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DARK CURRENT ANALYSIS AT CERN'S X-BAND FACILITY

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Abstract

Dark current is particularly relevant during operation in high-gradient linear accelerators. Resulting from the capture of field emitted electrons, dark current produces additional radiation that needs to be accounted for in experiments. In this paper, an analysis of dark current is presented for four accelerating structures that were tested and conditioned in CERN's X-band test facility for CLIC. The dependence on power, and therefore on accelerating gradient, of the dark current signals is presented. The Fowler-Nordheim equation for field emission seems to be in accordance with the experimental data. Moreover, the analysis shows that the current intensity decreases as a function of time due to conditioning, but discrete jumps in the dark current signals are present, probably caused by breakdown events that change the emitters' location and intensity.

INTRODUCTION

The operation of high-gradient (HG) linacs is limited by RF breakdowns (BD). These are vacuum arcs produced due to high surface electric fields present on the inner cavity walls. In addition to breakdowns, HG structures are also affected by the so-called dark current (DC), which is formed by field emitted electrons that are accelerated through the structure [1].

Dark current is an important phenomenon to be studied in HG structures because it can cause RF energy absorption, background noise in the beam position monitors, and also ionizing radiation. DC is also linked to the damaging RF breakdowns. The magnitude of the field emitted current follows the Fowler-Nordheim law [2], which can be expressed through the simplified expression

$$J = a\beta^2 E^2 e^{\frac{-b}{\beta E}} \tag{1}$$

where a and b are constants that depend on the metal work function, E is the surface electric field and β is the field enhancement factor in the emitters.

The RF conditioning is a procedure that aims at progressively adapting the HG accelerating structures to the high fields they need to sustain in normal operation. During conditioning, both accelerating gradient and pulse length are gradually increased keeping the breakdown rate (BDR) low. By the end of this procedure the accelerating prototypes are able to run within the CLIC constraints [3, 4], which means with an average gradient of 100 MV/m at 250 ns pulse length, for a BDR < 3×10^{-7} bpp/m (breakdowns per pulse per meter). The breakdown rate slowly decreases through the conditioning process [5], and that is related with a reduction in the dark current measured in normal pulses, as it will be shown in the following sections.

In this work we present the dark current analysis of the conditioning data taken in the CERN facility for several CLIC prototypes. First we introduce the data available and the analysis procedure. Later on we explain the main characteristics observed in the dark current behaviour during long term operation: the reduction of the emission during conditioning and the fitting to the Fowler-Nordheim law at different stages of it.

DARK CURRENT ANALYSIS

The analysis presented here makes use of the data recorded during the conditioning of several CLIC prototypes in the HG X-band test facilities available at CERN, no further explanation of the stands will be presented as they have been

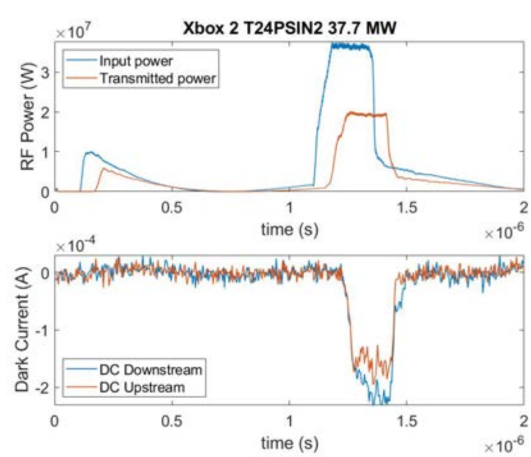

Figure 1: Example of traces measured at Xbox 2.

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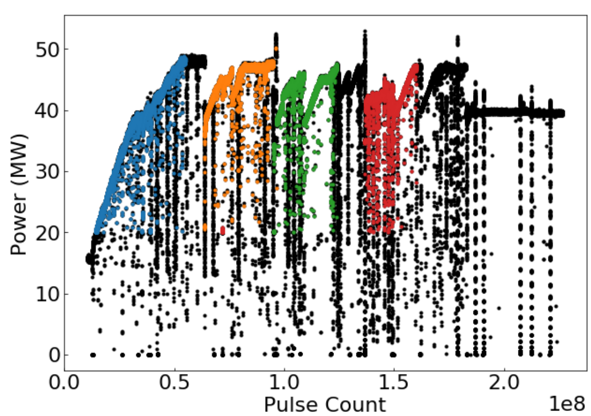
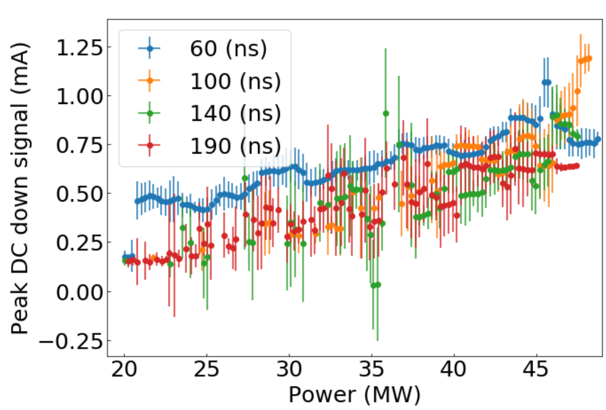
described in previous publications [6,7]. During the analysis we process traces like the example presented in Fig. 1. From the power signal, two relevant quantities can be obtained: peak power and pulse length. From the dark current signals, the peak value of the current registered in both downstream and upstream Faraday cups is obtained. Despite this some plots present downstream signal only, because it has a bigger magnitude and is enough for analysing field emission.

Generally, the pulse length is increased during conditioning after reaching the desired peak power at low BDR. This can be seen in Fig. 2a, where the RF power conditioning plot of the T24PSIN2, recorded at Xbox 2, is presented. Following that, the peak dark current value as a function of the input RF power is presented in Fig. 2b, where the conditioning ramps for different pulse lengths are overlapped, the color helps for its localization in the graph of Fig. 2a. Here it can be seen how the pulses of later stages of conditioning (red) present lower dark currents at same power levels compared with the early stages (blue). Another important point is the dependence on the RF power, which is visibly linear instead of exponential as it would be expected from Eq. 1. This happens because in long term operation the exponential growth as a function of power is compensated by a decay as a function of the number of pulses, where breakdown occurrences during conditioning change the emitters' location and intensity. In consequence, for analysing the pure field emission behaviour, power scans must be made in a short period of time with no breakdowns, so that the effects of the conditioning are avoided.



(a)



(b)

Figure 2: (a) RF power conditioning plot of the T24PSIN2 at Xbox 2, marking the different pulse length sectors. (b) Dark current versus RF power for different pulse lengths.

Dark Currents at Constant Power

To elucidate the emission reduction during conditioning, a selected fragment is presented in Fig. 3, which corresponds to a TD24 tested in Xbox 3. It can be seen that the RF power is approximately constant, despite of the fluctuations related with breakdown conditioning. The pulse length is also constant at a value slightly above 100 ns. Even though the field level is constant the dark current decreases. The current spikes that suddenly appear are related with breakdown occurrences, as the blue dots are aligned with the jumps. The BD positioning is calculated analysing the time of flight of transmitted and reflected RF signals in each BD [5], and plotted in the right axis of the top plot. The first and the last cell of the structure correspond to 0 and 67 ns, respectively. However, the relation is not linear, as the the group velocity differs from cell to cell due to tapering.

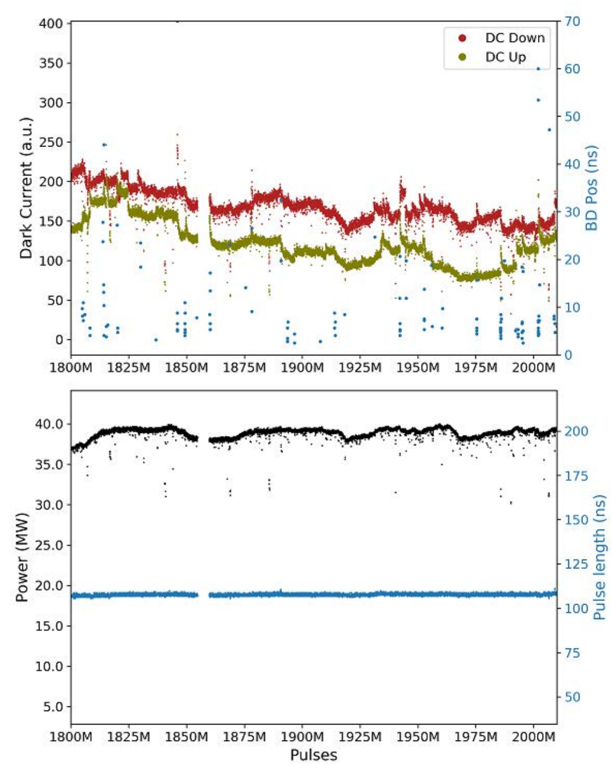


Figure 3: Fragment of conditioning of a TD24 tested in Xbox 3. The graph in the top shows the upstream and downstream dark currents measured, together with the breakdown positioning. The one in the bottom shows the power and the pulse length of the RF pulses.

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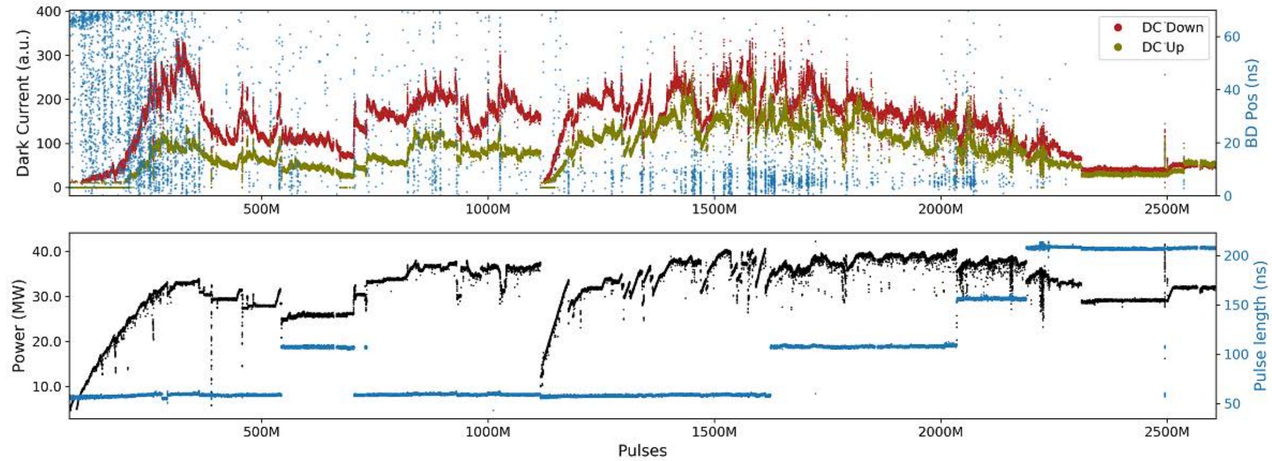

Figure 4: Full conditioning of a TD24 tested in Xbox 3. The graph in the top shows the upstream and downstream dark currents measured, together with the breakdown positioning. The one in the bottom shows the power and the pulse length.

Upstream to Downstream Ratio and BD Location

The full conditioning plot for the same TD24 CLIC prototype is presented in Fig. 4. One can see how the breakdown distribution along the structure is homogeneous at the beginning of conditioning and converges to the first cells in the later stages of the process. This is consistent with the upstream and downstream dark currents measured in normal pulses if we assume correlation between the BD positioning and the emitters' location. In the beginning every cell is emitting with about the same intensity, but the better capture in the downstream direction leads to higher signal in this Faraday cup; in the end, the first cells are emitting more, and are the ones closest to the upstream Faraday cup, this is why now both signals have the same level, even though the capture upstream is worse [8]. This correlation between emitting zones and breakdown positioning has been found also using short RF pulses for spatially resolved dark current measurements, as it is detailed in [9].

Dark Currents in Short Time Power Scans

To analyse the Fowler-Nordheim dependence, short time power scans were made for different structures in different stages of the conditioning. Figures 5a and 5b present the data for two TD24, one baked-out (BO) and another un-baked-out (UBO), before and after conditioning. It can be seen that the UBO emits more. From the Fowler-Nordheim plot the factor β can be obtained: In the TD24BO it goes down from 80 to 70, and in the TD24UBO goes from 94 to 60, proving that field emission consistently goes down due to conditioning. The same effect was observed doing radiation scans in a TD26CC tested in Xbox 2, Figures 5c and 5d present these results. The darker lines correspond to earlier stages, showing that it needed more power to achieve the same radiation as the conditioning was progressing. Nevertheless, the radiation does not scale linearly with the current, higher fields give higher energy electrons in addition, but beta scans can still be made despite of this consideration.

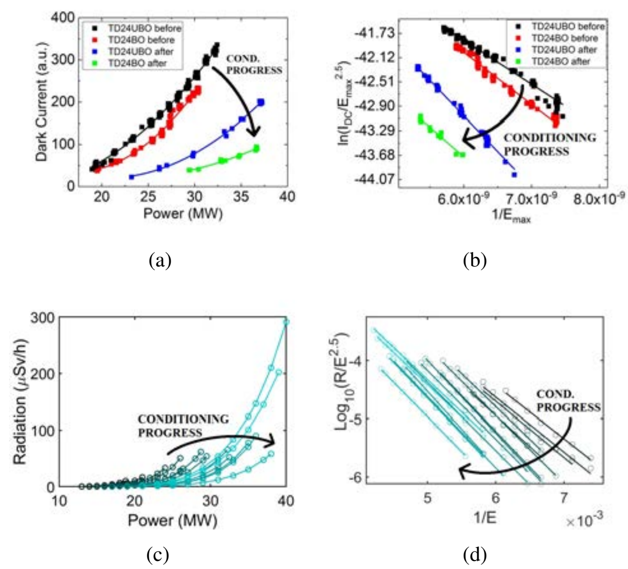

Figure 5: Power scans for two TD24 tested in Xbox 3: Dark current as a function of power (a), and Fowler-Nordheim plot for the same data (b). Power scans for a TD26CC tested in Xbox 2: Radiation as a function of power (c), and Fowler-Nordheim plot for the same data (d).

CONCLUSIONS

In this work, a detailed analysis of the dark current measured in the CERN X-band test facilities for several CLIC prototypes has been presented. Showing that the field emission consistently goes down as the structures progress in the conditioning. The evolution of the upstream to downstream ratio suggest that the areas dominating the emission are the ones with more breakdowns. Finally, Fowler-Nordheim plots of short time power scans developed for several structures show a reduction of the field enhancement factor β as the conditioning process takes effect.

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