# Monte Carlo Model of High-Gradient Conditioning and Operation

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**Mini-MeVArc**

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# Contents

# High-Voltage Conditioning

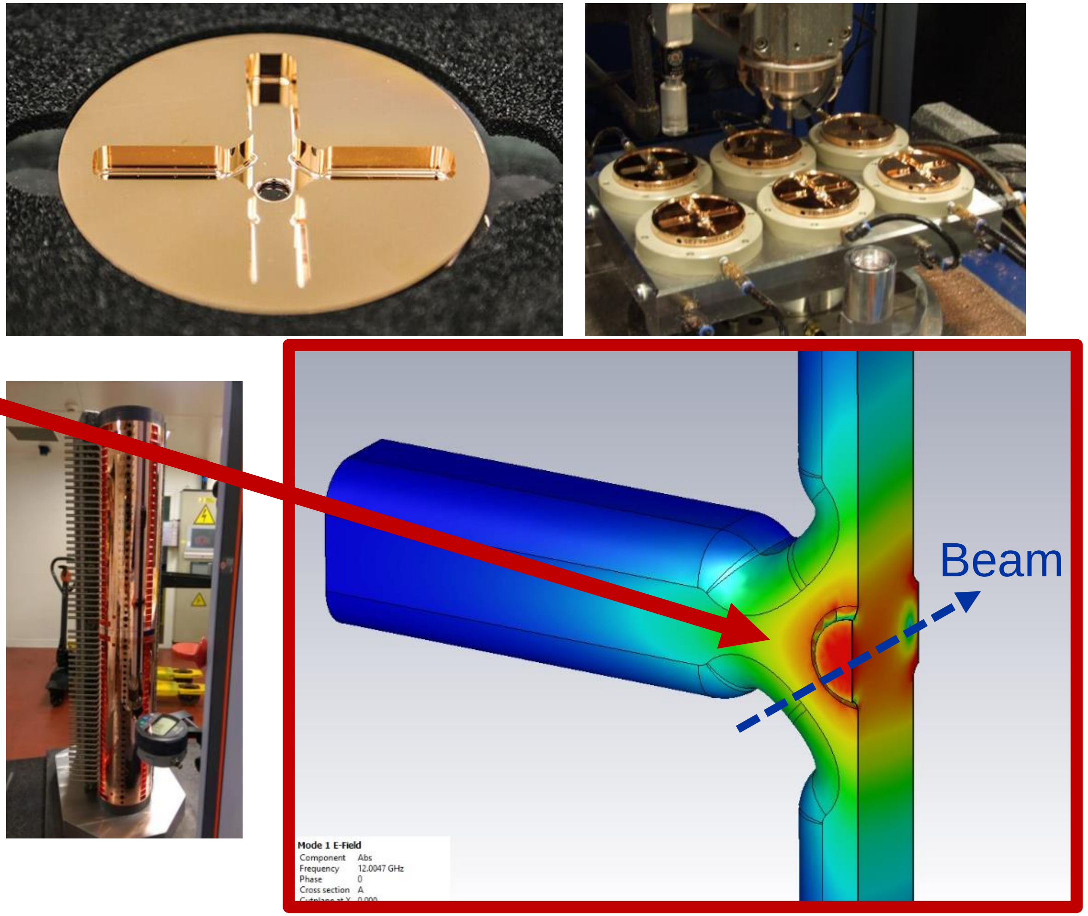
At CERN we regularly operate TW LINACs and other novel RF components at high power:

Peak surface fields ≈ 220MV/m

Peak input power: 40 - 50 MW.

RF Pulse length ≈ 200 ns ( 12 Joules per pulse).

**However, components can’t operate at this level immediately.**




Figures: Precision machined disc (top left), metrology of discs (top right), stacking and alignment (bottom left) and VNA measurement of an assembled and tuned travelling wave high gradient accelerating structure (bottom right).

# High-Voltage Conditioning

High-gradient structures (and high-power RF components) are often limited by breakdown.

To achieve stable high-power performance, they must be **conditioned**. At CERN, 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 achieved.**

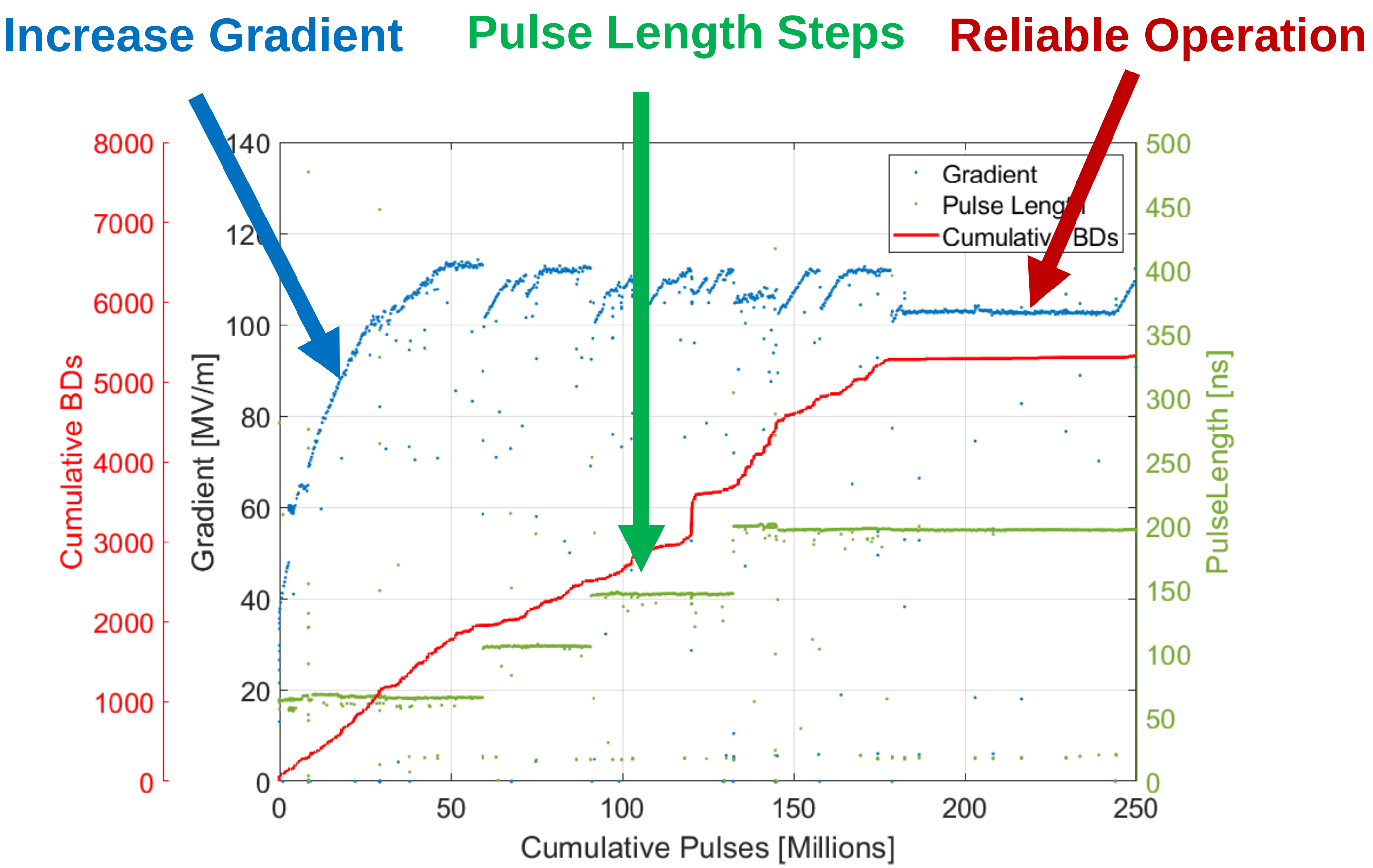



Figure: Preliminary conditioning of a PSI T24 structure tested at CERN.

# Automation of Conditioning

A conditioning algorithm was developed to automate the process.

Offers a consistent and reproducible method of component testing, in short: **the power is slowly increased while tracking an operator-selected BDR [1,2].**

Has since conditioned many components, similar procedures are in place at Daresbury, SLAC, and elsewhere within CERN [3,4].

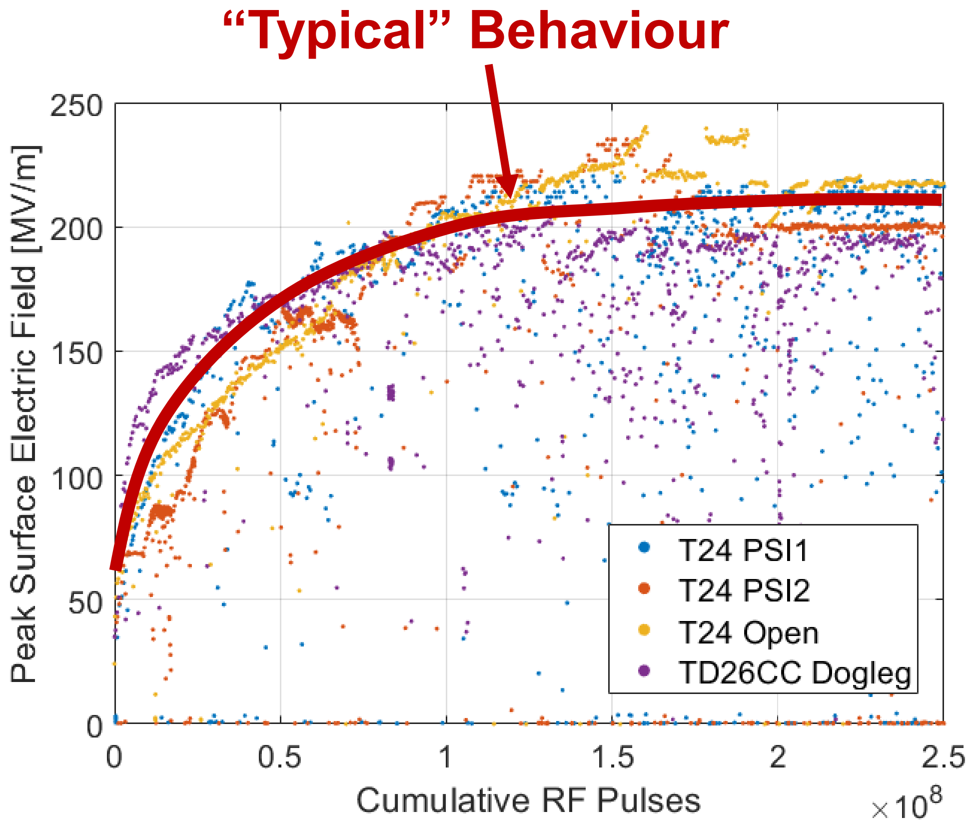
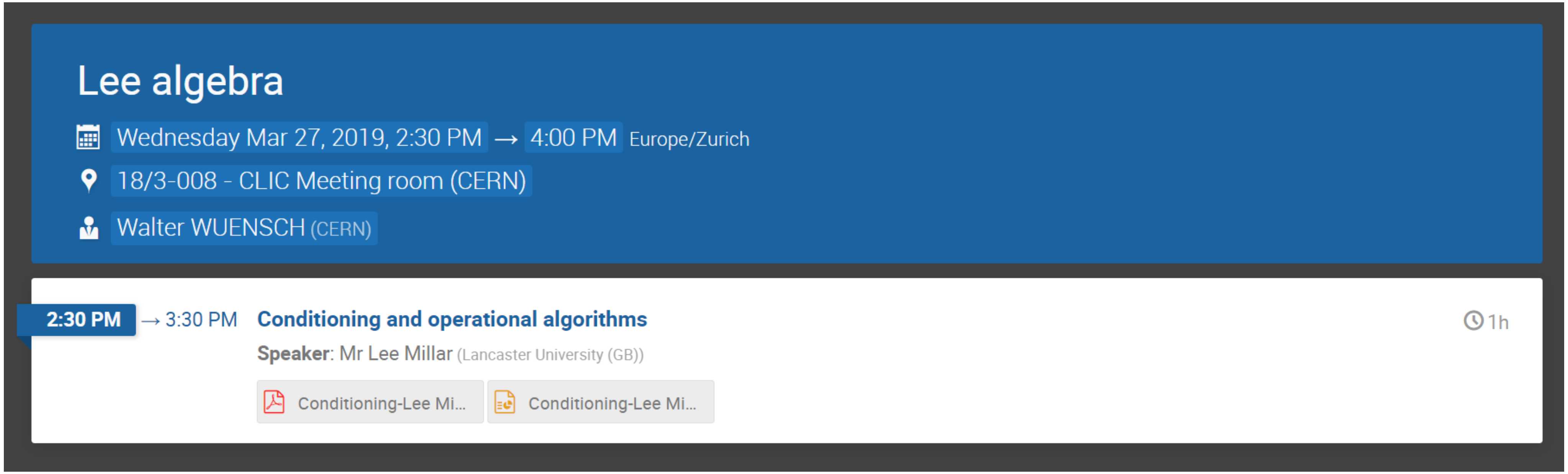



Figure: Preliminary conditioning of several X-band structures tested at CERN.

# Automation of Conditioning

**A bit of backstory…..**


Lee algebra

Wednesday Mar 27, 2019, 2:30 PM → 4:00 PM Europe/Zurich

18/3-008 - CLIC Meeting room (CERN)

Walter WUENSCH (CERN)

2:30 PM → 3:30 PM **Conditioning and operational algorithms** 1h

**Speaker**: Mr Lee Millar (Lancaster University (GB))

Conditioning-Lee Mi... Conditioning-Lee Mi...

# Why Model Conditioning?

**The Pragmatic Motivation:**

Conditioning procedures are largely anecdotal. Despite being essential the conditioning process has yet to be optimised (tests require a long timeframe/significant expense, difficult to do experimentally).

**The Physics Motivation:**

Many attempts have been made to connect theory to the measurements (e.g. probabilistic behaviour of BDs, BDR vs gradient), but they generally only address a single facet of the problem. Real operation is more complex, the model is an attempt to combine theoretical explanations and connect them to results.

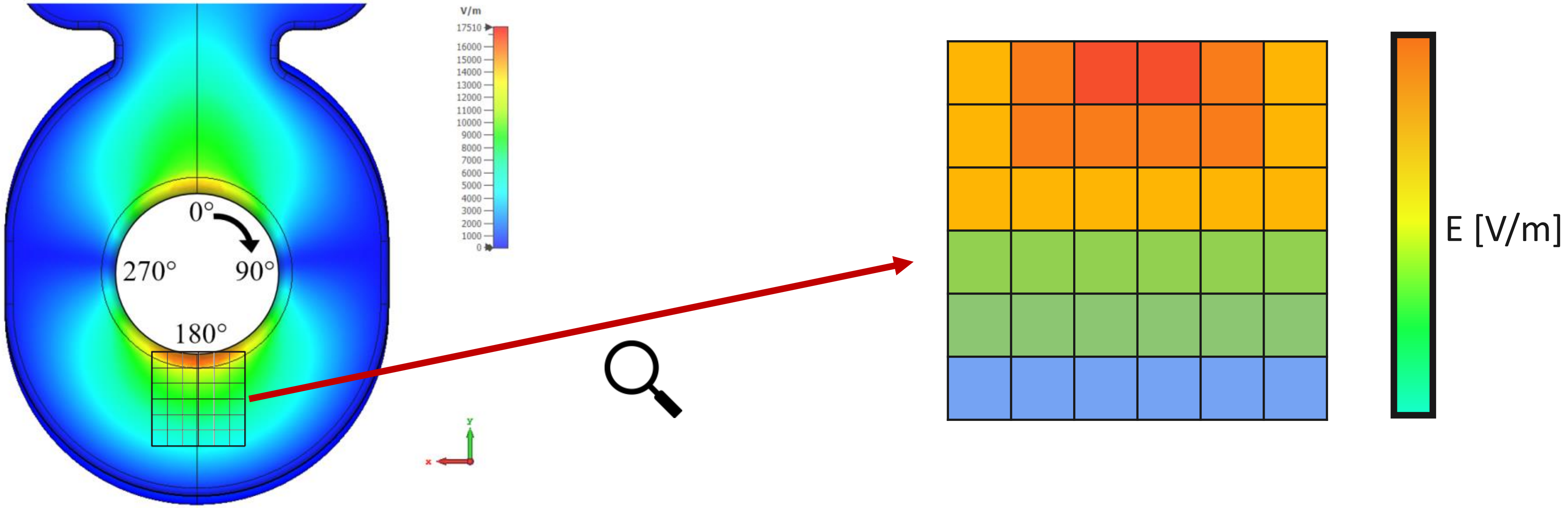
**The first attempt at a comprehensive integration of HG operation to address these issues.**

# Contents

# Simulation Setup: Assumptions of the Model

Field distributions often vary spatially, and the effect of breakdown is a local one. Application of a grid/mesh is then appropriate.

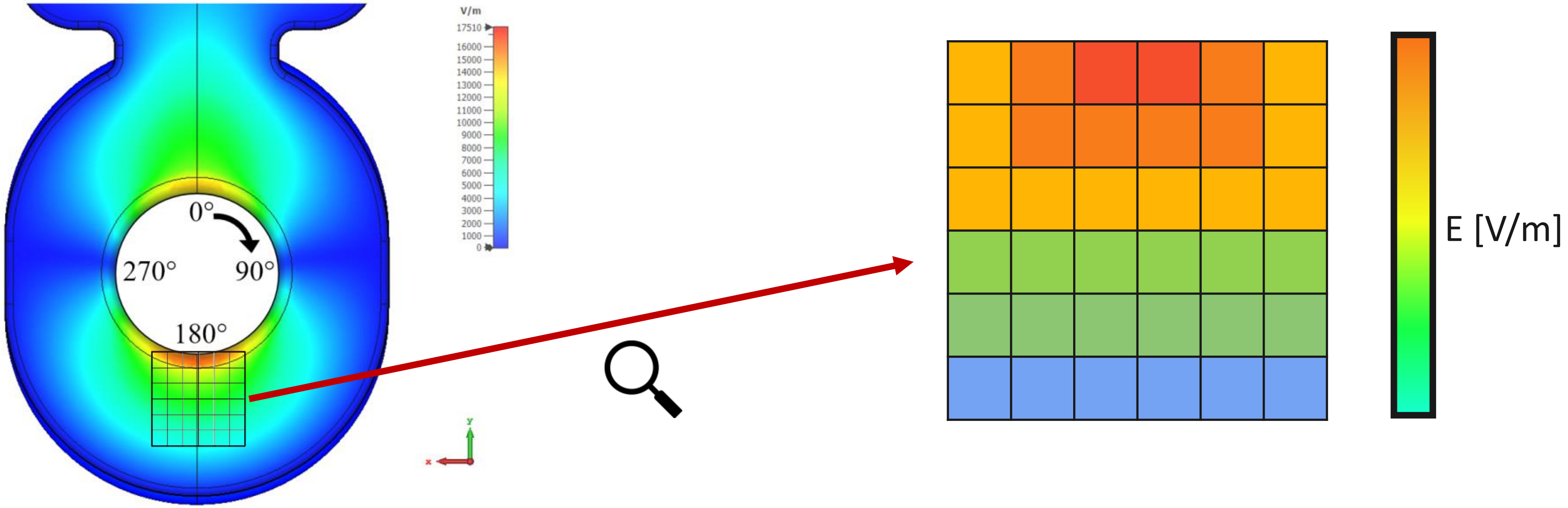
**Surface electric field in an RF cavity.**



# Simulation Setup: Assumptions of the Model

Each element exists in a given state and has a corresponding applied field. The assumptions and models which follow are applied **each element individually** to monitor how they evolve and accrue breakdowns.

Surface electric field in an RF cavity.



# Simulation Setup: Assumptions of the Model

**Asymptotic behaviour (no indefinite conditioning)**

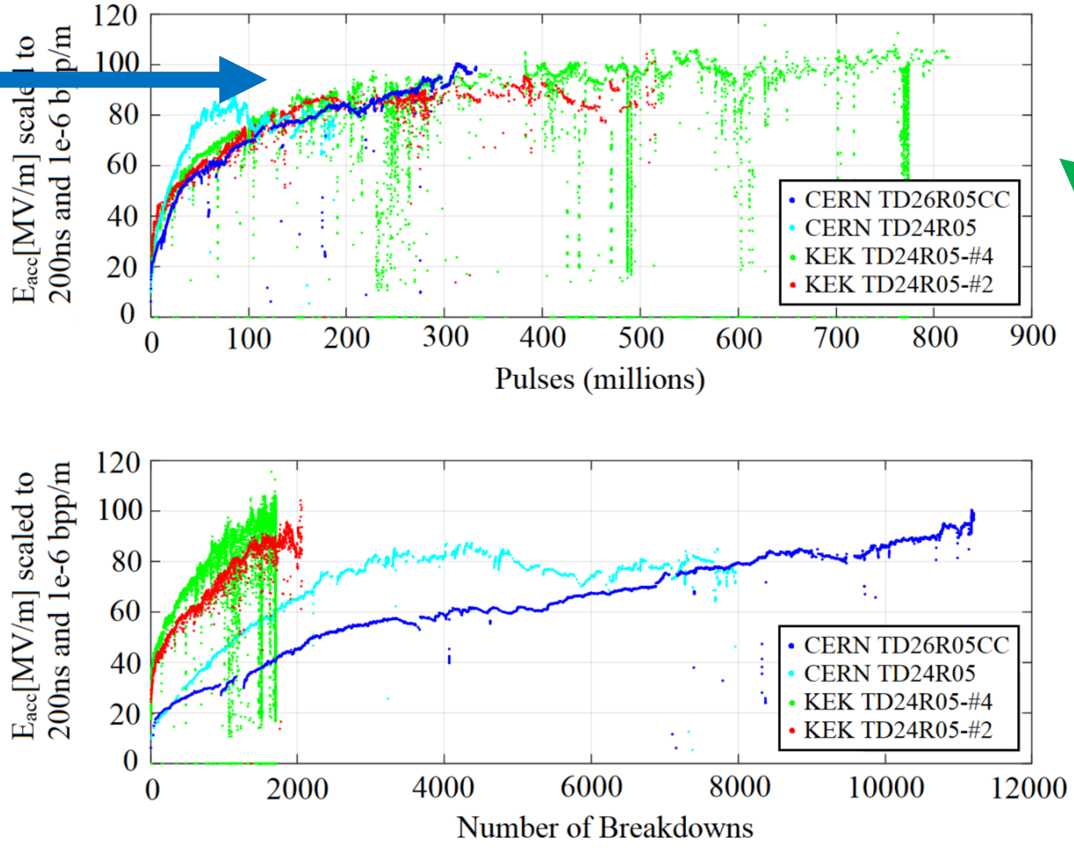
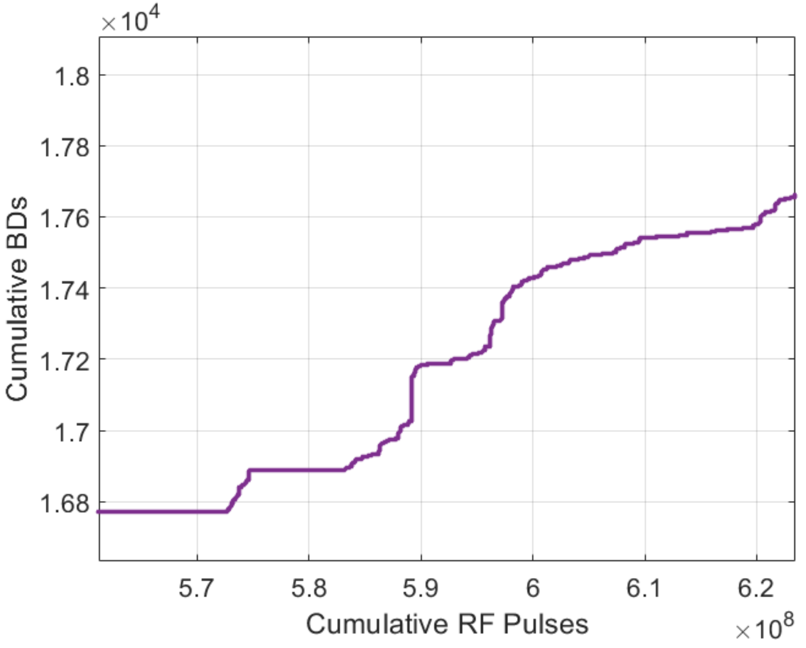



Figure: Scaled gradient vs. cumulative no. pulses (top) and scaled gradient vs. cumulative no. breakdowns (bottom) for four different structures [5].

**Structures proceed most comparably in pulses.**

# Simulation Setup: Assumptions of the Model

Breakdowns can occur individually or in groups,
**they can improve or worsen the surface.**




Figures: Cumulative breakdowns vs pulses for a TD26CC tested at CERN.

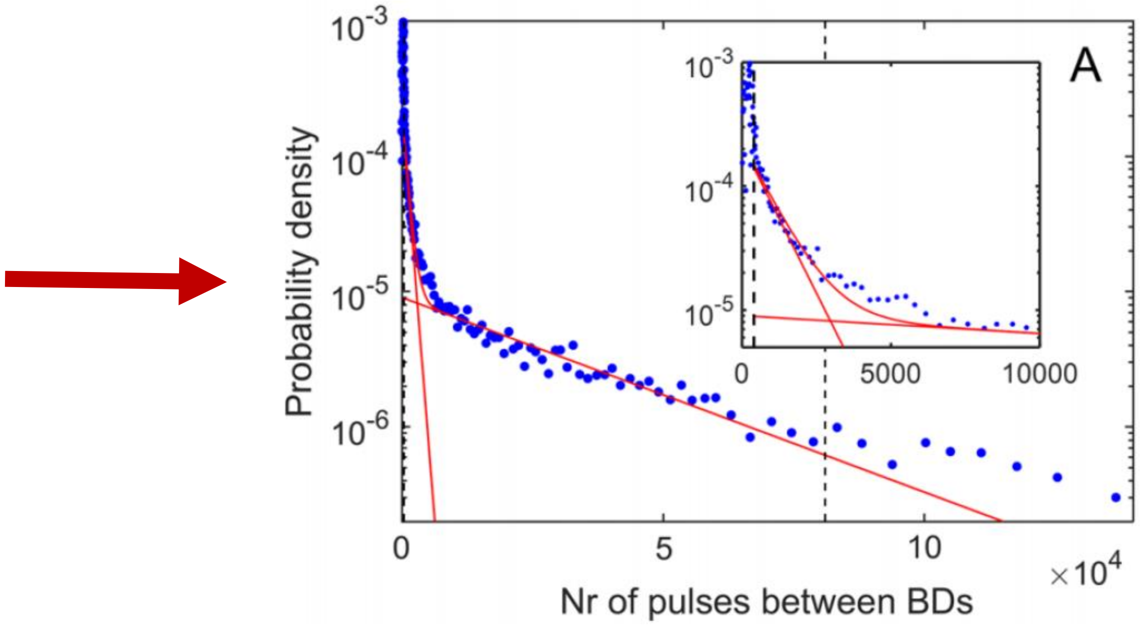



Figure: Probability distribution of the pulses between BDs for a structure tested at CERN and a two-exponential fit [6].

# Simulation Setup: Assumptions of the Model

I have condensed the process into **three key characteristics**, although many other facets of operation exist. To summarise:

1. Each pulse improves (conditions) the surface elements.

2. They asymptotically approach a limit, above which no improvement takes place.

3. Breakdowns may worsen or improve a given surface element.

The model is built around the idea of **progressive modification of the surface on a pulse-to-pulse basis.** The next step is applying these principles…

# Simulation Setup: Assumptions of the Model

To do so, we are going to define three terms:

$E_{Operate}$ = The electric field at which the device operates.

$E_{State}$ = The surface electric field level to which the device has been conditioned.

$E_{Sat}$ = The maximum achievable value for $E_{state}$. The saturation point for a given material in MV/m.

Details and more comprehensive descriptions in the bonus slides

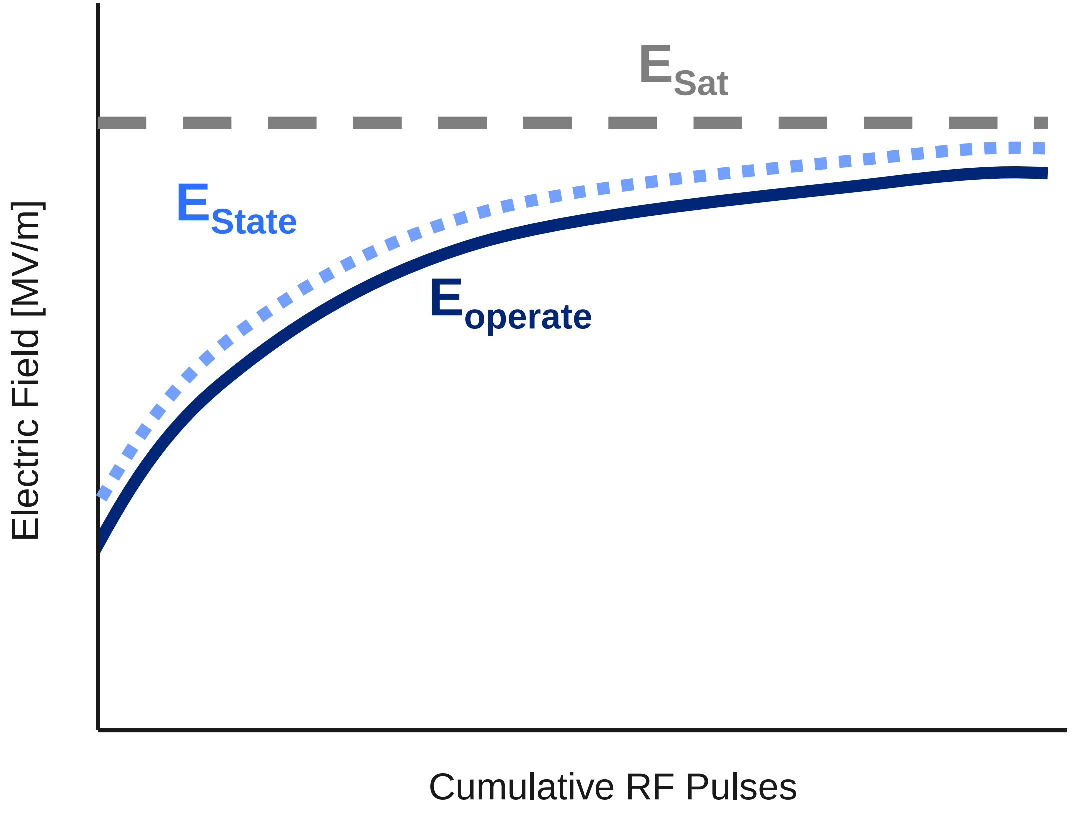



Figure: Visualisation of proposed quantities during conditioning.
For illustrative purposes only.

# Simulation Setup: Quantification of Conditioning

**Assuming each element has a conditioning rate (CR), the surface state ($E_{State}$) should asymptotically approach a limit ($E_{Sat}$):**

$$CR \propto \left[1 - \frac{E_{State}}{E_{Sat}}\right]$$

**However, to produce a significant conditioning effect the operating field ($E_{Operate}$) must be close to the level to which the surface is conditioned ($E_{State}$):**

$$CR \propto \frac{E_{Operate}}{E_{State}}\left[1 - \frac{E_{State}}{E_{Sat}}\right]$$

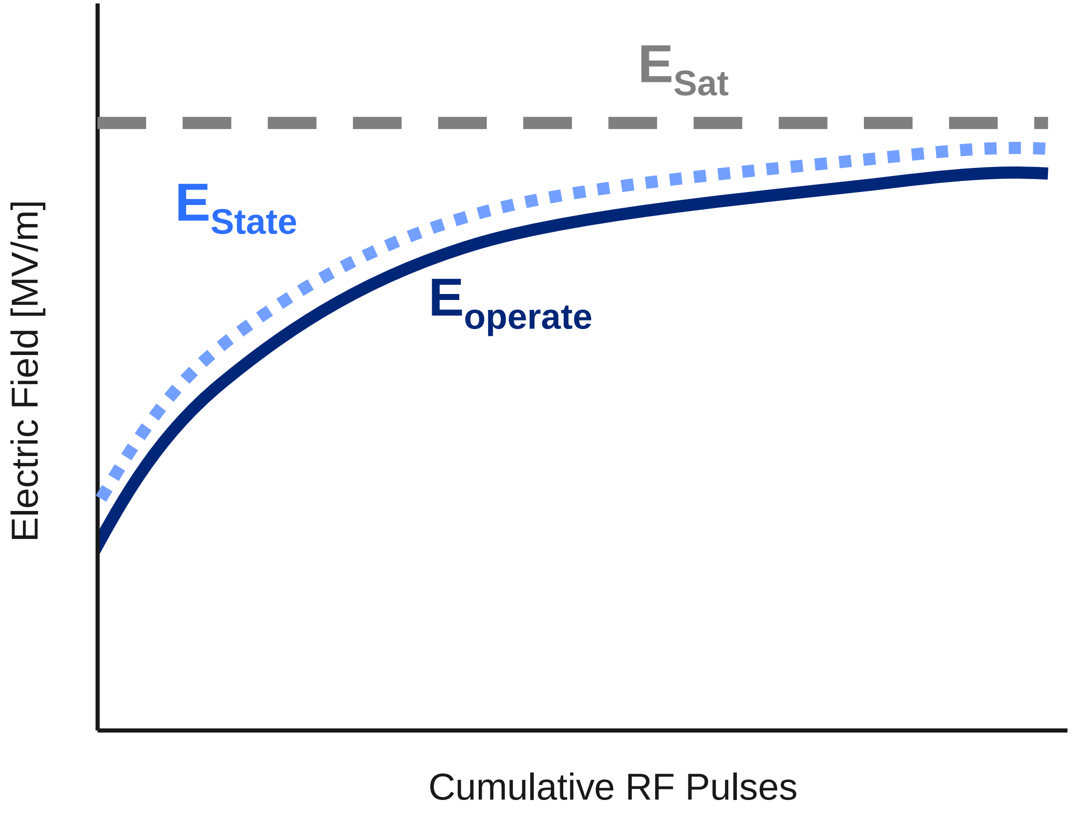



Figure: Visualisation of proposed quantities during conditioning.

# Simulation Setup: Quantification of Conditioning

**Adding a constant to facilitate tuning ($\gamma$), we can then modify the state of the surface every pulse i.e.**

$$\textbf{CR [per pulse]} = \gamma \cdot \frac{E_{Operate}}{E_{State}}\left[1 - \frac{E_{State}}{E_{Sat}}\right]$$

**The surface state after N pulses is then given:**

$$E_{State} = \sum_{i=0}^{N} CR(i) \qquad i = 1, 2, 3 \dots N$$

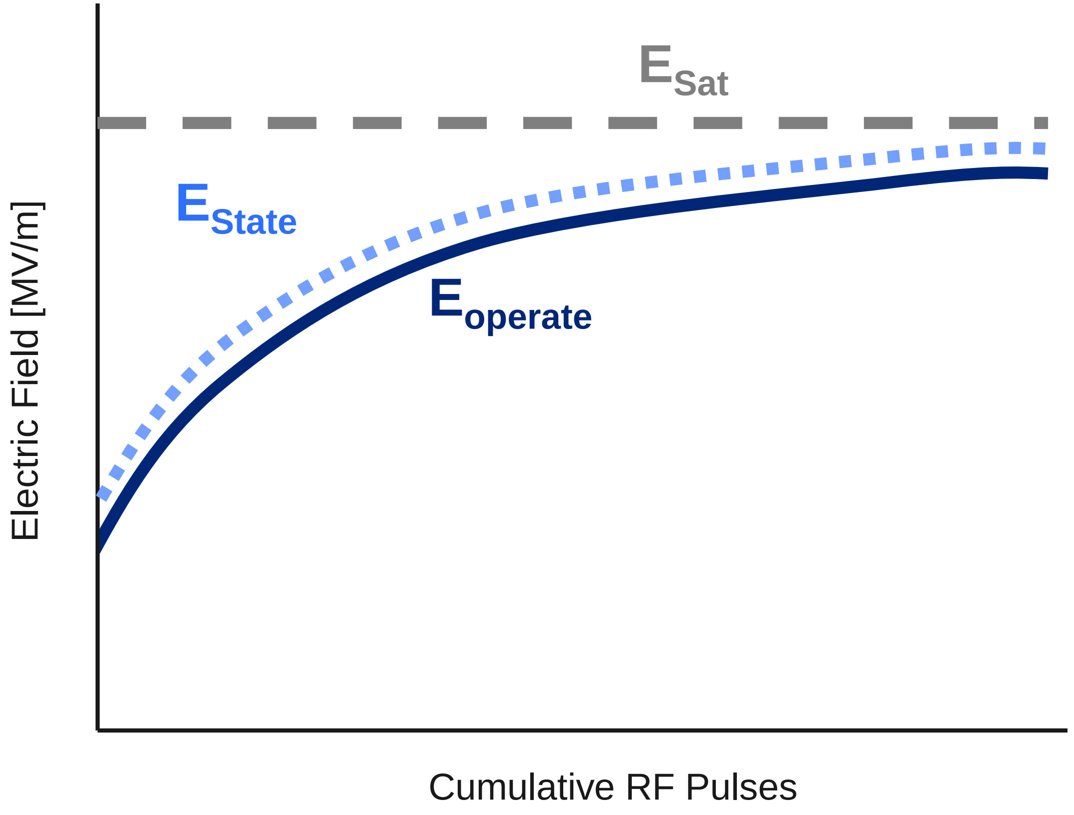
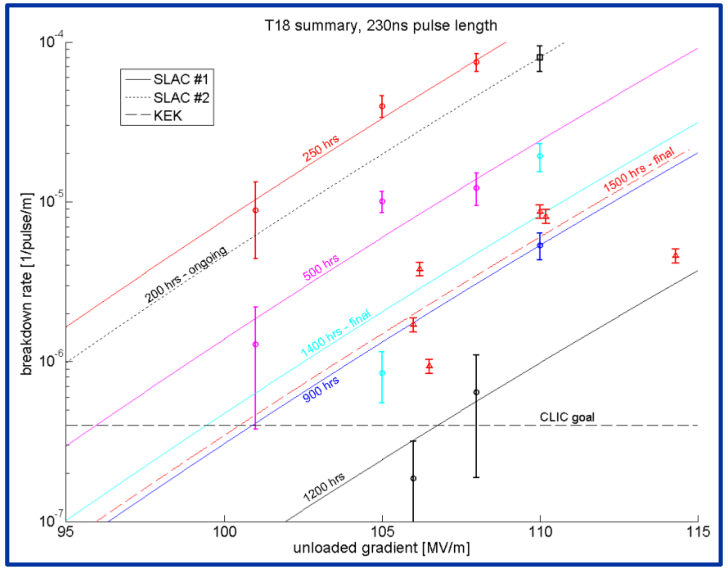
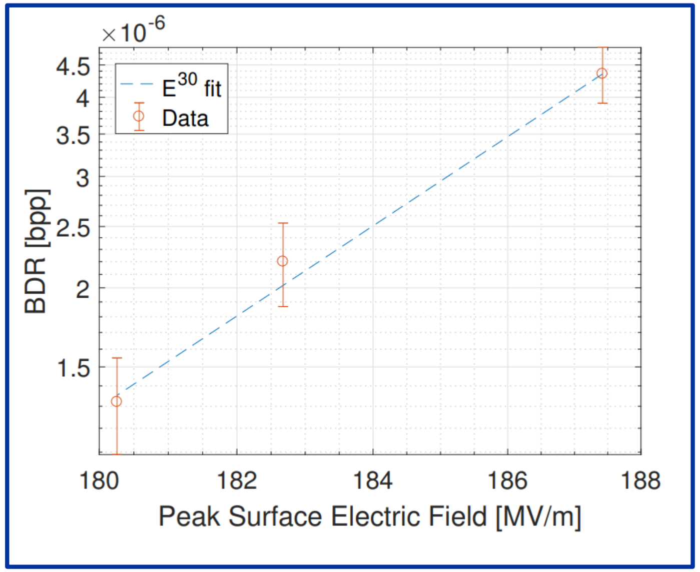


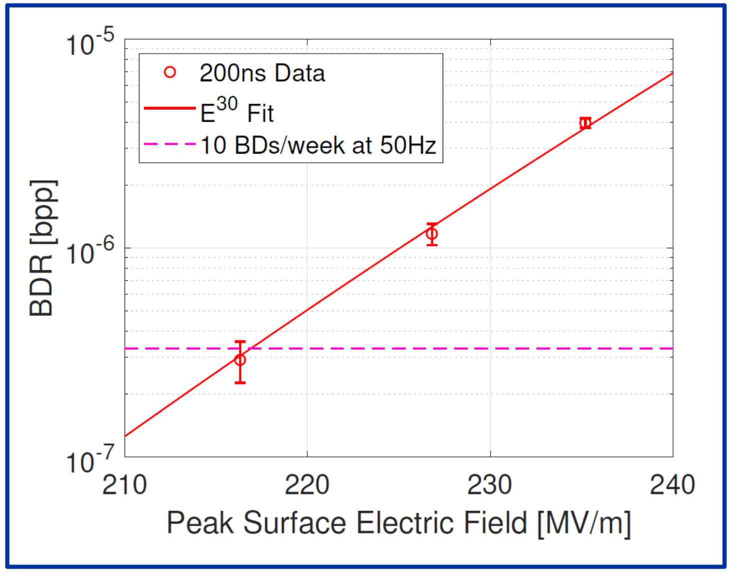

Figure: Visualisation of proposed quantities during conditioning.

# Simulation Setup: Probability of Breakdown

**In the CLIC structures the BDR scales strongly with the electric field. Some variance is present, but 30 is the frequently quoted exponent. Values measured in structure tests generally lie around this.**




Figures: $E^{30}$ fit to various HG structure test results [7,8].

# Simulation Setup: Probability of Breakdown

For the time being, it is assumed that changes in the operating field strongly affect the probability of breakdown ($P_{BD}$) as:

$$P_{BD} \propto E_{Operate}{}^{30}$$

However, the probability of BD decreases as we condition, hence:

$$P_{BD} \propto \left(\frac{E_{Operate}}{E_{State}}\right)^{30}$$

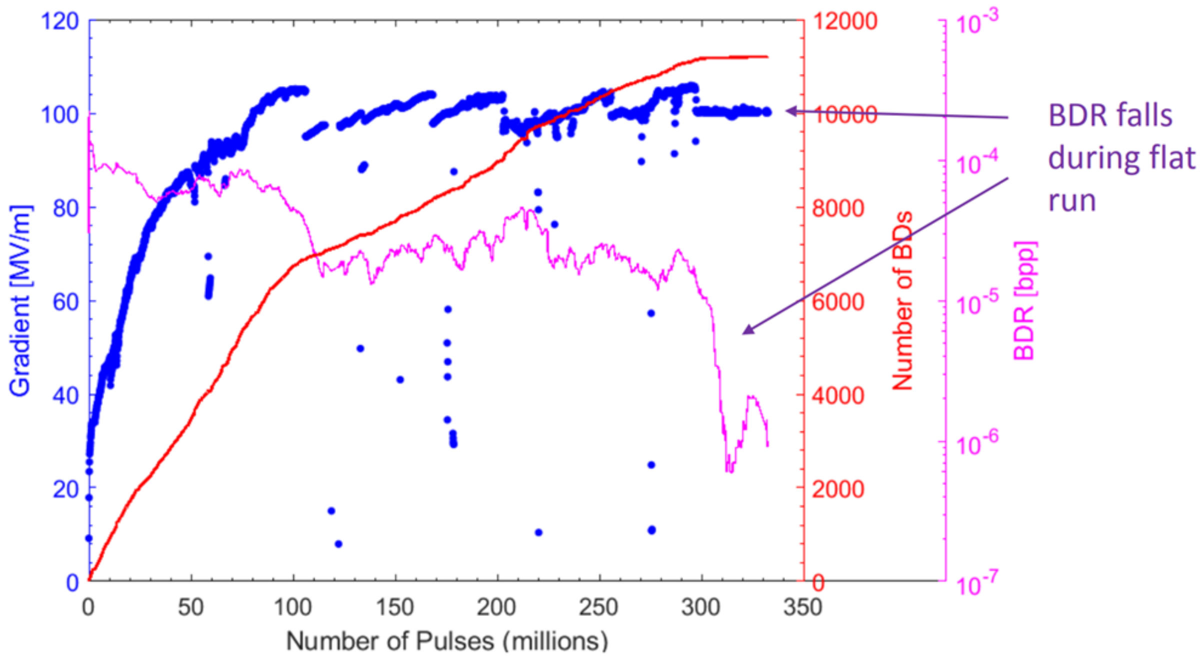
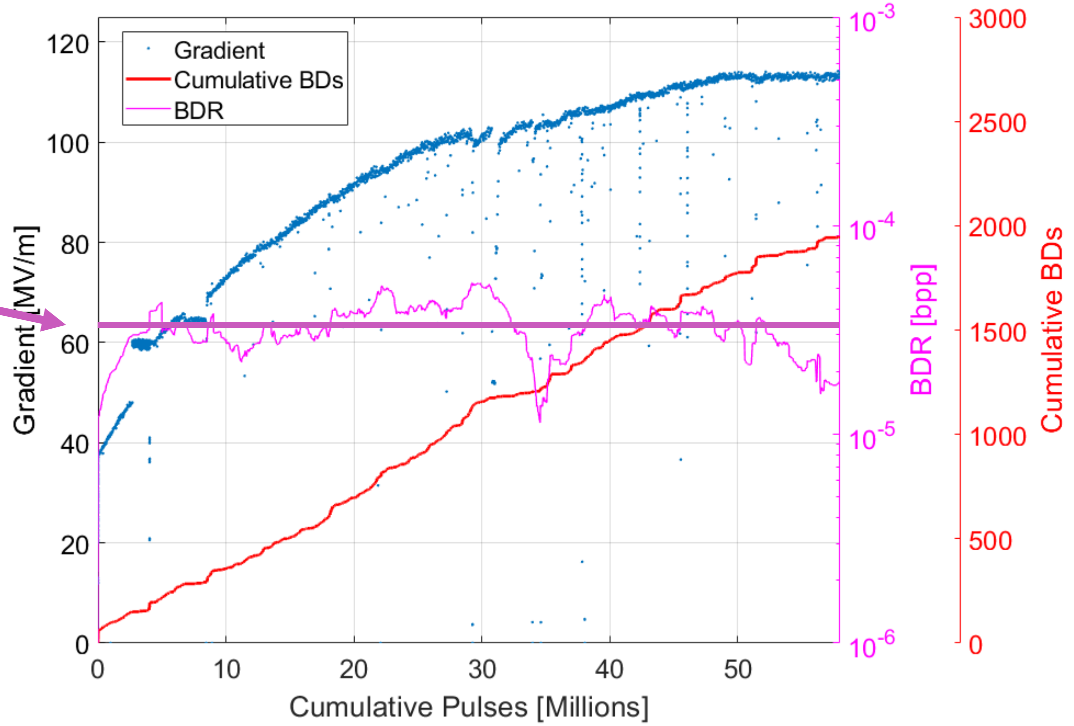



Figure: Conditioning curve of a CERN structure.

# Simulation Setup: Probability of Breakdown

**A reference probability is added to provide a reasonable BDR:**

$$P_{BD} = \left(\frac{E_{Operate}}{E_{State}}\right)^{30} \cdot P_{Reference}$$




**However, $P_{reference}$ applies to a whole device, not individual grid elements. The probability corresponding to each element in a grid of n elements is then:**

$$P_{Grid} = \sqrt[n]{1 - P_{Reference}}$$

# Simulation Setup: Probability of Breakdown

**The probability of a BD occurring for each grid element is then:**

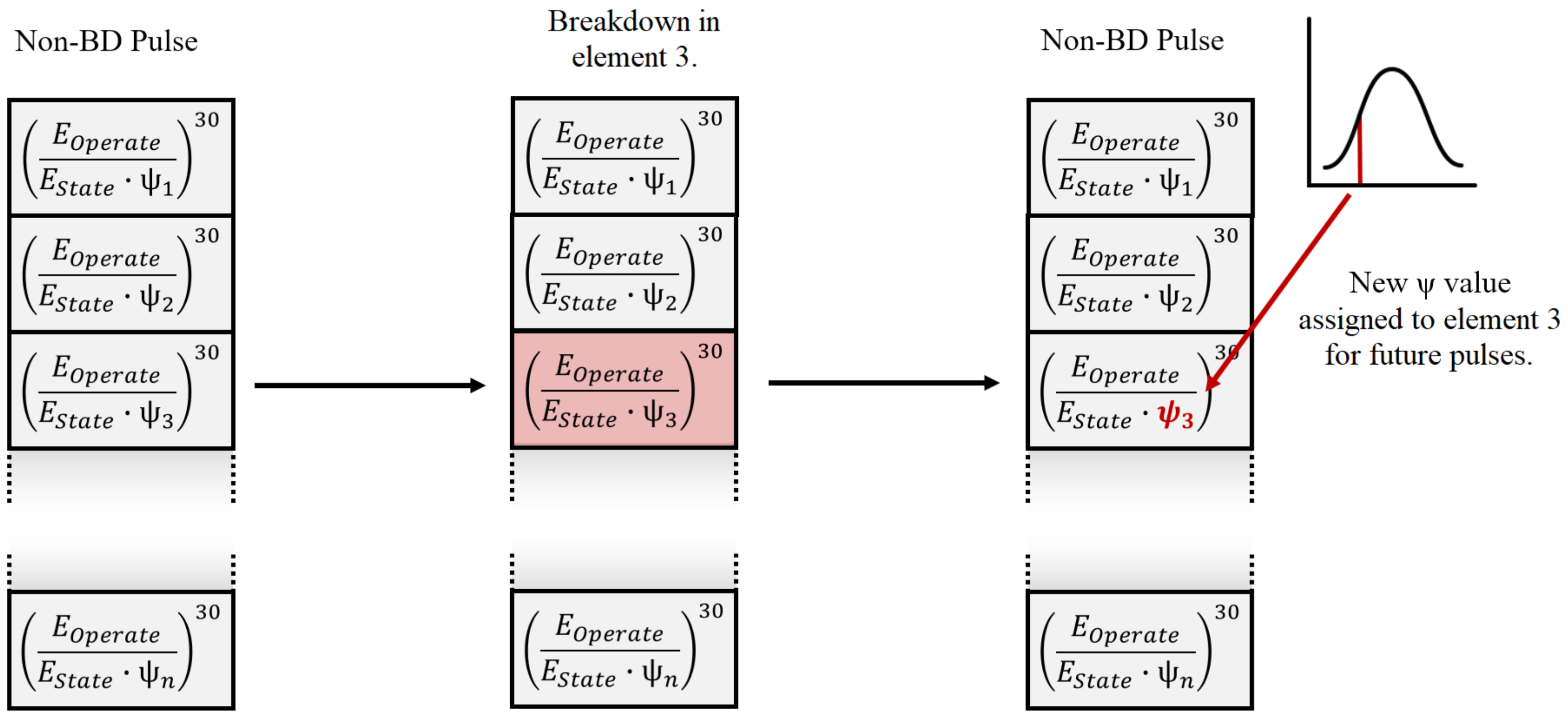
$$P_{BD} = \left(\frac{E_{Operate}}{E_{State}}\right)^{30} \cdot P_{Grid}$$

**Given that breakdown randomly improves or worsens the surface, a quasi-enhancement factor in the BD calculation for each element taken from a gaussian distribution as:**

$$P_{BD} = \left(\frac{E_{Operate}}{\psi \cdot E_{State}}\right)^{30} \cdot P_{Grid}$$

# Simulation Setup: Probability of Breakdown

**On every pulse, each element is checked for the occurrence of a breakdown. If a breakdown occurs the relevant grid element is assigned a new ψ value.**



# Summary: A (very) Simple Model Outline

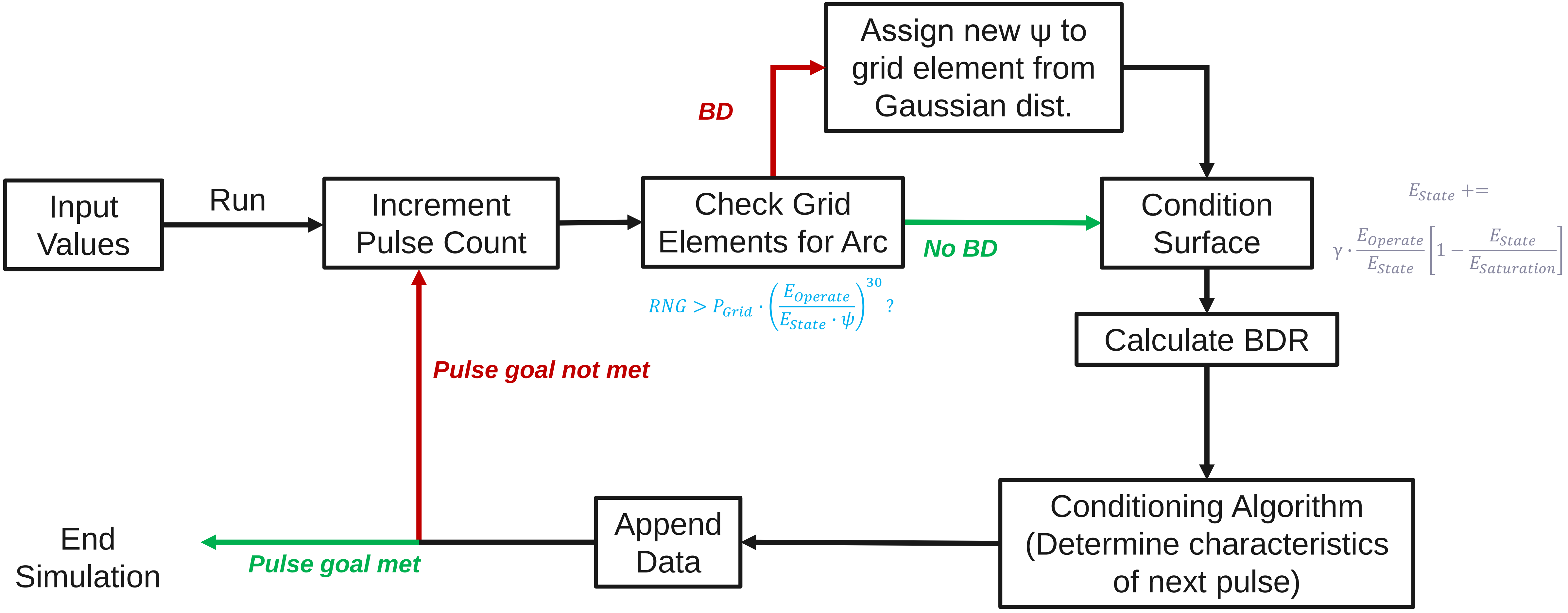



Figure: Simplified block diagram of the model showing the equations implemented.

# Summary: A (very) Simple Model Outline

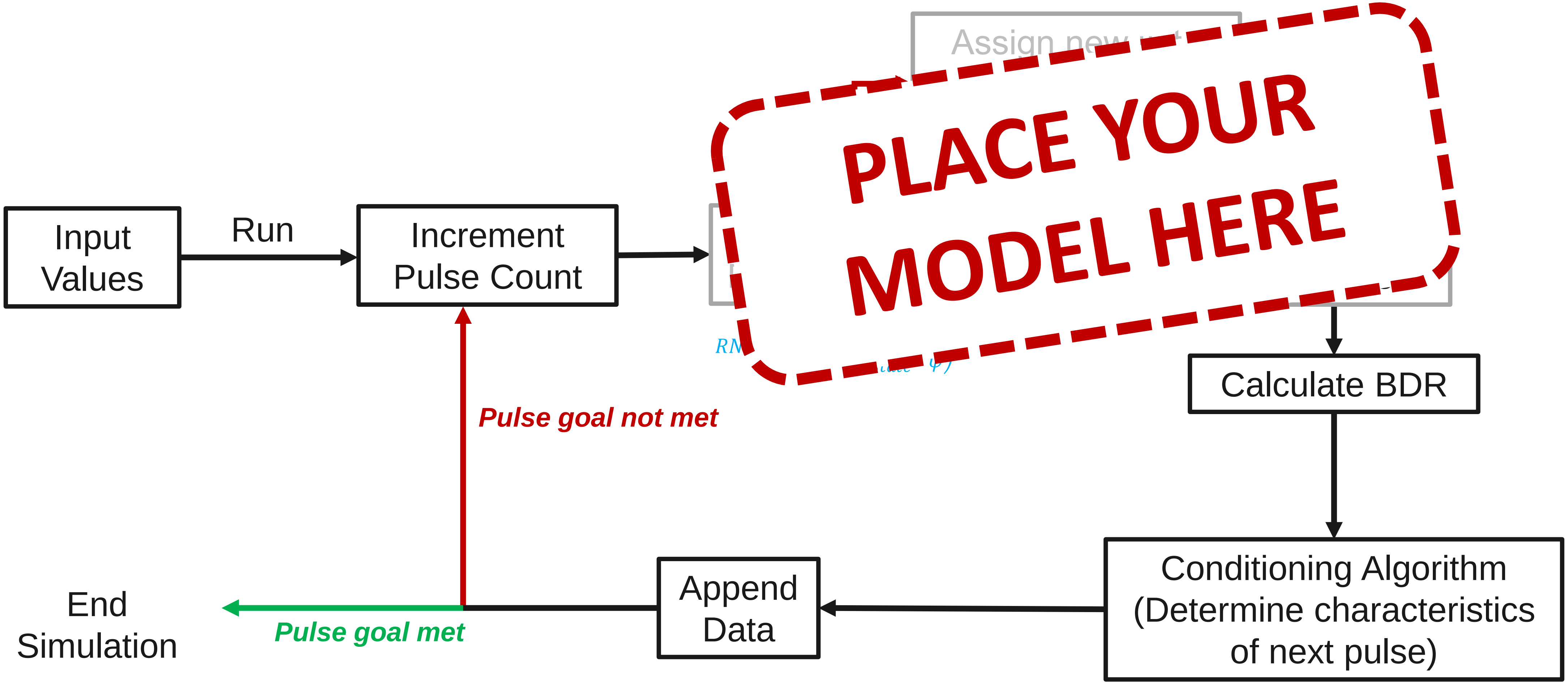
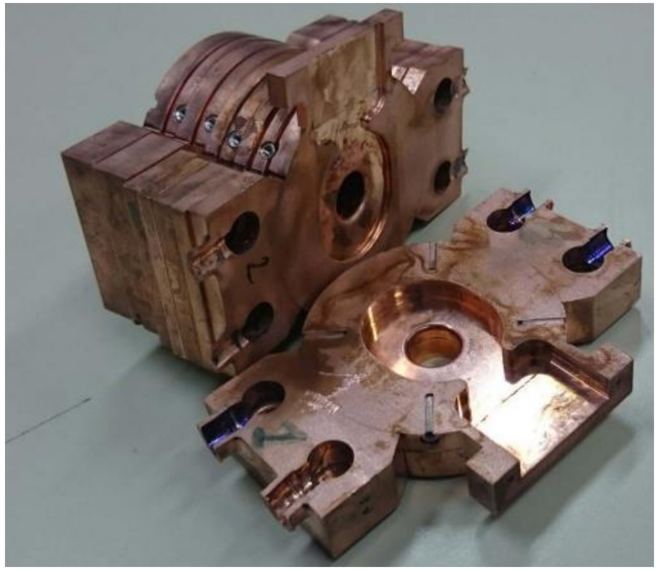



Figure: Simplified block diagram of the model showing the equations implemented.

# Contents

# A Visual Example

**Cavity after high-power test and cutting.**



**Face of a single cell.**

**Breakdown locations superimposed on electric field distribution.**

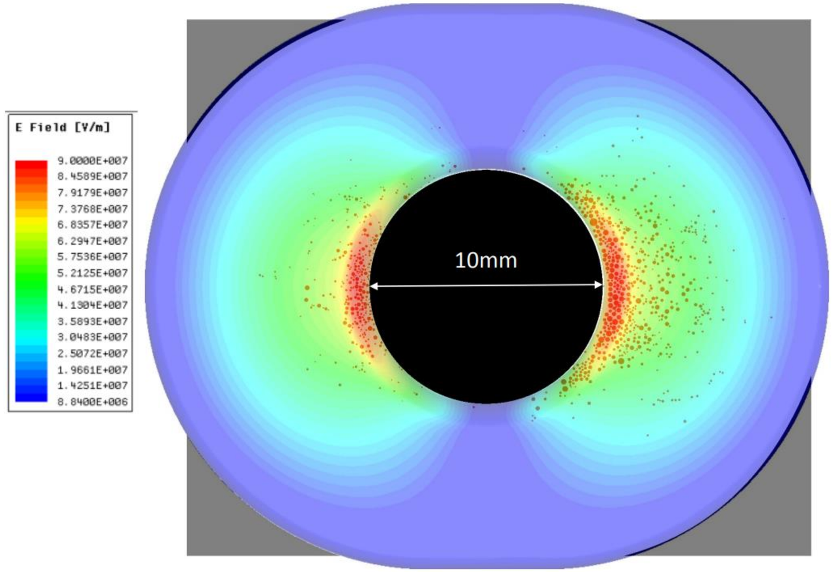
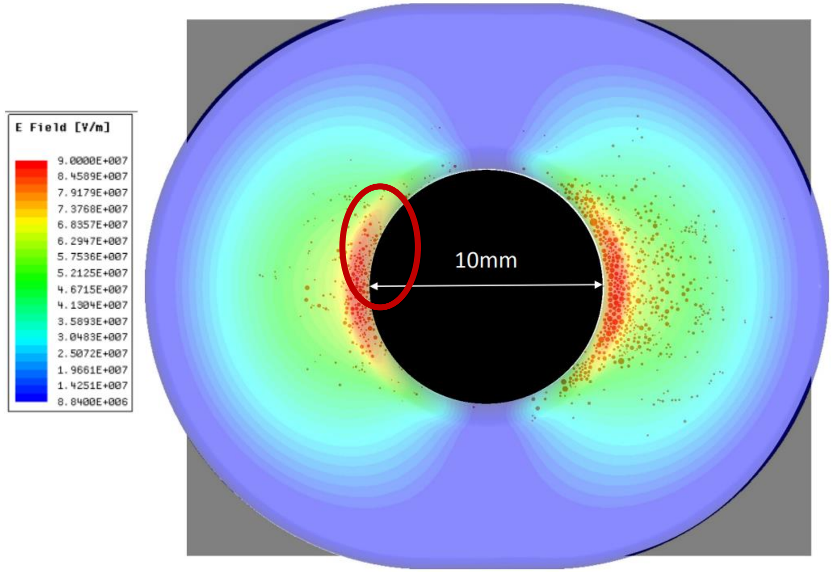


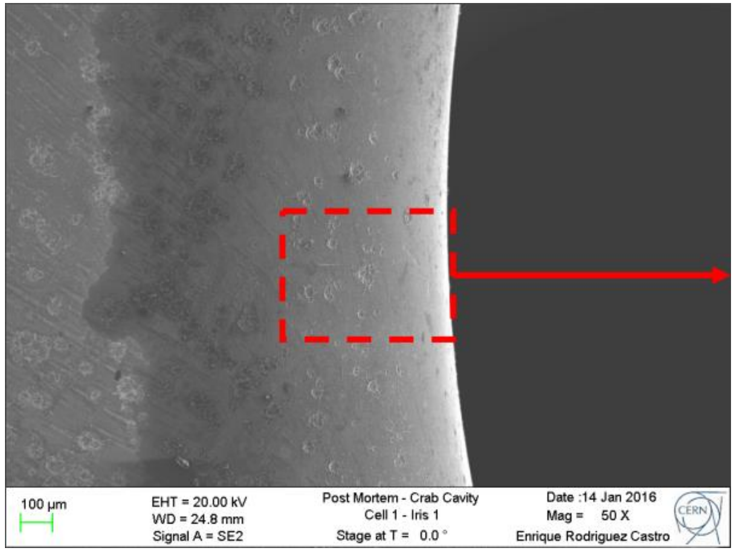

Figure: Images from the post-mortem examination of the CLIC crab cavity [9].

# A Visual Example

**Breakdown locations superimposed on electric field distribution.**




**Breakdown craters around an iris in the cavity.**




**Breakdown crater.**

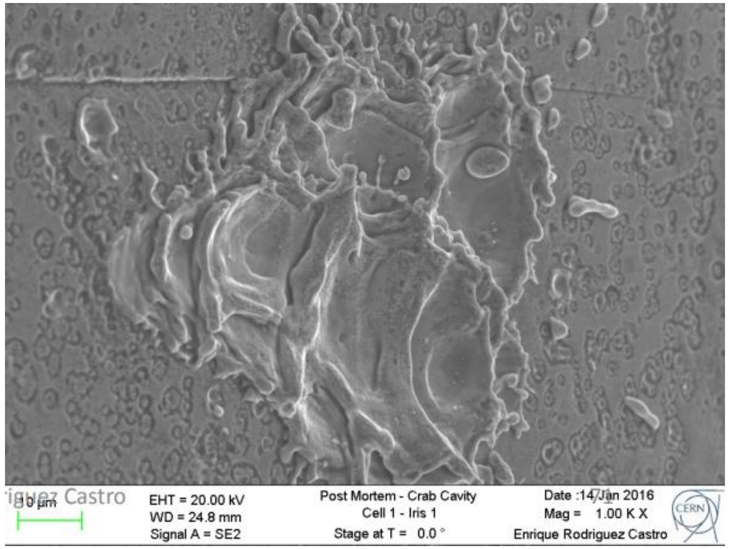
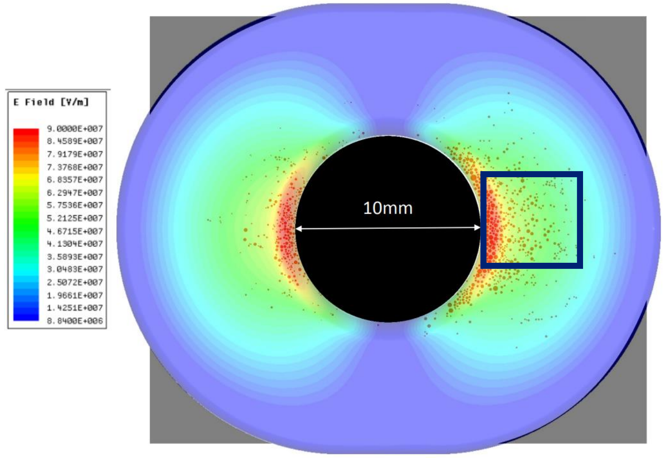


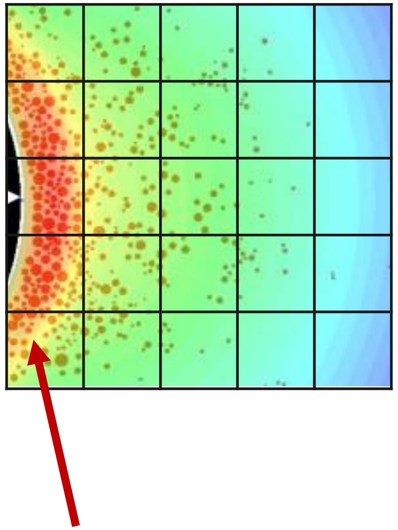

Figure: Images from the post-mortem examination of the CLIC crab cavity [9].

# A Visual Example

Select Surface

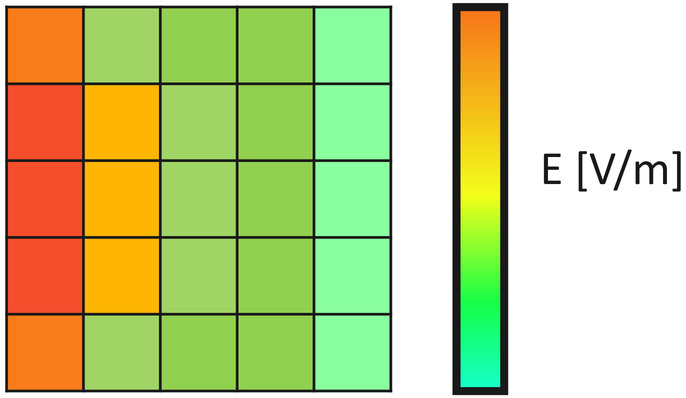



Apply grid/mesh.



Breakdown locations.

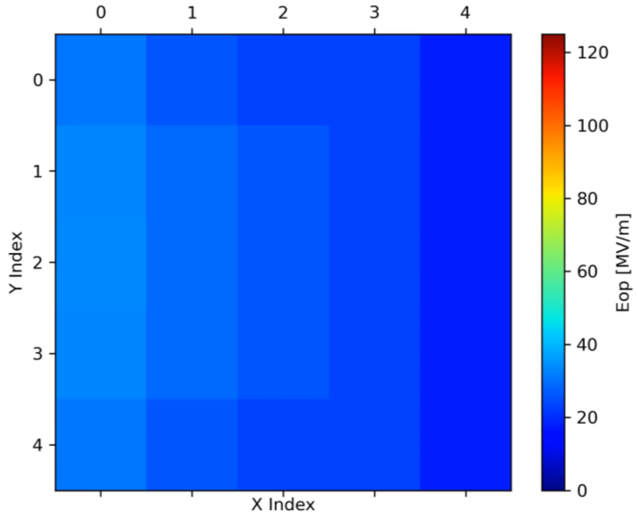
Relative Field Values are assigned.



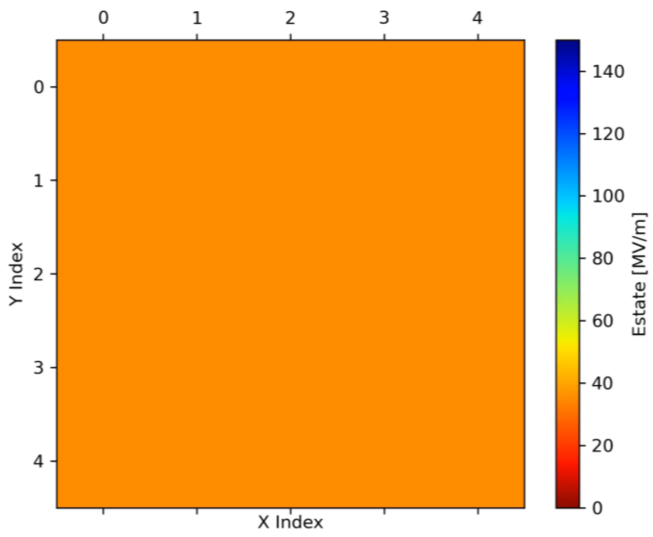
# A Visual Example

**Can then monitor quantities accessible in experiments ($E_{Op}$, global BDR) and others which cannot be directly measured ($E_{state}$, ψ values, etc).**

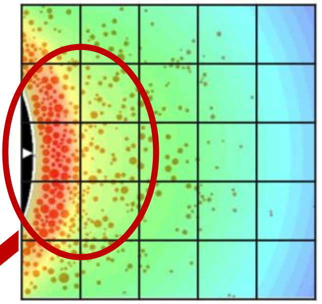
**$E_{op}$ Values (Applied Electric Field)**

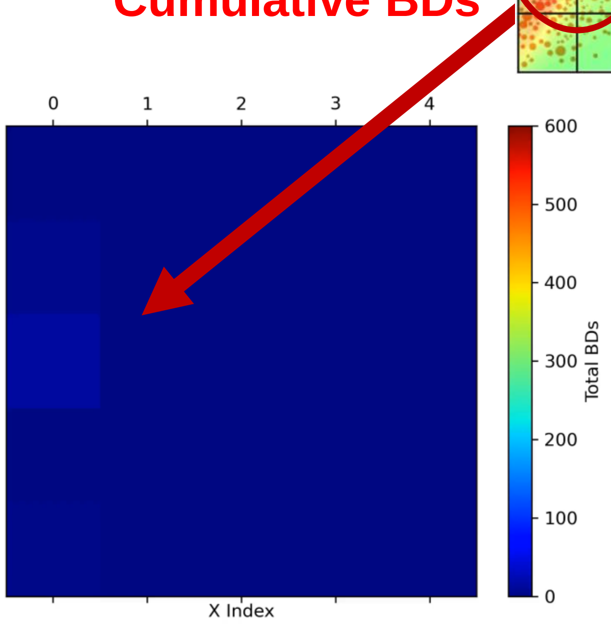



**$E_{state}$ Values**




**Cumulative BDs**

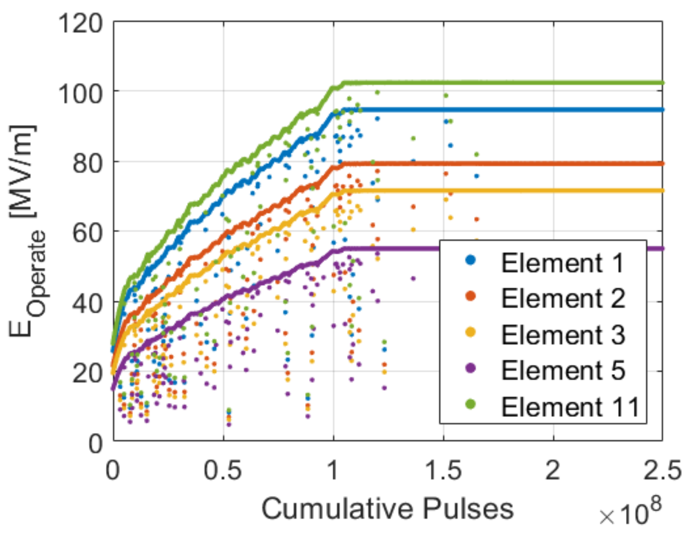




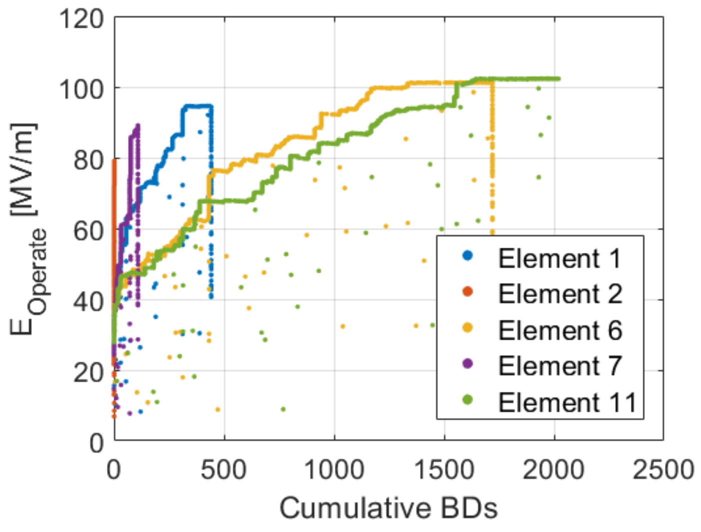
# A Visual Example

**And generate the more familiar plots…..**

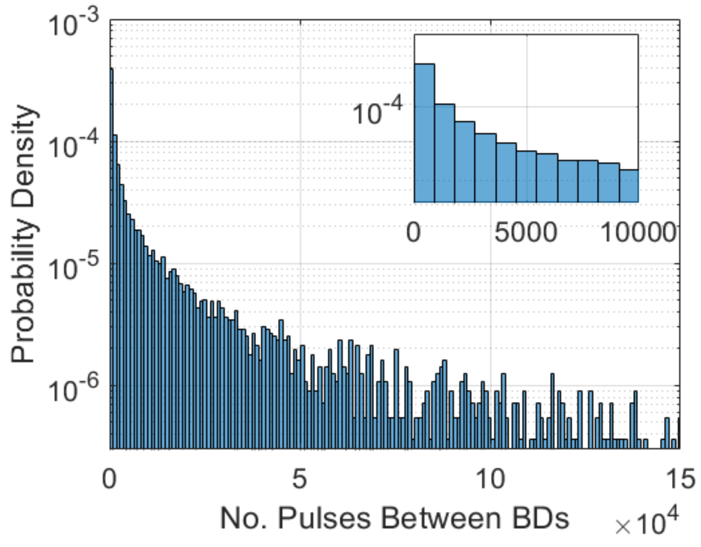
**$E_{op}$ Values (Applied Electric Field)**




**BD Accumulation**




**Probability Distributions**

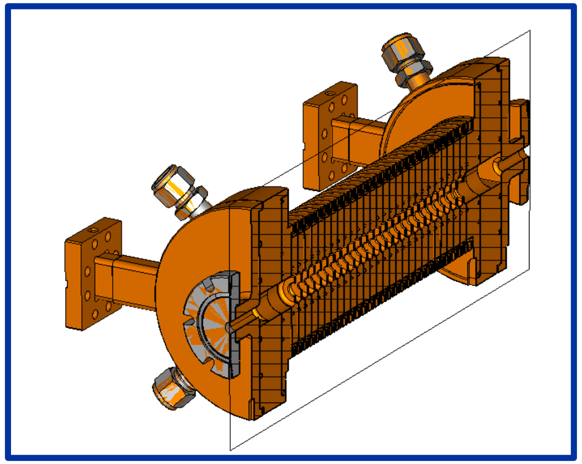


# Contents

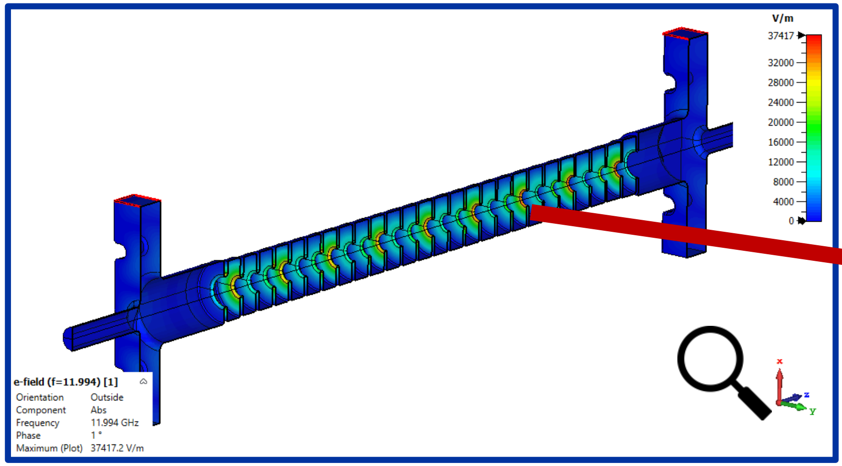
1. Overview of High-Gradient Conditioning.
2. Simulation Setup.
3. A Visual Example.
4. **Results of the Model.**
5. Conclusion and Future Work.

# Result 1: CLIC Prototype Structure

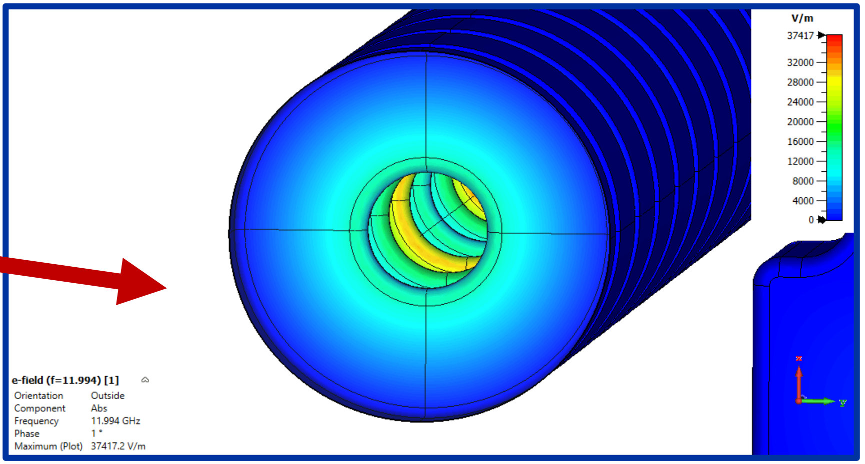
**Copper Cavity Cross-Section.**



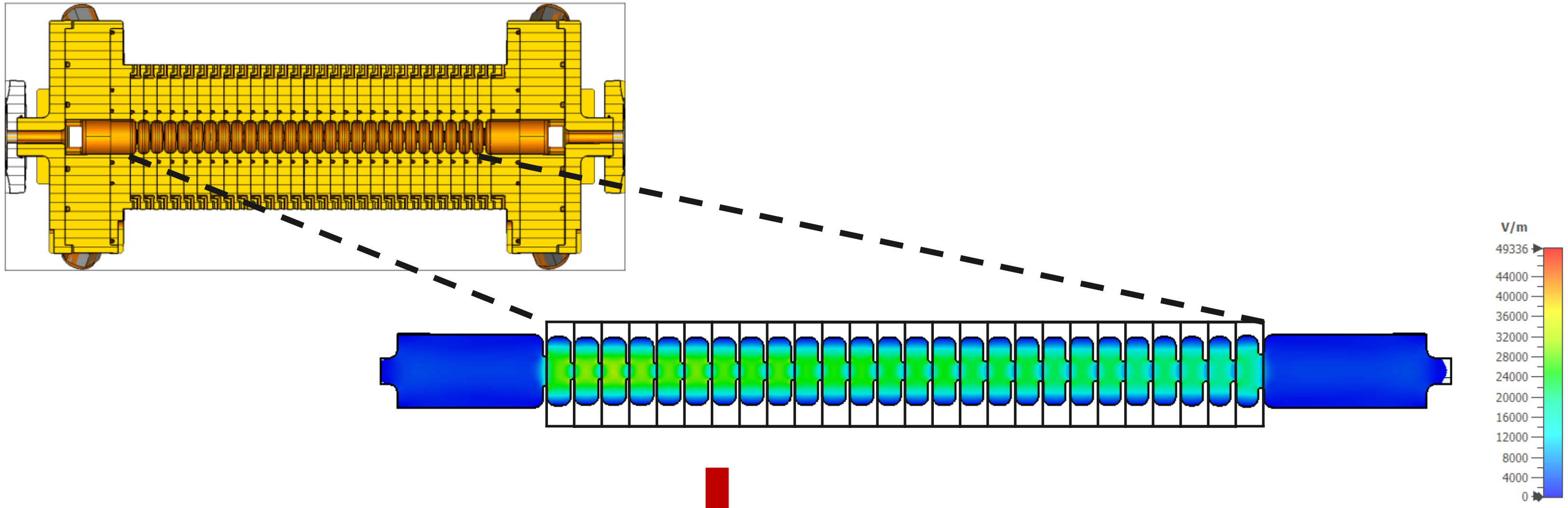
**E-Fields in the cells.**



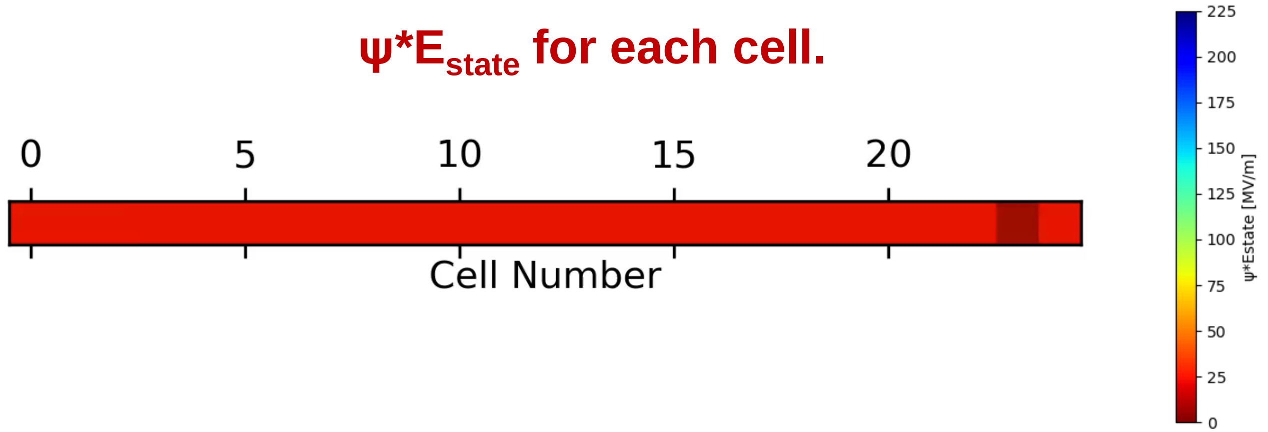

**E-Fields on cell Surface.**



# Result 1: CLIC Prototype Structure

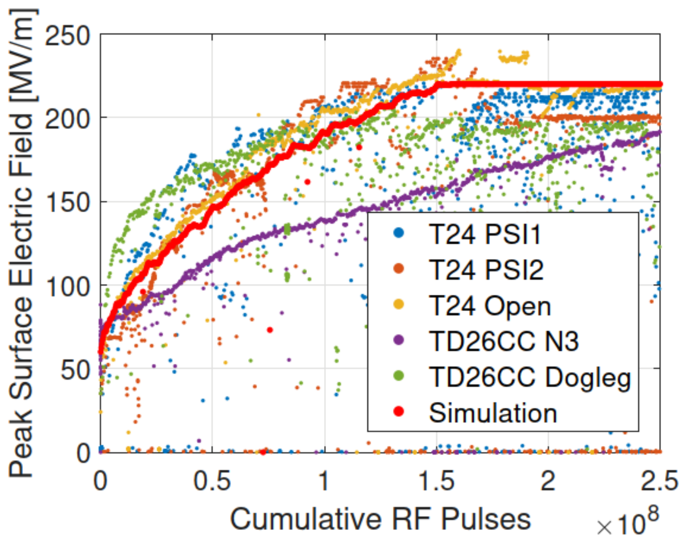


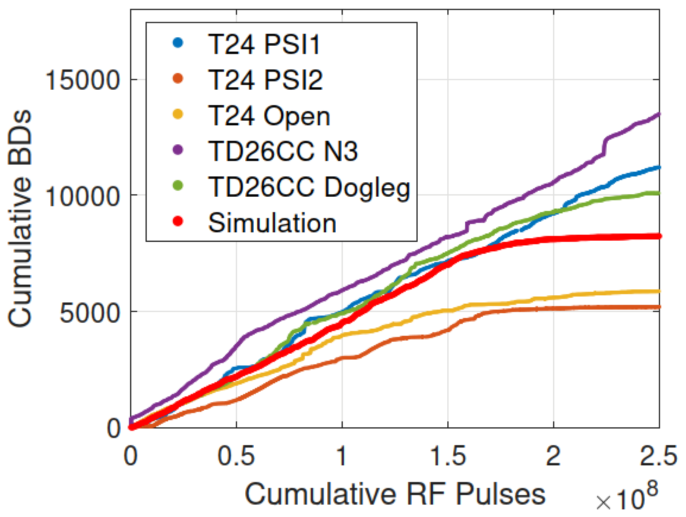

**Modelling each cell as an identical grid element.**

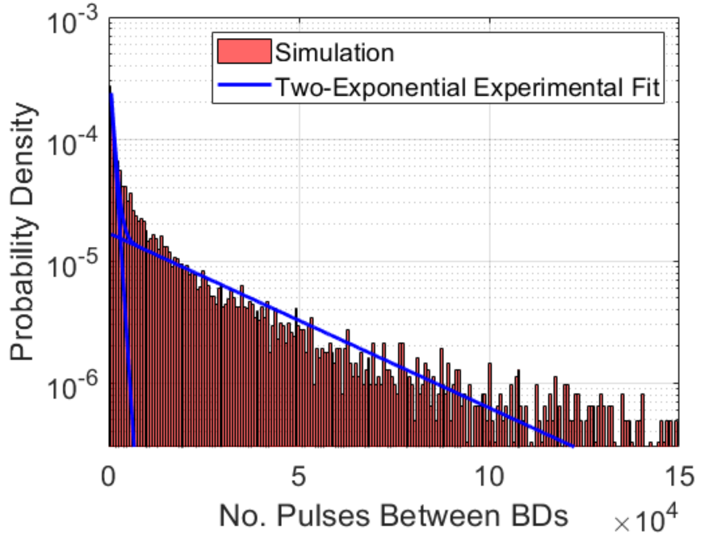


# Result 1: CLIC Prototype Structure

**Simulated conditioning in red**
**(25 grid elements).**



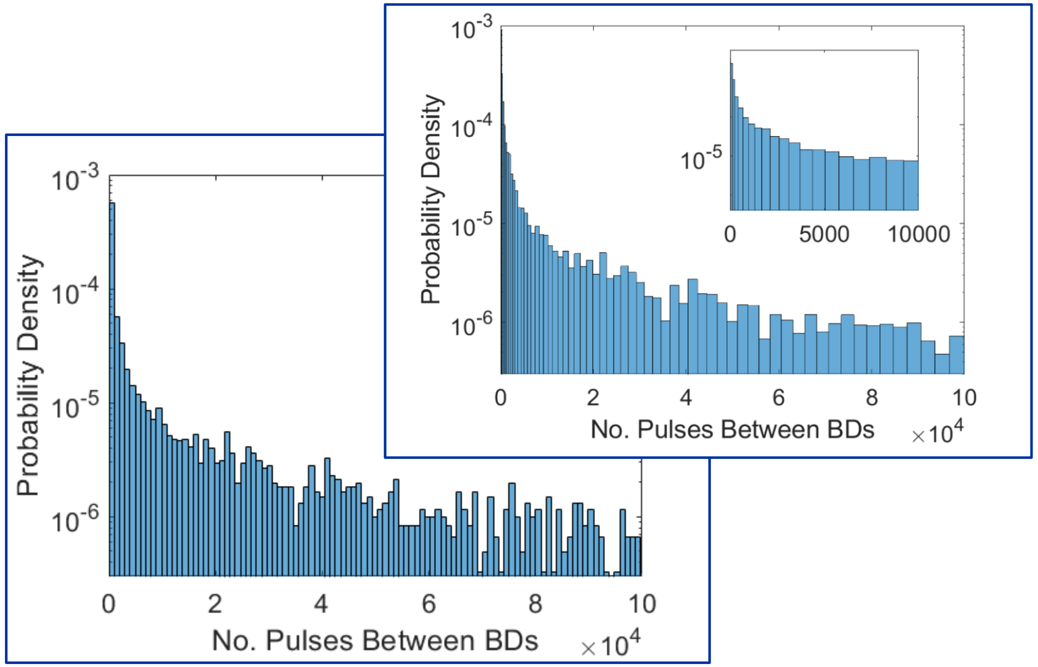



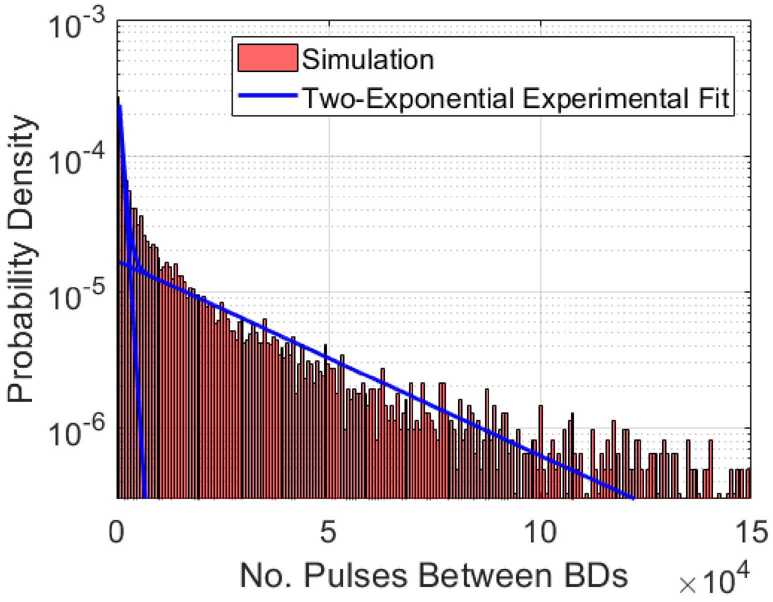
# Result 1: CLIC Prototype Structure

**Previously described as a "double Poisson" or having a "two-exponential" fit (referring to primary and secondary breakdowns). Similar behaviour emerges in simulation using a standard gaussian distribution.**

## Experimental Data Examples

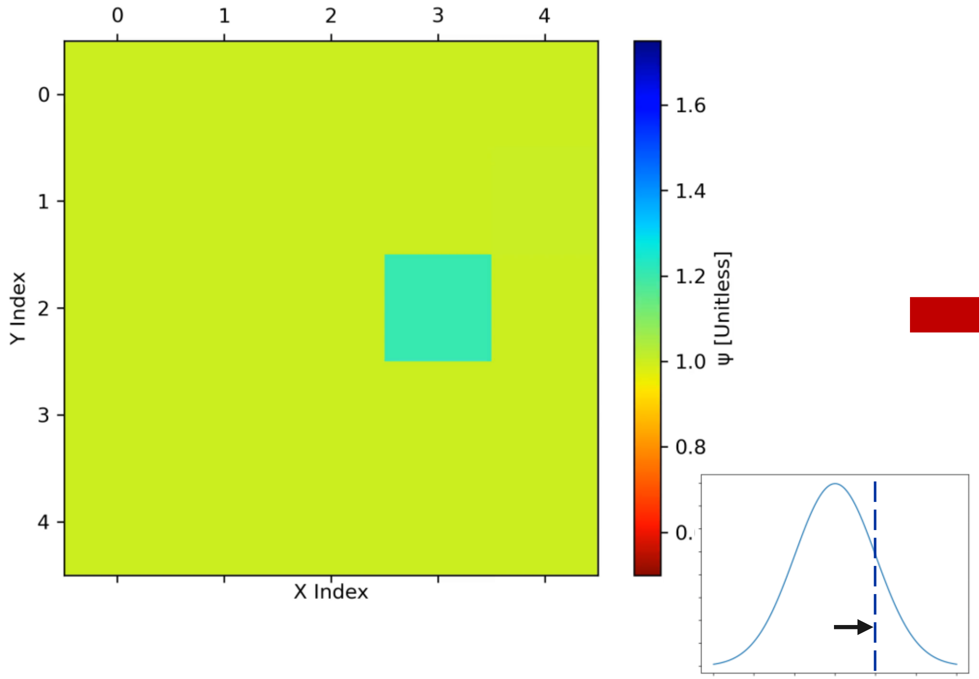


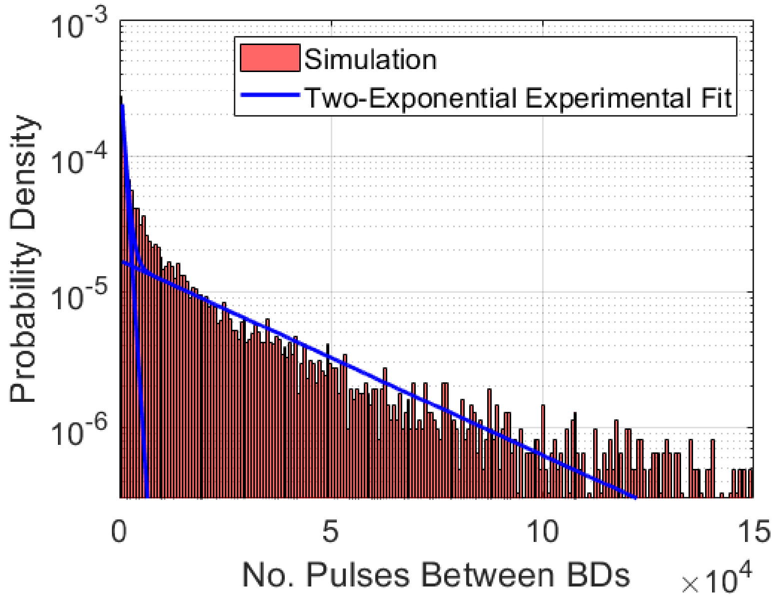

## Simulation



# Result 1: CLIC Prototype Structure

**Previously described as a “double Poisson” or having a “two-exponential” fit (referring to primary and secondary breakdowns), emerges naturally using a standard gaussian distribution.**



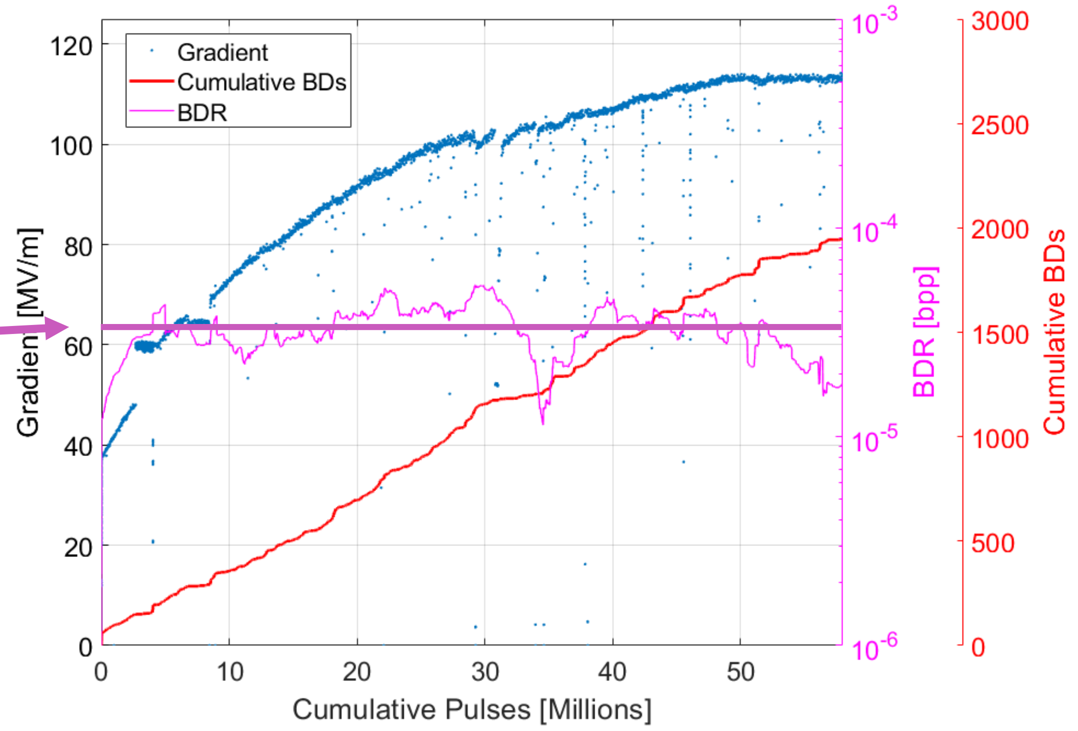




**Values tend towards stability.**

# Result 2: Adjusting CERN’s Conditioning Algorithm

One of the goals was to examine the **effects of changing the parameters in our conditioning algorithm.**

In the test stands, we track an operator-selected BDR. Little data exists on changing this value.



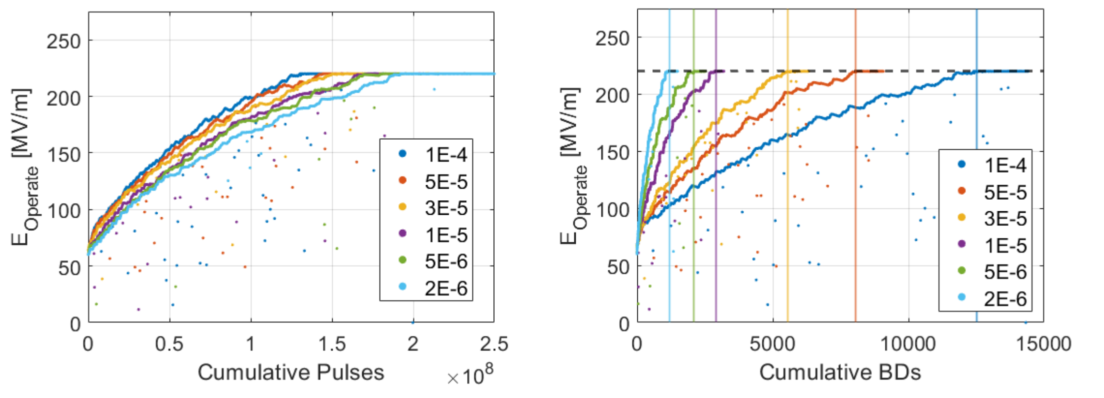
# Result 2: Adjusting CERN's Conditioning Algorithm

**Simulation predicts that reducing the BDR setpoint can reduce the BDs accrued without significantly prolonging conditioning. Results agree with experimental data.**

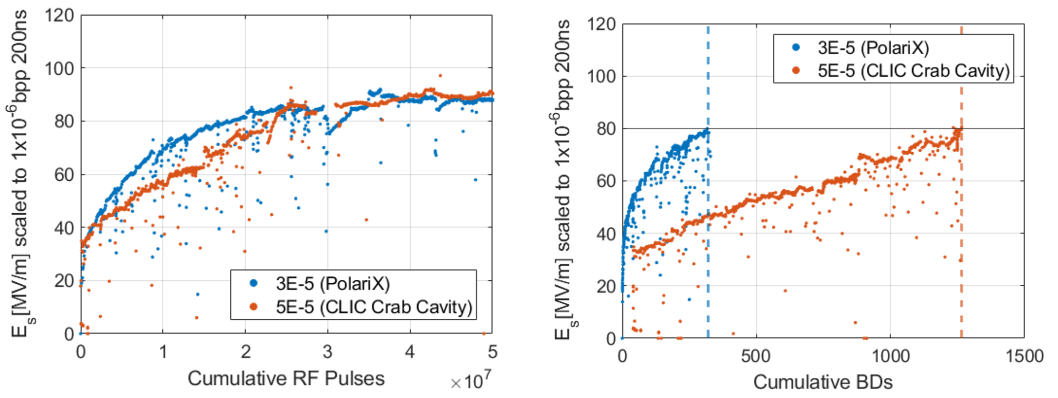
Fewer BDs at lower setpoints.

Offers an explanation for the results and an indication of how we can improve our process. Initial objective met ✔.

## Simulation




## Experiment



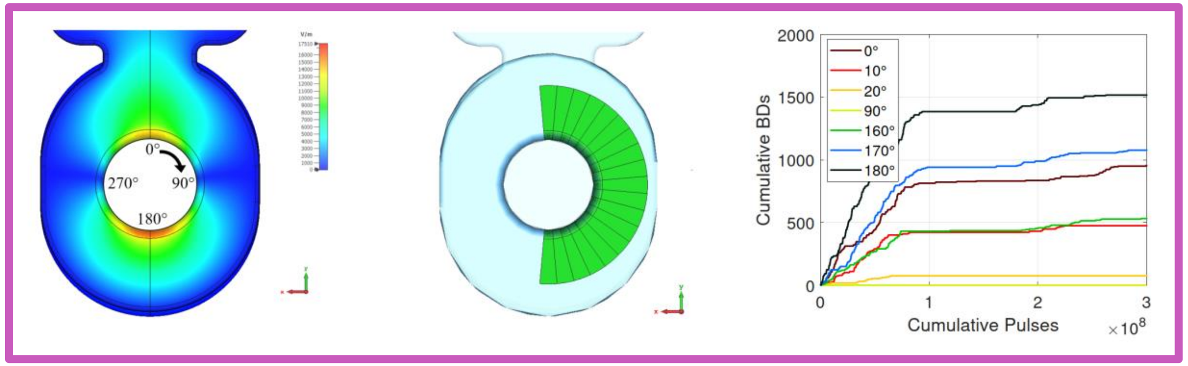
# Contents

# Conclusion & Future Work

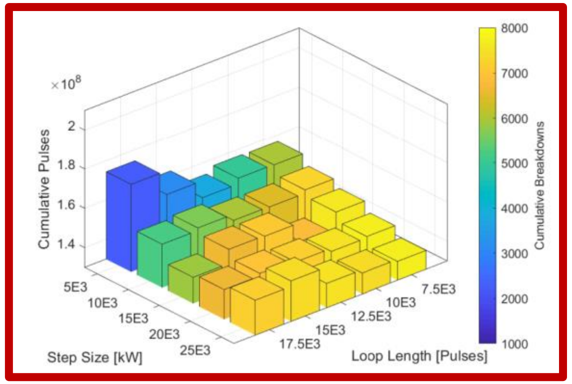
**A discretised model of conditioning has been created and the results align well with HG test data.  Future work includes:**

- **DC Case (fitting to LES data).**
- **Trial alternative probabilistic models/conditioning theories.**
- **Trial entirely different conditioning algorithms.**
- **Addition of a pulse length dependence, vacuum conditioning/other facets of operation.**

Spatially Resolved Conditioning




Algorithm optimisation.




Multi-structure simulations.

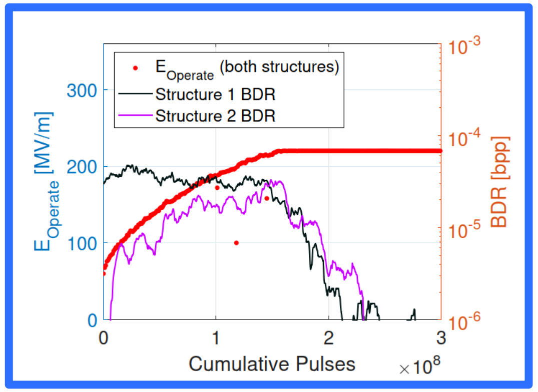



Figure: Additional ongoing Monte Carlo studies.

# Thank you. Questions?

# References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[3] – L. Cowie, G. Burt, W. Millar, and D. Scott, “High Power RF Conditioning on CLARA”, in 9th International Particle Accelerator Conference, 2018, p. THPAL085.

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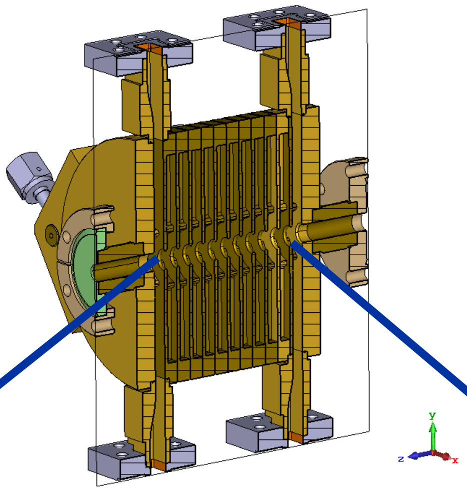
# BONUS SLIDE - Result 3: Spatially Resolved Conditioning

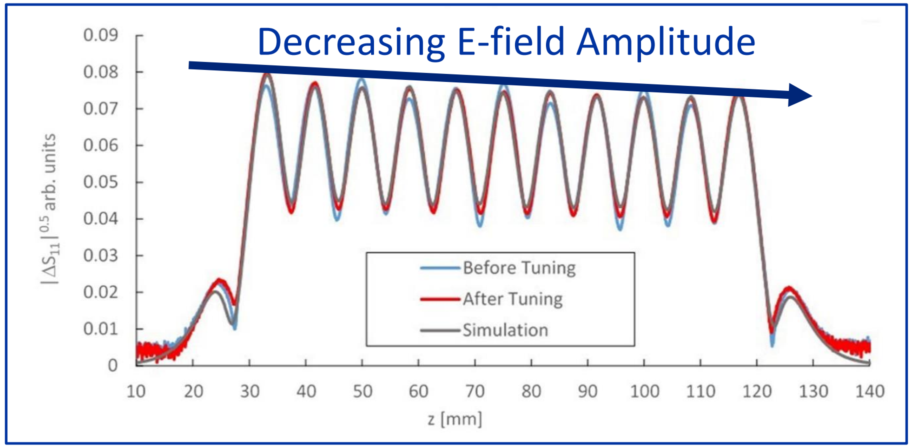
Fields typically vary across a surface and from cell to cell in accelerating structures.

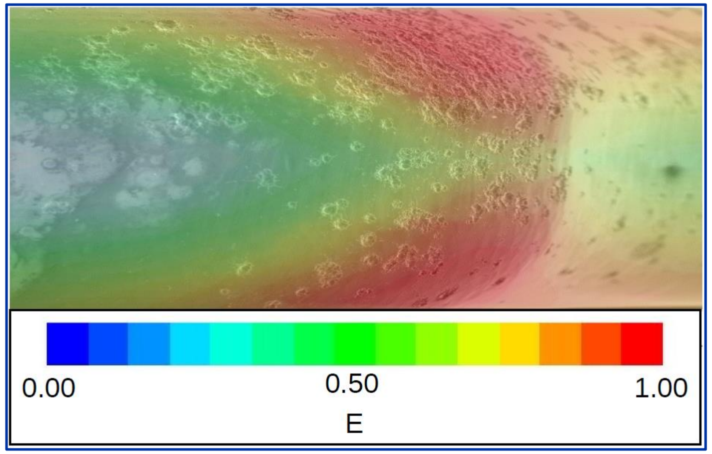
Regions experience varying levels of conditioning and in BD accumulation (both directly observed in tests).



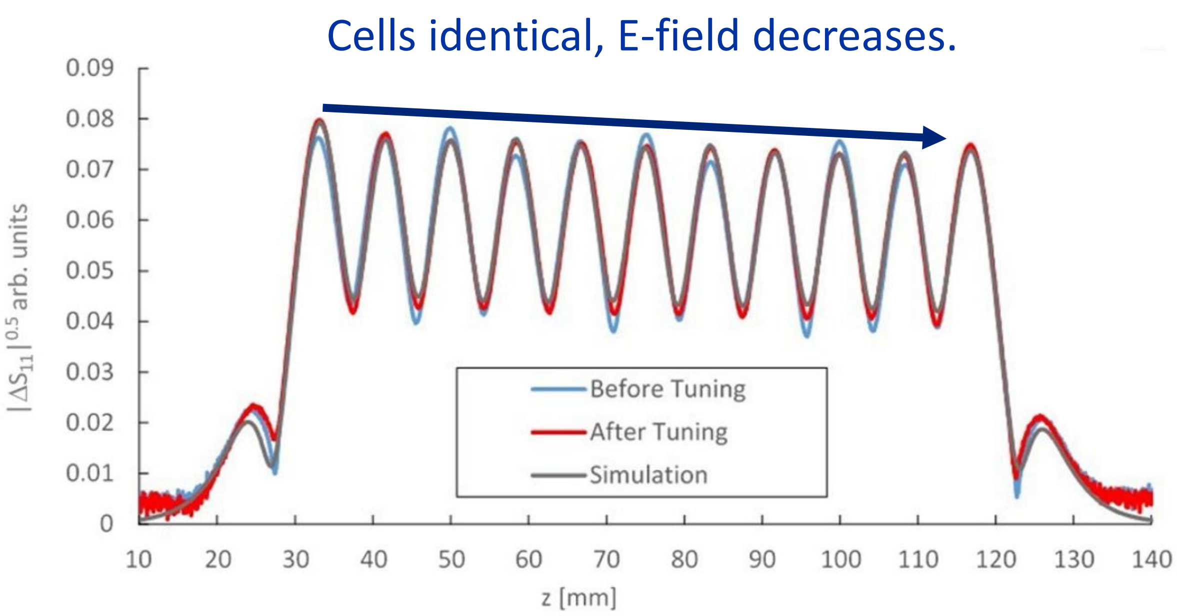
Cell to cell variance

Surface variance



# BONUS SLIDE - Result 3: Spatially Resolved Conditioning



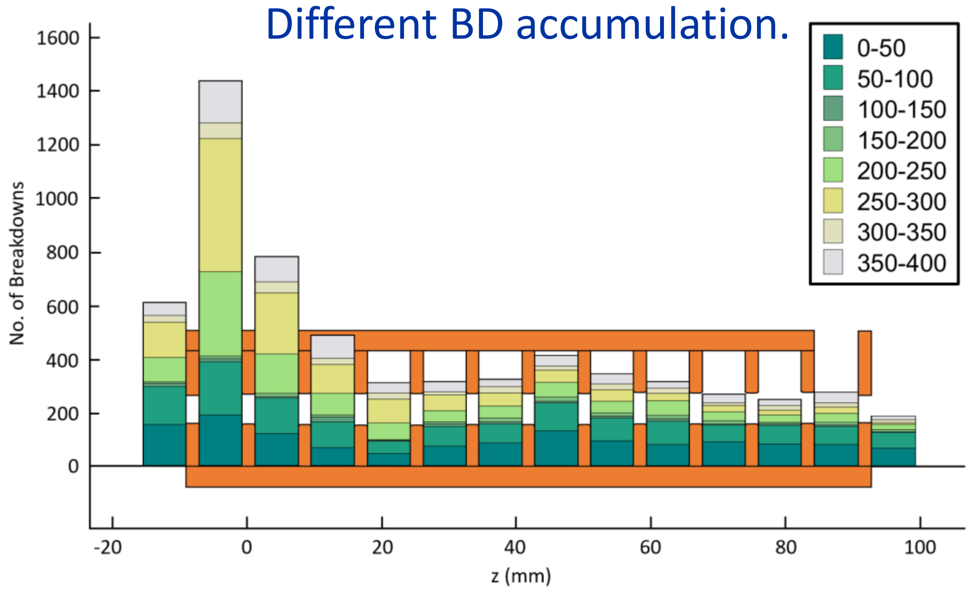
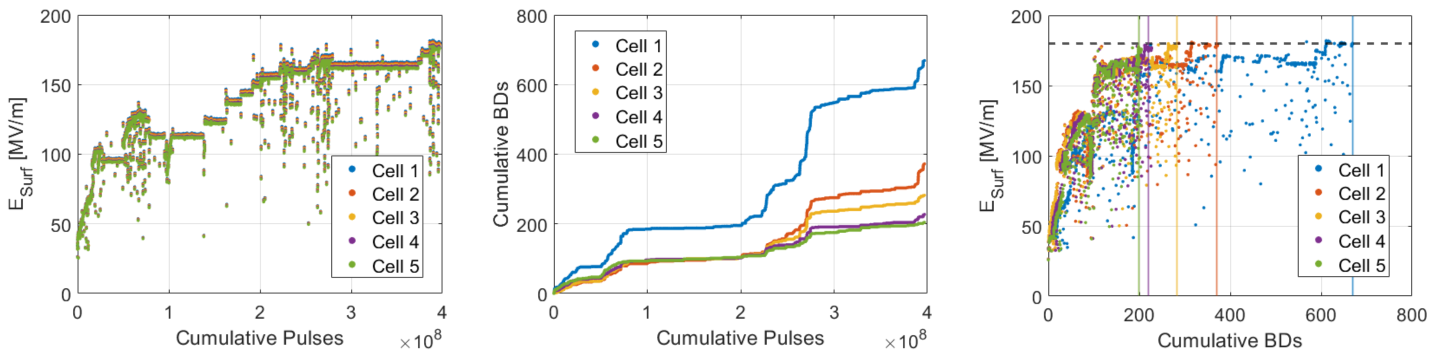



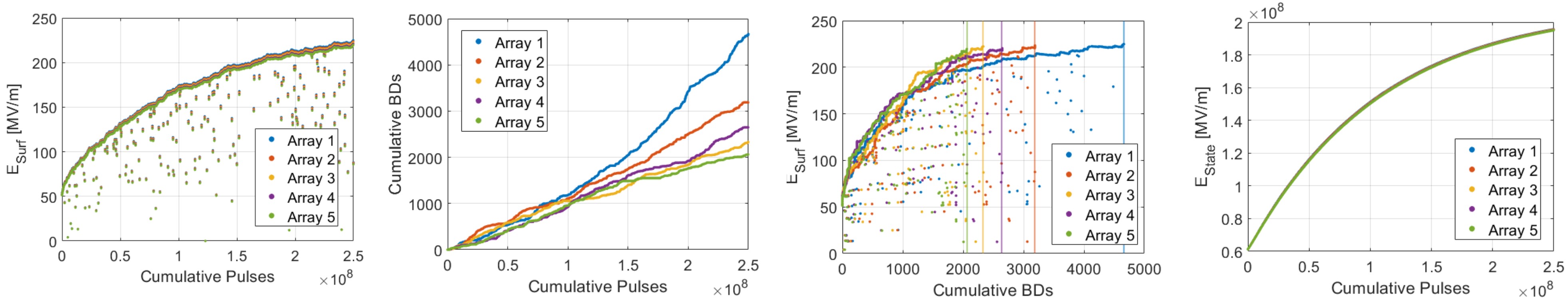

Figure: Number of breakdowns accrued in each cell for different windows of pulses (millions) during the test.

# BONUS SLIDE - Result 3: Spatially Resolved Conditioning

**Experiment**




**Simulation**




Experimental and simulation data shows cells reach virtually the same field (~97%) but accrue different numbers of breakdowns.

# BONUS SLIDE - Definition of Model Terms

$\mathbf{P_{Reference}}$ = The instantaneous probability of breakdown for a given device operating at the level to which it has been conditioned. **5E-5 bpp** selected as it is generally the max permissible BDR chosen in CERN structure tests.

$\mathbf{E_{Operate}}$ = The electric field level in MV/m at which the device operates.

$\mathbf{E_{State}}$ = The surface electric field level to which the device has been conditioned in MV/m. Operation at this field level results in a probability of breakdown which is equal to $P_{Baseline}$.

$\mathbf{E_{Sat}}$ = The saturation point for a given material in MV/m. Operation above this level does not result in any further improvement in $E_{State}$ and thus, this is the maximum surface field attainable at the reference breakdown rate (5E-5 bpp) after the device has been fully conditioned. Typically ≈ **250 MV/m** in our structures.

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