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MEASUREMENTS OF DARK CURRENT AND BREAKDOWN PROCESSES USING FARADAY CUPS AND FAST DIGITISERS AT THE XBAND LABORATORY FOR ACCELERATORS AND BEAMS (XLAB)

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Abstract

CLIC TD24 accelerating structures, manufactured by CERN, are undergoing high-power testing on the 12 GHz RF test stand, MelBOX, at the x-Band Laboratory for Accelerators and Beams (XLAB). Installed in late 2024, these are the first devices tested at the facility. The goal is to condition the structures for stable operation at gradients of 100 MV/m. The maximum gradient is limited by electrical breakdown, vacuum arc formation under high electric fields, which interrupts RF transmission and can damage the structure. To study breakdown dynamics and validate models of their initiation, detailed, time-resolved charge measurements are needed. Faraday cups upstream and downstream, combined with high-performance 5 GS/s, 12-bit, 3 GHz FEB digitisers, enable precise characterisation of both dark and breakdown current emissions. Fast digitiser readout allows continuous acquisition at the 400 Hz repetition rate, capturing breakdown events and several hundred preceding pulses. This dataset supports in-depth analysis of precursors. We present initial results from structure conditioning, including breakdown statistics, dark current trends, and preliminary analysis of breakdown behaviour.

INTRODUCTION

The Experimental Laboratory for Accelerators and Beams (XLAB) at the University of Melbourne (UoM) is now fully commissioned and operational [1]. The XLAB is the result of a long term long term collaboration between the UoM, CERN and the Australian Nuclear Science and Technology Organisation (ANSTO). The primary goal of XLAB is the testing of Compact Linear Collider (CLIC) accelerating structures and technology for the CLIC collaboration; while providing local researchers and students with opportunities to develop and refine experimental accelerator physics research skills.

The first of two CLIC TD24 accelerating structures, manufactured by CERN, is currently installed and undergoing high power high gradient testing at 12 GHz radio frequency (RF), on the test stand now known as Melbox, with the aim to verify that accelerating gradients of 100 $\mathrm{MVm^{-1}}$ are achievable and maintainable. Maximum achievable accelerating gradients are ultimately limited by the phenomenon of electrical breakdown, vacuum arc formation within the accelerating structure. The likelihood of a breakdown occurring is dependent on the applied electric field. During conditioning the RF power level is slowly increased such that the breakdown rate (breakdowns per pulse) is below the set point, nominally 5×10^{-6} $\mathrm{pulse^{-1}}$. Ultimately, for the final stage CLIC 3 TeV design to ensure luminosity losses of less than 1 %, the maximum allowable breakdown rate at 100 $\mathrm{MVm^{-1}}$ is 3×10^{-7} $\mathrm{pulse^{-1}m^{-1}}$ [2].

Understanding the breakdown process is critical to operating accelerating structures at increasingly higher powers. To improve the understanding and further develop the theories of breakdown formation accurate measurements of breakdown phenomena are required. A range of diagnostic devices are installed on the high gradient test stand to monitor the accelerating structures during conditioning. These devices include; RF directional couplers, Faraday cups (FCs), Cherenkov fibres and radiation monitors. The FCs are the key diagnostics for measuring the current released by the structure during both normal operation (dark current) and breakdowns. As such the FC readout system was recently upgraded to include a new high-speed digitiser from Spectrum, operating at 5 GS/s, 12-bit, 3 GHz bandwidth, with the aim of better measuring temporal and transient phenomena. Preliminary results from this system are presented here.

MELBOX - HIGH GRADIENT TEST STAND

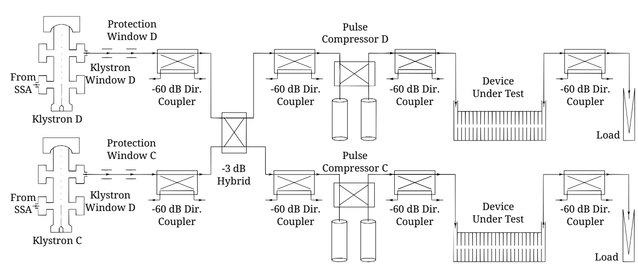

Figure 1: The MelBOX high power RF network. -60 dB directional couplers installed throughout the network are readout by NI-PXI DAQ and are the key diagnostic for monitoring and measuring RF power.

MelBOX at XLAB is half of XBOX3 that was previously installed and operated at CERN, provided to the University of Melbourne as a long term loan through the CLIC collaboration [3–6].

A National Instruments (NI) PXI crate and associated digitisers and vector signal generators form the backbone of

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the RF control and data acquisition system. This includes the generation of the low level RF (LLRF) signal at 2.4 GHz which is mixed up to the required 12 GHz and subsequently amplified by two MicroWave Amps solid state amplifiers (SSAs).

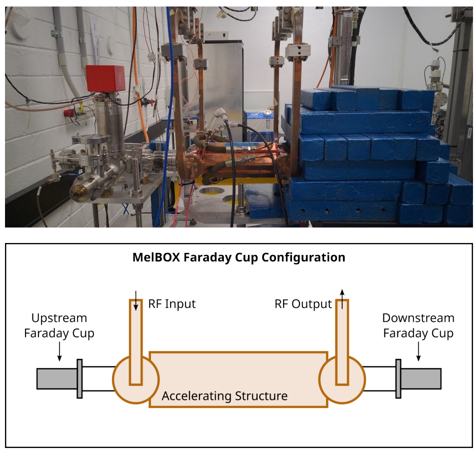

Figure 2: A photo of the structure with FCs installed at either end (above). A diagram depicting the location of the Faraday cups (below).

The output of the amplifiers drives the input for two Canon (Toshiba) E37113 6 MW klystrons that are operated in tandem at up to 400 Hz and 6 µs pulse lengths. Power from the kylstrons is directed to devices under test (DUT) via the high-power RF network a schematic of which is provided in Fig. 1. The power from the two klystrons is combined with a hybrid and directed down either of the two test lines by switching the phase. Each test line has a pulse compressor (PC) to bring the peak power up to ~50 MW and 300 ns pulse lengths [7, 8]. At several key locations along the network there are -60 dB directional couplers, these along with vacuum measurements, and the FCs are the main diagnostics used for breakdown detection and all the signals from them are digitised by the NI PXI. Any power remaining after the DUTs is dissipated in stainless steel loads at the end of the lines.

FARADAY CUP - DATA ACQUISITION SYSTEM

Overview

At Melbox two FCs designed for electron energies up to 35 MeV and manufactured by RadiaBeams are/will be installed (currently only one structure is installed for testing) on each of the structures one DS and one US, as shown in Fig. 2. These are integrated into the PXI DAQ system, where they are readout using 80 MHz bandwidth, 250 MS/s, 14 bit digitisers. All signals collected by the PXI are sampled and saved periodically, once a minute or in the event of a breakdown, in which case the breakdown pulse and the pulse prior are saved. During breakdowns the peak current can saturate the inputs, it can therefore be concluded that peak breakdown currents exceed 100 mA.

Spectrum DAQ

A new DAQ system consisting of Spectrum digitisers was recently installed to supplement the NI-PXI system. The Spectrum digitisers operate at 5 GS/s with 3 GHz bandwidth and 12 bit resolution. The main motivation for adding these digitisers is a much higher readout rate which allows for every pulse to be saved even when the MelBOX is running

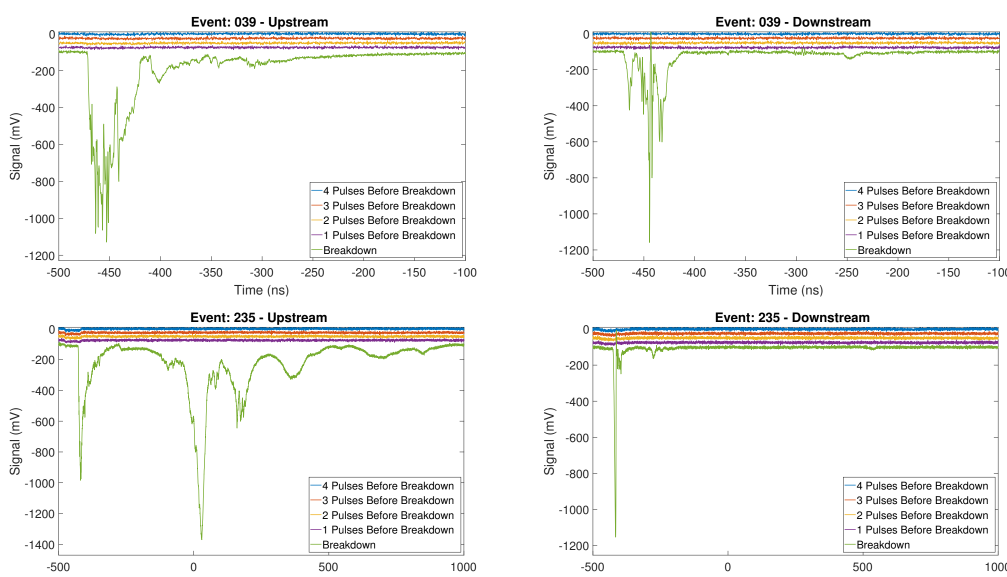

Figure 3: Two example breakdown events. Event 39 above and 235 below, upstream signals are shown on the left and downstream signals on the right. In all cases the breakdown pulse and the four pulses preceding are shown, each subsequent pulse is offset by 25 mV for clarity.

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at the full repetition rate of 400 Hz. The preliminary results from commissioning this system were presented in [9].

Results

The Spectrum DAQ was configured to save the current pulse and the previous 49 pulses in the event of a breakdown. The data presented below were collected during conditioning of the structure with 70 ns flat-top pulse RF pulse and power in the range of 30-35 MW corresponding to accelerating gradients of approximately 80-87 MV/m.

Examples of the breakdown and dark current signals are presented in Fig. 3. These examples show two events, 39 above and 235 below, and the upstream and downstream FC signals on the left and right, respectively. As well as the breakdown signals the four preceding dark current signals for each are shown (only four of the 49 preceding pulses collected are shown for clarity). In Event 39 the dark current signal is in the noise, while in Event 235 a small signal is visible. These have been included to illustrate the significant difference in dark current and breakdown signal intensity often two to three orders of magnitude. This large dynamic range presents a problem for the DAQ and optimisations and solutions are being investigated. Another, interesting feature of the breakdown signals is their duration while the RF pulse flat-top is 70 ns long, the breakdown current is collected over several hundred nanoseconds, and in the case of Event 235 upstream over more than a microsecond. Future work will explore characterisation and interpretation of the structure present in the breakdown signals and cross-correlate it with the corresponding RF signals.

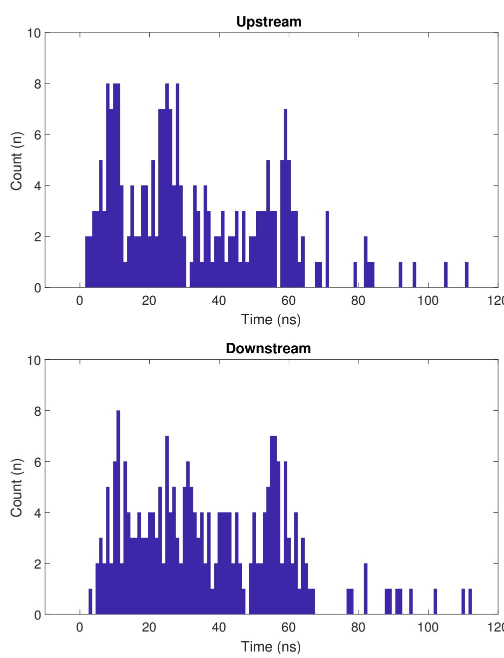

Figure 4: The distribution of breakdown arrival times at the upstream (above) and downstream (below) FCs.

Analysis of the timing of all the events collected during this period of operation was also performed. The time of the breakdown was determined from the leading edge of the breakdown signal. The threshold for which was determined by the peak of the dark current signal in the previous pulse. Creating histograms of the arrival times produced in Fig. 4 for the upstream and downstream signals, above and below respectively. These histograms are indicative of where/when in the RF pulse the breakdowns occur. Examining these distributions it can be seen that the majority of events occur within the expected 70 ns window of the RF flat-top. This is consistent with previous analyses with the RF signals.

Finally, the arrival time difference between upstream and downstream signals was calculated and the distribution plotted in Fig. 5. It is indicative of the breakdown location along the longitudinal axis of the structure. Although the absolute positions need further calibration, the distribution skewness of the distribution suggests a higher incidence of downstream breakdowns than upstream. This contradicts earlier RF based analyses and requires additional investigation to reconcile.

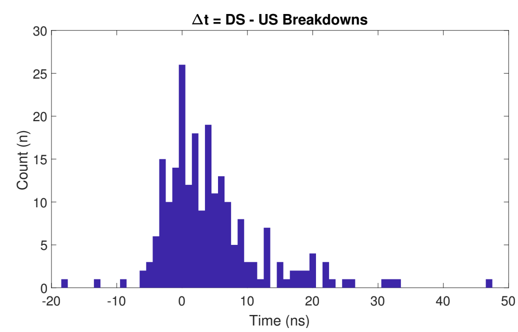

Figure 5: The distribution of the difference in arrival times between the upstream and downstream breakdown signals at the FCs. This time difference, Δt, could provide and indication of the location of the breakdown event within the accelerating structure.

CONCLUSION

High power testing of CLIC accelerating structures is underway at the XLAB. A new DAQ system for the FC readout has been installed and is now used in routine operation. Early results from the system confirm that operation at a readout rate of 400 Hz is stable. Structure within breakdown events is evident and future work will seek to characterise it. Temporal analysis of the results are consistent with the hypothesis that the majority of breakdowns occur during the flat-top of the RF pulse. The results also indicate that ToF analysis of the FC signals maybe be used in order to determine the location of breakdowns along the longitudinal axis of the structure. Future work will seek to build on these promising results.

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