Applying Machine Learning to Breakdown Prediction in High-Gradient RF Cavities

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Introduction

Recent developments have shown machine learning is an intelligent and effective approach to analyzing large amounts of data. In this context, a machine learning framework has been developed and applied to Compact Linear Collider (CLIC) high-gradient structure test data to search for previously unrecognised features related to the incidence of RF breakdowns [1].

Test Stand and Data Overview

XBOX-2 is one of three X-band (12GHz) test stands at CERN developed to investigate high-gradient phenomena. The test stand is principally comprised of a 50MW klystron, pulse compressor, and high-power RF load, as shown in Figure 1.

To train the machine learning model, 90 GB of data logged in XB2 during a six month period of operation was selected [2]. The chosen data includes RF waveforms, Faraday cup readings, vacuum levels, and temperature signals.

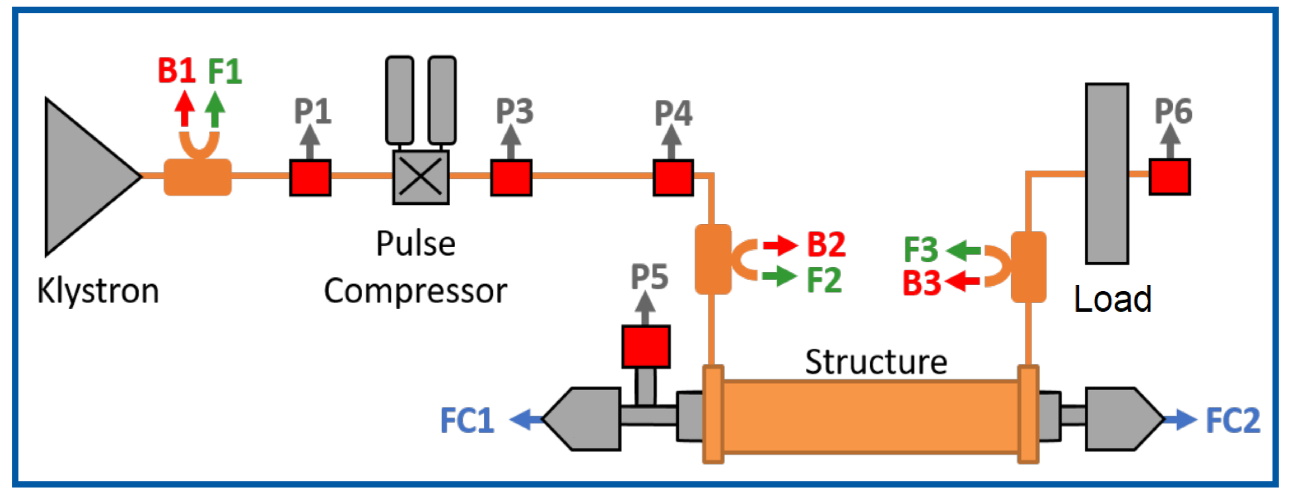

Figure 1: Diagram of CERN's XBOX2 test stand showing the backward (B) and the forward (F) RF signals, the upstream and downstream Faraday cup signals (FC1 and FC2), and the ion pumps (P1..6).

Application of Machine Learning

The multi-dimensional data was first processed via 2D t-SNE (t-distributed Stochastic Neighbour Embedding), visible in Figure 2. This method is unsupervised, i.e. no information about whether a breakdown occurred or not, was given. Clear clusters emerged from the data, with each cluster pertaining to a different set of fixed operating conditions (i.e. input power and pulse length) labelled r1 to r9 in the left plot, or breakdowns in the middle plot.

No clear separation is possible in the right plot for distinguishing events which are healthy in the next pulse from events which lead to a breakdown in the next pulse. As such, supervised machine learning was then applied to the dataset.

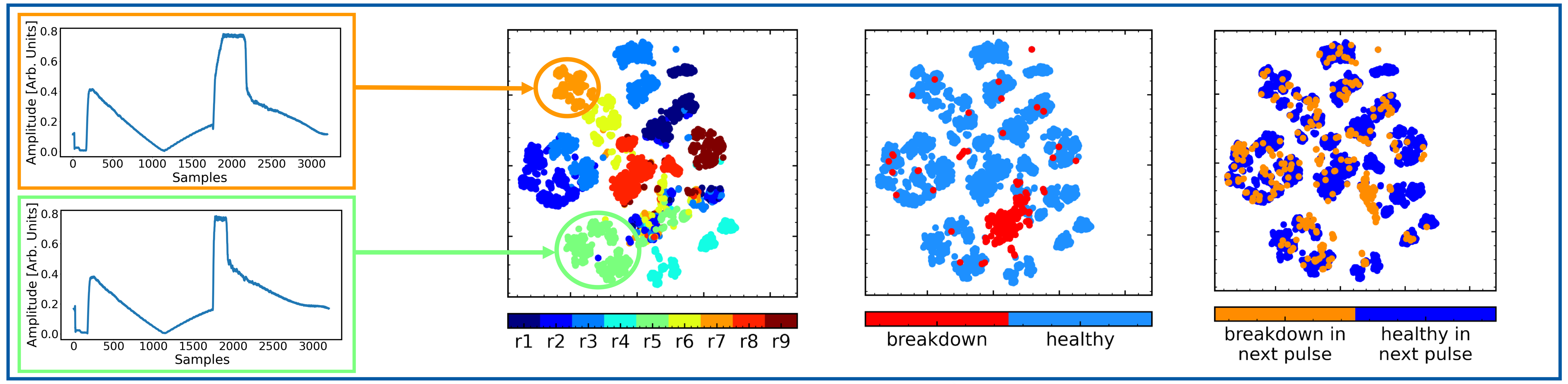

Figure 2: Results of 2D t-SNE of the dataset with arbitrary axes (right) and two example RF waveforms corresponding to different clusters (left) [3].

Breakdown Prediction

The majority of structure breakdowns were correctly predicted and explainable AI was then employed to make physical interpretation of the learned model parameters possible. Two key findings have emerged:

1. **The cavity pressure should be monitored with increased temporal resolution to explore the vacuum activity associated with arc formation.**
2. **Following a breakdown, the dark current signal is strongly linked to the probability of another breakdown occurring shortly thereafter (See Fig. 3).**

Further work is required to validate the first finding and exclude the possibility of a clock misalignment or aliasing. Figure 3 shows the weighted importance of the Faraday cup signal in predicting breakdowns.

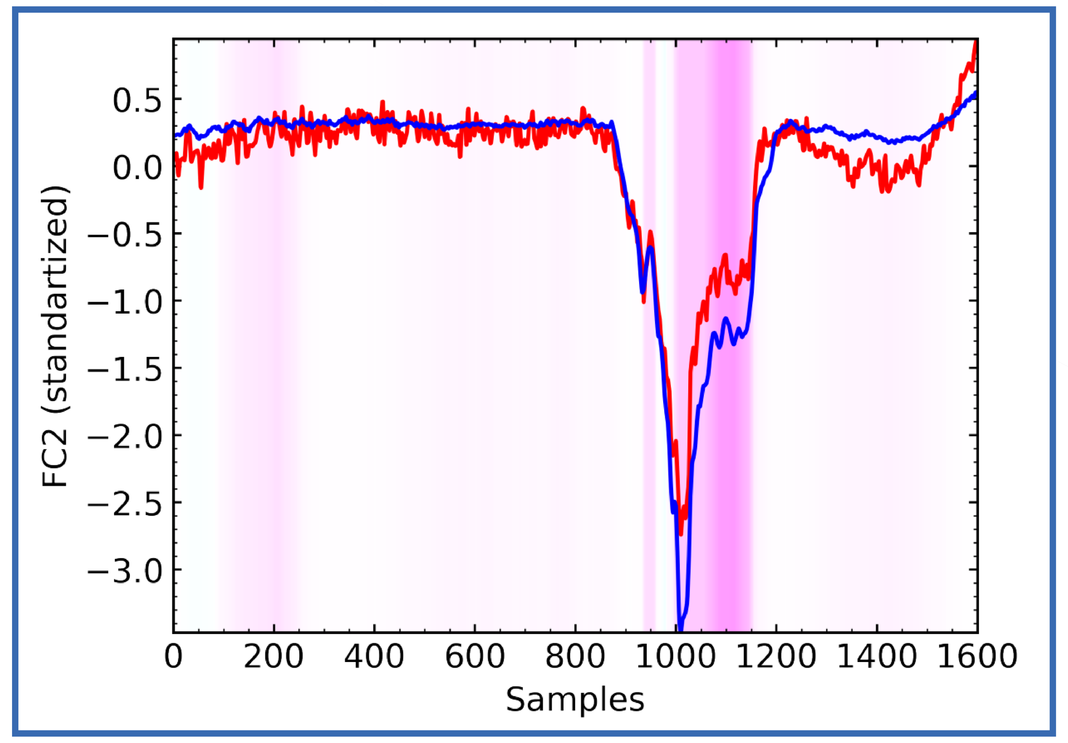

Figure 3: Faraday cup waveforms and the samples' weighted importance (pink) in predicting breakdowns [3].

Conclusion and Future Work

A machine learning framework has been developed and successfully applied to existing CERN high-gradient test stand data for the first time.

Ultimately, the goals of the framework are to develop an operational tool for breakdown reduction and improve the understanding of the probabilistic behaviour and physics of breakdown.

The first results suggest that in some cases pressure rises may occur prior to breakdowns however further work is required to validate this result. Secondly, the shape of the dark current signal appears to be strongly linked the probability of a follow-up breakdown occurring soon after a primary event. The full methodology and results are currently under review for publication [3].

References

[1] - https://github.com/cobermai/rfstudies

[2] - L. Millar, "Behaviour of High Gradient RF Structures During Long-Term Operation", 2018, workshop on Mechanisms of Vacuum Arcs (Mini MeVArc), Uppsala University, Sweden. [Online]. Available: https://indico.cern.ch/event/750619/contributions/3206320/

[3] - C. Obermair et al, "Explainable Machine Learning for Breakdown Prediction in High Gradient RF Cavities ", Status: Under review. Preliminary version available on arXiv: https://arxiv.org/pdf/2202.05610.pdf

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