SPATIALLY RESOLVED DARK CURRENT IN HIGH GRADIENT TRAVELLING WAVE STRUCTURES

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Abstract

High-gradient accelerating structures are known to produce field-emitted current from regions of high surface field, which are captured and accelerated by the fields within the structure. This current is routinely measured in structures under test in the CLIC (Compact Linear Collider) high-gradient test stands using Faraday cups. This paper presents a novel technique to spatially resolve the longitudinal distribution of field emitted current by analysing downstream Faraday cup signals when the structure is fed with RF pulses much shorter than its filling time. Results from this method applied to X-band cavities operating at 100 MV/m are presented, and are compared to breakdown position distributions. A decay in emitted current as conditioning progressed in regions with a low breakdown rate and large jumps in regions with a large breakdown rate are observed.

INTRODUCTION

As part of the development program for the Compact Linear Collider (CLIC) [1], high-gradient accelerating structures are tested at high power without beam in the XBox test stands at CERN [2, 3]. Among other diagnostics, Faraday cups are mounted on the beam axis on the upstream and downstream ends of the structure. Due to the high peak surface electric fields, on the order of 230 MV/m, that occur within the structure at nominal power, electrons are field-emitted from the structure surface and can be measured as current in the Faraday cups.

The field-emitted current, known as 'dark current', has been used to gain insight into the conditioning of structures. Currently, the Faraday cups only provide information about dark current emitted from the structure as a whole [4]. The method described here allows information about the spatial distribution of the dark current sources to be obtained using only hardware already in place. The spatially resolved field emission profile may in the future be used to monitor the conditioning process, identify cells with anomalous behaviour before developing into hot cells, and guide the RF design process.

METHOD

The structures under test at the XBoxes have low group velocity (values of 0.01c - 0.02c are typical) [5, 6] and support accelerating fields on the order of 100 MV/m which can accelerate field-emitted electrons to near c within a few millimetres, which means that captured electrons travel from the emission site to the Faraday cup much faster than the RF pulse itself [4]. Because of this, a ramp in the downstream dark current signal can be observed as the structure is gradually filled with RF and more area gets exposed to high enough electric fields to cause measurable field emission, as can be seen in Fig. 1.

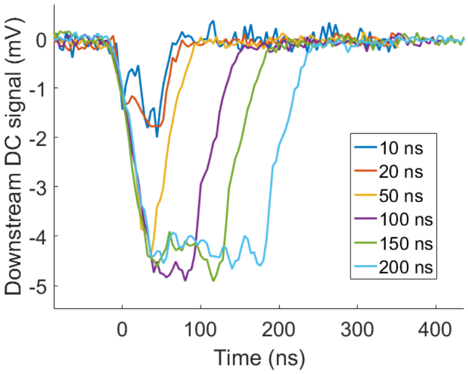

Figure 1: Dark current signals measured at the downstream Faraday cup with different RF pulse lengths.

The bandwidth of the structure and high power RF system is sufficient to allow pulses shorter than the filling time of the structures to be delivered to the structure. One can take advantage of this by generating very short RF pulses of about 10 ns long to use as a diagnostic method, in contrast with typical pulse lengths between 50 ns and 200 ns used for conditioning and operation. As the short pulse propagates through the structure, different longitudinal sections of the structure become exposed to high electric fields and undergo field emission. Under these conditions, the signal measured at the downstream Faraday cup at different points in time represents field emission from a different positions in the structure. This allows the field emission characteristics of the structure to be mapped longitudinally.

Measurements of dark current with short pulses at different field levels were taken regularly over the course of conditioning of the T24PSI1 and T24PSI2 structures [6] in XBox 2 and the T24N4 structure in XBox 3. The RF pulse shape for this measurement was chosen to minimise the duration of field emission - the shortest attainable pulse had a duration of 8.8 ns over which the field exceeded 90% of the peak value.

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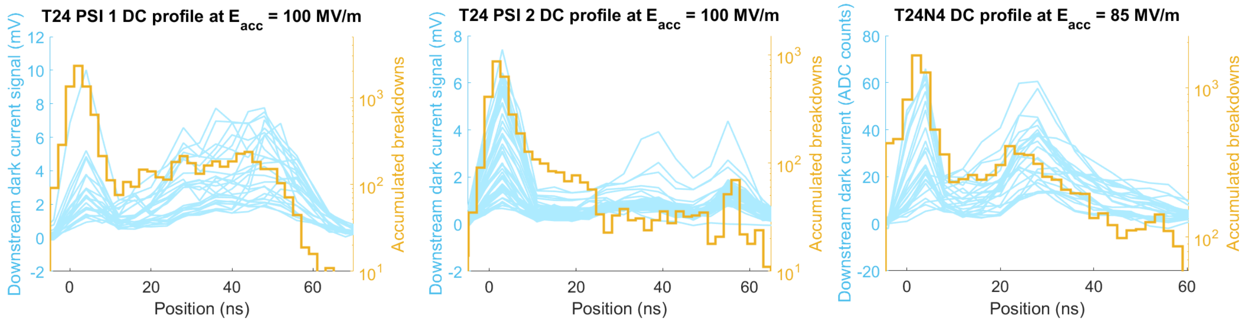

Figure 2: Measured dark current signal magnitude with a short pulse at a fixed accelerating gradient over the entire duration of the measurement (blue). Accumulated breakdown locations over the same time period, shown in units of pulse propagation time where 0 is the RF input of the structure (yellow).

SPATIAL CORRELATION

The magnitude of all the dark current measurements performed using this setup for each structure is shown in Fig. 2. As the operating gradient of each structure varied throughout its conditioning, care was taken to compare currents at a consistent gradient in the short-pulse measurement. This value was chosen to be the nominal operating value of 100 MV/m for measurements in XBox 2, and 85 MV/m in XBox 3 owing to limitations in available klystron power and the low pulse compression efficiency attained with the diagnostic pulse shape. The field emission history is compared with the history of breakdown locations in the time period over which the short pulse measurements were performed.

The breakdown locations have been deduced from the relative timing of deviations in the transmitted and reflected RF signals caused by the breakdown [7]. As both the dark current measurement and the breakdown localisation method use the propagation time of transient signals through the structure, their position values are expected to be consistent, and have been plotted in Fig. 2 in units of propagation time, where 0 represents the RF input of the structure and one filling time (about 60 ns [5, 6]) represents the RF output. From this comparison, one can see that locations in which more breakdowns have occurred tend to also have had higher activity in terms of field emission over the course of the conditioning history.

TEMPORAL CORRELATION

As the data was taken over an extended time period for each structure, a temporal correlation of field emission with breakdown rate could also be deduced. The most interesting case was the T24PSI2 structure which underwent an initial period of relatively aggressive conditioning, reaching a maximum accelerating gradient of 115 MV/m, after which the gradient was reduced to perform a series of long-term breakdown rate measurements at gradients between 103 MV/m and 112 MV/m.

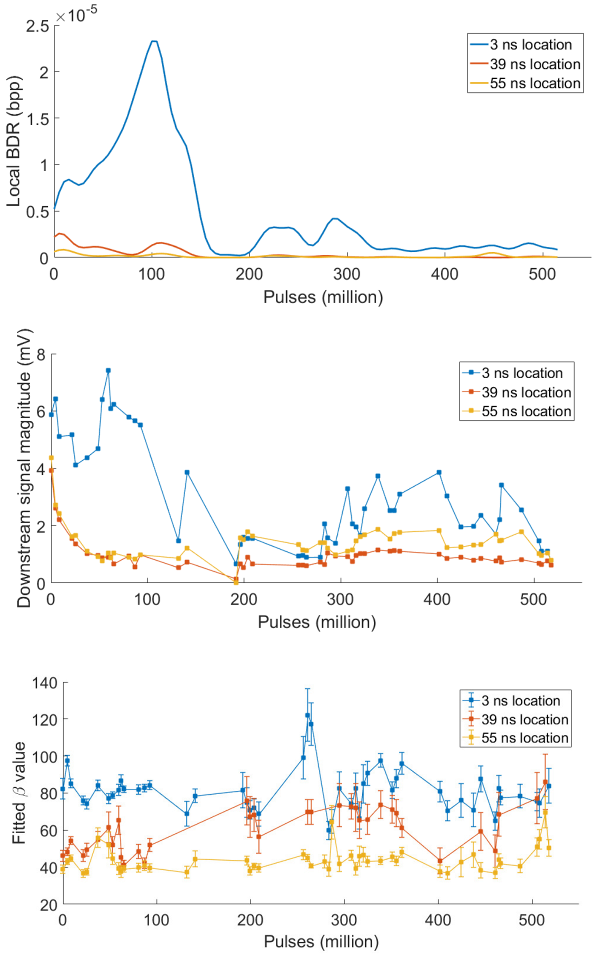

Figure 3: Evolution of the local breakdown rate (top), current magnitude (middle), and fitted β (bottom) in the T24PSI2 structure at selected locations over a given time window. Points with a 95% confidence interval greater than 15 have been omitted from the β plot.

The local breakdown rate, dark current and fitted Fowler-Nordheim β value (discussed in more detail below) at three locations (beginning, middle and end) in the structure over the conditioning history of the structure in XBox 2 are shown in Fig. 3. The initial conditioning period ended at about 150 million pulse mark, and coincides with a sharp drop in the breakdown rate. The 3 ns location, where the majority of the breakdowns in the structure have occurred, exhibited a significant reduction in dark current after the reduction in breakdown rate at that location. By contrast, the other two locations shown, in which the breakdown rate was much lower than at the input of the structure over the entire conditioning process, exhibited an exponential-like decay in dark current between the 0 and 100 million pulse marks, after which the dark current remained relatively low.

FIELD ENHANCEMENT FACTOR

Another piece of information that can be obtained from the short-pulse measurement is the distribution of Fowler-Nordheim β factor, obtained by measuring the dependence of the dark current on the surface field level [4]. This value gives an indication of the amount of field enhancement caused by microscopic surface features or phenomena. The fitted β value for three locations in the T24PSI2 structure over time is shown in Fig. 3. Unlike the dark current magnitude, no dependence on local breakdown rate or conditioning progress is readily apparent.

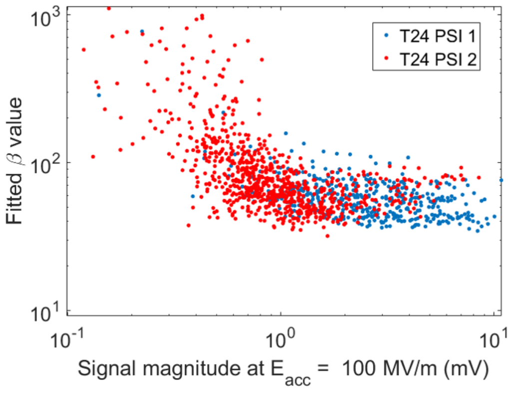

Figure 4: Correlation of fitted β value with signal magnitude.

It was found that dark current signals with a poor signal-to-noise ratio tended to produce excessively large β values. This bias is shown in Fig. 4, and should be taken into account by considering only points with a large enough dark current signal to obtain an unbiased β measurement. Most of the points shown in Fig. 3 have a signal magnitude of at least 1 mV, above which the bias appears to be small.

The fitted β value was found to be consistently higher nearer to the input port of the structure, with a gradual decrease moving towards the output port, as shown for the T24PSI1 structure in Fig. 5. This skew remained even when considering only points with a large enough signal magnitude to cause negligible bias in the β value, and was observed in all three structures.

Dispersion of the short RF pulse was investigated as a potential explanation for this, since the varying group velocity of different frequency components of the pulse could cause it to spread in time and decrease in peak field, resulting in cells closer the the end of the structure experiencing a different surface electric field from the one assumed. An RF simulation in CST Microwave Studio [8] was performed on the geometry of the T24PSI structures and used to determine the surface field at each iris as a function of time using the actual pulse shape used in the measurements. It was found that the dispersion of the pulse was not significant, and thus not likely to be the cause of the skew in fitted β.

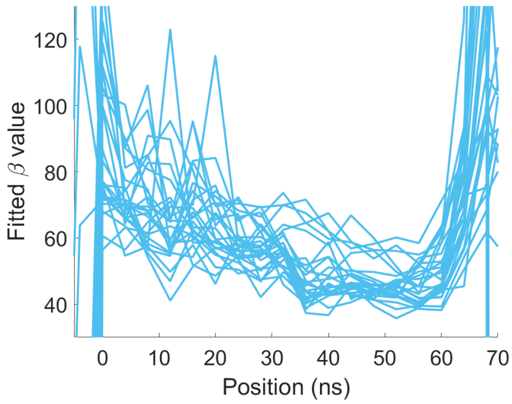

Figure 5: Distribution of the fitted β value within the T24PSI1 structure over the entire duration of the measurement.

CONCLUSION

A new diagnostic technique for measuring the spatial distribution of field emission in travelling wave accelerating structures has been demonstrated and shown to give consistent results for different structure designs and test stands.

A good correlation between local field emission and breakdown rate has been found, in both time and location, suggesting that either areas damaged by breakdowns [9] emit more current, or that areas that emit more current are more likely to have breakdowns. It also shows that this effect decays with conditioning. The field emission β value does not exhibit any clear evolution or dependence on breakdowns, but appears to vary along the length of the structure. The fact that the dark current varies with the breakdown history independently of the field enhancement factor suggests that the field emission might come from a large number of similar field emitters whose population can vary.

It was established that neither bias in the β calculation nor dispersion in the RF pulse are the cause of the skew in fitted β. A possible avenue for future work is a study of the effects of electron capture and transport between the emission site and the Faraday cup by measuring the frequency dependence of the phenomena presented in this paper or particle-in-cell (PIC) simulations of emitted electrons in the structures under test. Determining the direction of causality between dark current emission and breakdowns could also be considered.

ACKNOWLEDGEMENTS

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