Application of Machine Learning to Breakdown Prediction in CERN's High-Gradient Test Stands

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Abstract

Recent developments have shown machine learning to be an intelligent approach to analysing large quantities of data. In this context the use of a machine learning framework in conjunction with high-gradient structure test data is being investigated to search for potential breakdown precursors.

With this approach, fast, reliable, and simple rule based models may be derived which may then be translated to a physical interpretation to shed light on the physics of breakdown and develop operational tools to mitigate the occurrence of arcs in modern high-gradient facilities.

Test Stand Overview

XBOX-2 is one of three X-band (12GHz) test stands at CERN developed to investigate high-gradient phenomena. The test stand is comprised of a 50MW klystron, pulse compressor and high-power RF load. Vacuum and temperature signals are also recorded throughout the waveguide network. The arrangement of the structure test slot is shown Figure 1.

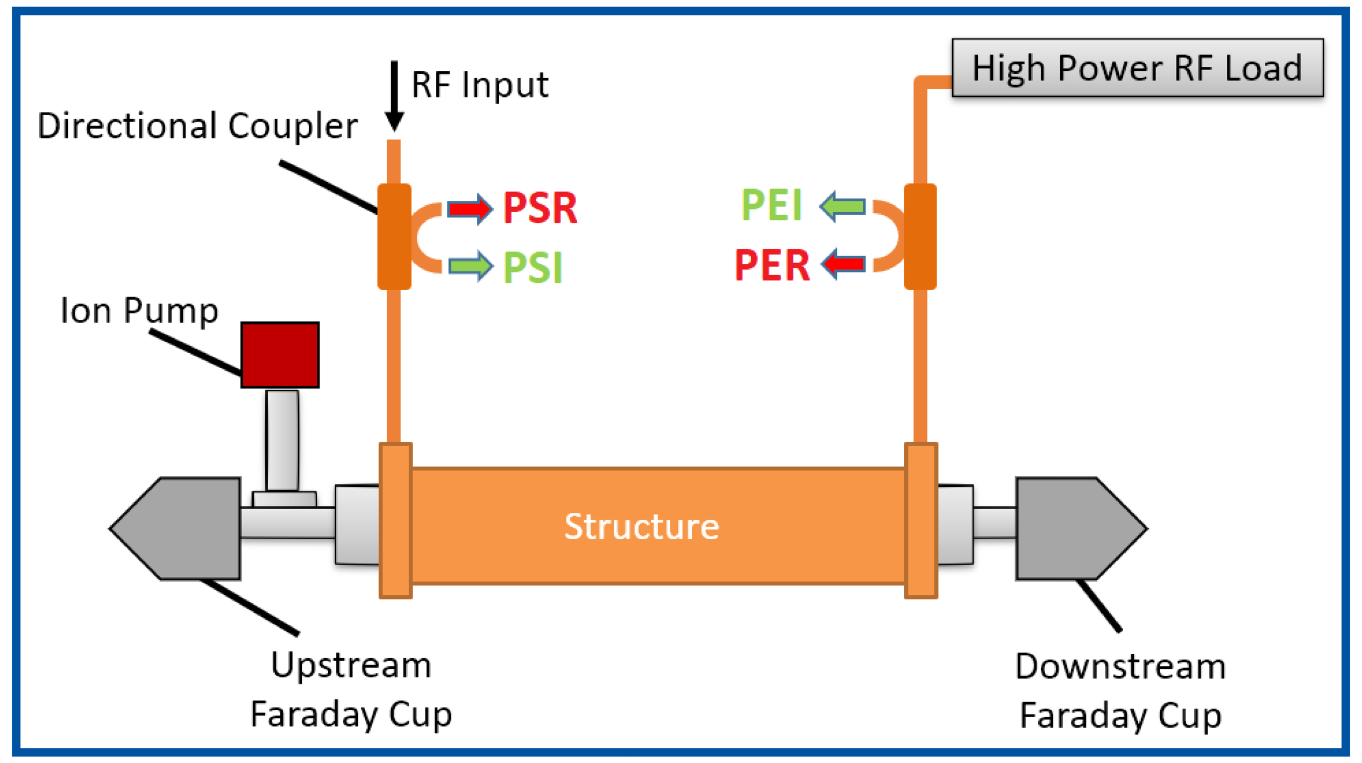

Figure 1: Diagram of the XB2 test slot. The acquired RF signals and their labels are shown by the red and green arrows.

Data Overview

To train the model 90 GB of data logged in XB2 during a six month period of operation was selected. The data is comprised of RF waveforms, Faraday cup signals, temperature and vacuum signals.

During the test the structure was operated under several sets of fixed conditions to investigate dependency of breakdown on field and pulse length as are visible in Figure 2. A single set (run) is outlined in orange. Further details of the test are reported elsewhere [1].

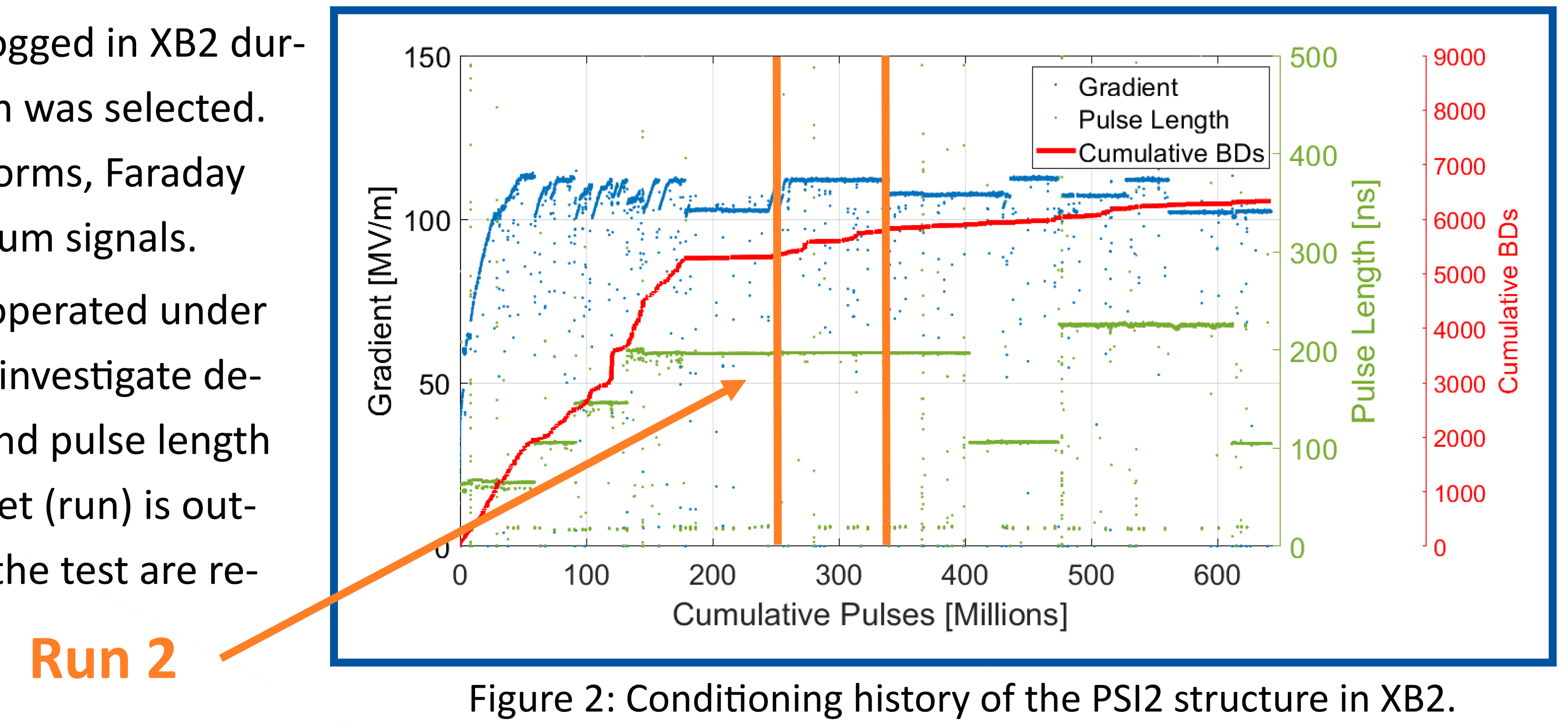

Figure 2: Conditioning history of the PSI2 structure in XB2.

Application of Machine Learning

Unsupervised learning was first applied in order to examine the data for inherent groupings and structures. The multi-dimensional data was processed via 2D t-SNE (t-distributed stochastic neighbour embedding) such that it can be inspected in a two dimensional plot. Preliminary results are visible in Figure 3 and show that the signals from the test stand are clustered, with each cluster pertaining to a different set of fixed operational settings. The signals pertaining to breakdown pulses are also largely clustered (shown in red) although some anomalous cases remain. The data was taken forward for supervised machine learning to search for breakdown precursors. In this method the algorithm examines the data to learn the mapping function from the input to the output. The goal is then to predict breakdown events based on the signals immediately prior.

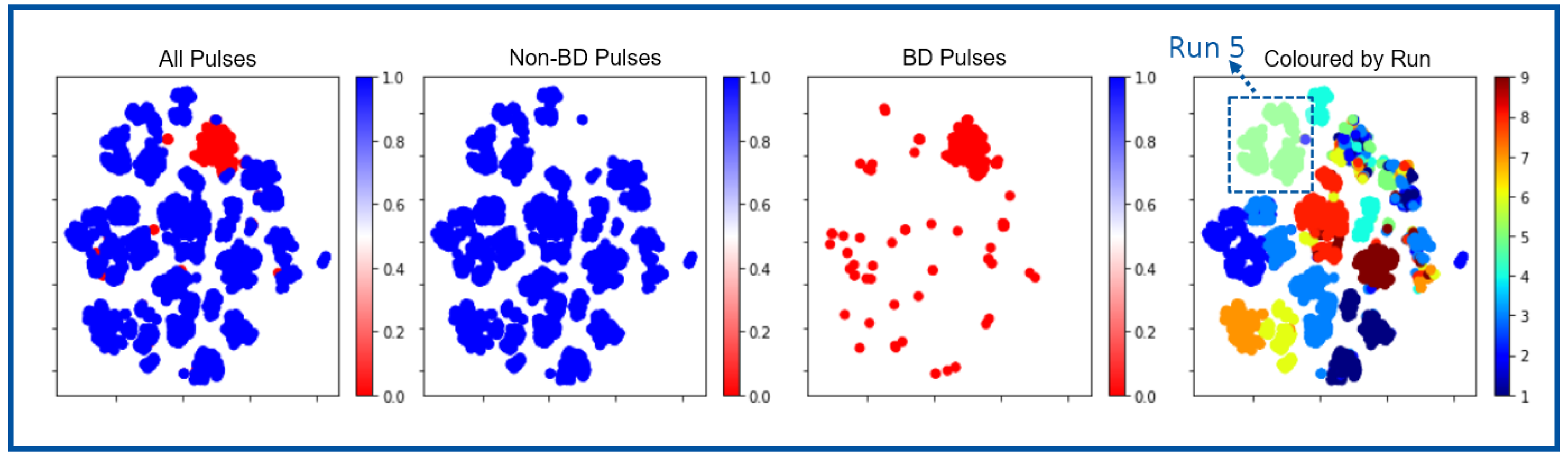

Figure 3: Results of 2D t-SNE of the XB2 dataset with the points corresponding to the fifth run outlined [2]. Axes are arbitrary.

Preliminary Results of the Framework

The use of explainable AI makes physical interpretation of the learned model parameters possible. Figure 4 shows the weighted importance of each value in several time domain signals. Results showed that breakdowns were typically characterised by a measurable change in the structure vacuum level several pulses prior however additional work is ongoing to ensure this result is not the product of a systematic clock misalignment in the acquisition system.

Full details of the methodology are currently being prepared for publication [3].

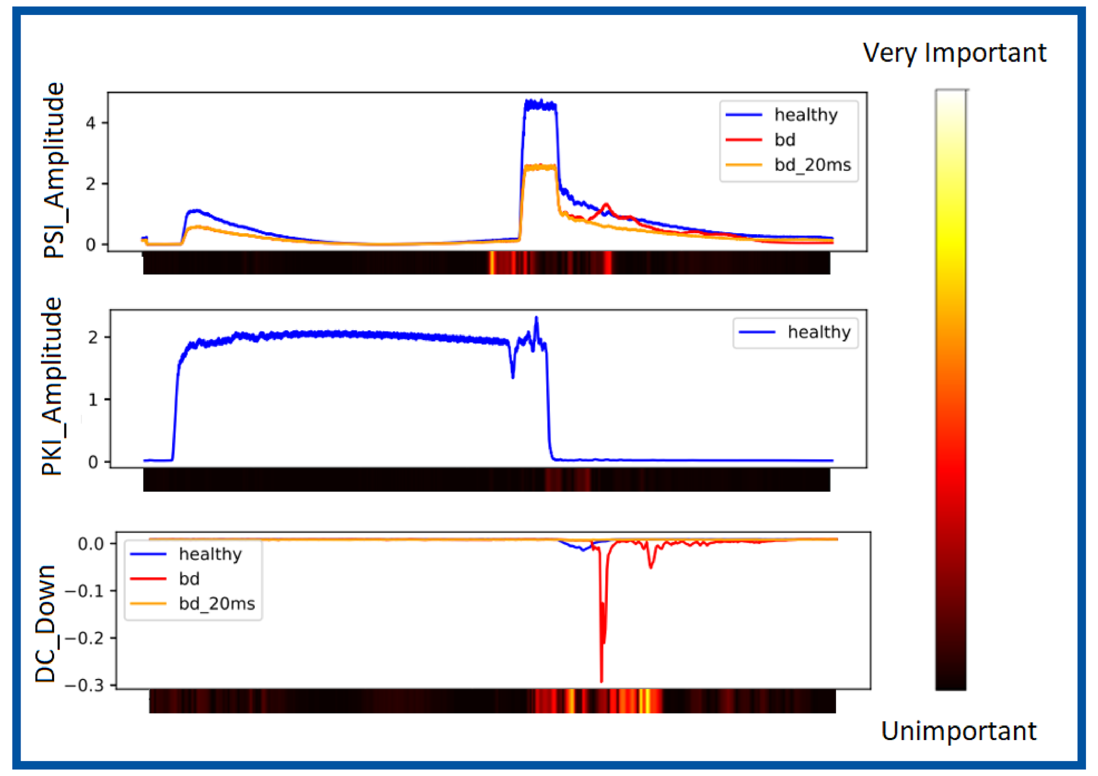

Figure 4: Example waveforms and their weighted important in predicting breakdowns [2,3].

Conclusion and Future Work

A machine learning framework has been developed and successfully applied to existing CERN high-gradient test stand data. The data has been successfully transformed, explored, and examined for the presence of potential breakdown precursors. Preliminary results indicate that small vacuum spikes may occur immediately prior to breakdown but the possibility that this result been produced artificially by a systematic acquisition error is currently under investigation. The framework is now being applied to other datasets and the preliminary results are being verified experimentally. Ultimately, the goals of the framework are to develop an operational tool for breakdown reduction while also improving the understanding of the probabilistic behaviour and physics of breakdown.

[1] - 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/

[2] - C. Obermair, "Machine Learning Study of CLIC RF Breakdowns", 2020, RF Development Meeting, CERN, Switzerland [Online]. Available: https://indico.cern.ch/event/957293/contributions/4023360/

[3] - C. Obermair et al, "Reverse Engineering Physical Properties of RF Cavities with Explainable Machine Learning", Status: Pending submission.

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