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ADVANCED EXPERIMENTAL TECHNIQUES FOR RF AND DC BREAKDOWN RESEARCH

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Abstract

Advanced experimental techniques are being developed to analyze RF and DC breakdown events. First measurements with a specially built spectrometer have been made with a DC spark setup [1] at CERN and will soon be installed in the CLIC 30GHz accelerating structure test stand to allow comparison between DC and RF breakdown phenomena. This spectrometer is able to measure the light intensity development during a breakdown in narrow wavelength bands in the visible and near infrared range. This will give information about the important aspects of the breakdown including chemical elements, temperature, plasma parameters and possibly precursors of a breakdown.

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Abstract

Advanced experimental techniques are being developed to analyze RF and DC breakdown events. First measurements with a specially built spectrometer have been made with a DC spark setup [1] at CERN and will soon be installed in the CLIC 30GHz accelerating structure test stand to allow comparison between DC and RF breakdown phenomena. This spectrometer is able to measure the light intensity development during a breakdown in narrow wavelength bands in the visible and near infrared range. This will give information about the important aspects of the breakdown including chemical elements, temperature, plasma parameters and possibly precursors of a breakdown.

INTRODUCTION

The main motivation for RF breakdown research in the framework of CLIC accelerating structure development [2] is to improve the understanding of the limitation of accelerating gradients in room temperature cavities caused by breakdowns. Breakdowns affect the uptime of an accelerator and a degradation of the performance of accelerating structures due to accumulated breakdown events has been observed. Since there is no rigorous and complete model of the physics of breakdowns, this research can give new input for breakdown theory and will give feedback to accelerating structure designers how to reduce the detrimental effects of breakdowns. The experiments and the theory will be applied to both DC and RF breakdowns which occur in UHV and at room temperature.

BREAKDOWN WORKING MODEL

As a working model for the motivation, conception and design of dedicated experiments, a nine-stage-mechanism is considered to cover the main effects during a breakdown. These effects appear in chronological order:

1. An electric field is applied to a surface, along with a power flow in the case of RF. This surface may be generally imperfect due to machining marks, scratches, gaps, impurities, contamination and so on (the pre-conditioned state).
2. Field-emitting tips form and/or grow within fractions of nanoseconds [3].
3. Tip heating due to field emission of electrons. The field enhancement factor of the tip leads to the emission of electrons from the tip. The resulting current flowing through the tip causes ohmic heating. With rising temperature, also thermionic and Schottky emission of electrons starts to play a significant role resulting in a steady increase of current flowing through the tip. Derived from Fowler-Nordheim based calculations, these tips seem to be of nm-scale size [4].
4. Conditions evolve to where an electron cascade can begin. Two ideas have been proposed: The tip can liquefy and then evaporate from high temperature building up a metal vapour cloud close to the surface or the tip can break and produce small clusters of solid or liquid metal. Most of the tips will not heat up to this point and will cool down when the electric field has vanished.
5. A metal plasma forms above the surface.
6. This plasma absorbs up to 80% of all RF energy stored in the structures in the RF case. In DC, it seems probable, that at this point a conducting channel built by the metal plasma between anode and cathode is established. The delay between the application of the electric field and the absorption breakdown differs and seems to have a flat time distribution during the pulse when the field is existent.
7. There is a strong interaction between the plasma and the surface, e.g. ion bombardment. The final effect will be a damaged area of the size of tens to hundreds of microns.
8. The plasma expands and cools down and partly ionized metal is ejected out of the structure.
9. The surface cools down. In the case of conditioning, the surface ends up in a state where it can support a higher applied field.

DIAGNOSTICS

Most steps of the breakdown working model can be investigated by experiments, however, the formation of the tip on the surface can at the moment only be studied by atomistic surface simulations. Measurements of the electron emission (dark current) are standard in RF and DC. A rising emission of heat radiation from the tip should be detectable, but there is no detector for the assumed very low intensity and the expected wavelength range in the IR. The further heating of the tip will increase the intensity of the emitted light which is

expected to contain wavelengths in the near IR and visible range. Since the steps up to that point take place on a very small timescale, detectors with a very high temporal resolution are necessary to extract information about the development of the temperature of the tip (black-body radiation) and the metal vapour (spectral lines from metal ions).

The heating of the plasma and the cool down can be studied very well by time-resolved spectroscopy. The expected spectrum contains a black-body background (continuum) from the hot surface under the plasma and a plasma emission which is not yet well known. It is dependent on the plasma density, temperature and composition. It is not known if the plasma dissolves and leaves a cloud of metal vapour containing light radiating ions behind or if it disappears by another mechanism [5]. Time resolved spectroscopy will help to distinguish the plasma- respectively metal-vapour parameters during a breakdown with nanosecond temporal resolution. It will be possible to measure the plasma temperature, plasma density, background temperature and plasma composition for each development stage of the breakdown. Furthermore, in certain plasma density and temperature regimes, more effects of high electric and magnetic fields on ions could be in the spectrum.

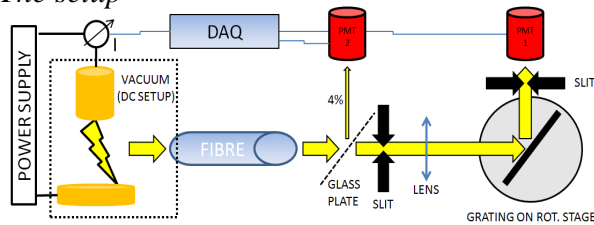## TIME-RESOLVED SPECTROSCOPY

The setup

Figure 1: The setup for time-resolved spectroscopy

The monochromator for the time-resolved spectroscopy has been designed to deal with very low light intensity levels (F/4). It is based on a grating (300lines/mm) mounted on a rotational stage driven by a high precision servo motor. Even though sparks are bright and can be seen by eye, the collection of the light is difficult. The light from the DC sparks is collected by a 1mm optical fibre inside the vacuum. This fibre is polished at the end pointing to the sparc and is 10mm away. The spectrometer is connected to this fibre by an optical vacuum feed-through and another fibre. In the RF case, the light coming out of the structure is collected by a lens outside the vacuum chamber and then focussed into a 1mm optical fibre going to the monochromator. The distance from the location of the breakdown is 38cm including a metallic mirror and a vacuum window. Losses due to the coupling of the light are estimated to be in the order of 50% in DC and 95% in RF. The resolution is limited by the available light intensity and detector sensitivity and is at the moment 15nm with a 200μm input and output slit. These values give a S/N-ratio of the dispersed light signal

of two in the DC setup. The detector after the grating is a PMT with a spectral response range from 300nm to 850nm (780ps rise-time sampled at 1GSa/s), but the S/N-ratio of two has only been reached in the range from 350nm to 650nm due to the low light intensity. A second PMT is placed before the grating and measures the intensity of the undispersed light which allows normalizing of the intensity waveforms of the dispersed light to allow construction of the spectrum from many breakdowns which vary in intensity. The calibration is done regularly with a HgAr-lamp as a standard.

Principle of operation

One wavelength interval can be measured for each breakdown. For this, the assumption has to be made that all breakdowns are based on the same effects and develop similarly. Therefore, a full spectrum needs at least the number of breakdowns which are necessary to cover the spectrum with the desired wavelength intervals (1nm intervals to improve statistics even optical resolution is worse). In addition, a trigger based on the integrated intensity for the undispersed light has been implemented into the DAQ software. This trigger accepts only waveforms which have an integrated intensity above a certain threshold to maintain S/N-ratio. After each breakdown with sufficient intensity, the grating is moved to the next wavelength interval. In DC, the trigger signal is derived from the current flowing through the arc and in RF by the electrons emitted out of the structure which are collected by a faraday cup [5].

FIRST RESULTS FROM THE DC SETUP

The spectrometer has first been used in the DC setup. Figure 2 shows the development of the intensity of the undispersed light during one microsecond for a typical breakdown with copper electrodes.
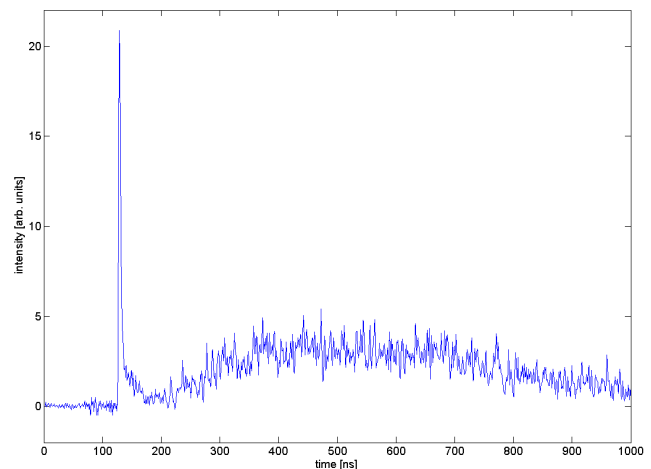

Figure 2: Typical time development of the undispersed light intensity emitted by a DC spark with copper electrodes. The system triggered at 126ns. Sampling rate is 1Gsample/s to sample even very short peaks.

After the trigger at 126ns, the light intensity rises within 2ns to a short peak of about 4ns FWHM and

immediately drops with the same slew rate to a value of only about one eighth of the peak maximum. Afterwards, the intensity rises again for about 300ns to twice the intensity after the peak and then decays down to baseline within approximately 700ns. The intensity ratio of the first and the second peak vary from breakdown to breakdown, and even breakdowns with no peak at the beginning have been observed. The latter breakdowns appear much more often in copper (~30%) than in molybdenum (~10%). Also more complicated patterns have been observed: The first peak is still there, but the second part of the waveform shows bumps and no smooth change of intensity. This behaviour is possibly caused by a separation of the plasma to multiple smaller plasma which then develop differently in time. The interpretation of the waveforms is still ongoing and will be supplemented by the time resolved spectroscopy.

CONCLUSION AND OUTLOOK

Time resolved spectroscopy offers a wide spectrum of analytical possibilities to investigate the physics of breakdowns, e.g. plasma parameters, temperatures, time development and yet unobserved effects. The system described above shows the capability to do these measurements but needs further improvement. A setup with higher resolution (1nm), better sensitivity and wider spectral response (UV-NIR) is under development. Electrical parameters from RF and DC will be taken into account in the analysis. The measured values for the above mentioned plasma parameters and timings will give feedback to plasma simulations, surface simulations and structure design. The system is now set up in the RF setup and upgraded to deal with lower light intensities.
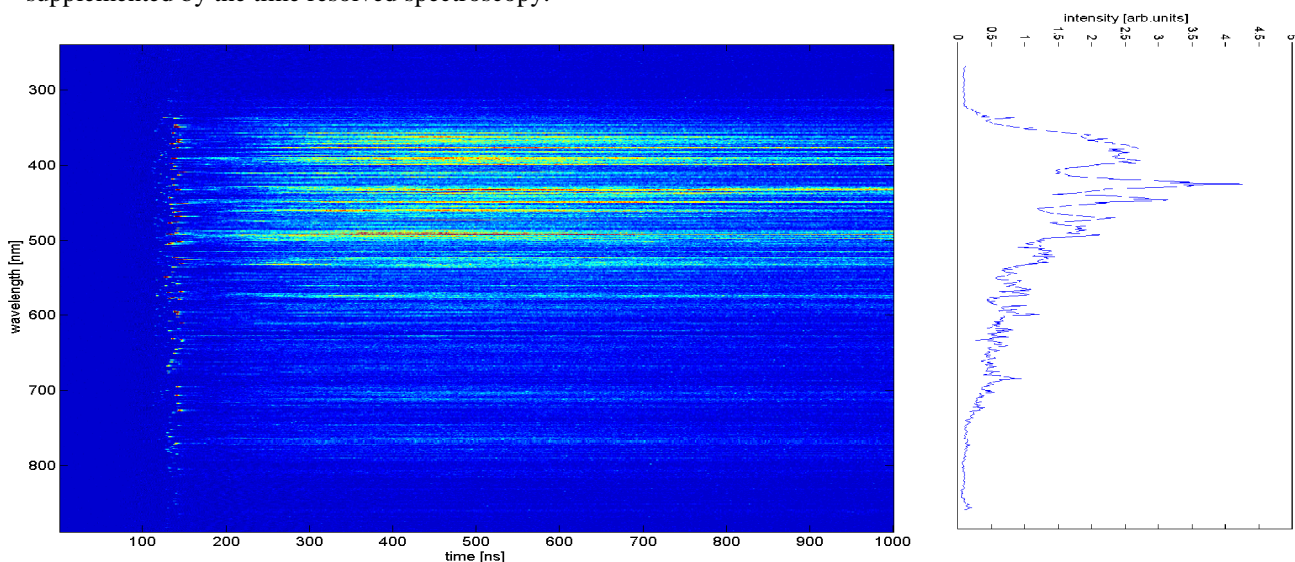

Figure 3: Time resolved spectrum of copper sparks in the DC setup. Each horizontal line corresponds to the intensity waveform of a single breakdown. Triggered at 126ns. The plot on the right is the projected spectrum, normalized to the undispersed light intensity.

Figure 3 shows a time resolved spectrum of sparks in the DC setup with copper electrodes. Each line of the plot represents a plot like Figure 2 but with colour-coded intensity. Each horizontal line corresponds to one breakdown event recorded at a certain wavelength interval. Notice that the PMTs S/N ratio is best between 300nm and 600nm. There are dim signals at longer wavelength which will be studied later with a suitable detector for that range. The plot on the right hand side of figure 3 is the projection with integration of each line over time and normalized to the undispersed light intensity. One can see that this spectrum contains a continuum background and some lines. The lines are consistent with copper lines but due to the poor resolution, a clear assignment to atomic transitions is not yet possible. The spectrum of the initial, 4ns peak will be studied separately but need more statistics and higher resolution.

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