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Dark currents studies with the Uppsala X-band Spectrometer at XBox test stand at CERN

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Introduction

Vacuum arcs is the phenomenon which limits the performance of normal conducting accelerator cavities. It closely depends on electron field emission, which is consider a precursor for the creation of a vacuum discharge. These processes are still not fully understood, but we know that they depend on the physical properties of the surfaces and bulk materials used in the accelerator structures. We need to come at these problems with a multidisciplinary approach, comprising accelerator, material and surface physics, for both experimental and theoretical analysis.

The field emission current emitted during operation of the RF cavity is typically refer to as the dark current. Behavior of the dark current can give useful information about changes inside the structure during conditioning and thus into the physics of the vacuum arcs. The Uppsala group uses a magnetic spectrometer to look at the changes, both spatially on the screen and by measuring the energy spectrum of the escaping electrons [1] during conditioning of CLIC X-band structures in dedicated high-power RF test stand at CERN [2]. The spectrometer was originally designed to measure the electrons from the breakdown events with much higher intensities than the dark current signals. In this paper we present the attempt to measure the dark current with the same setup.

Experimental description

Our spectrometer consists of a dipole magnet, a collimator, a fluorescent screen and a fast camera to measure the spatial and the energy distribution of the electrons and ions ejected from the accelerating structure in different operating conditions as shown on Fig. 1. These measurements can be correlated with e.g. the location of the breakdown inside the structure, using information from the incident, reflected and transmitted RF powers, giving in that way a complete picture of the vacuum breakdown phenomenon.

The setup is equipped with a slit or a pin-hole collimator in order to obtain the spatial information about the ejected electrons or ions within one RF pulse. The majority of particles will be stopped but small number will continue further entering the magnetic field of a dipole magnet. After the magnet we can observe an energy-dependent pattern formed by the particles impinging on a fluorescent screen. The screen plane forms a 30 degree angle with the beam axis in order to allow for a direct optical line to the camera at 90 degree angle. We use a mirror to reflect the image onto the CCD camera capable of acquiring 50fps. The details of the setup can be found in [1].

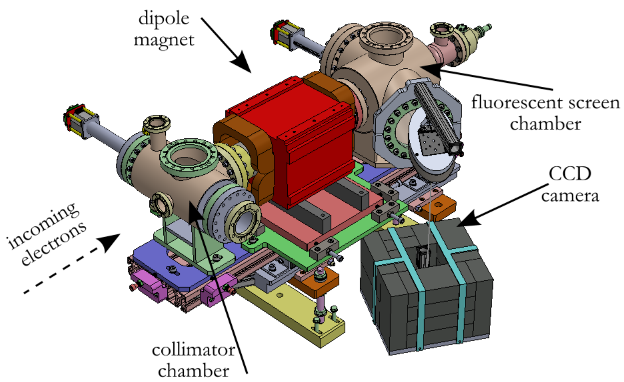

Figure 1: 3D-model of the diagnostic setup. The charged particles ejected from the accelerating structure during RF pulse travel first through the collimator chamber, then magnet and are capture on a fluorescent screen inside the screen chamber. A Faraday cup is located at the end of the setup.

Results

As mentioned earlier, the setup was optimized for breakdown signals, which typically deliver an order of magnitude higher number of electrons. The signals registered during non-breakdown pulses are therefore much weaker and more difficult to analyze. In order to improve on low statistic we typically combine signals from many consecutive pulses during 1 second (50 pulses at 50Hz operation).

Magnet scans with dark current

Magnet scans are performed by step-vise increase of the current in the magnet and collection of dark current images at each step. Each step takes 8 seconds with data acquisition time of 1 second when 50 consecutive pulses are recorded. The additional 7 seconds are sufficient for magnet to stabilize at the new value while minimizing the effects of a drift in RF power.

In the left column of Fig. 2, we present the data collected in such a way at 5 different setting of the dipole magnet.

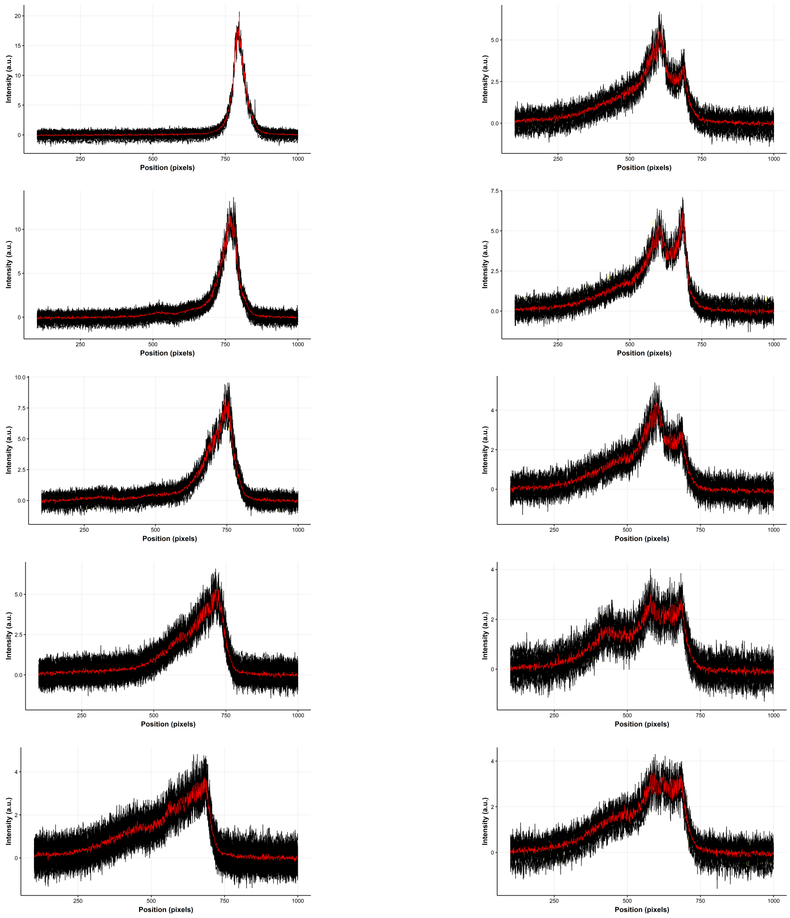

Figure 2: Left column: 5 distributions of electrons from dark current collected at different magnetic field during magnet scan. Right column: 5 distributions of electrons from dark current collected at fixed magnetic field with magnet current set to 0.5Amps. Each plot consists of 50 superimposed pulses plus a total average indicated in red.

Each plot consist of 50 consecutive pulses plus an average of all of them superimpose on the same graph. The whole magnet scan measurement was done withing few minutes and no breakdown occurred during that time. We observe that while the position of the spectrum shift with the increasing magnetic field and shape changes, the consecutive pulses are very similar. There is no indication of a single emitting spot inside the cavity but it rather resembles an isotropic distribution of field emitting sites along the cavity. Single emitter spot would results in a sharp, narrow peak in the spectrum as is the case for breakdown events, c.f. Fig. 3. We can see that the energy of escaping electrons changes at each breakdown event. This indicates that electrons originate from single iris and are accelerated collectively along the cavity by the remaining RF field.

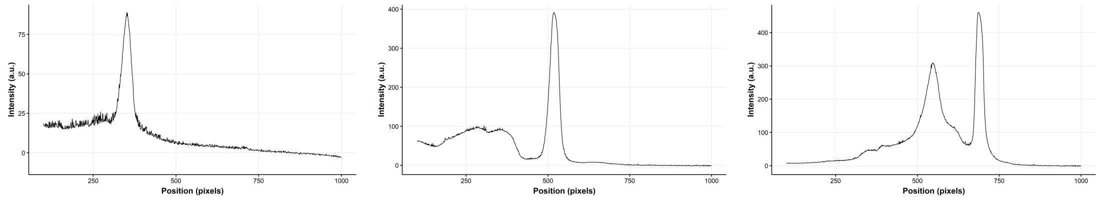

Figure 3: Three consecutive breakdown events. The magnet current was set to 0.5Amps during this period. Change in position along the x-axis towards the smaller values indicates larger bending radius in the magnet and thus lower energy of the particles.

While we did not observe any significant variation of the emitted electron currents between consecutive RF pulses in the short time scale (seconds to minutes), we did see variation between the spectra before and after breakdown events. This is illustrated with plots in the right column in Fig. 2. The 5 plots presented there are taken at constant magnetic field during run with 97 breakdowns. One or more breakdown occurred between these dark current measurement and we note the change in recorded shape of the distributions. Clearly breakdown events change the landscape of the field emitting surfaces, perhaps activating and extinguishing individual sites, leading to enhancement of the electron intensity in certain energy range of the spectrum. With more sensitive setup one could extract from these changes the information of the position of the new field emitters and perhaps predict where likely the next breakdown can occur.

The more isotropic behaviour of dark current electrons was confirmed by the observation of the electron energy spectra at different RF power level. With increased power available in the cavity we would expect a distribution of the dark current emitted electrons accessing higher energies. This is indeed what we observed, see Fig. 4. The figure shows energy spectra for 3 incoming power levels: 21, 26 and 30.5 MW. We note that the tail of high energy electrons increases accordingly to the accessible power and therefore the accelerating field present inside the cavity. Again we measure only broad, continuous spectra of the electrons giving indication of a isotropic distribution of the field emitters inside the cavity.

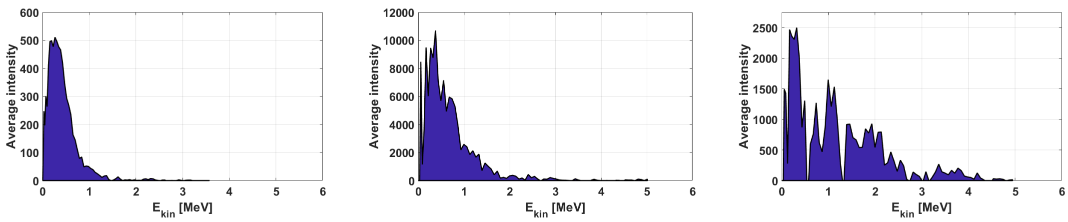

Figure 4: Energy of the dark current electrons measured at 3 different values of the incoming RF power, from left to right: 20 MW, 26 MW and 30.5 MW.

Scans in power

In the experiments performed at Xbox1 we run scans in RF power of the cavity to investigate how the measured intensity relates to typical measurements with Faraday cup or radiation detector.

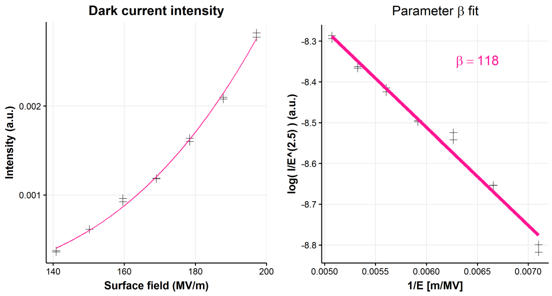

Figure 5: Dark current intensity measured by the spectrometer as a function of surface electric field (left). Fitting of the Fowler-Nordheim curve and extracting enhancement factor beta (right).

We observed very good agreement with underlying theory of field emission [3] [4]; however we measure rather high enhancement factor β, see Fig. 5, of the order of 120.

The enhancement factor β accounts for the increase in a local (microscopic) field value E_{local} from the ideal surface field E. Commonly considered explanation for the existence of the enhancement factor is a locally lowered work function combined with some geometric field enhancement. To verify the observation of the high enhancement factor we looked at the data recorded simultaneously by the radiation detectors present in the bunker, see Fig. 6.

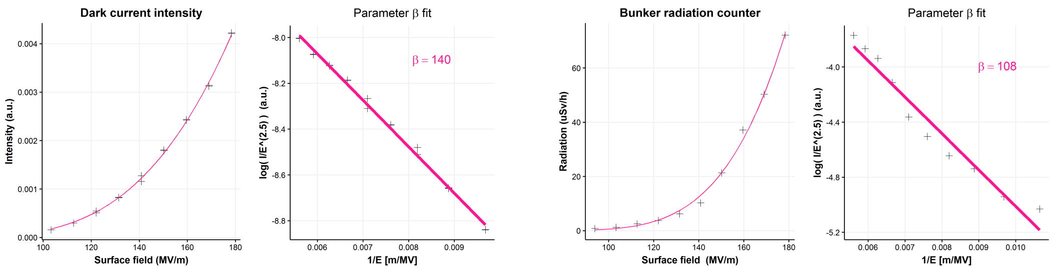

Figure 6: Dark current intensity measured by the spectrometer (left) and by the radiation detector in the bunker (right) as a function of surface electric field.

The data from the radiation detector confirmed high value of the enhancement factor. The value of the factor beta can be compared to the results from the in-SEM experiments performed in Uppsala, where we studied field emission from a copper sample inside the scanning electron microscope [5]. The samples used in these experiments, while only 12 mm diameter, have followed the same heat treatment as a prototypes of accelerating structures for CLIC during bonding process. They are exposed to the high electric DC field provided by an approaching microscopic needle. In the setup we can precisely control the distance and the voltage at the needle, while measuring the field emitted current. We typically measure enhancement factor beta of the order of ten to twenty, see Fig. 7, much lower than the value obtained at Xbox1.

The discrepancy in the magnitude of the β factor is probably related to the collective behaviour of the dark current electrons with many emitters contributing. The emission can come from sites with varying work function of the material and geometrical structure. In the case of in-SEM experiments we have a single, very well defined emitting site and the obtained β is closer to the theoretical definition.

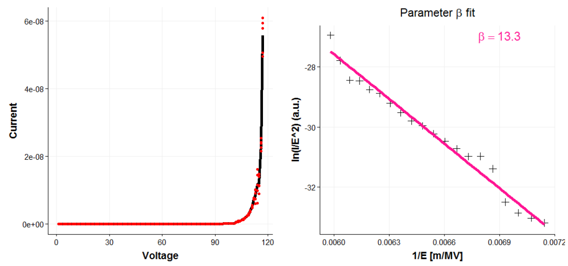

Figure 7: Current-Voltage curve measured at in-SEM setup with fitted beta parameter.

Conclusion

The Uppsala magnetic spectrometer was used to study distributions and energy of dark current electrons escaping the CLIC accelerating structure during conditioning runs at XBox1 test stand.

The data indicate that there is very little change in the pulse-to-pulse characteristics of the dark current, even in the time scale of minutes, unless a breakdown occurred inside the structure. The resulting energy distribution of emitted electrons is therefore broad and continuous to the limit given by the accelerating gradient present in the structure.

The breakdown events often reset the emitting sites which we observe by measuring changes in the energy spectra. Since the breakdown affects only one or two irises the measured changes are small. With more sensitive setup though these could be used to pinpoint the location of the new emitters and perhaps predict the location of the next breakdown.

Study of the dark current behaviour in function of surface field shows a very good agreement with underline theory of field emission however requires much higher values of the enhancement factor β to scale the data. This again confirms that the observed current is a superposition of the currents emanating from multiple emission sites.

Acknowledgement

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