforms of CuI lines and continuum in dc

The intensity waveform of the time-resolved and wavelength filtered light is different whether the measured wavelength interval contains an emission line or not. To illustrate this, the wavelength interval around 522 nm which covers the strong CuI emission line at 521.82 nm is plotted in figure 8.11 together with a part of the continuum background around 518 nm in figure 8.12. In addition to the higher overall intensity of the wavelength filtered waveform of the line emission compared to the continuum emission, the line emission shows an intensity double-peak structure. The first peak reaches its maximum after around 500 ns and is a common feature of all emission waveforms, including the total emission which always peaks at that position. The second peak was only observed in the wavelength filtered emission of CuI lines and peaks about 800 ns after the first one and was never visible in the continuum.

Since the total intensity waveform includes the line emission, the falling edge after its peak features a small bump at the position in time where the second line emission peak is located and does not follow the monotone decay of the associated current waveform.

The second peak is likely to originate from plasma cooldown and density decrease. At the beginning of the discharge when energy from the capacitor is still available, dense and hot plasma effects like Stark broadening and multiple-ionized copper decays create a bright and continuous spectrum. Afterwards, the energy supply drops and the plasma expands into the surrounding vacuum, stopping dense plasma effects, which leads to a domination of emission lines in the spectrum. Interpreting these spectra, one has to keep in mind that the emitted light is not originating from a point source but a volumetric plasma with boundary effects from the plasma to vacuum transitions, suggesting that light from processes happening at different density and temperature zones is captured at the same time. Black body emission from the molten surface will also contribute to the spectrum. The shape of the line emission waveforms is not connected to the lifetimes of the corresponding excitation levels since these are in the order of 10 ns for the 521.82 nm and 515.32 nm lines and 500 ns for the 510.55 nm line, but are all of equal emission lengths in the experimentally captured waveforms.

A similar double peak structure was found in the emission waveforms of the CuI lines at 324.75 nm and 327.4 nm as plotted in figure 8.10 left plot. These transitions are the only two transitions to ground state which are possible in the copper atom and feature therefore the strongest emission lines. This explains why the second peak is higher in intensity than the first one since all excitations have to decay via these two transitions. The right plot in figure 8.10 shows the emission of a convolution of CuII lines located around 436 nm to 437 nm. Here, no second peak is present and the intensity decays similarly to the current which is in accordance to the model that CuII ions can only be created in the hot and dense plasma and are not present anymore when the plasma cools down and expands below a certain threshold.
Figure 8.11: Time-resolved intensity of a dc breakdown, total intensity normalized to 1 (black line with standard deviation in green/light gray). Wavelength filtered intensity of 522 nm ± 0.5 nm (covers 521.82 nm CuI line) normalized with same factor as total intensity (blue/dark gray line with standard deviation in red/gray).

Figure 8.12: Same as figure 8.11 but for wavelength interval 518 nm ± 0.5 nm, corresponding to continuum background with sufficient distance from spectral lines.
8.3 Time-resolved spectroscopy of breakdowns in rf structures

Time-resolved rf breakdown light emission spectroscopy was carried out to compare these waveforms to previously shown dc waveform measurements. Since the light intensity which could be coupled out of the 30 GHz structures was too low to get a usable light waveform, a second attempt to do these measurements was done at SLAC with a copper C10 structure where the extractable light intensity was expected to be higher due to geometry and pulse length of the input rf pulses, which emerged to be the case. While the integrated spectroscopy measurements done with the CCD detector and presented in chapter 6 could profit from the increased light intensity input, the intensity coupled into the PMT used for the time-resolved measurements was still below the intensities seen in dc. In addition, the method of increasing the signal output of the PMT by increasing the termination resistance value did not work out here due to the high electric noise picked up from the surrounding high power electronics and the long 50Ω signal cables from the setup inside the bunker to the DAQ system in the control area, which gave significant reflections and ringing when not correctly terminated into 50Ω.

For these measurements, the spectrograph was equipped with a multichannel PMT in order to be able to acquire four waveforms at the same time with the available four channel digital storage oscilloscope which was used as DAQ system in connection with an attached PC. The system is described in more detail in section 4.5. When using the 1200 l/mm grating of the spectrograph, each channel covers ±1 nm around a central wavelength which can be shifted for all channels at the same time by rotating the grating. Although the light throughput of the spectrograph is a factor of eight worse with the 1200 l/mm grating than with the 150 l/mm grating, the higher resolution grating was selected because the other one would not allow the separation of single lines around the important wavelength range from 500 nm to 530 nm, which is needed for comparison with dc data.

The four central wavelengths which were acquired with the PMT are 515 nm, covering the 515.32 nm CuI line, 495 nm and 527 nm, covering the 495.37 nm and 527.65 nm CuII lines and 532 nm, covering the 531.78 nm CuIII line. This selection was inspired by the maximum efficiency of the PMTs quantum efficiency and the grating efficiency in this wavelength range as well as the goal to cover a line of each species and available transition data from [32]. This paper shows a method of calculating the plasma density and electron temperature in an LTE plasma derived from the Saha equation in [46].

Waveform data was taken at different power levels and pulse lengths without the possibility of a trigger signal synchronized to the input power pulse (see 8.1). The achieved light intensity was, despite several attempts to increase the collection efficiency, still worse than the intensity achieved in the dc system. Most waveforms were only composed of several single-photon spikes which do not allow any conclusion about the emission intensity waveform shape.

A complementary to the overall description of the light emission waveform shape and features can be found in section 8.1. Figures 8.13 and 8.14 show the intensity waveforms of the above mentioned wavelength intervals recorded at 42 MW input power at 200 ns pulse length in the SLAC C10 structure.

Figure 8.13: Wavelength interval emission waveforms for 495 nm (CuII, left plot) and 515 nm (CuI, right plot) lines. C10 structure running at 42 MW, 200ns pulse length.

Even though this dataset possesses the highest integrated intensity in all acquired datasets, the extractable information is limited. First of all, a remarkable feature is the initial peak of equal intensity at
all four wavelengths. This peak is a real light signal, it does not appear during breakdowns when the shutter of the spectrograph is closed, excluding electromagnetic noise as source of this peak. Since the quantum efficiency of the used PMT is flat over the used wavelength range, one can assume a continuous spectrum of this first peak. The FWHM of this peak is approximately 80 ns. The second observable peak in these waveforms reaches its maximum about 1 µs after the end of the first sharp peak. This is about two times later than the second peak maximum position of the waveforms acquired in dc, whereas the total emission time of 3-4 µs is equal in rf and dc.
Chapter 9

Summary and conclusion

The overall goal of this thesis is the experimental comparison of rf and dc breakdowns using a diverse selection of diagnostics in order to gain a better understanding of the breakdown phenomenon by quantifying effects under different conditions. The comparison also serves the practical purpose of checking the relevance of the breakdown rate and other data taken in the dc setup to the rf structure design. This is important for the CLIC high-gradient rf structure research project since dc tests are faster, cheaper and less complex than high-power tests of full rf structures. In the scope of this comparison, breakdowns in rf and dc were examined using optical spectroscopy. The obtained data was then correlated with electrical breakdown data and other measurements taken in parallel. Optical spectroscopy - integrated and time-resolved - proved to be a valuable extension of the standard diagnostics in the rf and dc setups and provided a deeper insight into the breakdown processes and their dynamics. The results of the experimental work can be summarized in the following points.

Time-integrated spectroscopy:

- Both rf and dc breakdowns show the typical emission spectra of the sample material which has been used. No other materials, especially impurities from typical machining and surface treatment remnants like hydrogen, carbon and oxygen showed significant emission lines. Consequently, impurities are unlikely to play a role in the processes taking place when the breakdown has been initiated and shows its maximum light emission.

- No contribution of metals other than the bulk structure or sample material to the spectrum could be observed in rf and dc conditioning phases. Only an artificially surface oxidized copper sample showed oxygen lines in the first few breakdowns. This points to the conclusion that once the surface was affected by a breakdown, it looses all advantages of prior surface treatment. Also, an explanation for the need of a conditioning phase for the removal of dust particles and impurities does not seem likely as long as these are not made out of the bulk material.

- A continuum background is present in both rf and dc spectra. It varies only slightly in intensity over the observed wavelength range. Nevertheless, it contains about 3/4 of the total emitted intensity while the emission lines contribute only with 1/4. The underlying emission process must therefore show line broadening effects like Stark, Zeeman, Doppler or pressure broadening, but the used equipment is not able to distinguish between these effects due to the breakdown dynamics and its low light output. Black-body radiation can be excluded because the maximum would be in the infrared in contrary to the observed maximum in the green since copper does not reach high enough temperatures before vaporizing under these conditions.

- The intensity ratios of the observed copper lines are constant from breakdown to breakdown in rf and dc. In dc, the correlations between gradient and line ratios have been checked and were found to be constant over the accessible gradient range. A similar measurement in rf was not possible due to power limitations of the rf test setup.

- Plasma electron temperature calculations based on line ratios resulted in temperatures of the order of 1 eV. These have to be interpreted as average temperature over the light emitting phase of the breakdown due to the integrating nature of the used CCD detector. Nevertheless, different pairs of emission
lines result in different electron temperatures. Still being in the range of 0.3 eV to 1.3 eV, these values point on the fact that the breakdown plasma never reaches full thermodynamic equilibrium, otherwise the line ratios would be expected to lead to the same temperature.

- In the non-breakdown pulses of sustainable gradients in dc or unperturbed operation in rf, visible light from the gap and the structure respectively was observed. In dc, this light lasts as long as the voltage is applied to the gap, but in rf, the light emission was too weak to determine the time structure experimentally. Spectra of this light taken in rf and dc showed both a continuous spectrum with an intensity rise above 620 nm when copper samples respectively structures were used. An equal test done in the dc setup with a molybdenum sample showed a flat spectrum. This light emission has been interpreted as being an optical transition radiation (OTR) from electrons accelerated in the electric field and then passing the boundary between UHV and the metal. The intensity rise above 620 nm in copper arises from the special electron band configuration of copper (thus giving copper its typical reddish color), molybdenum does not have similar features in the observed wavelength range.

- As described in the theory of OTR, the OTR light intensity is linear proportional to the electron current hitting the surface as long as these are non-relativistic as it is the case in the dc setup. The measurement of this intensity at different gradients has been successfully used to calculate the field enhancement factor $\beta$ of the surface field emitter using a fit to the Fowler-Nordheim field emission law. This method allows the measurement of $\beta$ at higher electric field gradients than the direct current measurement using an electrometer would, because of an increased likelihood for a breakdown which would destroy it.

- The optical equipment used was capable of identifying the contribution of other elements to the breakdown. Here, a breakdown taking place between a copper gasket and a stainless steel flange in a rf structure has been observed by spectroscopy. This diagnostic technique allows the identification of possible problems with other materials used in rf structures and subjected to high-power rf like flanges, damping material etc..

**Time-resolved spectroscopy:**

- Time-resolved spectroscopy is possible in rf and dc when using adapted light collection techniques, high throughput equipment and sensitive photomultiplier detectors, but it was not possible to take a full time-resolved spectrum at once. A fragmentation of the spectrum into wavelength intervals and the scan of those with separate breakdowns was necessary to obtain the desired spectrum. A crosscheck with the integrated spectrum of the CCD camera showed a good agreement between both, even though the normalization from breakdown to breakdown was difficult and will require upgrades on rf and dc setups to be able to precisely measure the energy dissipated by the breakdown.

- Breakdowns in rf and dc are short, transient phenomena. The total length of unfiltered light emission is shorter than 4 $\mu$s and peaks in intensity after about 1 $\mu$s, but a factor of four to ten longer than the rf pulses and the maximum power peak in dc. At the beginning of the breakdown, light emission peaks of several tens of ns length and intensities higher than the second peak mentioned before have been observed. The origin is still unclear, a spectrum of only the first peak could not be fully obtained due to its very low integrated intensity, compared to the following emission peak. Also due to this reason, this peak cannot be made responsible for the continuum background observed in the integrated spectroscopy. To study this phenomena in more detail, fast gated CCD cameras would have to be used to gather the spectrum of this first peak using only one breakdown. This will additionally require an electronic switching of the HV power supply of the dc setup, as proposed during the experiments summarized here which would enable to get a precise trigger for the detectors.

- The time-resolved spectrum can be divided into two parts: The continuum background, lasting about 2 $\mu$s and the overlaying emission lines, lasting up to 4 $\mu$s. This is well in accordance with the measured time-integrated spectra, showing the same composition of continuum background and emission lines. This result can be interpreted with different plasma density and temperature regimes of the breakdown plasma: at the beginning, the plasma is dense and emits a continuum due to several line broadening and continuum emission processes. The plasma will expand into the vacuum and cool down at the same time, passing over into a low density and low temperature regime where discrete line emission processes - which will also disappear with continuing cool down and plasma dilution - dominate.
• The shape of the time-resolved dc breakdown emission waveforms of the main emission lines at a fixed wavelength is constant from breakdown to breakdown. These waveforms - exclusively CuI emission line due to their high emission intensity - show a double peak structure: the first peak can be attributed to the overlaying continuum emission and the second peak to the then dominating line emission. The distance between both peaks is about 1 µs.

• The light intensities measured for rf breakdowns were in general too low to do time-resolved spectroscopy with sufficient resolution. Even though these measurements have been carried out in the CTF2 30 GHz and ASTA 12 GHz facility with specially designed light collection systems, the intensity was still too low to do measurements with data of dc setup equivalent quality. Despite these intensity problems, the overall light emission waveform structure was found to be approximately equivalent in shape and duration to the ones measured in dc.

To be able to do the measurements described in this thesis and in the above summary, preparatory work had to be done on the rf and dc facilities used for these experiments. This work is summarized in the following points:

**Preparatory work:**

• The CERN 30 GHz structure test facility is equipped with a rf DAQ system in order to measure all high-power test relevant rf power values. After the installation of each test structure used for the spectroscopy, this rf DAQ system had to be calibrated manually, but emerged to be drifting with time and ambient temperature. To compensate this, an automatic power calibration system was designed, built and tested. It includes the necessary rf network supplying calibrated power to the DAQ inputs and the corresponding control and analysis software. The time necessary for a calibration run was reduced from one day to less than one minute and no manual intervention on the waveguide was necessary anymore. Regular calibration runs eliminated temperature drifts and resulted in a rf power error below $0.2\,\text{dB} \pm 2\%$.

• The method of calculating the missing energy in rf breakdowns was revised and a term for the ohmic attenuation for the reflected power as function of the breakdown position was added. The error of the missing energy calculation without that correction is estimated to up to 25% in case of an immediate breakdown, causing full reflection at the output coupler cell of the structure. Due to the resolution of the 30 GHz rf system, the position of the breakdown cannot be determined with a sufficient precision to implement this correction in the analysis software. This will be done in the future 12 GHz high-power test stand at CERN.

• To figure out the influence of the circuit of the dc setup power supply on the waveform shape of the measured data and to determine the impedance characteristics of the spark, an extended circuit model has been developed and simulated with equivalent input values as the ones used in the real experiments. Elements added to the existing circuit were parasitic inductances, capacitance and resistances mainly found in the transmission lines and grounding schemes of the real setup. The simulation proved to reproduce the measured waveforms. A later experiment with a short-circuited spark-gap showed that the main features of the measured waveforms originate from the external circuit rather than from the breakdown plasma. As a result, one can conclude that the breakdown itself is a very low resistance conductor and only has a very low influence on the total system’s behaviour. Furthermore, the circuit model allowed the power dissipating circuit elements to be identified and quantified: the discharge capacitor and the parasitic resistances in the circuit dissipate practically all power stored in the capacitor. In result, only less than 1% of the total energy is available for the breakdown. These results lead to the basic design of a new, semiconductor based power supply for the dc setup, with controlled system impedance and advanced electrical diagnostic methods. This will allow a better characterization of the electric behaviour of the breakdown plasma and its evolution within the full breakdown process.

The basic conclusion is that rf and dc breakdowns are similar in their underlying physics processes as far as they concern the optical emission processes from the breakdown plasma. Since these are highly depending on the plasma parameters and composition, similar spectral emission characteristics are very unlikely to be caused by totally different physics processes. These plasma parameters are also likely to change only
slightly as a function of the initial surface parameters, the available energy and the field configuration. Optical diagnostics have been successfully applied for breakdown physics research and high-gradient structure tests. They also, in addition, have the potential to be used as standard equipment for these tasks.

At the point of finalization of this thesis, several theory and experimental groups are doing breakdown related research. On the theoretical side, this includes a full scale model of the breakdown from the initiation by surface processes using molecular dynamics simulation to the plasma simulation using PIC codes. On the experimental side, more and more dedicated breakdown physics experiments such as the ones presented in this thesis are evolving in parallel to the measurements done during the high-power rf structure and in the dc setups. Both theory and experiment are working in close collaboration by defining new measurement tasks from the developing breakdown model and by benchmarking the simulations by comparison with experimental data.

The experiments presented in this thesis should also be seen as a motivation for future experiments in this field. Potentially, more precise measurements of, for example, the missing energy and multichannel time-resolved spectroscopy can reveal even more details of the very first ns of the breakdown. The minimum requirements of the instruments to be used for these tasks and the experimental regions of interest can be found in this thesis.
Appendix A

List of physical properties of copper and molybdenum

Figure A.1: Copper (blue, solid line) and molybdenum (red, dashed line) reflectance for normal incident light in the wavelength range of 250 nm to 2000 nm. From [68].
### APPENDIX A. LIST OF PHYSICAL PROPERTIES OF COPPER AND MOLYBDENUM

<table>
<thead>
<tr>
<th>Property</th>
<th>Crystallographic orientation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic weight</td>
<td>N/A</td>
<td>63.546</td>
<td>g mol⁻¹</td>
</tr>
<tr>
<td>Density, 298K</td>
<td>N/A</td>
<td>8940</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>N/A</td>
<td>1358</td>
<td>K</td>
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<tr>
<td>Resistivity, 300K</td>
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<td>nS m⁻¹</td>
</tr>
<tr>
<td>Specific heat capacity, 298K</td>
<td>N/A</td>
<td>24.440</td>
<td>J mol⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>average</td>
<td>400</td>
<td>W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Work function</td>
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<td>4.65</td>
<td>eV</td>
</tr>
<tr>
<td>Work function (100)</td>
<td></td>
<td>4.59</td>
<td>eV</td>
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<td>eV</td>
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<tr>
<td>Work function (111)</td>
<td></td>
<td>4.94</td>
<td>eV</td>
</tr>
</tbody>
</table>

Table A.1: Selection of physical properties for copper. From [68].

<table>
<thead>
<tr>
<th>Property</th>
<th>Crystallographic orientation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic weight</td>
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<td>g mol⁻¹</td>
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<td>kg m⁻³</td>
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<tr>
<td>Melting temperature</td>
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<td>K</td>
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<td>average</td>
<td>138</td>
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<tr>
<td>Work function</td>
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<td>4.6</td>
<td>eV</td>
</tr>
</tbody>
</table>

Table A.2: Selection of physical properties for molybdenum. From [68].
Appendix B

Detailed breakdown spectra

On the following pages, the detailed breakdown spectra taken in the CERN dc spark setup are plotted. All copper spectra were taken in setup one, all molybdenum spectra in setup two. Both setups were equipped with a 28 nF main capacitor. The spectrometer settings, the voltages and gap sizes used for the acquisition of these spectra are given in the corresponding captions. All indicated line positions are from the NIST database \[73\], except the CuII line at 757.9 nm, which was identified by S. Mordyk, Institute of Applied Physics (IAP), NAS Ukraine (NASU), Sumy, Ukraine.

The lines in the molybdenum spectra are not fully identifiable due to the high density of molybdenum lines in the observed wavelength range and due to impurities in the sample material.

In all spectra, the position of each known elemental line is indicated by vertical lines (see table \[B.1\]), the length of each line is proportional to the relative intensities found in \[73\]. These intensities are only for orientation purposes, the experimental conditions during which the spectra and the relative line intensities were measured were different, see chapter 6 for details.

<table>
<thead>
<tr>
<th>Line style</th>
<th>Line color</th>
<th>Ionization level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dotted</td>
<td>red</td>
<td>Neutral (CuI, MoI)</td>
</tr>
<tr>
<td>Dashed-dotted</td>
<td>green</td>
<td>Single ionized (CuII, MoII)</td>
</tr>
<tr>
<td>Dashed</td>
<td>orange</td>
<td>Double ionized (CuIII)</td>
</tr>
</tbody>
</table>

Table B.1: Legend for vertical lines indicating elemental line positions in the detailed spectra.
Figure B.1: Detailed spectrum of a copper spark in the CERN dc spark setup. 8 kV, 20 µm gap. Spectrometer set to 10 µm slit width, 1200 l/mm grating.
Figure B.2: See [B.1] for details.
Figure B.3: See B.1 for details.
Figure B.4: See [B.1] for details.
Figure B.5: See [B.1] for details.
Figure B.6: See [B.1] for details.
Figure B.7: See B.1 for details.
Figure B.8: See [B.1] for details.
Figure B.9: See B.1 for details.
Figure B.10: See B.1 for details.
Figure B.11: See B.1 for details.
Figure B.12: Detailed spectrum of a molybdenum spark in the CERN dc spark setup. 11 kV, 20 µm gap. Spectrometer set to 10 µm slit width, 1200 l/mm grating.
Figure B.13: See B.12 for details.
Figure B.14: See [B.12] for details.
Figure B.15: See B.12 for details.
Figure B.16: See B.12 for details.
Figure B.17: See B.12 for details.
Figure B.18: See B.12 for details.
Figure B.19: See B.12 for details.
Figure B.20: See B.12 for details.
Figure B.21: See B.12 for details.
Figure B.22: See [B.12] for details.
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[73] National Institute of Standards and Technology, USA. *NIST Atomic Spectra Database*.


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