Predicting Secondary RF Breakdowns

David Jakeman

Email: David.Jakeman@stfc.ac.uk

Introduction - T24 PSI Structure

a. Upstream Faraday Cup

b. Ion Pump

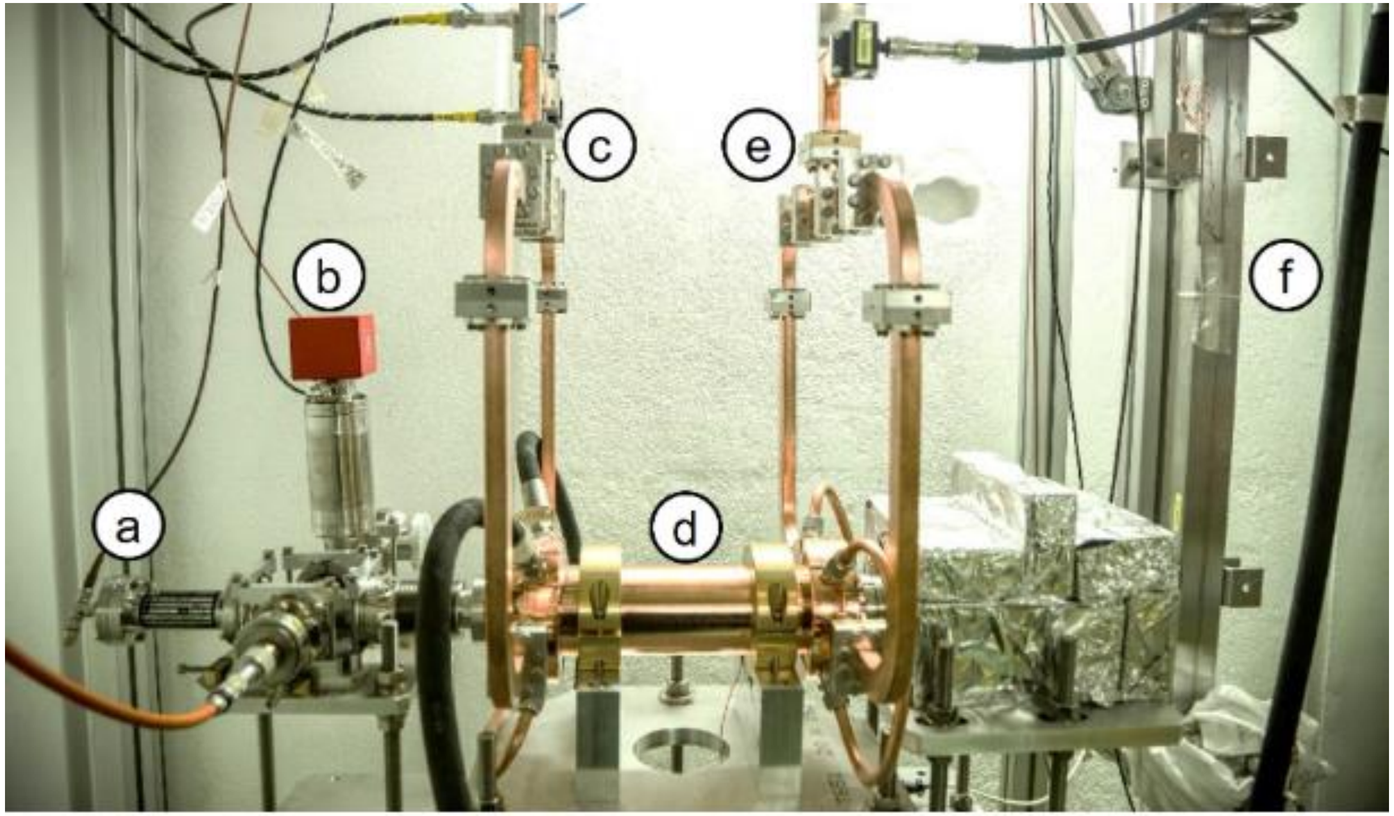
c. RF Input

d. RF Cavity

e. Cavity Waveguide Manifold

f. RF Load

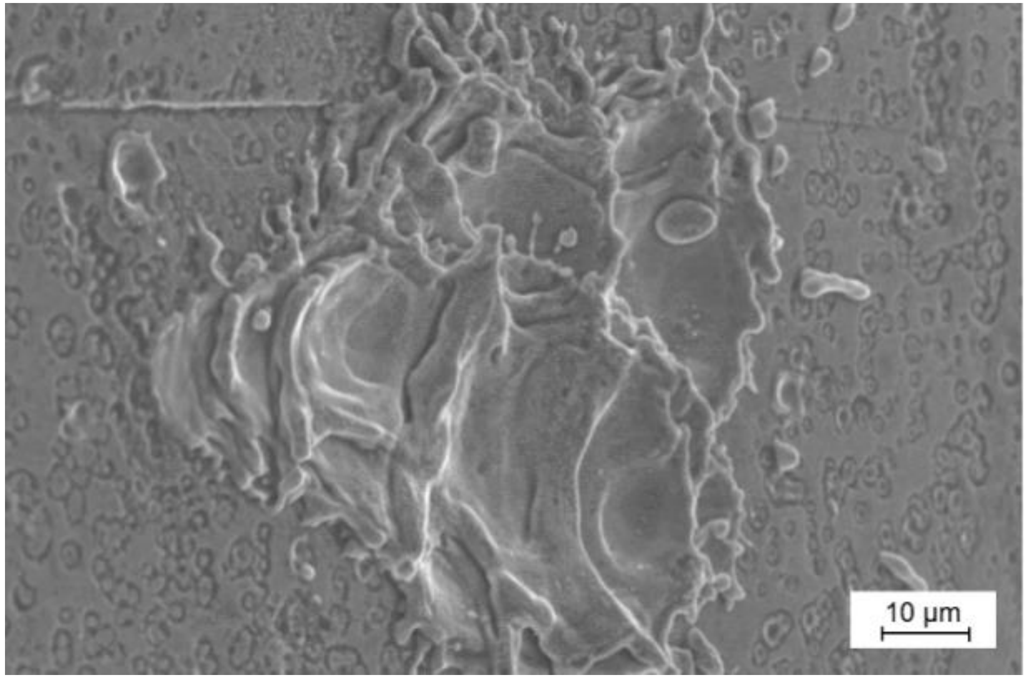
Note: Downstream Faraday Cup in Lead Shielding



Picture from: [3]

Effects of Breakdowns

- **Plasma degrades the beam.**
- **Limits the power that can be applied to RF cavity.**
- **Causes damage to the cavity.**

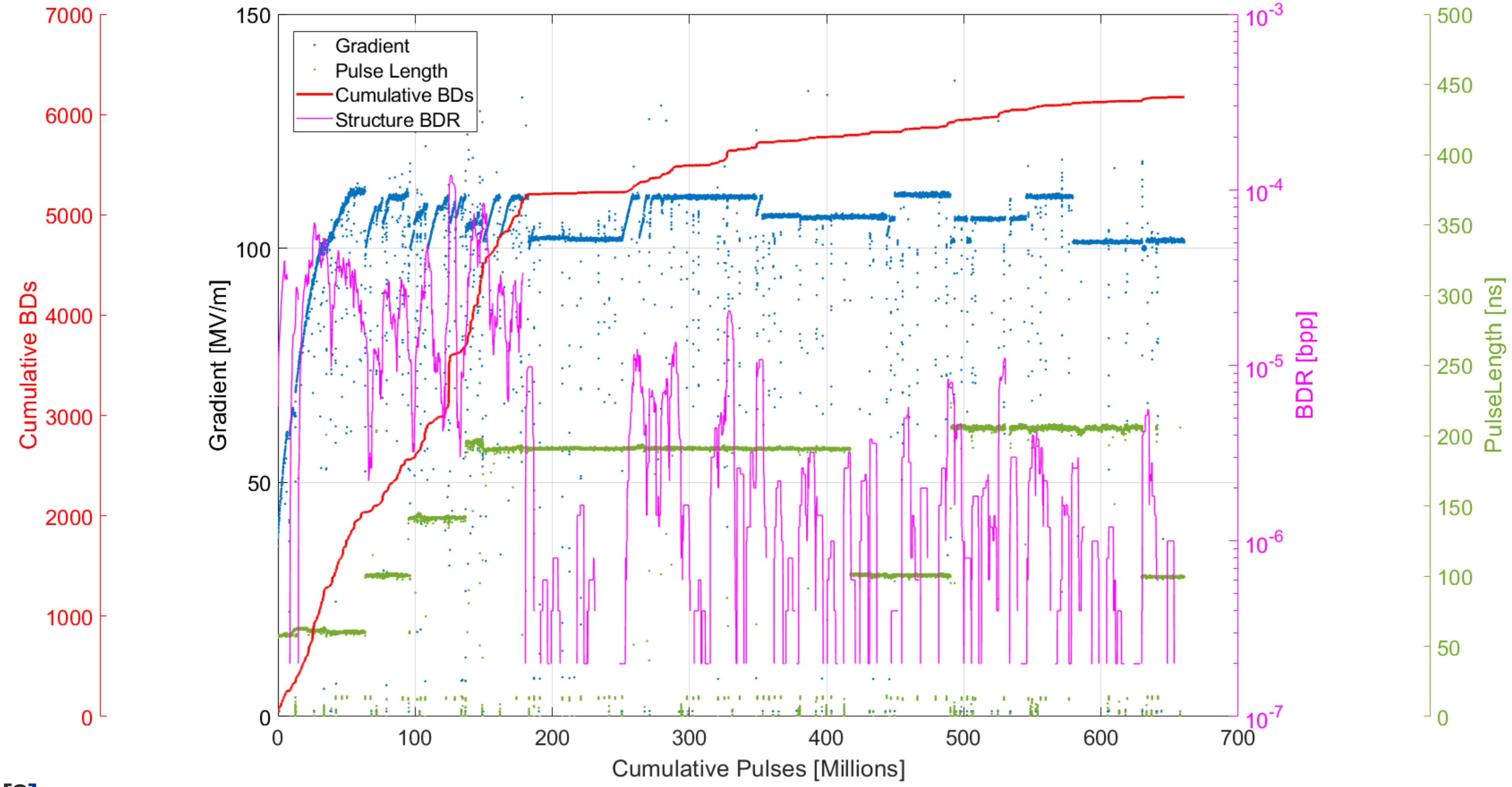


Picture from: [3]

Advantages of Predicting Breakdowns

- **We can begin to investigate preventative measures – can we stop breakdowns occurring?**
- **We can use the predictions to improve beam reliability (Could we de-phase arcing cavities? i.e temporarily make cavity invisible to the beam)**
- **We can progress our understanding of breakdowns.**

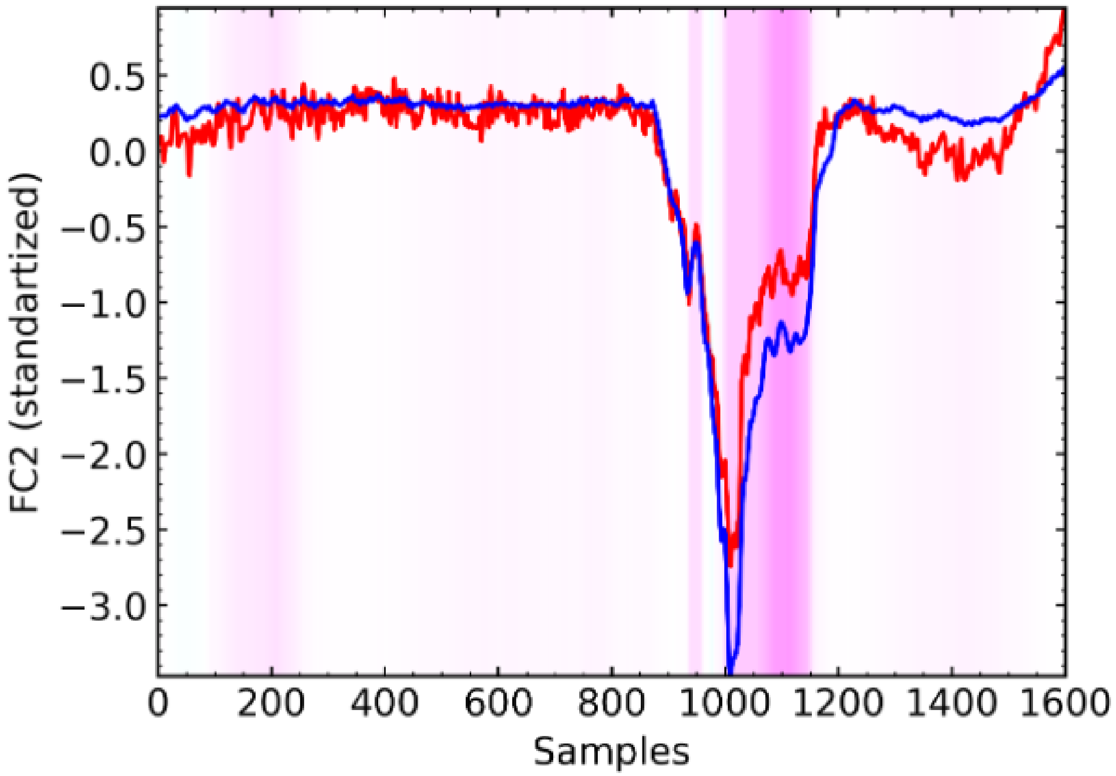
T24 PSI2 Conditioning History in XBOX-2



Picture from: [3]

Introduction – Machine Learning

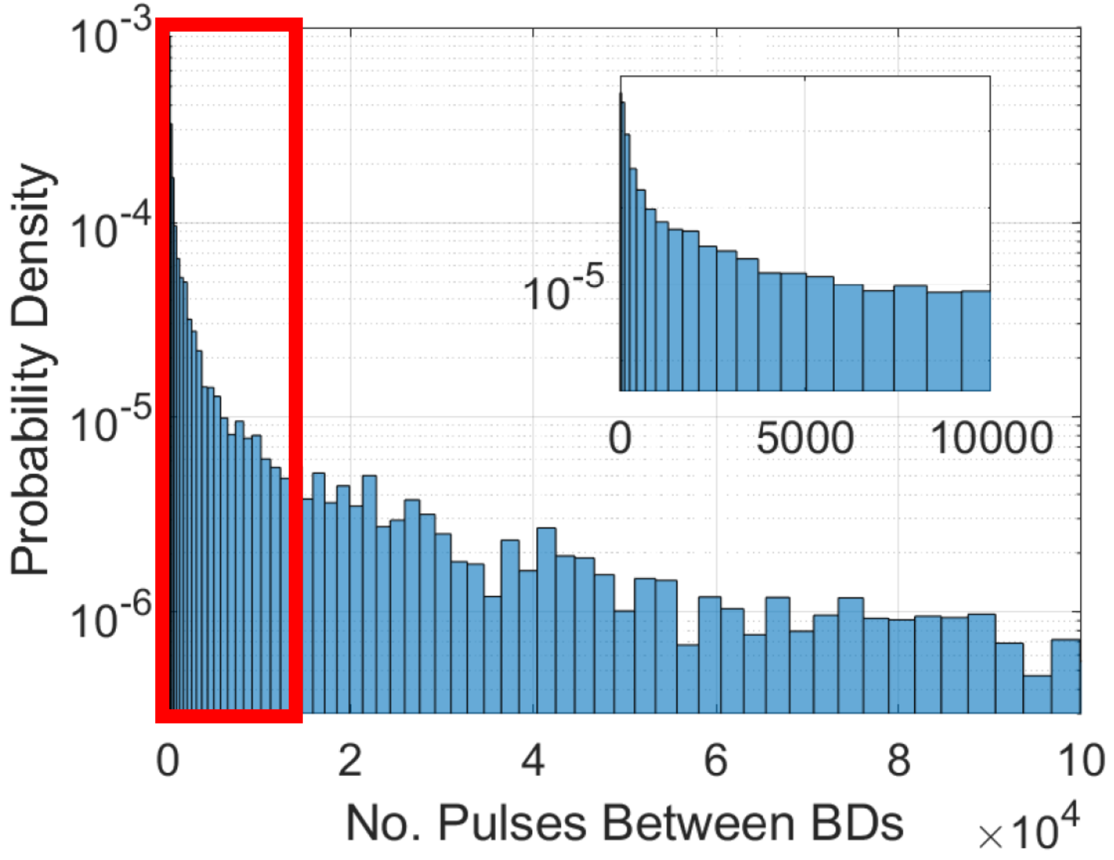
- **Machine Learning Study was conducted in 2020/2021**
- Machine Learning algorithm could predict secondary breakdowns ~95% of the time.
- **Predictions could be made using Faraday Cup Signals or the Pressure readings**.
- Highlighted region was particularly important in predicting an RF breakdown [3]
- There is a need to determine how the ML made these predictions.



Picture from: [3]

Distribution of Breakdowns

Follow-Up Breakdowns predicted my ML



Picture from: [4]

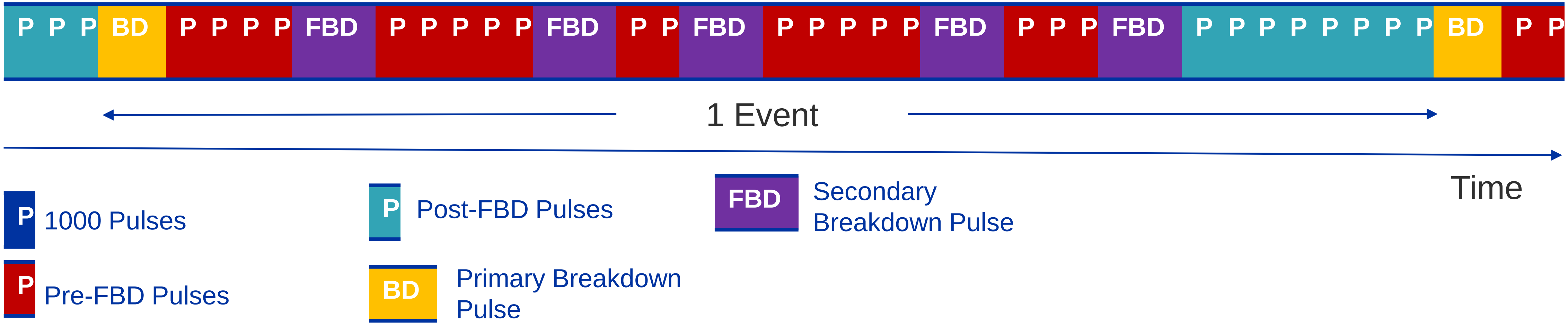
Nomenclature

- **P - Pulse**
  - One cycle of the RF signal on the RF applied to the structure
- **BD – Primary Breakdown**
  - Breakdown occurs > 6000 pulses after previous breakdown
- **FBD – Follow-Up / Secondary Breakdown**
  - Breakdown occurs < 6000 pulses after previous breakdown [2]

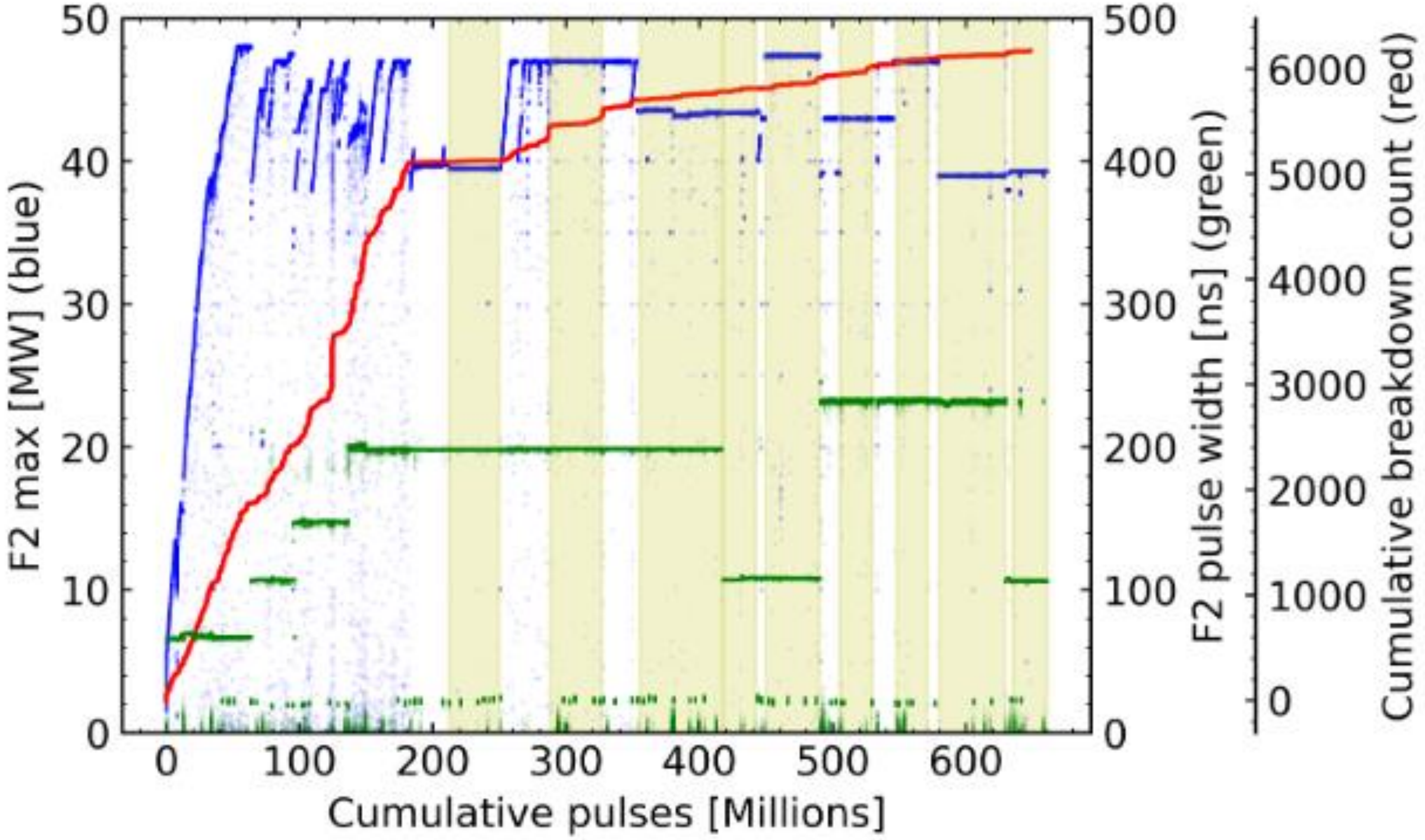
Nomenclature

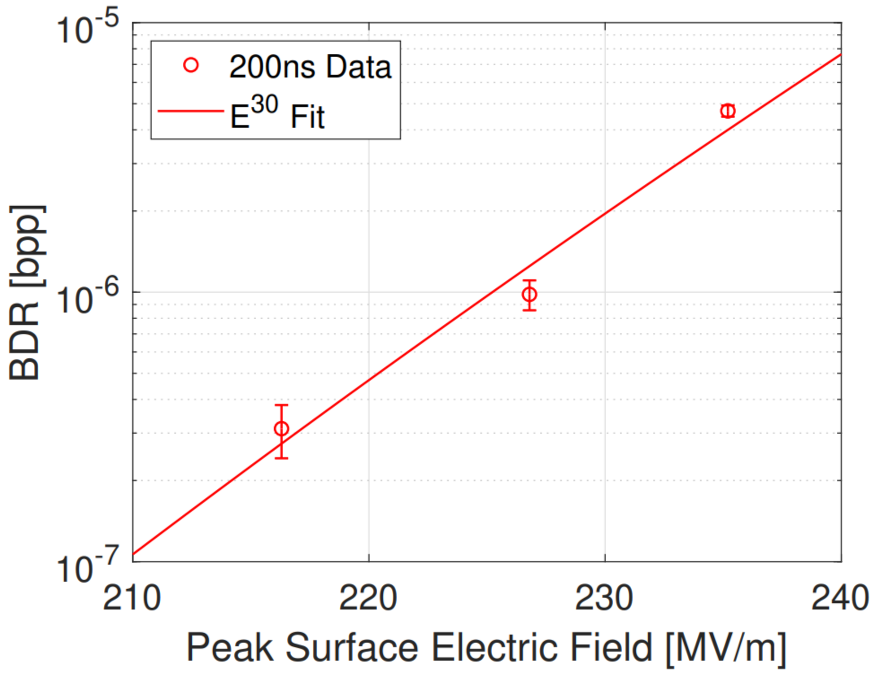
- **Pre-FBD Pulse**
  - RF pulses that occur between FBD’s
- **Post-FBD Pulse**
  - RF pulses that occur between last FBD and the next BD – when the system is running “stably”.
- **Event**
  - Everything associated with a primary breakdown

Working Example



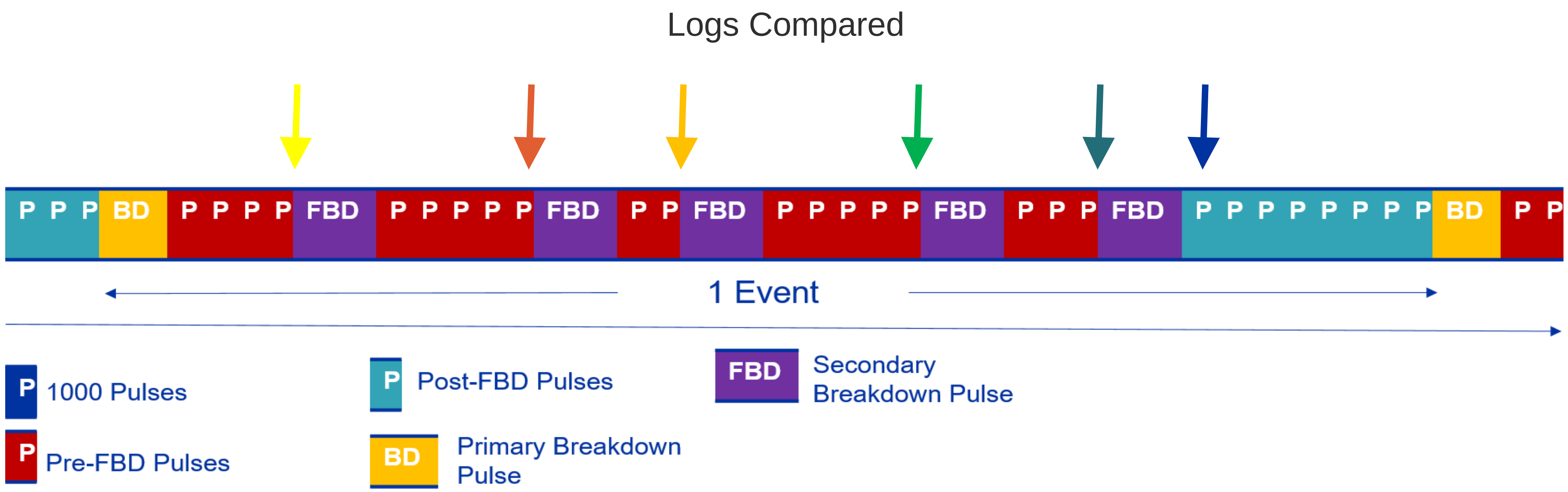
Data Collection





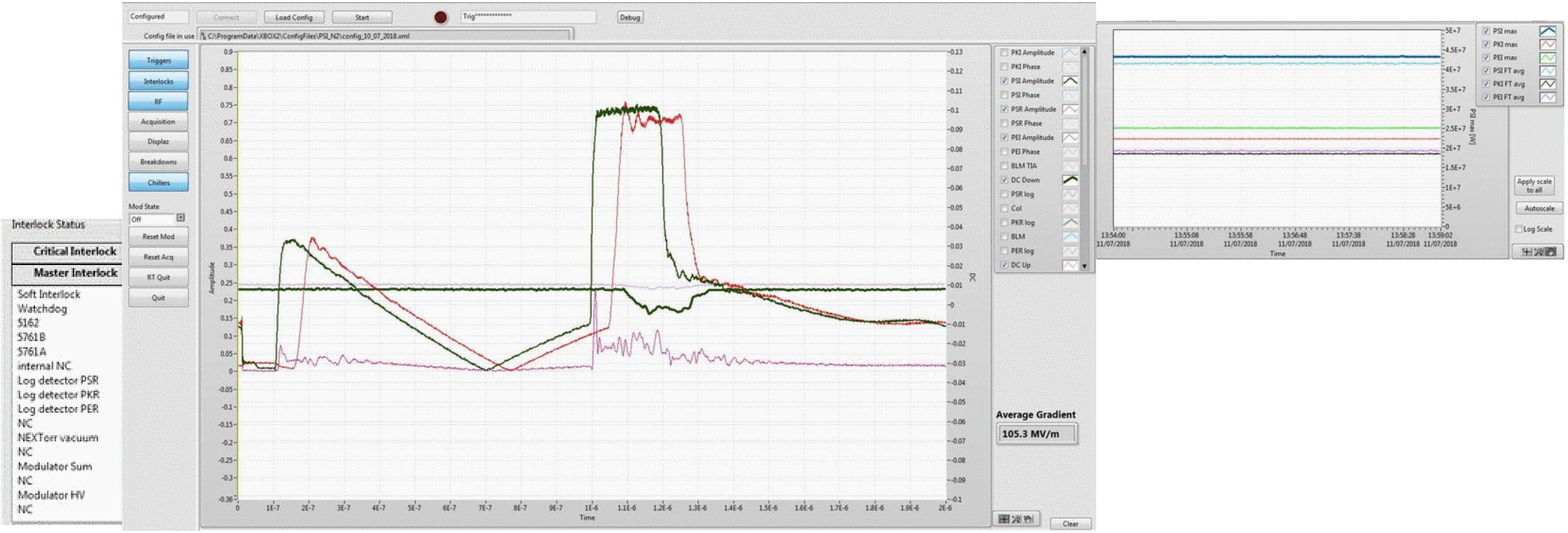
Pictures from: [3] and [4]

Hypothesis 1: Higher Field Emission = Higher Probability of Breakdown



Test Stand Operation

- If a breakdown occurs, the test stand interlocks the power to 0 MW and ramps the power back up.



Picture from: [4]

Hypothesis 1: Higher Field Emission = Higher Probability of Breakdown

- **In order to be able to compare the logs, scaling of the logs is needed to account for the change in input power.**

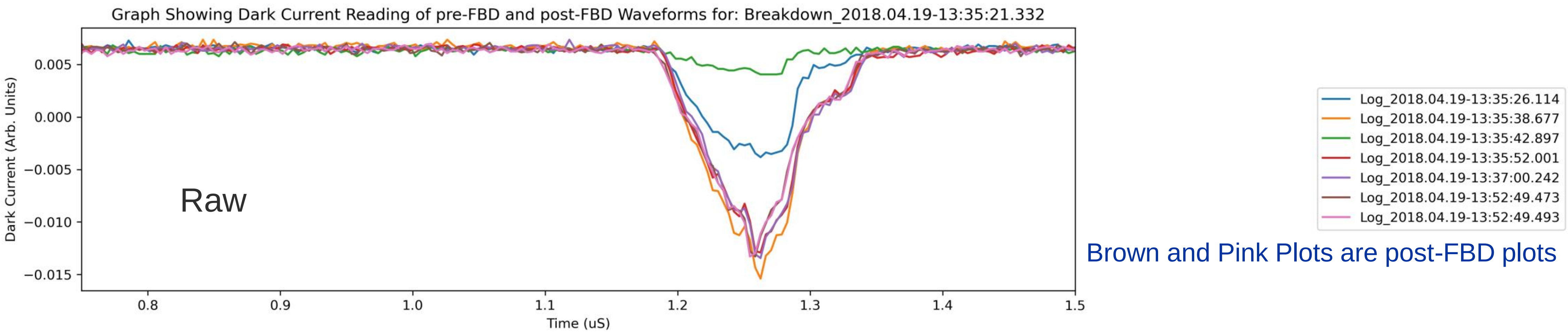
- **Therefore, the Faraday Cup signals have been scale using the Fowler-Nordheim equation:**

$$\bar{I}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\varphi^{-0.5}} A_e(\beta E_0)^{2.5}}{\varphi^{1.75}} \, exp\left(-\frac{6.53 \times 10^{9} \times \varphi^{1.5}}{\beta E_0}\right)$$

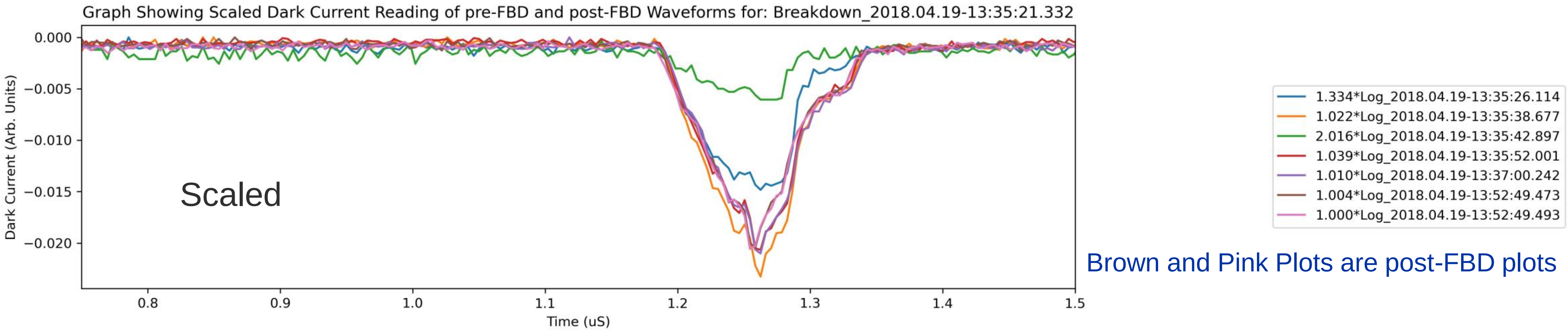
Please note: This scaling is not perfect – Capture and Transport phenomena makes scaling more complicated

- **We are examining the amplitude of the preceding dark current signal as an indicator.**

Hypothesis 1: Higher Field Emission = Higher Probability of Breakdown

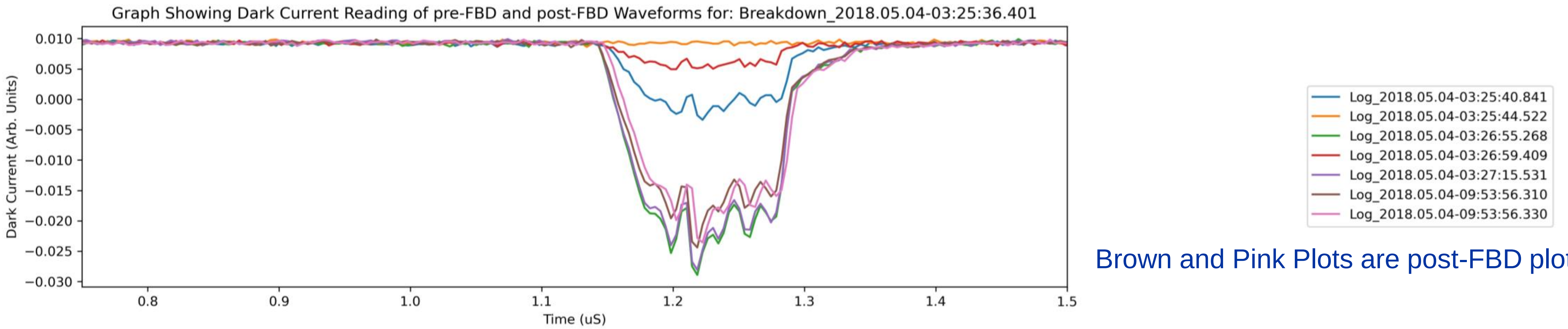


Brown and Pink Plots are post-FBD plots

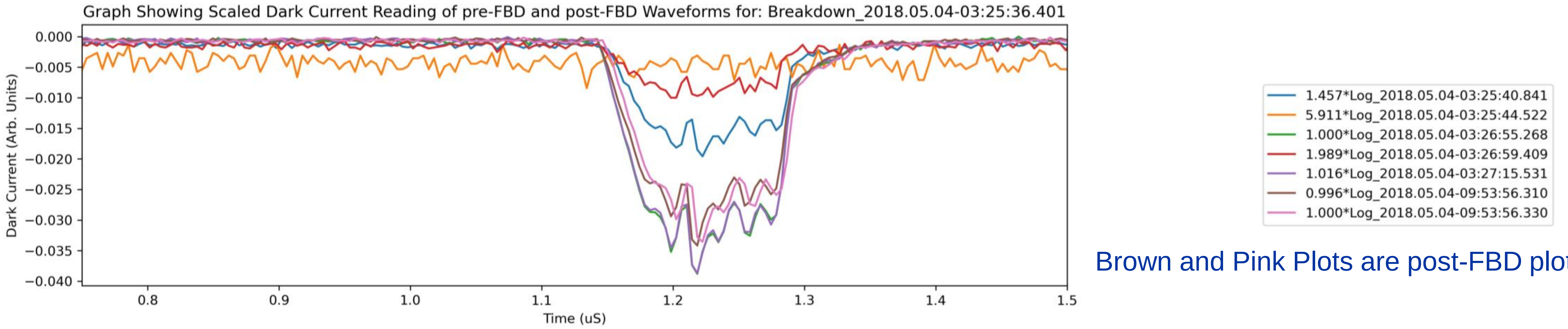


Brown and Pink Plots are post-FBD plots

Hypothesis 1: Higher Field Emission = Higher Probability of Breakdown

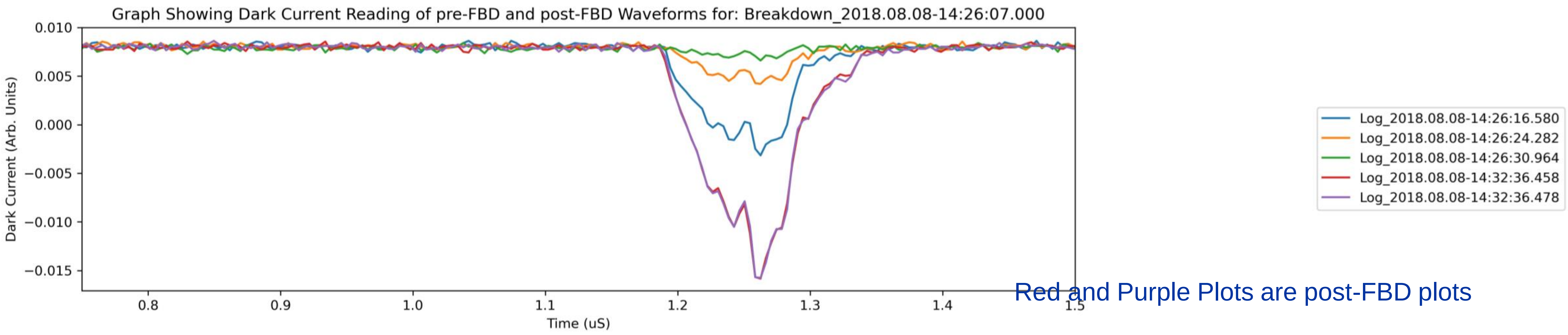


Brown and Pink Plots are post-FBD plots

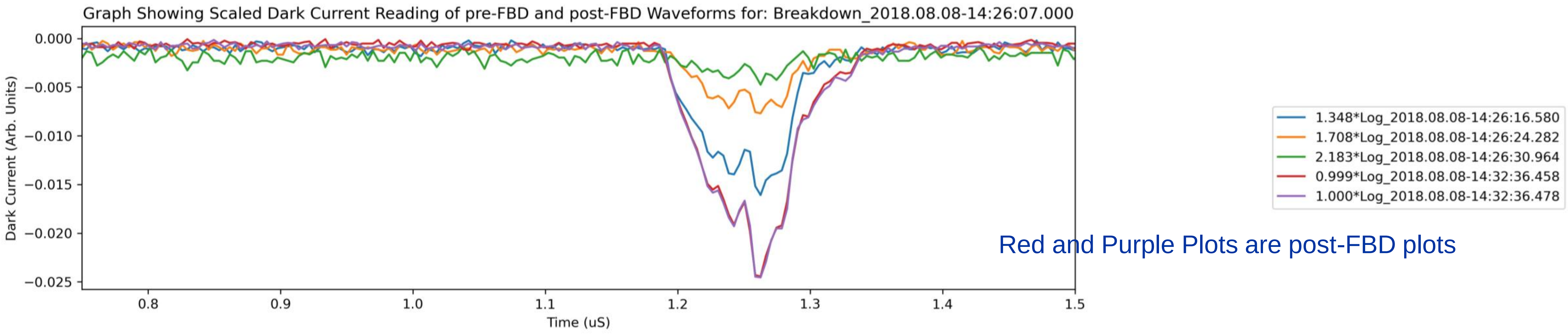


Brown and Pink Plots are post-FBD plots

Hypothesis 1: Higher Field Emission = Higher Probability of Breakdown



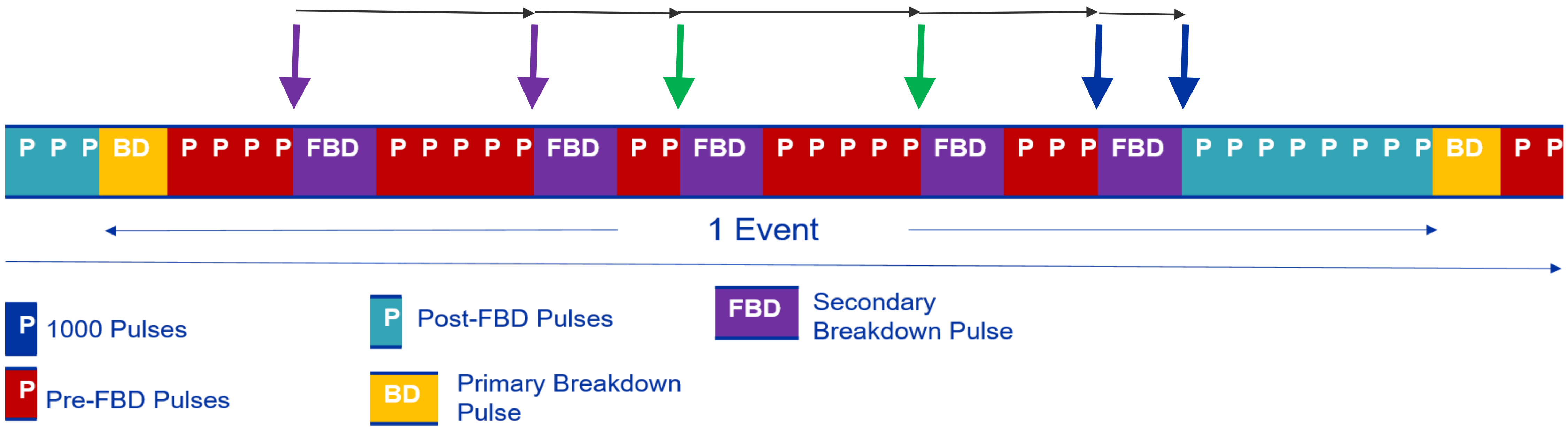
Red and Purple Plots are post-FBD plots



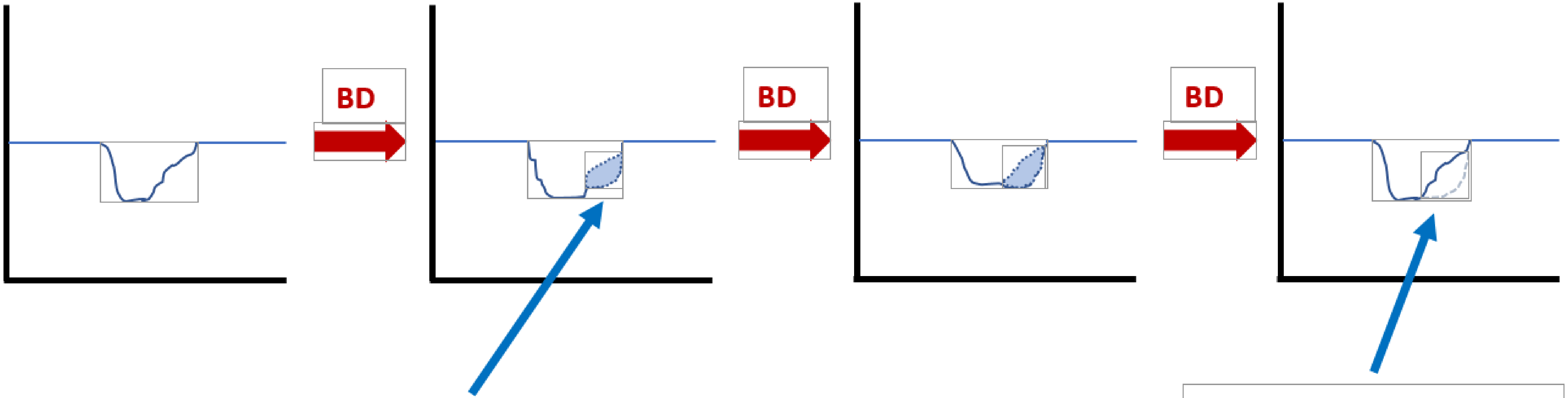
Red and Purple Plots are post-FBD plots

Hypothesis 2: Specific Emission Site Distributions are More Likely to Result in Breakdowns

How does preceding log signal change?



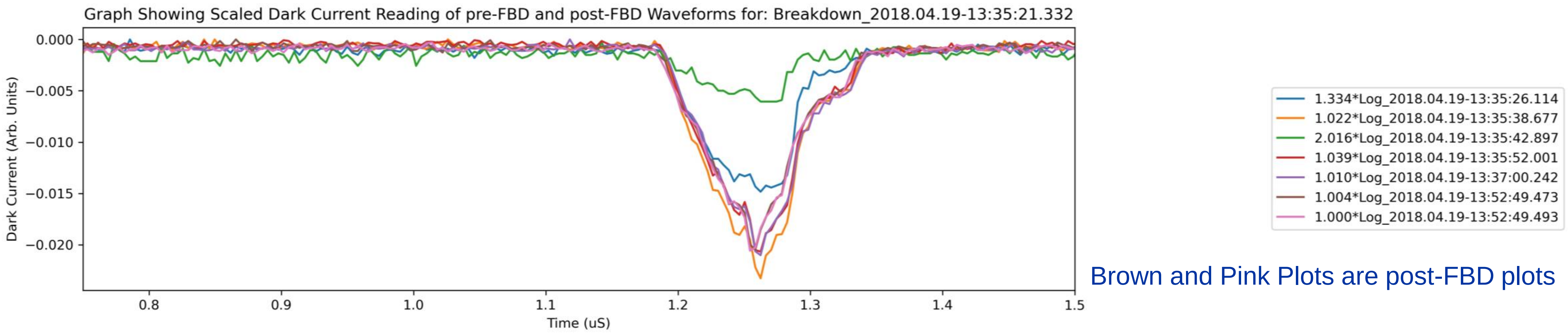
An Illustrative Example: Signal Evolution



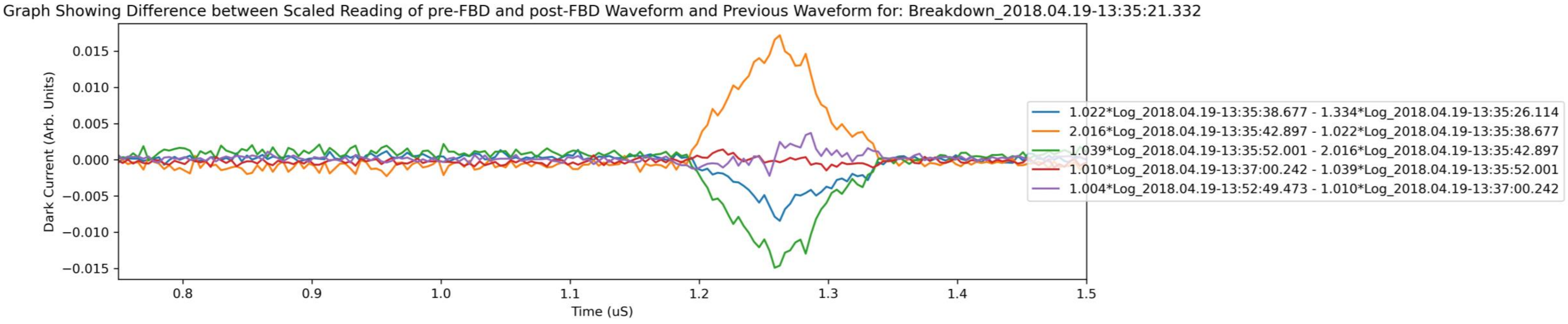
BD results in significantly more emission at the structure output. Changes integral somewhat, not the peak amplitude.

Emission site(s) removed again after several BDs. Integral reduced again.

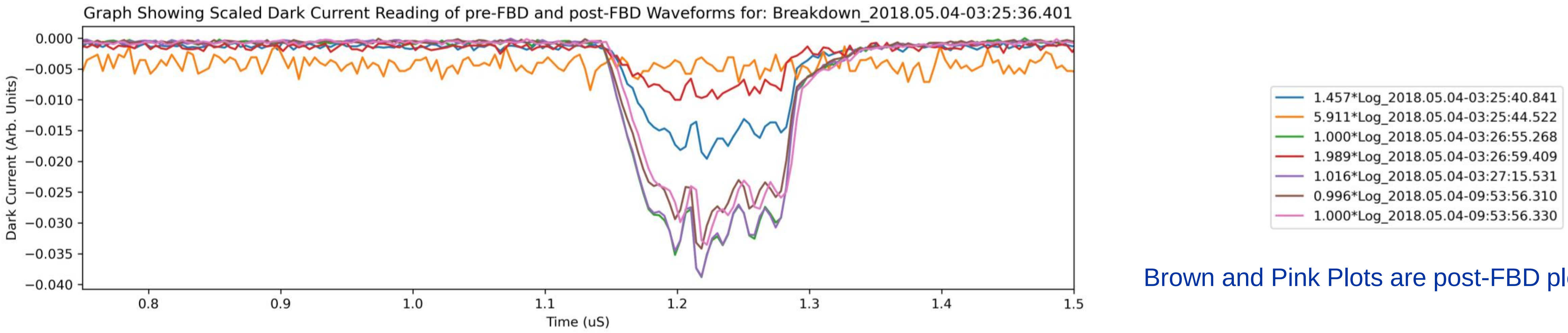
Hypothesis 2: Specific Emission Site Distributions are More Likely to Result in Breakdowns



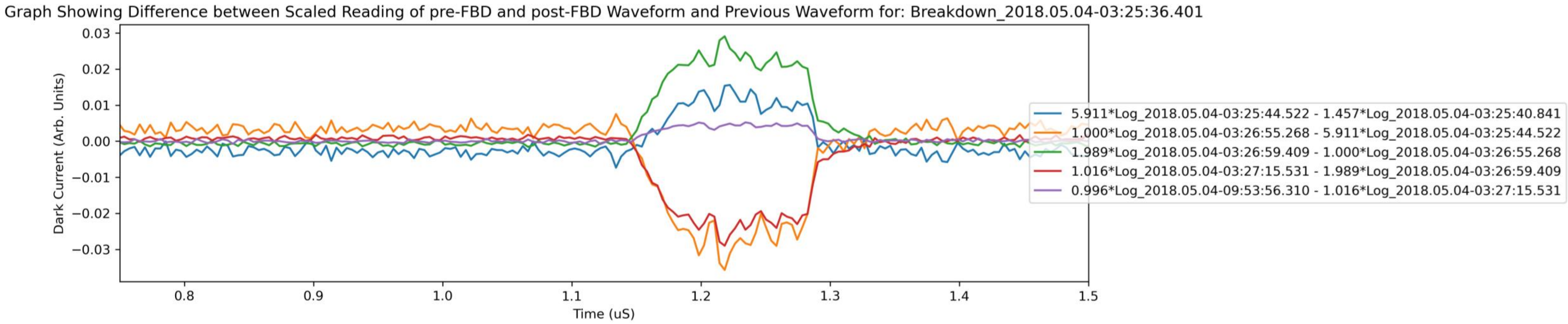
Brown and Pink Plots are post-FBD plots



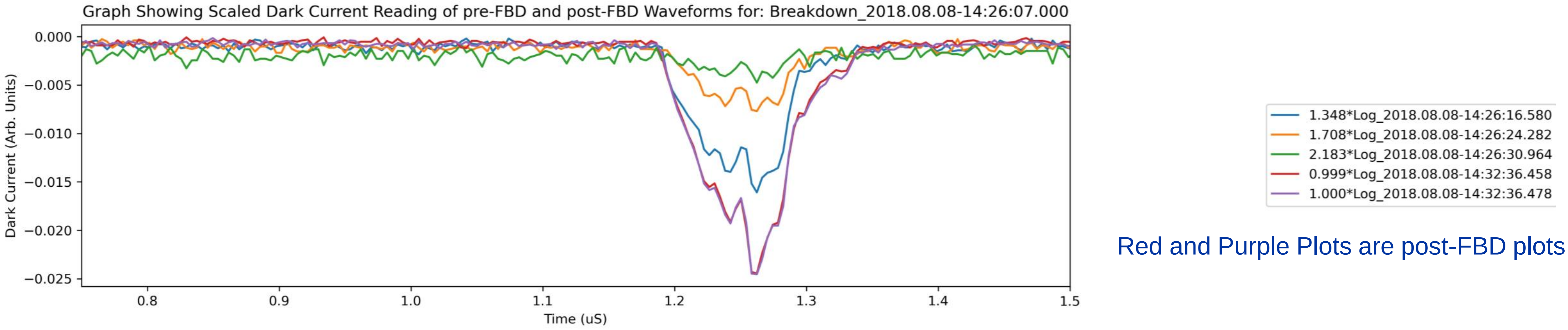
Hypothesis 2: Specific Emission Site Distributions are More Likely to Result in Breakdowns



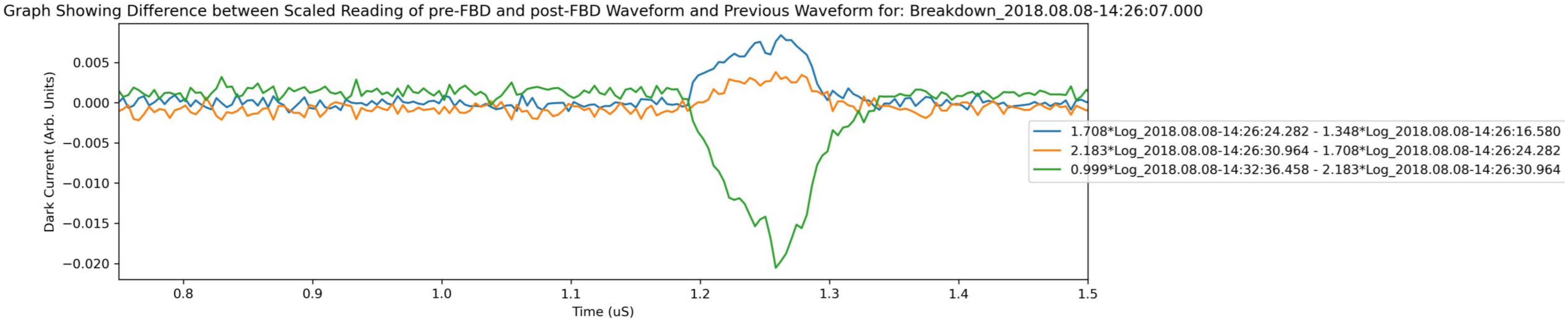
Brown and Pink Plots are post-FBD plots



Hypothesis 2: Specific Emission Site Distributions are More Likely to Result in Breakdowns



Red and Purple Plots are post-FBD plots



Conclusion

- **We haven't determined how the Machine Learning predicted the breakdowns (yet).**
- **We are examining the amplitude of the preceding dark current signal as an indicator.**
- **We are examining the evolution of preceding dark current signals as an indicator.**
- **We have taken the first steps in validating the ML findings.**

Future Work

- **Continue the studies discussed.**

- **Collate the results with breakdown location – this would determine the point at which the dark current signal changes.**

- **Look into evolution characteristics – Are there any indicating characteristics between the preceding non-breakdown pulses? Do the conditions for breakdown evolve on a pulse to pulse basis in a measureable way?**

References

- **[1] Spatially Resolved Dark Current In High Gradient Travelling Wave Structures; J Paszkievicz, PN Burrows, W Wuensch**

- **[2] Statistics of Vacuum Breakdown in the High-Gradient and Low-Rate Regime; W Wuensch, A Degiovanni, S Calatroni, A Korsbäch, F Djurabekova, R Rajamäki, J Giner-Navarro**

- **[3]Explainable Machine Learning for Breakdown Prediction in High Gradient RF Cavities; C Obermair, T Cartier-Michaud, A Apollonio, W Millar, L Felsberger, L Fischl, H Severin Bovbjerg, D Wollman, W Wuensch, N Catalan-Lasheras, M Boronat, F Pernkobf, G Burt**

- **[4] High-Power Test of Two Prototype X-band Accelerating Structures Based on SwissFEL Fabrication Technology; N Catalan-Lasheras, W Wuensch, W Millar, et al. (Under Review)**