Radio Frequency (RF) Breakdown analysis at CERN's High Gradient Test Stands: a Machine Learning approach

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Testing and conditioning of High Gradient, X-Band Radio Frequency (RF) accelerating cavities for the future Compact Linear Collider project (CLIC) is undertaken at dedicated CERN test facilities. One such facility, the X-Band Laboratory for Accelerators and Beams (X-LAB), a collaboration with CERN and other international partners, is under construction at the University of Melbourne, due to be operational by early 2023.

A primary failure mode limiting the operation of RF accelerating cavities is RF Breakdown. RF Breakdowns occur when extreme electric fields liberate electrons from the cavity surface and cause plasma buildup, leading to catastrophic power reflection. Recent investigations have attempted to predict Breakdown events using Machine Learning and Time-Series Classification (TSC), in order to increase beam availability, reduce damage to accelerator components, and improve understanding of Breakdown mechanisms.

In this work, we review existing applications of Machine Learning to the Breakdown problem, and compare recent findings with current Breakdown theory, namely the Mobile Dislocation Density Fluctuation (MDDF) model [1]. The MDDF model theorises that Breakdowns occur due to a runaway increase in the population of mobile dislocations (line defects) in the surface of copper RF cavities. However, pressure spikes are observed to occur seconds before breakdown events [2], which contradicts the shorter timescale predicted by the MDDF model. We apply machine learning algorithms to data from existing CERN facilities to investigate the origin of this disagreement between the MDDF model and current Machine Learning results. These algorithms recognise patterns in waveforms associated with Breakdown events, and can therefore differentiate between non-events (routine operation) and Breakdown. This work provides crucial insight into Breakdown timescales, and underpins future research programs at the X-LAB.

[1] E. Z. Engelberg et al. *Dark current spikes as an indicator of mobile dislocation dynamics under intense dc electric fields*. In: *Phys. Rev. Accel. Beams* 23 (12 Dec. 2020), p. 123501. DOI: 10.1103/PhysRevAccelBeams.23.123501.

[2] Obermair et al. *Explainable Machine Learning for Breakdown Prediction in High Gradient RF Cavities.* 2022. DOI: 10.48550/ARXIV.2202.05610.