Searching for Rare Events in the Field Emitted Current of High-Field RF Cavities

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International Workshop on the Mechanisms of Vacuum Arcs (Hybrid MeVArc 2022)

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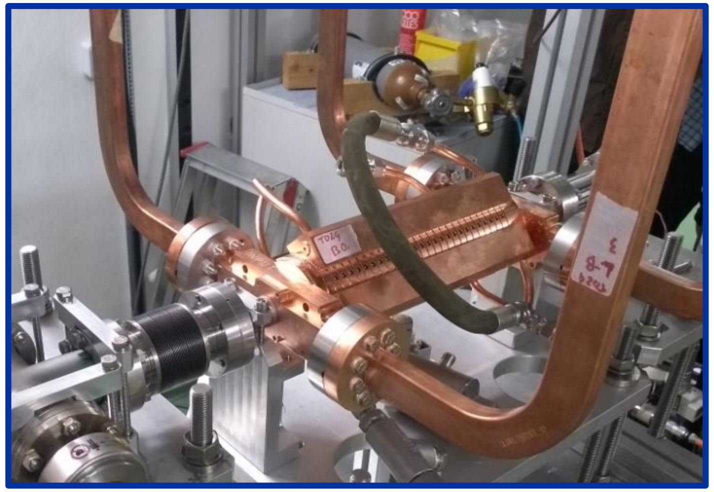
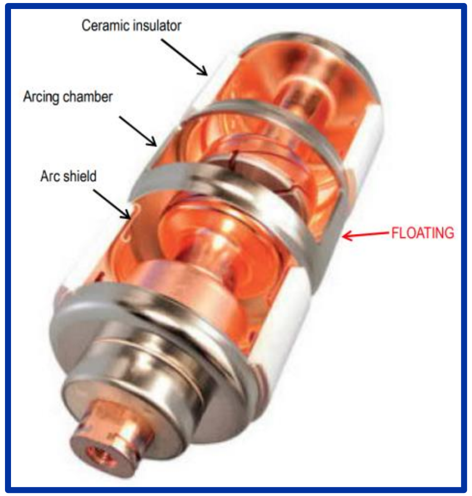
Introduction

Breakdowns (or vacuum arcs) are a limiting factor in a variety of high-field devices.

However, the mechanisms associated with the nucleation of breakdowns, and the conditioning process, are not yet understood..





Figures: A TD24 RF cavity for the CLIC project (left), a Siemens vacuum interrupter (centre) [1], and electrodes for a Radium electric dipole moment experiment (right) [2].

A Recap of Previous Work

Previously, it was proposed that it may be explained by the movement of dislocations (irregularities / crystallographic defects in the material lattice) due to the stress of the applied field [3].

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Editors' Suggestion

Theory of electric field breakdown nucleation due to mobile dislocations

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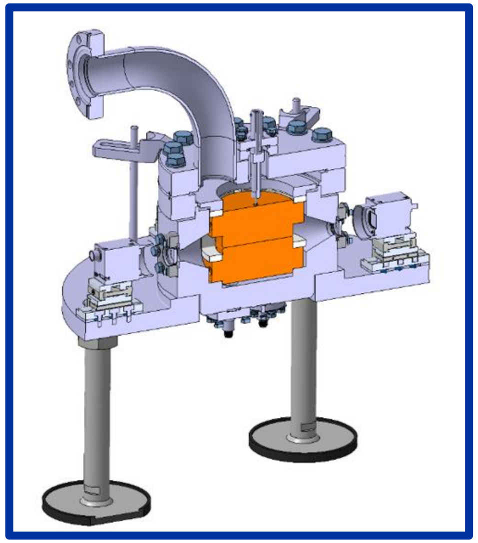
Based on this model, it was suggested that fluctuations in the mobile dislocation density may result in measurable spikes in the field emitted current between two given electrodes.

A Recap of Previous Work

With the help of CERN’s Large Electrode System (LES), subcritical (non-breakdown) current spikes were then measured [3]. The frequency of these events correlated with the applied voltage. Excellent result and an excellent paper! → https://doi.org/10.1103/PhysRevAccelBeams.23.123501



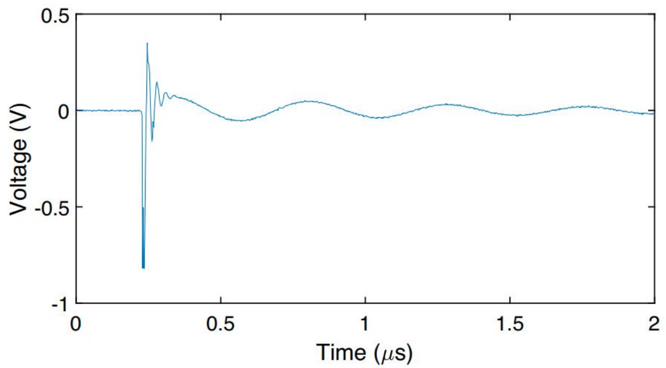


FIG. 4. Example oscilloscope trace of a subcritical (i.e., prebreakdown) current spike, recorded at a high sample rate of 500 MHz.

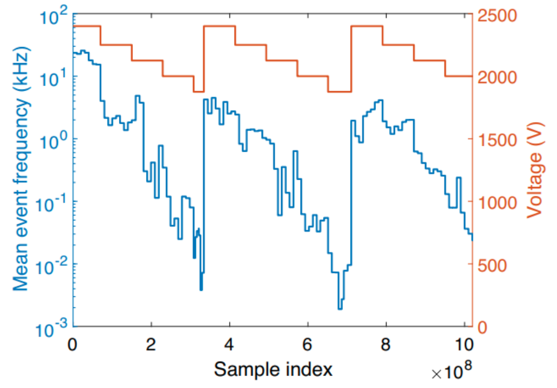
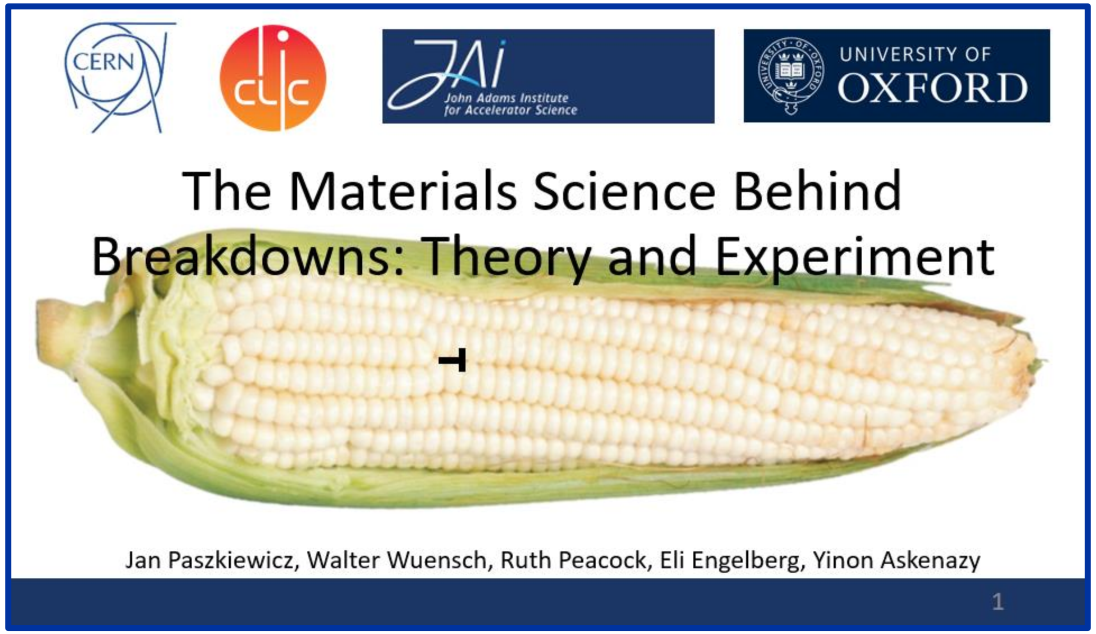


FIG. 8. Applied voltage and spike frequency over the course of measurement series C. The time in the horizontal axis is shown in units of oscilloscope samples, with the time intervals between the windows emitted.

Figures: A cross-section of CERN’s, a subcritical current spike (centre) [3], and the frequency of the current spikes vs. the applied voltage [3].

A Recap of Previous Work

An attempt was made to measure the same phenomenon in CERN's RF test stands (the Xboxes), but no candidate was found (see the talk below [4]). Today's presentation is a continuation of this work.



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CERN’s RF Test Facility

To test the X-band (11.994 GHz) components for CLIC (and other projects), a high-power test facility has been established at CERN.

A few numbers for a typical cavity:

- **Peak surface E-field: ≈ 220MV/m**
- **Input power: ≈ 40MW.**
- **RF pulse length: ≈ 200 ns**
- **Energy per pulse: ≈ 8J.**
- **Pulse rep. rate: 50-200 Hz.**

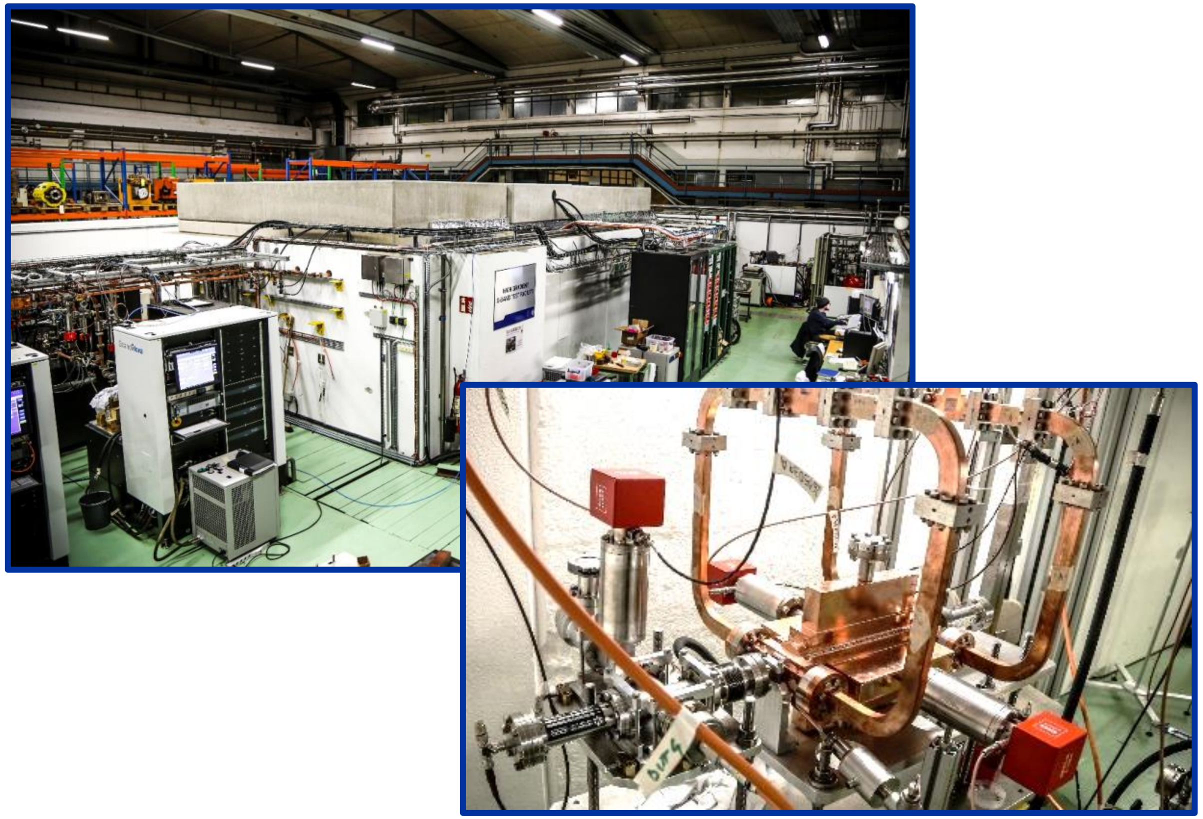


Figure: Exterior of the X-band high gradient test facility (top) and an X-band structure being tested (bottom).

High-Field Conditioning

High-gradient structures (and various other high-field components) cannot operate at this level immediately.

They must first be conditioned. The procedure generally looks something like this:

I. **Increasing gradient/power while keeping constant BDR.**

II. **Drop the power, increase the pulse length (50, 100, 150, 200ns) and ramp back up.**

III. **Finally, the BDR drops. Stable operation is achieved.**

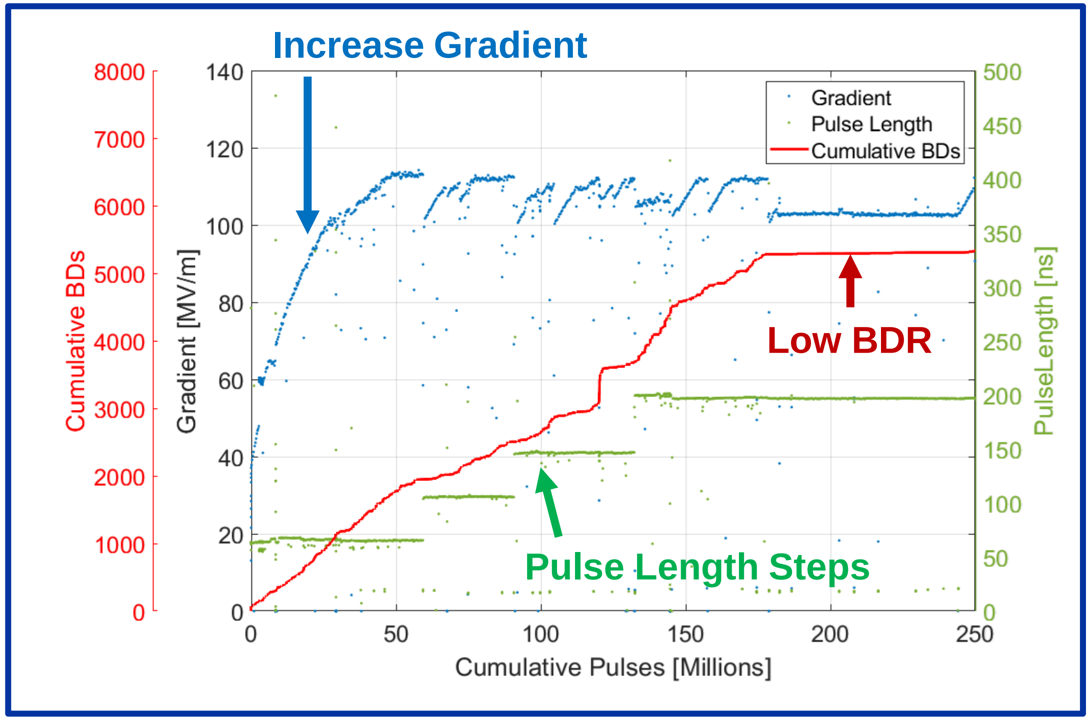
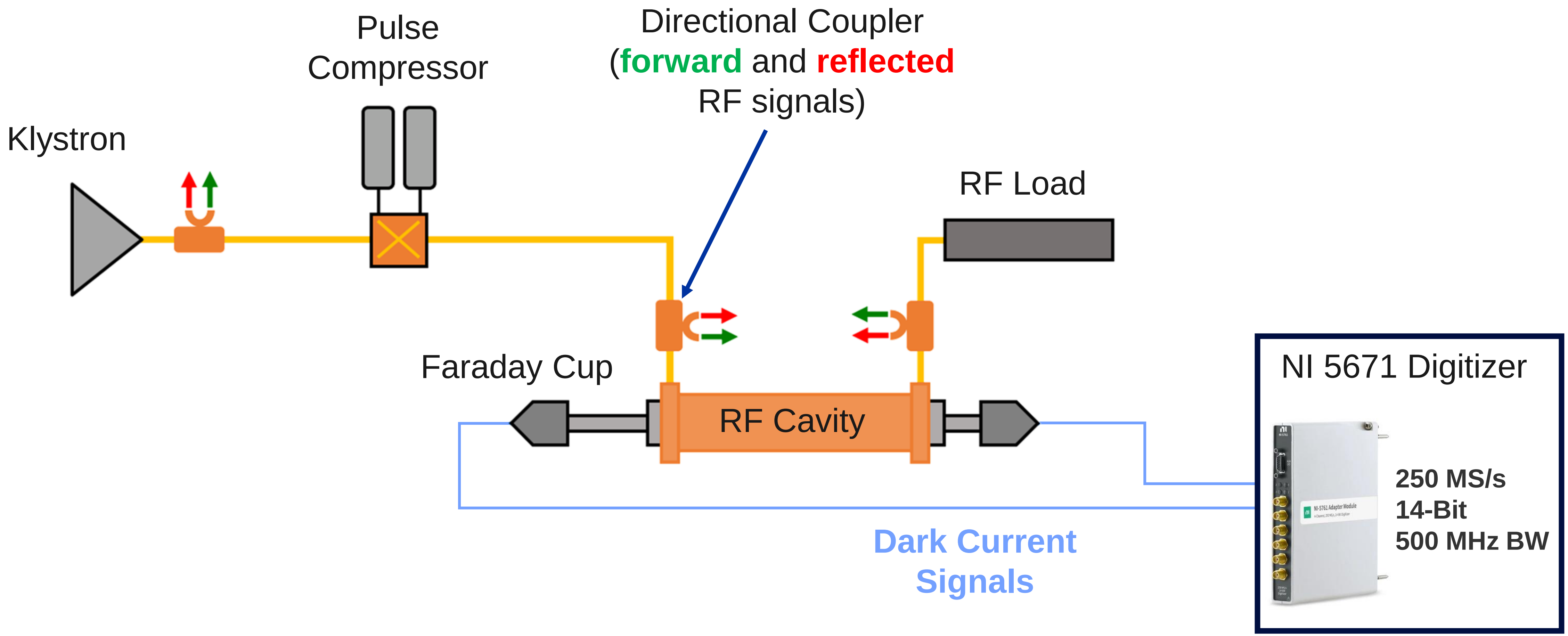


Figure: Typical conditioning procedure for a CERN accelerator cavity.

X-Band Test Stand Setup (Simplified)



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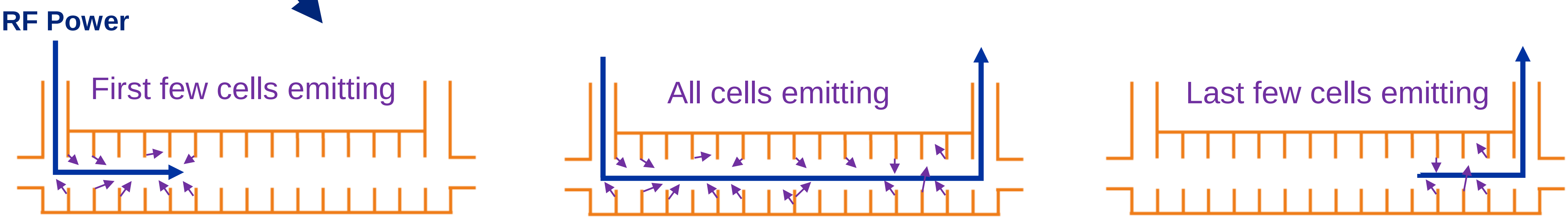
Dark (Field-Emitted) Current in RF Cavities

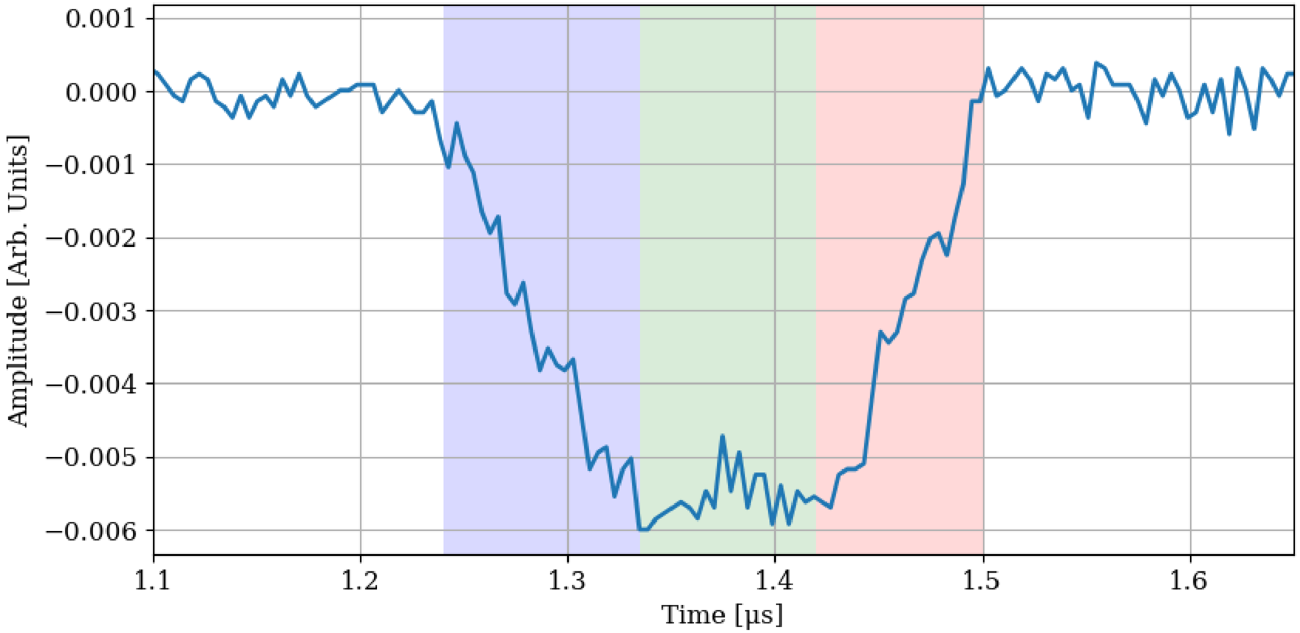
Figure: Cutaway section of a LINAC [6].

Structures fill (and begin to emit) as shown below. All cells are emitting after the structure fill time (~60 ns for CLIC cavities). Other effects (dispersion, electron dynamics) are also at work.



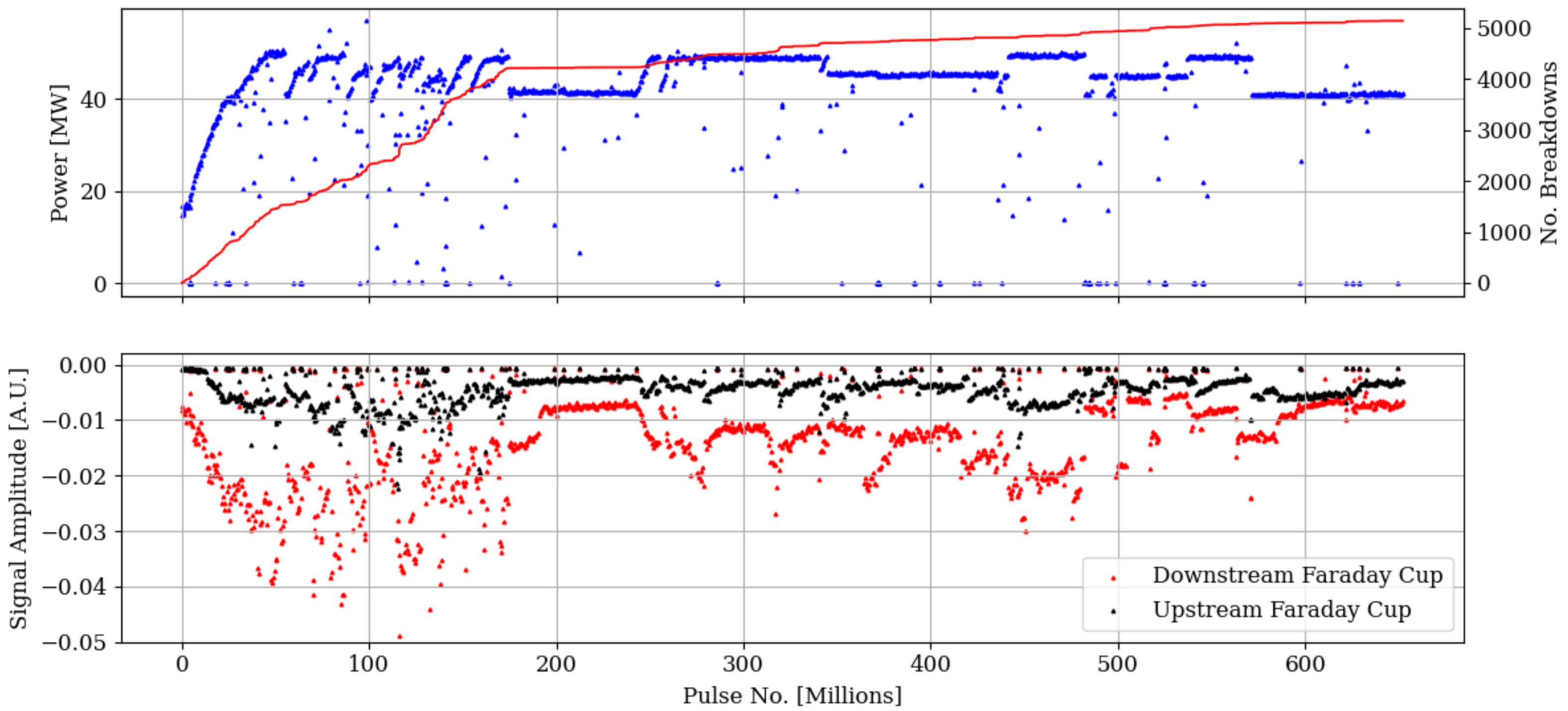
Dark Current in RF Cavities

Structure filling. All cells emitting. Structure emptying.



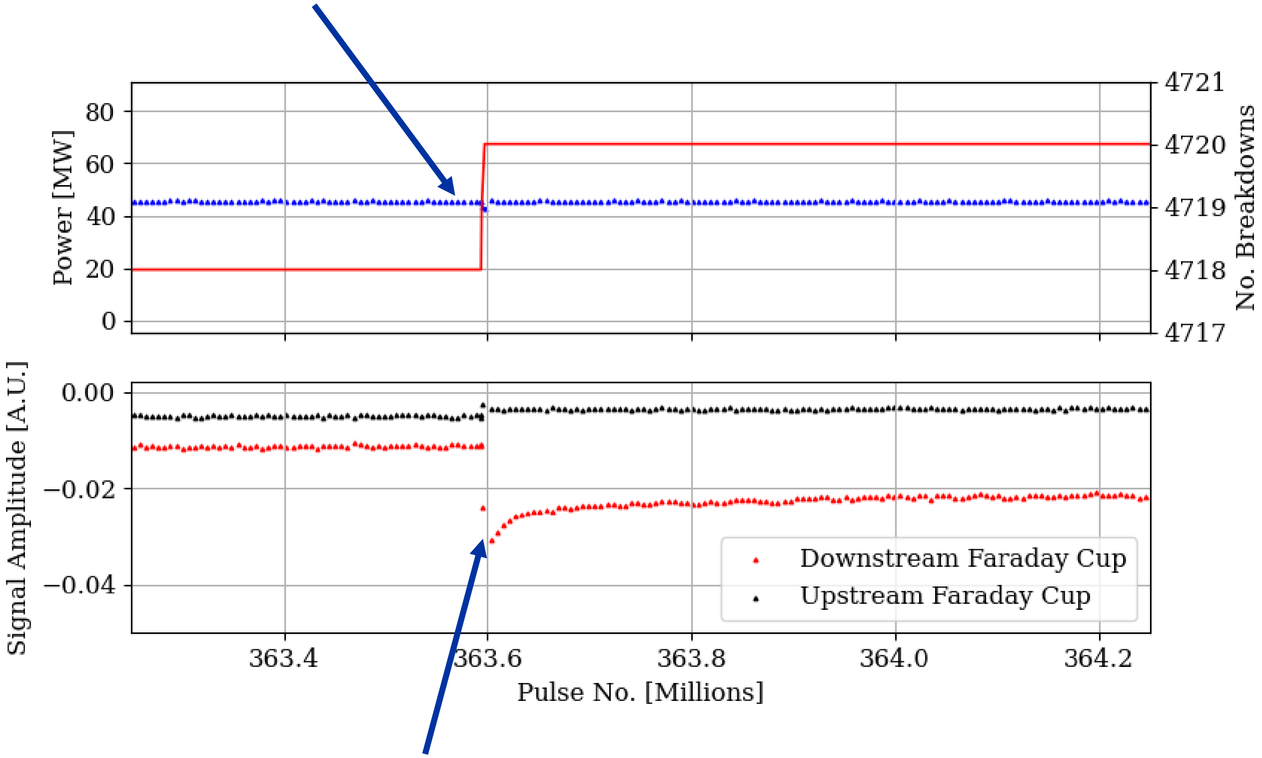
Dark Current Evolution

During conditioning, the emitted current evolves with the occurrence of breakdowns and with conditioning.



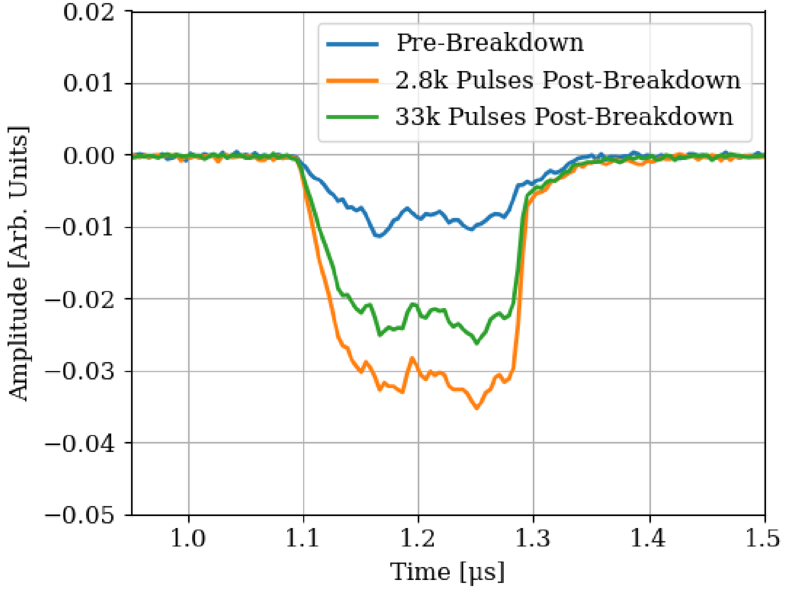
Dark Current Evolution – A Closer Look

Two breakdowns occur.



Faraday cup signal increases, then decays.

Downstream Faraday Cup Signals



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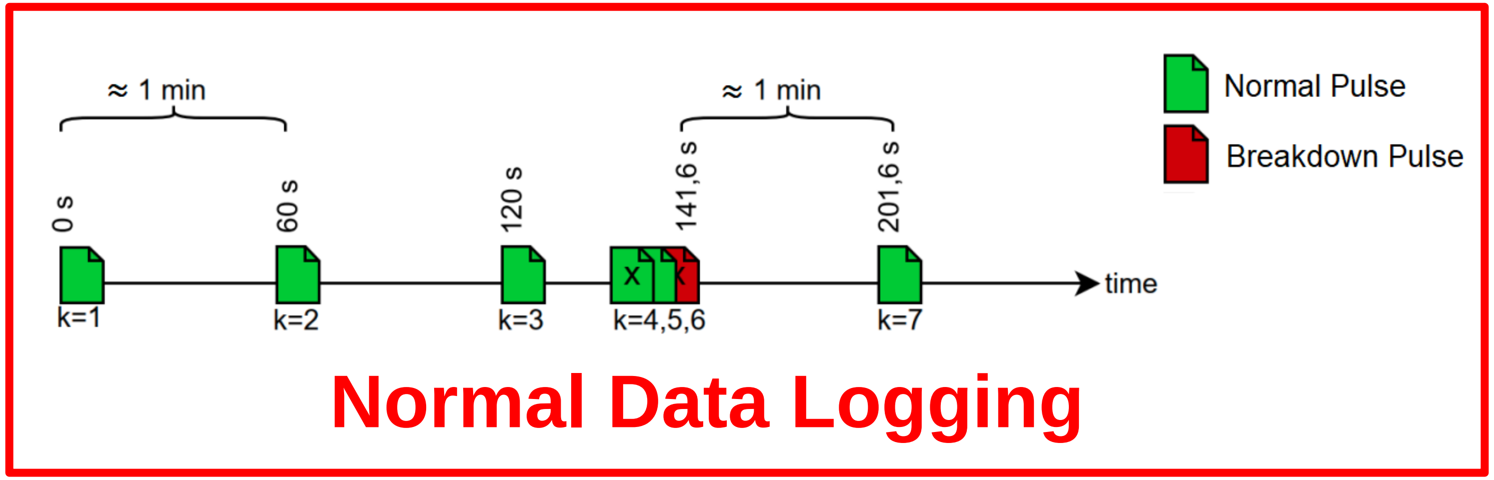
Searching for Rare Events

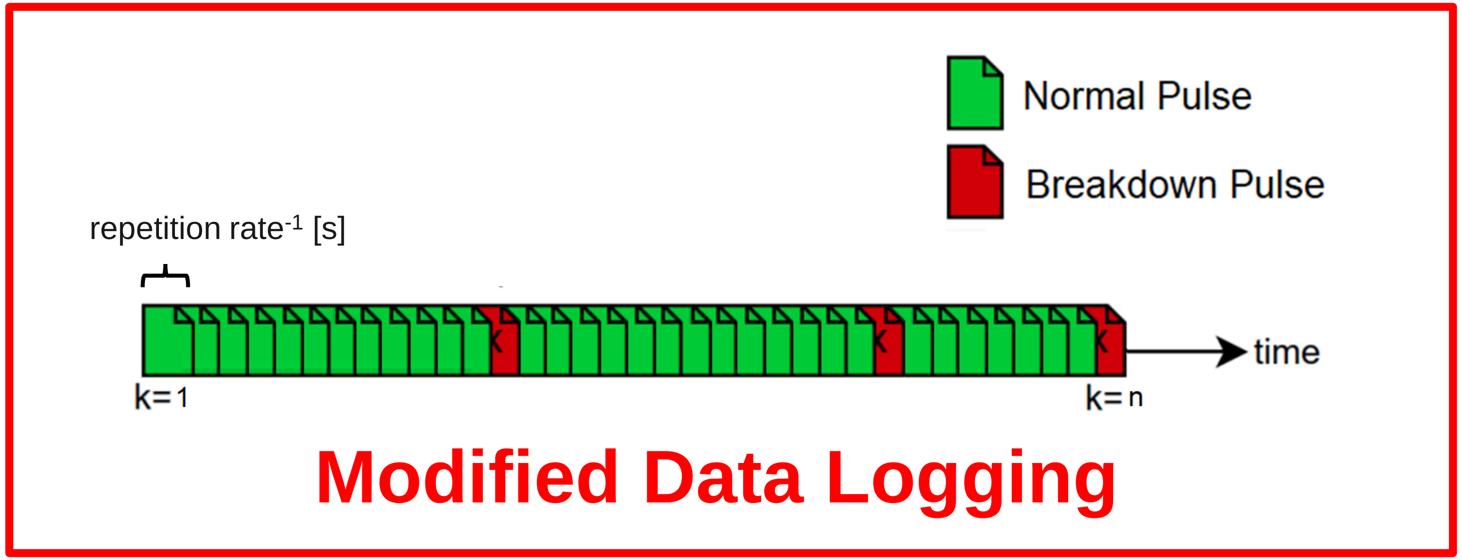
We produce ~0.2 MB of data per RF pulse. At a rep rate of 100 Hz this equates to 1.728 TB per day for a single structure! Not feasible to store it all.

Instead, we store one pulse per minute, breakdowns, and the two pulses preceding breakdowns. Typically results ~0.5 GB per day for a single structure.

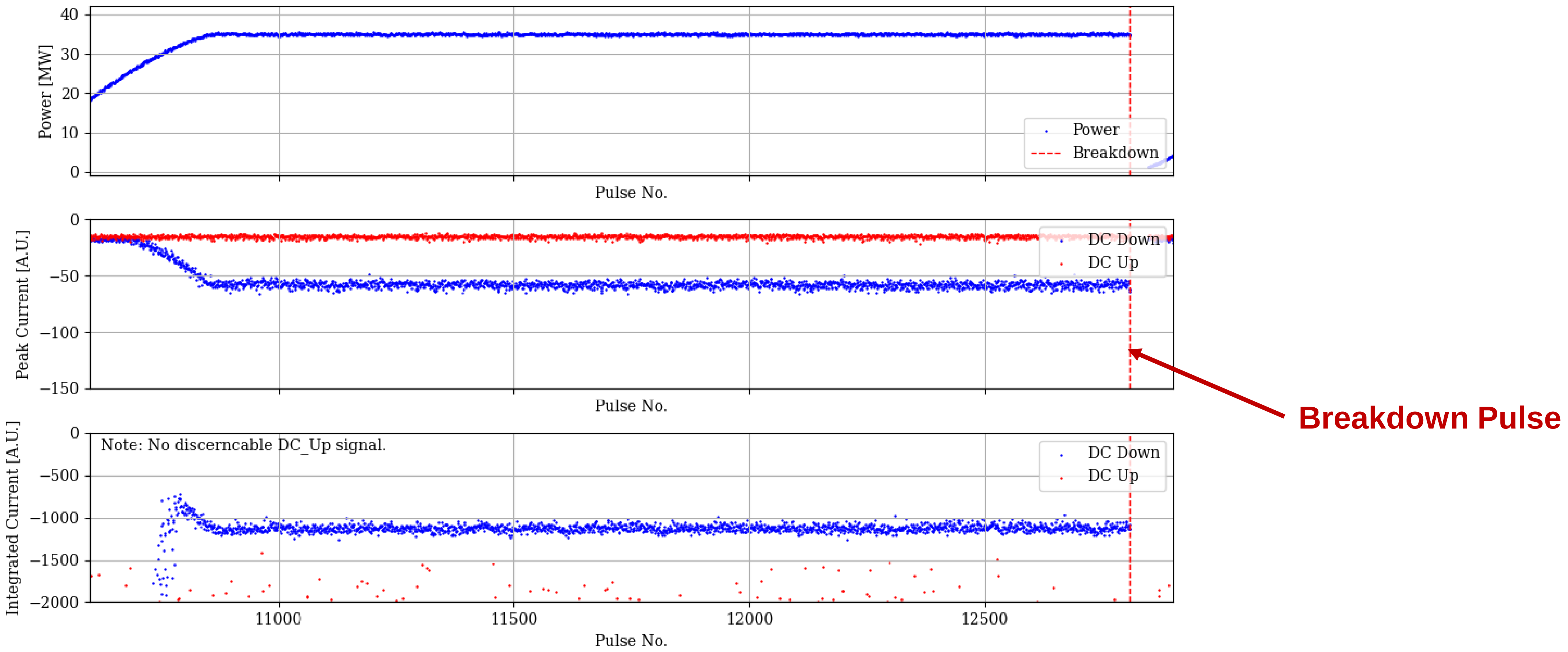


Searching for Rare Events

For this study, the acquisition system was modified to log every pulse ➔ We can monitor for changes in the lead up to breakdowns on a pulse-to-pulse basis. Repetition rate limited to ~5 Hz.



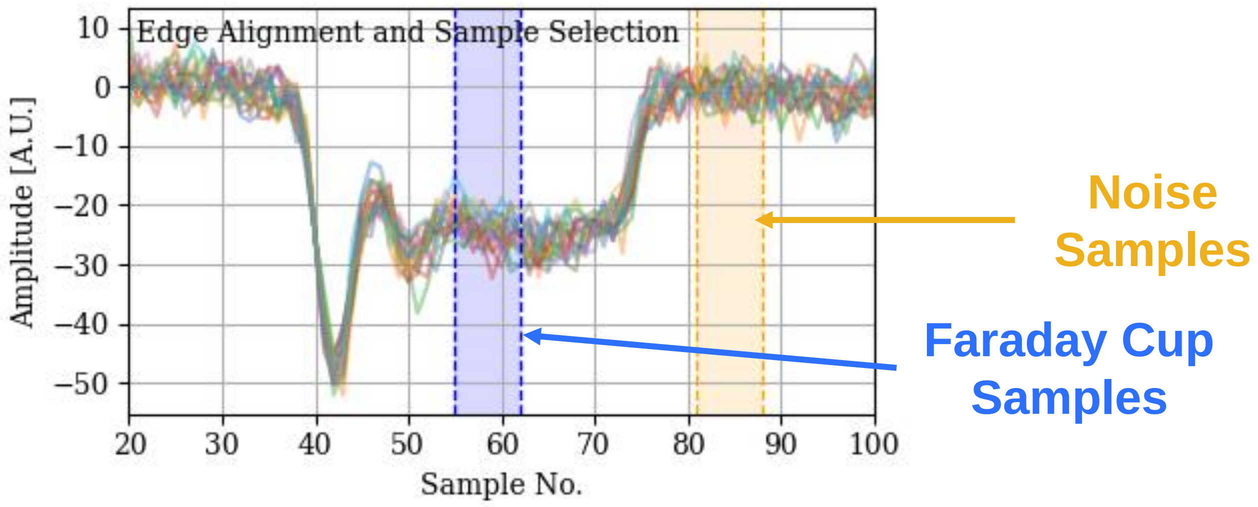
Pulse-to-Pulse Conditioning

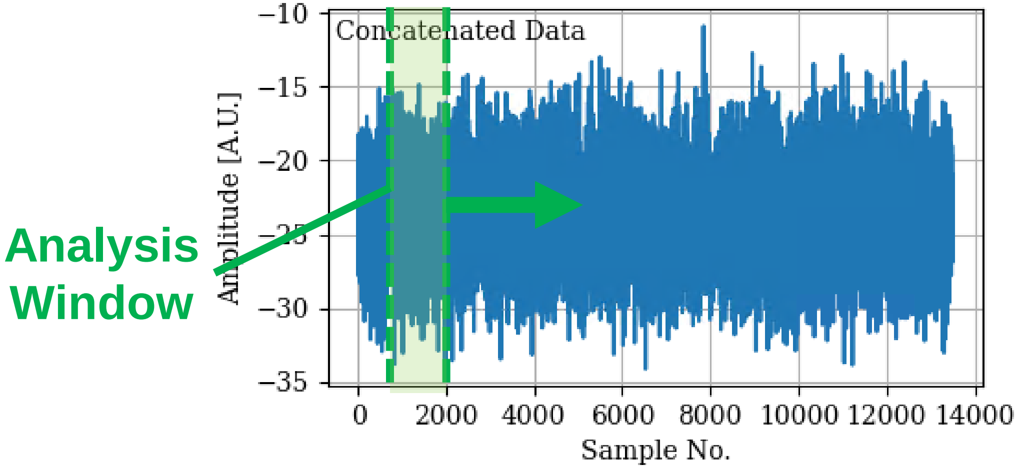


Dark Current Evolution

The Faraday cup signals are also logged for every pulse.

- **Samples corresponding to when the structure is full of RF power (all cells emitting) are taken and concatenated.**
- **Properties may then be monitored leading up to, and following, breakdown events.**
- **RF signals also monitored to ensure changes are not attributed to drift/noise in input power.**



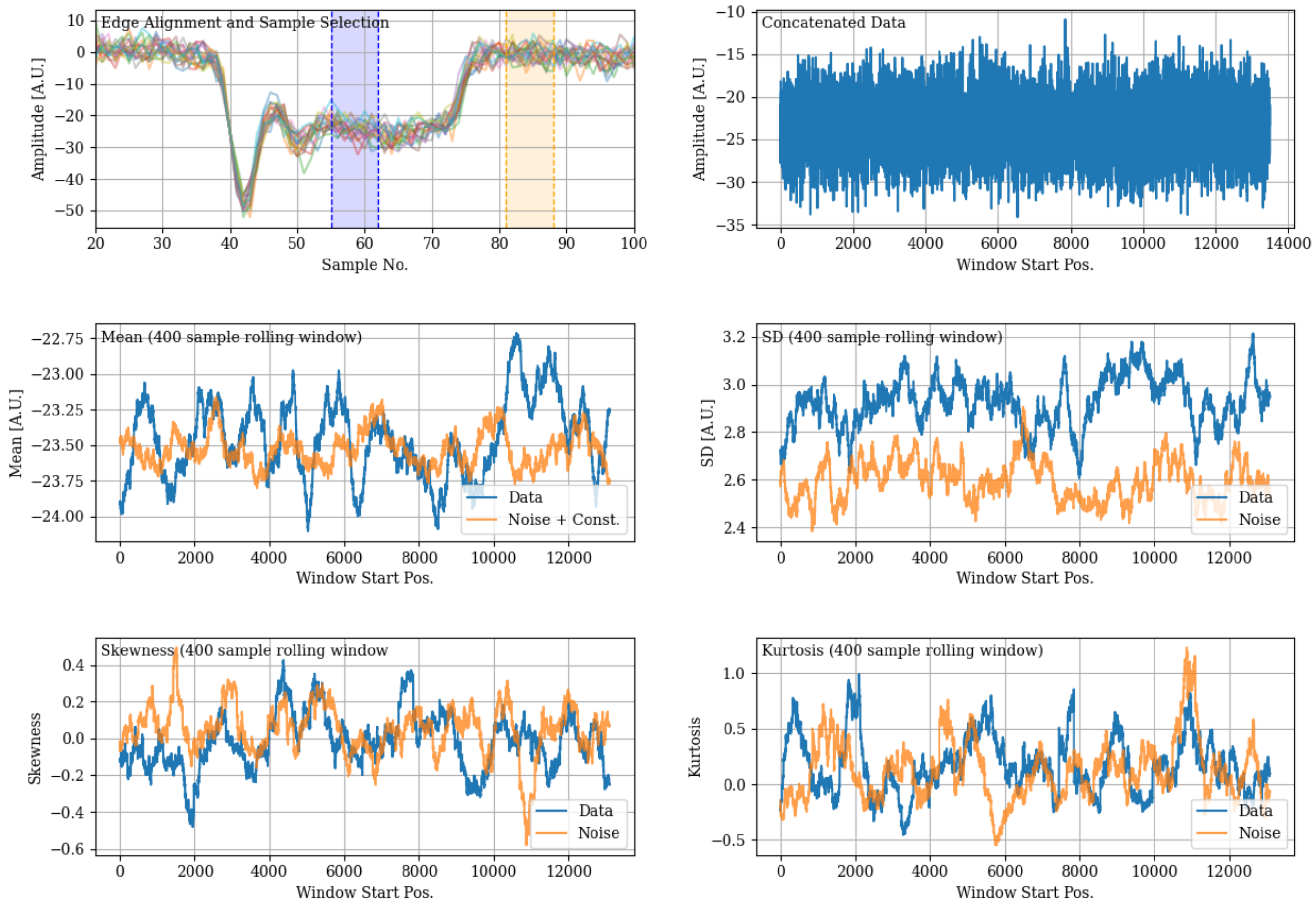


Dark Current Evolution

Analysis ongoing, but no new phenomena observed during preliminary checks ☹.

However, there is still more work to be done:

- **The biggest issue – limited and non-ideal data (only a few breakdowns at short pulse length and low voltage).**
- **Data to be taken and compared at different operating voltages (lower voltage = longer time spent waiting for breakdowns).**



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Conclusions

The field emitted current in RF cavities evolves during operation, even in the absence of breakdowns. A framework has been developed to log and monitor this current on a pulse-to-pulse basis:

- **Preliminary measurements were performed and used to develop/trial the methodology.**
- **No new phenomena observed in this data. However, the measurement conditions were sub-optimal (short pulse, low field).**
- **CERN's test facility is now online again after a pause in operation. Discussions are also underway with University of Valencia (Thanks to Marçà) about taking data with their high-power test facility (high SNR, very RF long pulse, ideal for this work).**

Outlook → let the search continue!

Thank you. Questions?

References

[1] – Roy A. Ready, et al., “*Surface processing and discharge-conditioning of high voltage electrodes for the Ra EDM experiment,”* Nuclear Instruments and Methods in Physics Research Section A, Volume 1014,165738, **DOI: https://doi.org/10.1016/j.nima.2021.165738.**

[2] – T. Patton et al., "*Characterization of the breakdown voltage of vacuum interrupters by different procedures*," 2020 29th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), Padova, Italy, 2021, pp. 350-354, **DOI: https://doi.org/10.1109/ISDEIV46977.2021.9587022**.

[3] – E. Engelberg et al. "Theory of electric field breakdown nucleation due to mobile dislocations" Phys. Rev AB, 22 (2019) 083501, **DOI:https://doi.org/10.1103/PhysRevAccelBeams.22.083501**

[4] - https://indico.cern.ch/event/917715/contributions/3857193

[5] - D. Banon Caballero et al., “Dark Current Analysis at CERN’s X-Band Facility”, proceedings of the 10th Int. Particle Accelerator Conf (IPAC2019) pp. 2944-2947, **DOI:**10.18429/JACoW-IPAC2019-WEPRB059

[6] – Exhibit in the National Museum of American History, Washington, DC, USA. Photography was permitted in the museum without restriction, URL: https://commons.wikimedia.org/wiki/File:Linear_accelerator_%28cutaway_secti

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