Monte Carlo Model of High-Gradient Conditioning and Operation

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9th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2021)

12/03/2021

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2. Motivation.
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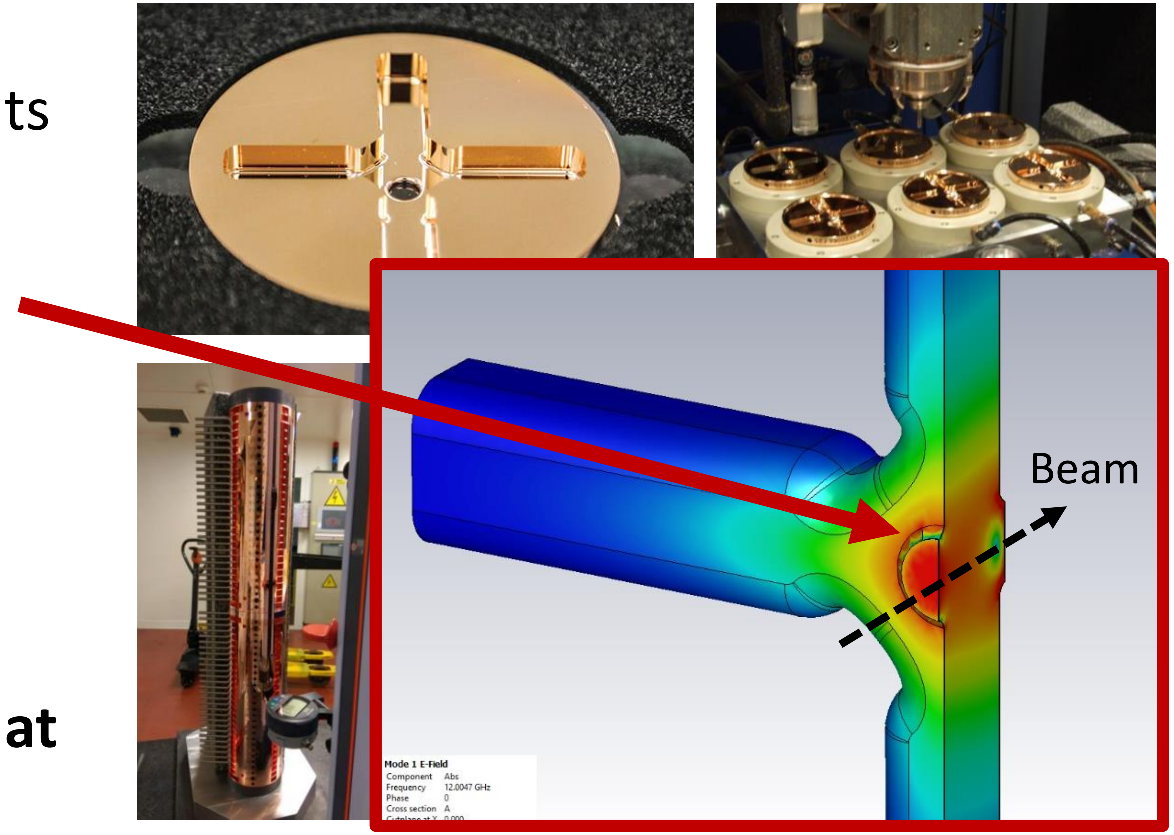
High-Voltage Conditioning

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

- 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 Power Conditioning

Limited by breakdown (vacuum arcing) and must be conditioned:

I. **Increasing gradient/power while keeping constant breakdown rate.**

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

III. **Finally, the BDR drops and we run reliably.**

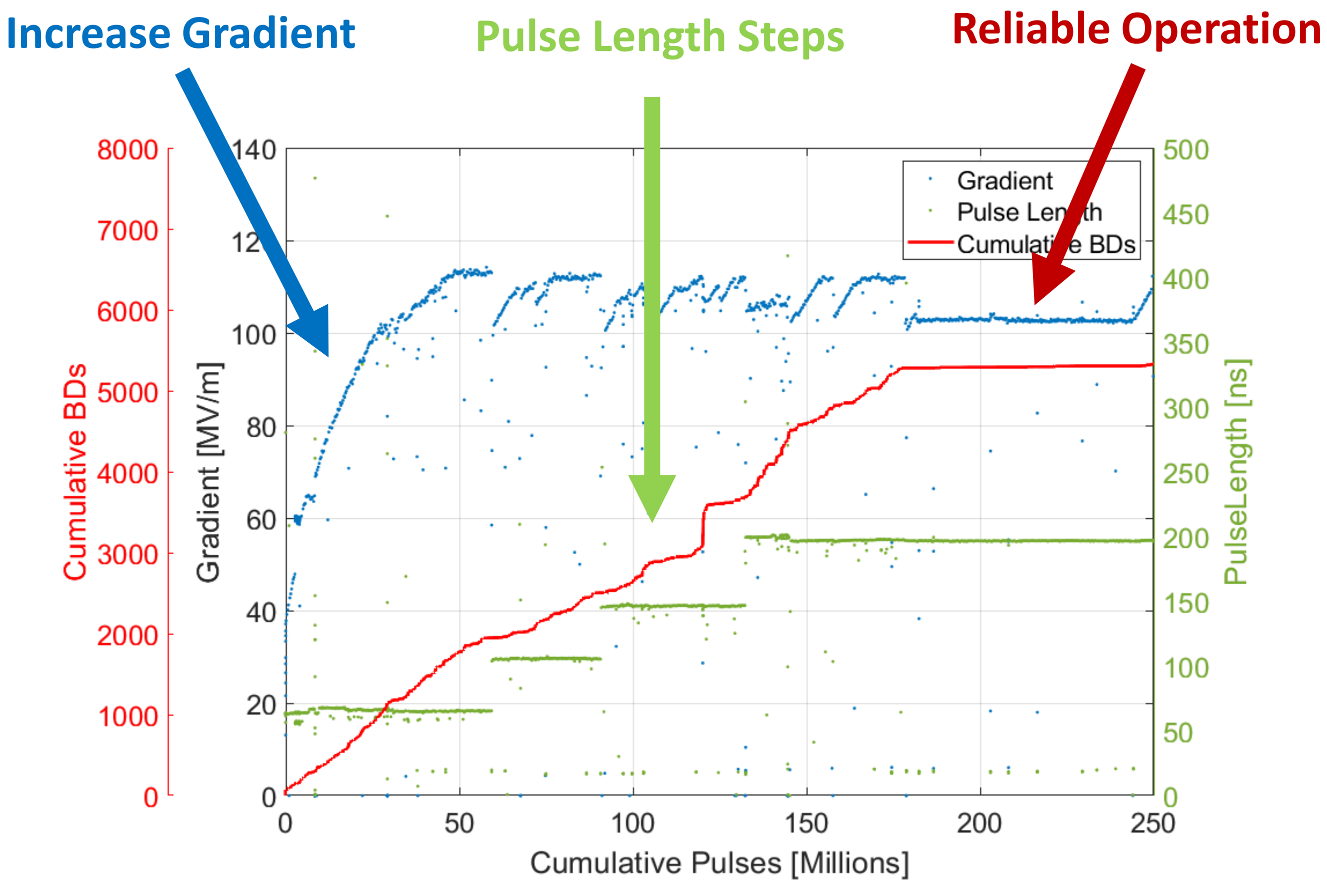


Figure: Test results of the PSI2 structure showing a typical conditioning curve.

CERN’s Test Facility

To investigate the phenomena and test new accelerating structures/RF components three X-band (12GHz) test stands have been developed at CERN.

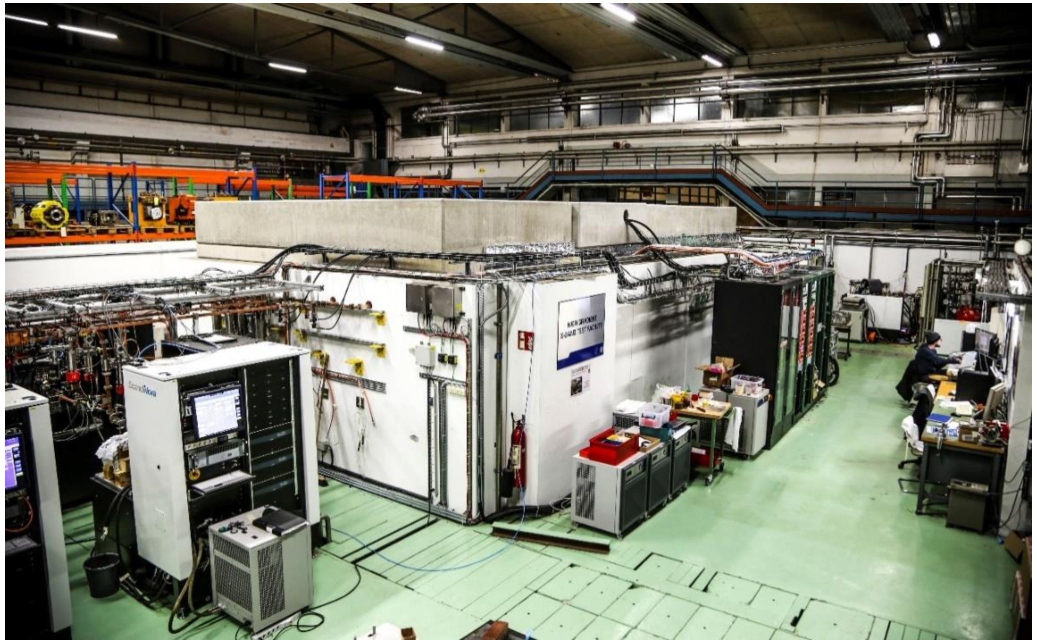


Figure: Exterior of the 12GHz high-gradient test facility at CERN.

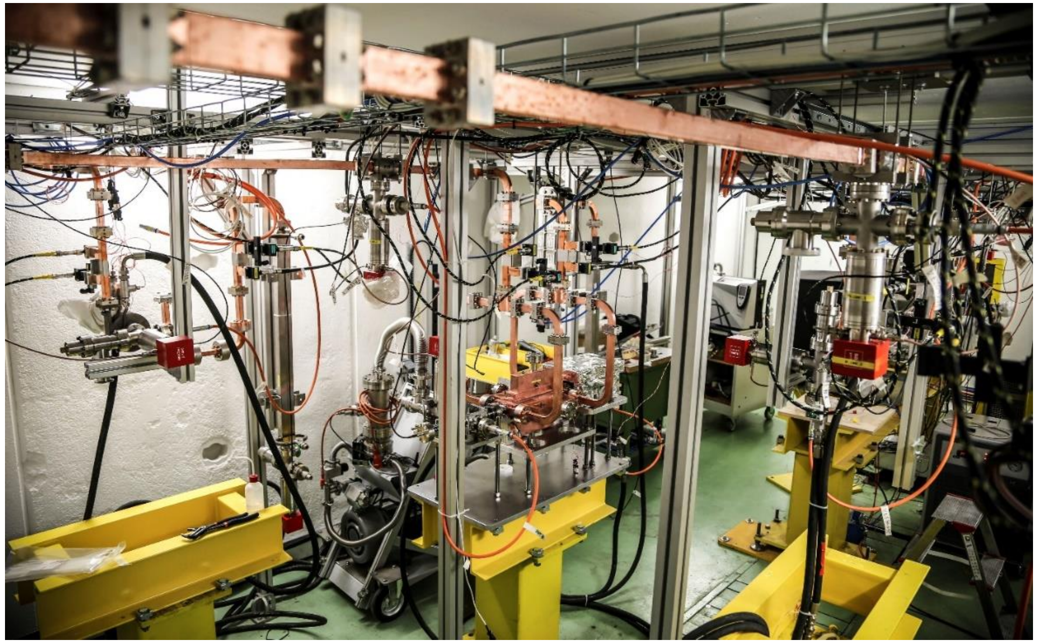
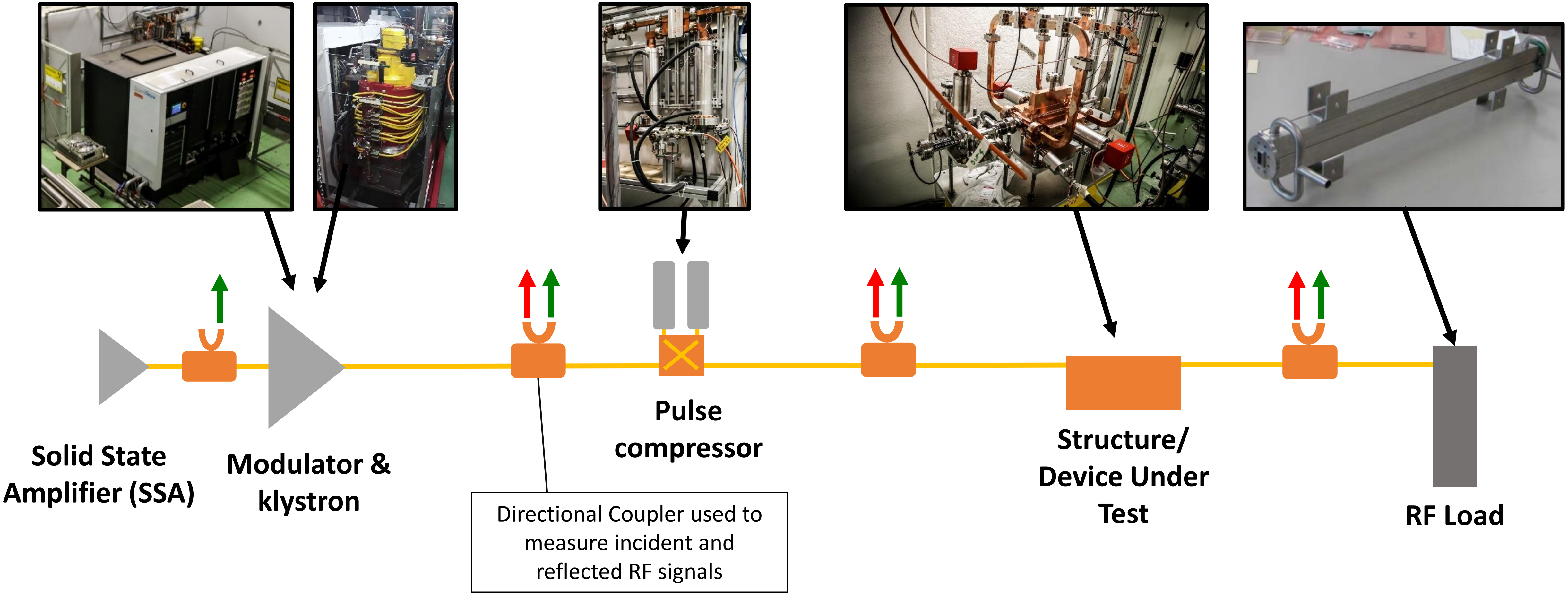


Figure: Accelerating structures under test inside the bunker.

Typical Test Stand Set-up



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How is Conditioning Performed?

Typically an operator monitors the component.

Some facilities have a partially automated process in place i.e. SLAC, CERN, KEK, Daresbury Laboratory [1,2,3].

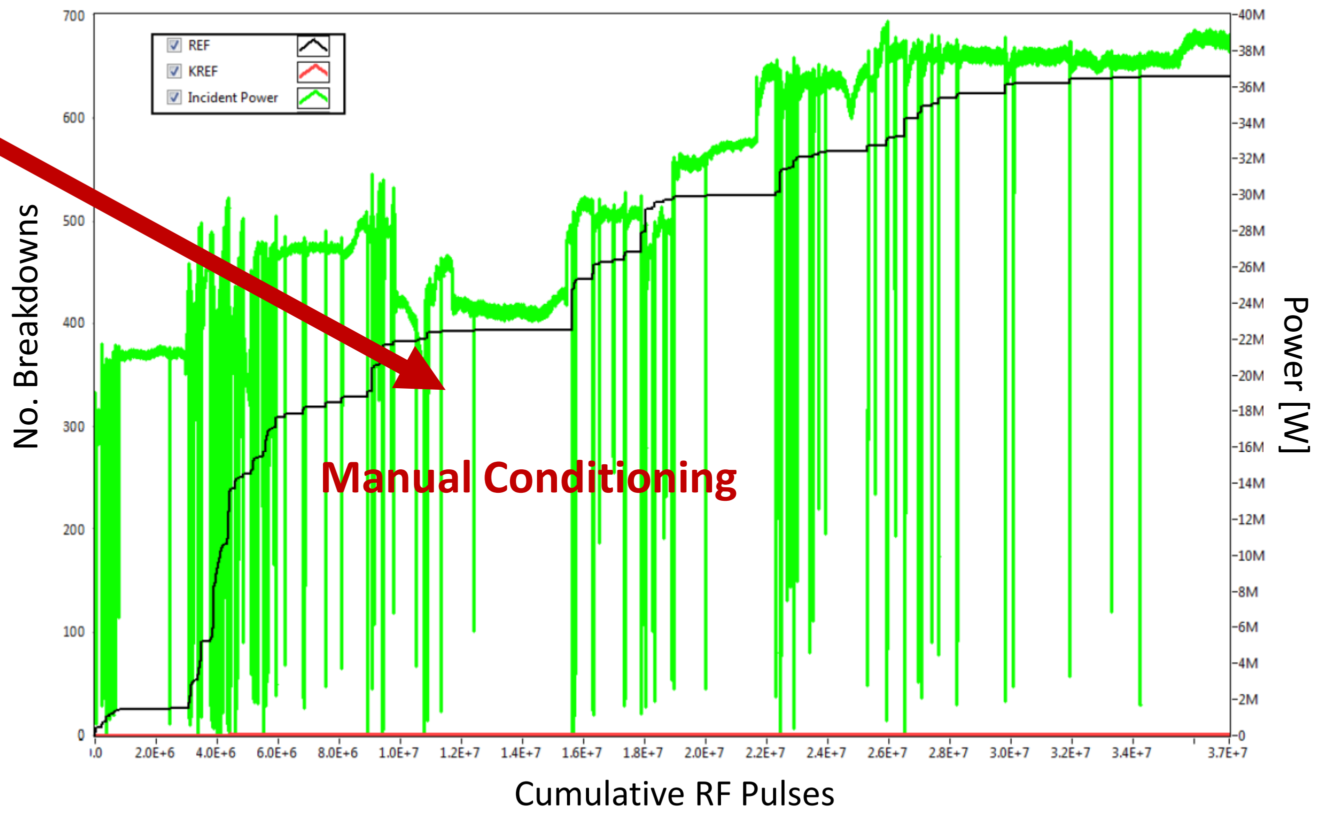


Figure: Conditioning of a T24 CLIC structure tested at CERN where the input power was ramped manually.

How is Conditioning Performed?

We have conditioned many structures however the method has been **implemented anecdotally.**

Any tuning/added features were a consequence of operational observations i.e. **responsive implementation.**

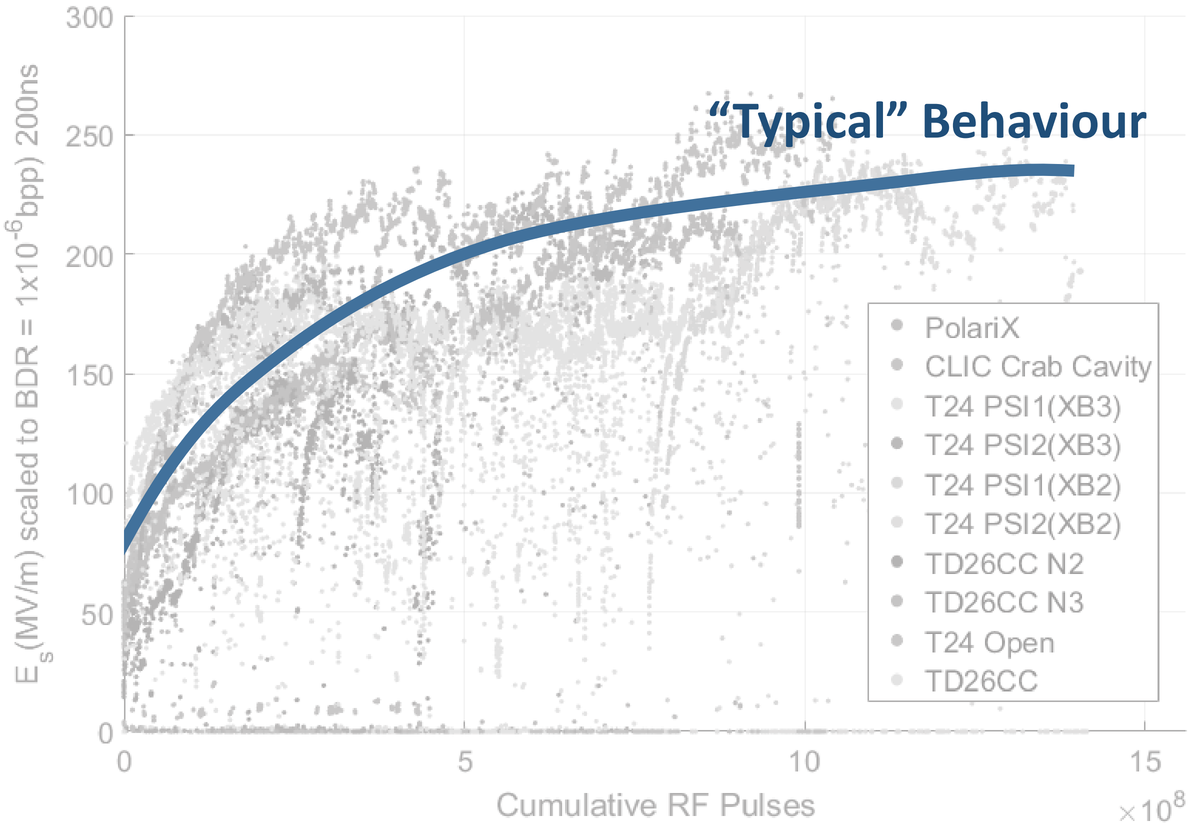


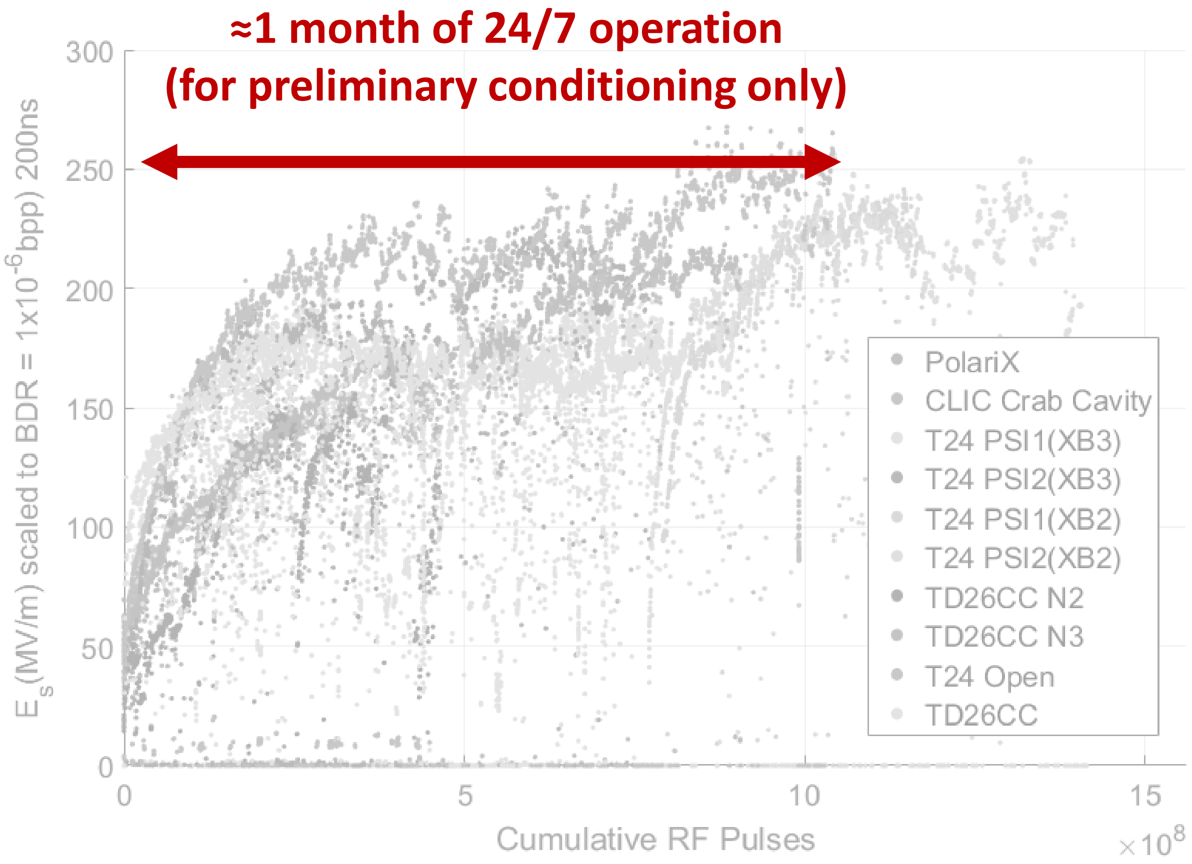
Figure: Initial conditioning of many structures conditioned to date normalised to BDR and Pulse length. Note the asymptotic behaviour.

Motivation for Simulation

Tests require a long timeframe and significant expense (months to years, tens of thousands of pounds).

Would be nice to examine different conditioning methods without the risk (and monetary /temporal expense) of sacrificing real components and electricity.

Could also shed some light on the probabilistic behaviour/physics.



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Disclaimer: Types of Conditioning

BDR/Intrinsic Conditioning:

Modification of the cavity material properties through repeated exposure to high fields.

Largely stochastic behaviour.

Results in a sustained increase in propensity for establishing high fields.

I'll be referring to this one today.

Vacuum/Extrinsic Conditioning:

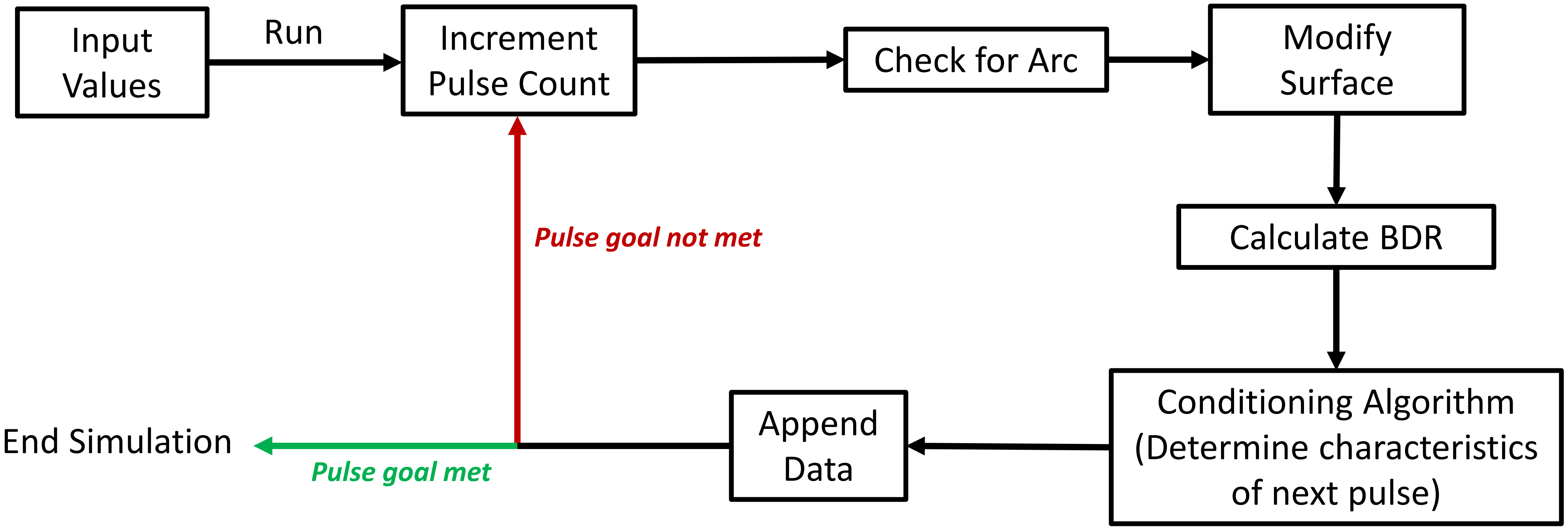
Limited by vacuum activity.

Related to the removal of contamination on the surface. Breakdown may also be nucleated by such residual particulates.

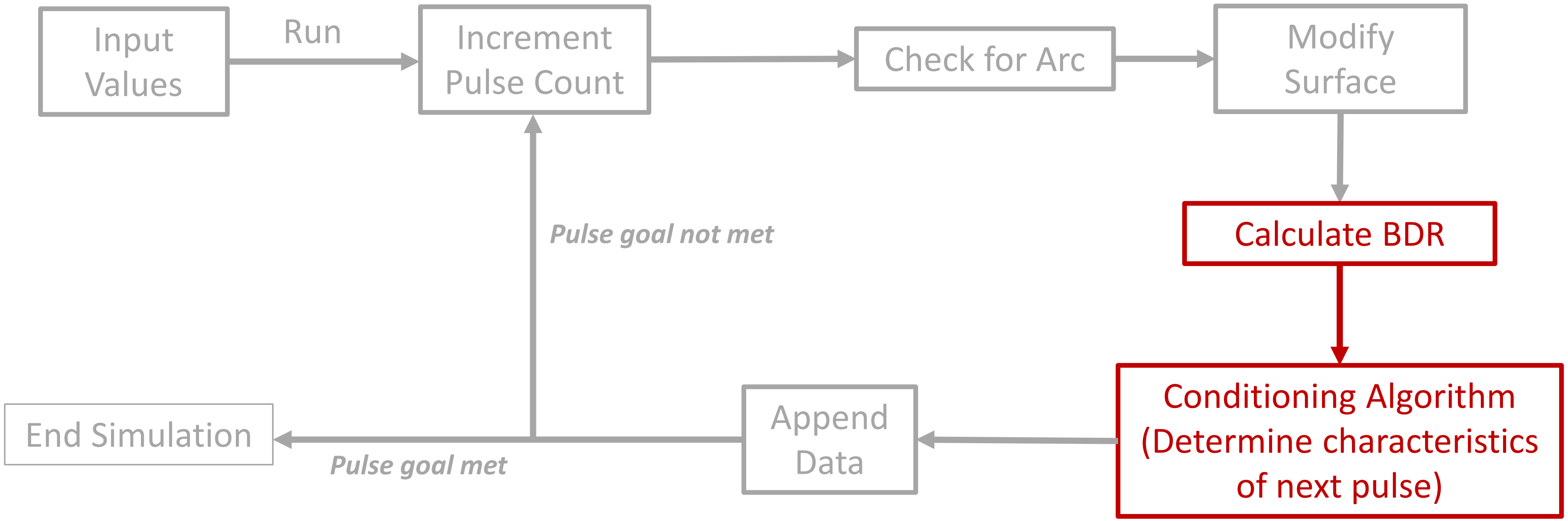
Prevalent at low power in the early stages of conditioning, "cleans" component.

See paper by Anton Saressalo [4].

Overview of the Model

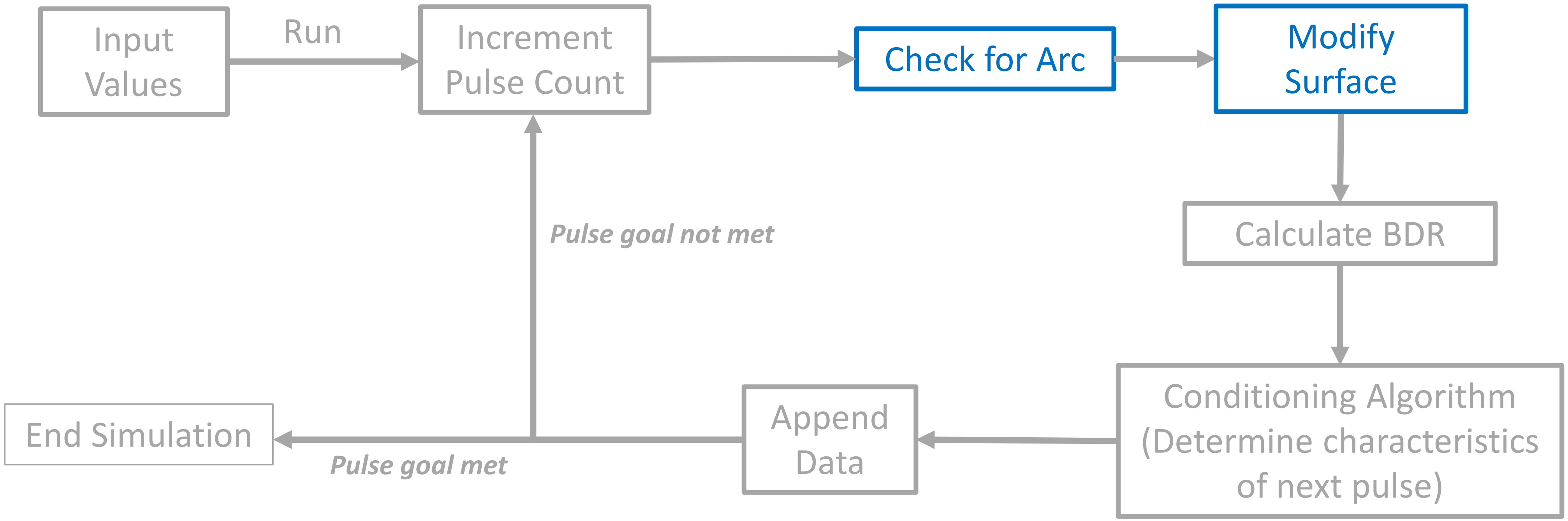


Overview of the Model



Then we can investigate the effect of these.

Overview of the Model



But first we need to model these functions...

Assumptions of the Model: Conditioning

Recent evidence suggests that:

- Structures condition on the **number of pulses not the number of breakdowns [5]**.
- Cleanliness of preparation shown to affect number of breakdowns during conditioning, **not ultimate performance[6].**

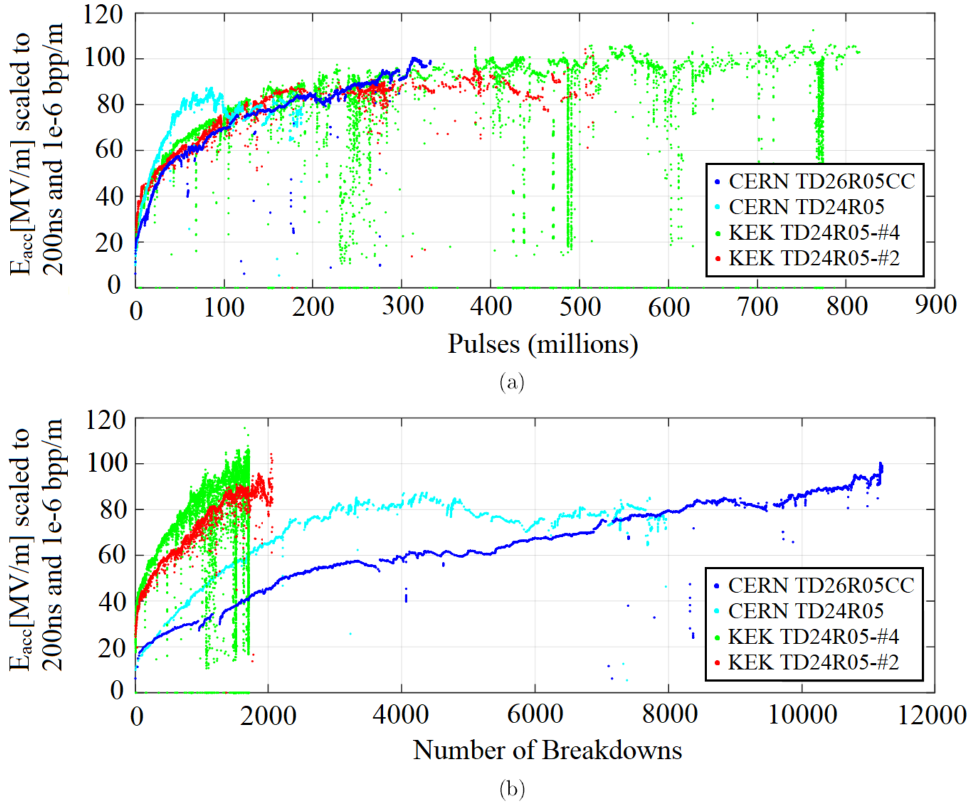


Figure: Scaled gradient vs. cumulative no. pulses (top) and scaled gradient vs. cumulative no. breakdowns (bottom) for four different structures[5].

Assumptions of the Model: Limit

However we cannot condition indefinitely, there is a material dependent intrinsic limit which cannot be exceeded **(the asymptotic behaviour shown below)**.

Quasi-limit

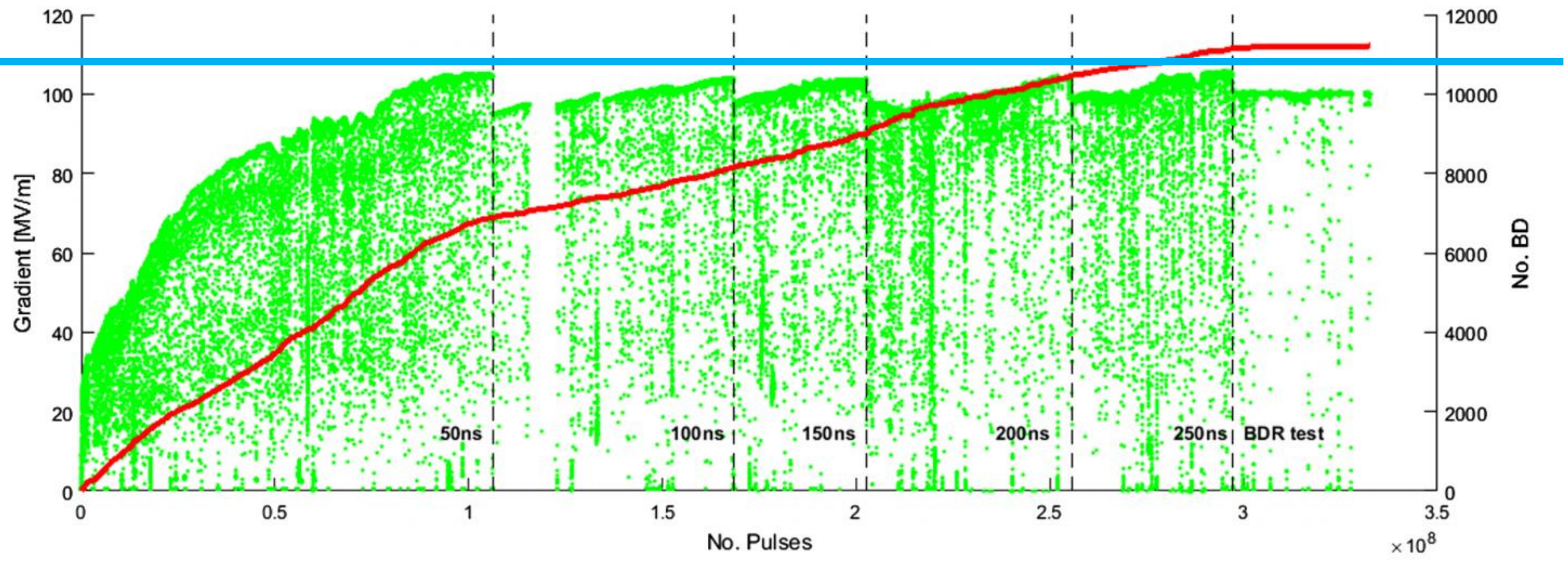


Figure: Full conditioning history of a TD26CC [3].

Terms of the Model

Convenient to define in terms of the electric field due to the existing empirical scalings [7]:

$\mathbf{E}_{\mathbf{Operate}}$= The field at which we operate.

$\mathbf{E}_{\mathbf{State}}$ = Represents the conditioned state of the surface, modified pulse to pulse.

$\mathbf{E}_{\mathbf{Sat}}$ = Saturation point/field above which the surface no longer improves (or accumulates damage faster). Assumed to be ≈ 250MV/m for copper at room temperature.

Not the only important quantity though!

Terms of the Model

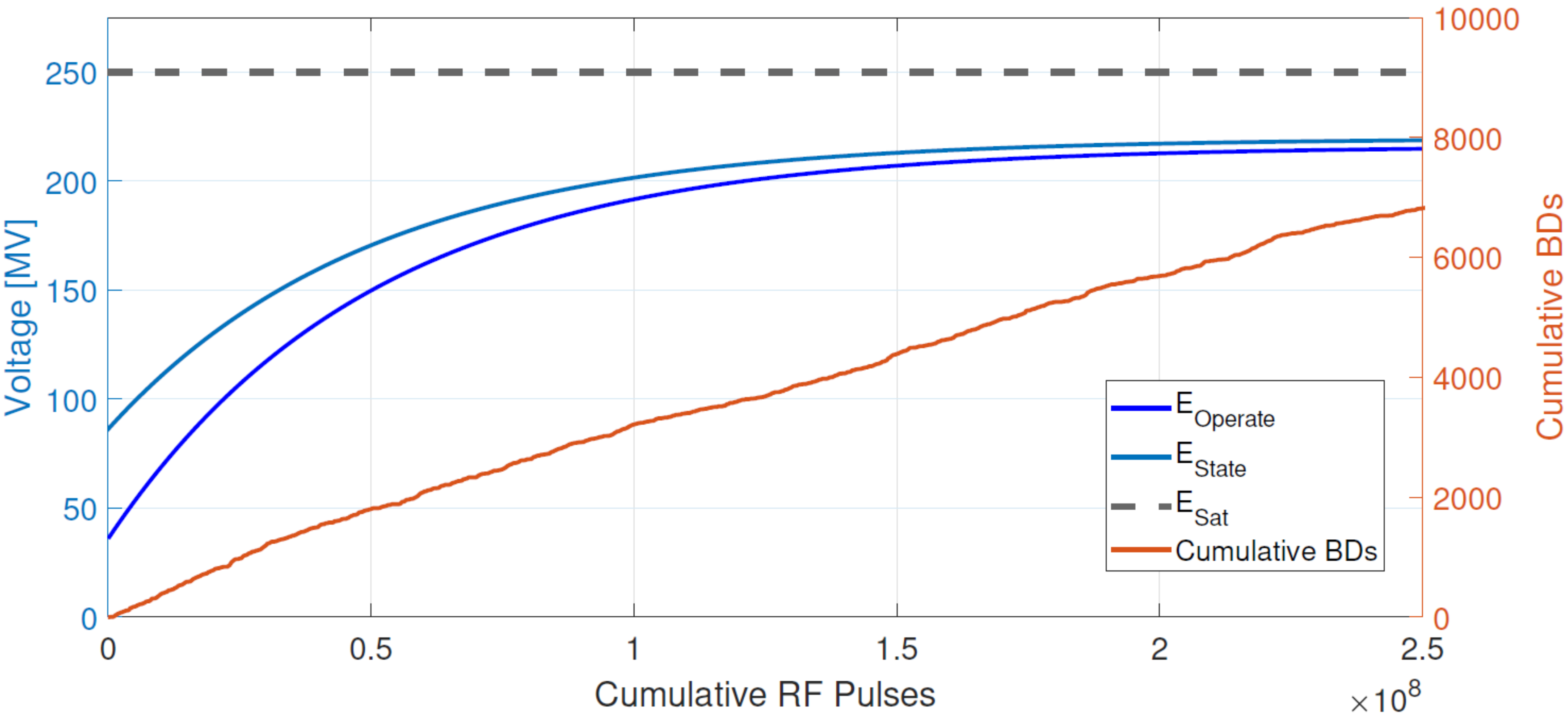


Figure: Visualisation of proposed quantities during conditioning.

Conditioning Simulation

Need a term to modify the surface every pulse i.e. describe the conditioning rate (CR) per pulse.

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

To produce a significant conditioning effect the operating field must be close to the level to which the surface is conditioned. Should also asymptotically approach the limit.

Conditioning Simulator: BD Probability

Empirically noted that surface electric field and BDR have a strong relation [7].

$$BDR \propto E^{30}$$

Probability of breakdown (PBD) decreases sharply as we conditioning:

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

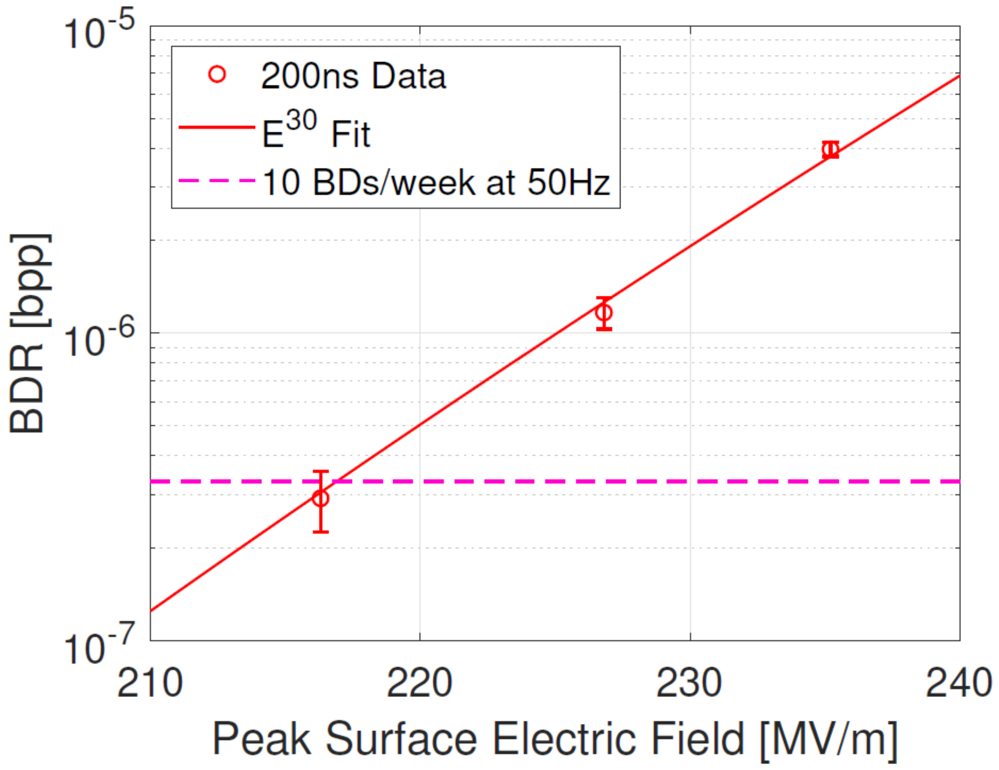
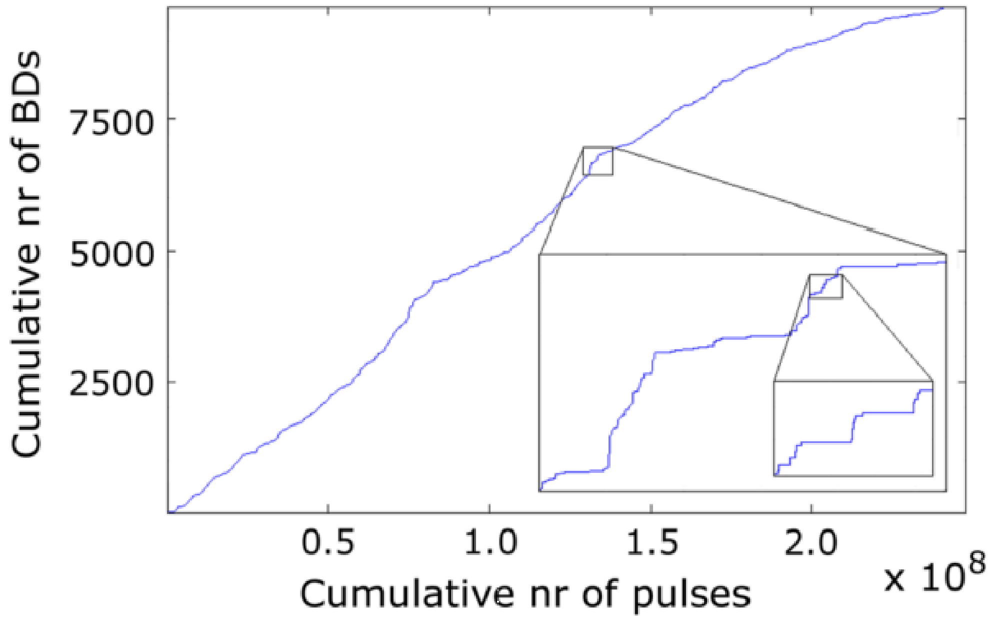


Figure: The measured BDR as a function of peak surface electric field for the T24 PSI2 structure tested in CERN's Xbox-2 test stand at a pulse lengths 200ns.

Comparison with Real Data

While primary breakdowns occur stochastically, they tend to occur in groups (have follow-ups)[8].



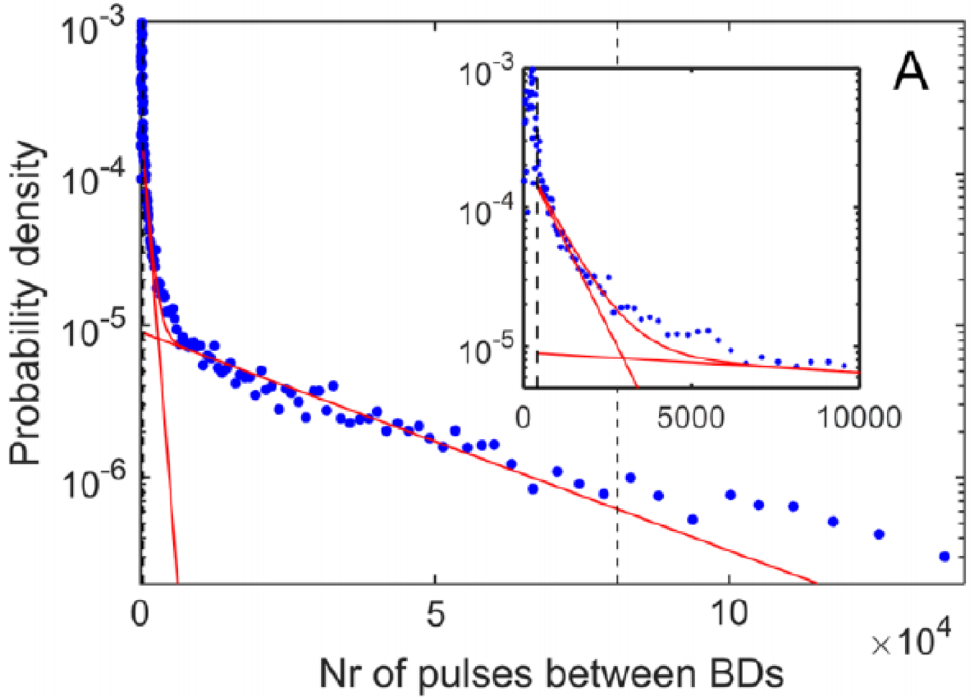


Figure: Cumulative number of breakdowns as a function of cumulative RF Pulses for a TD26CC structure tested in Xbox-1 and a distribution showing the number of pulses between breakdowns with a double fit in red[8].

Conditioning Simulator: Grid Approach

A breakdown randomly improves or worsens the surface. We opted for an quasi-enhancement factor in the BD calculation taken from a gaussian distribution.

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

The effect is also local however, so we have opted for a grid-based approach. For the preliminary simulations, 26 elements corresponding to the cells in a prototype accelerating structure.

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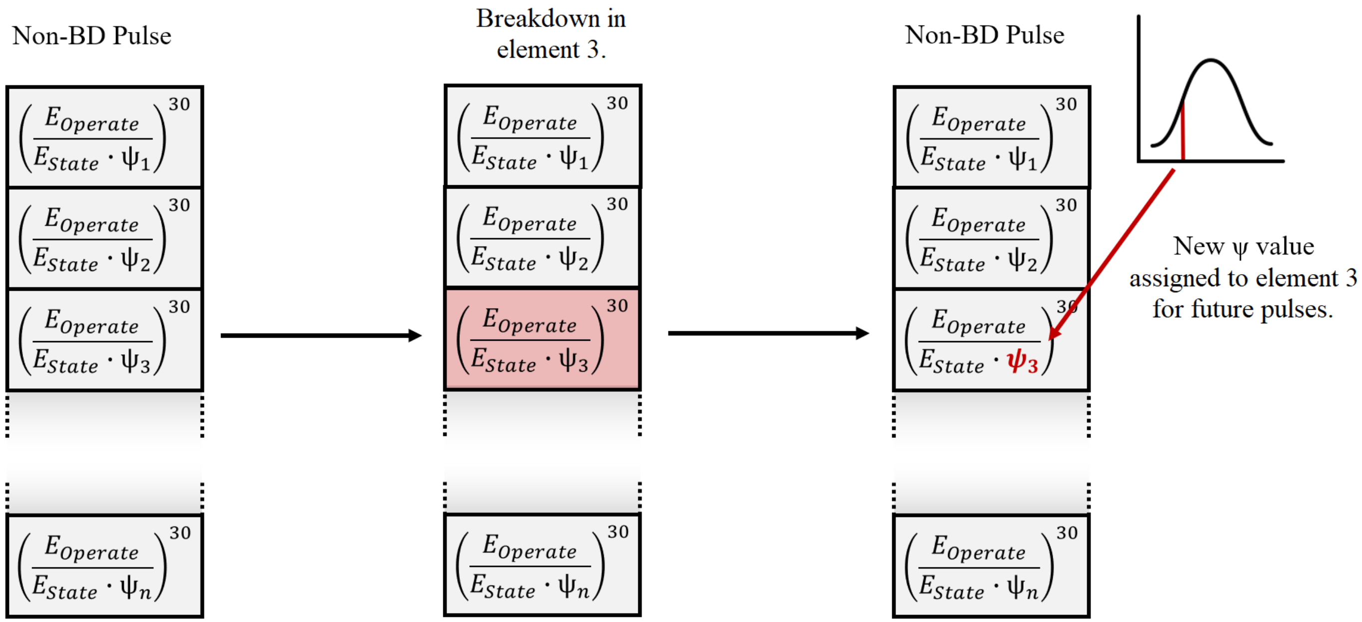
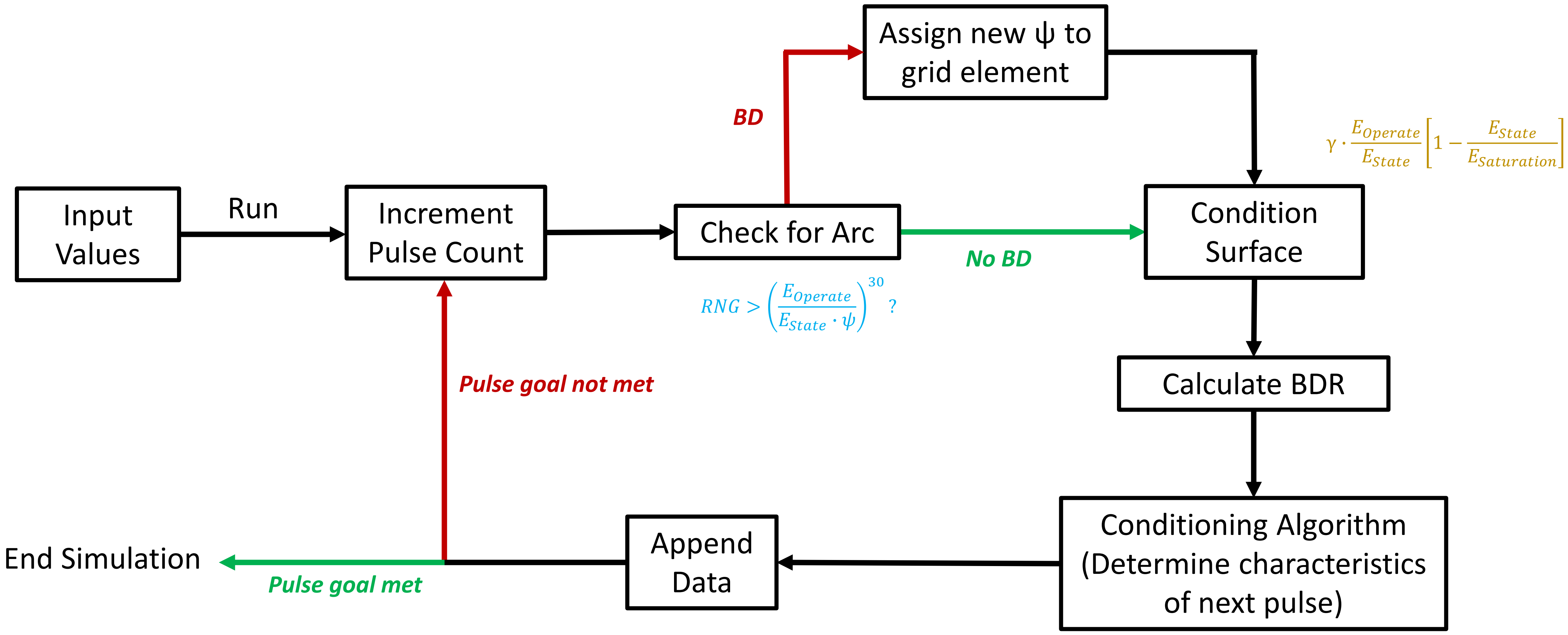


Conditioning Simulation: Broad overview



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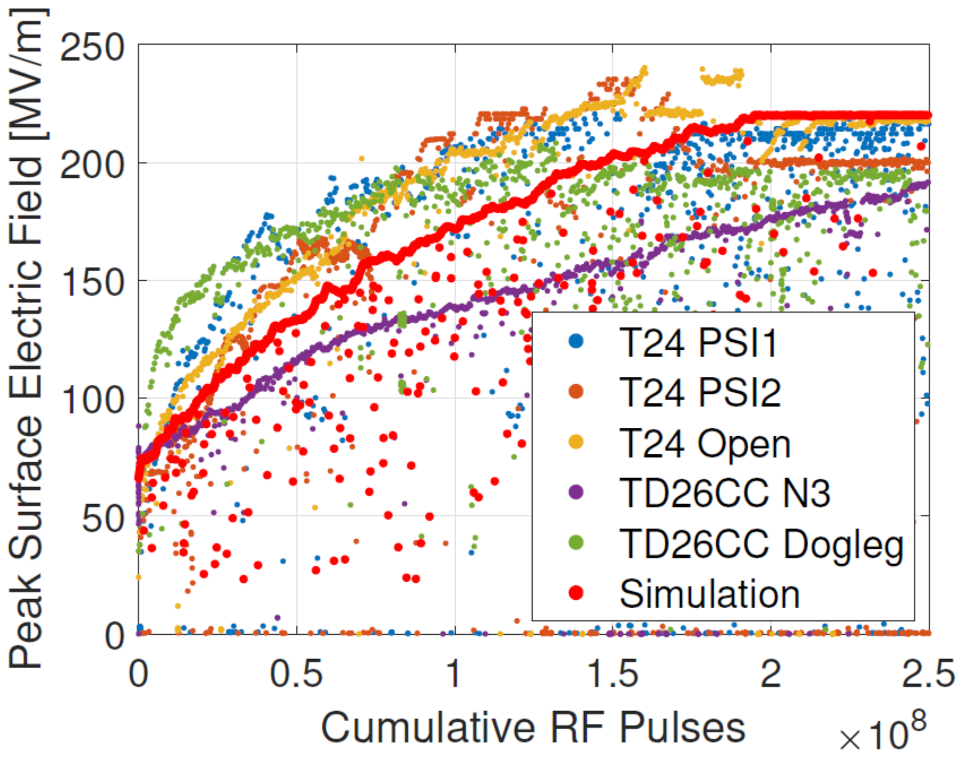
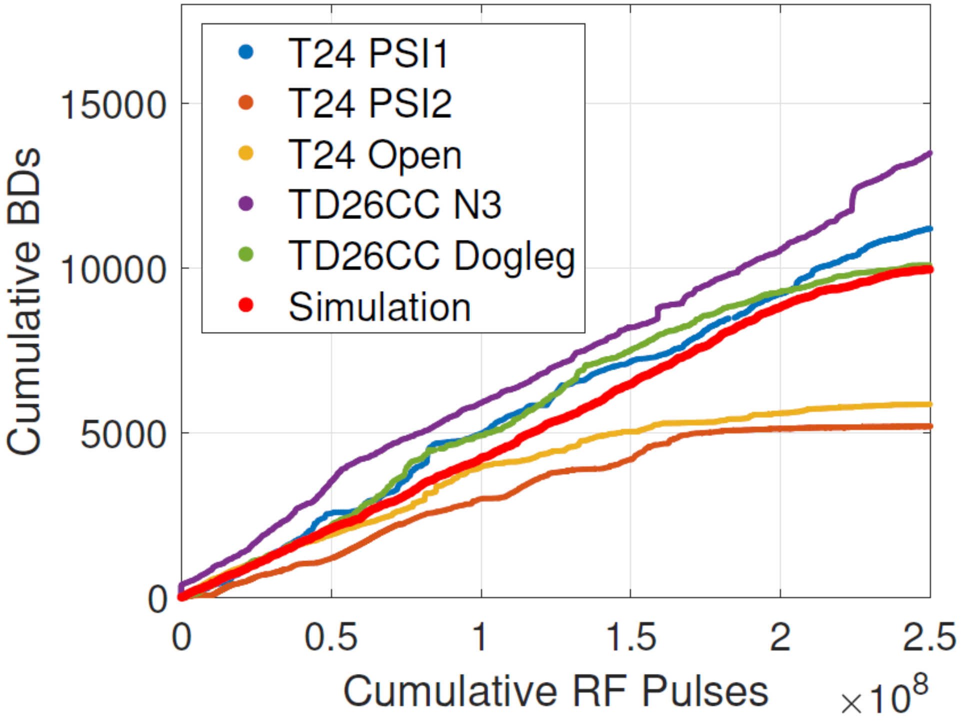
Comparison with Real Data

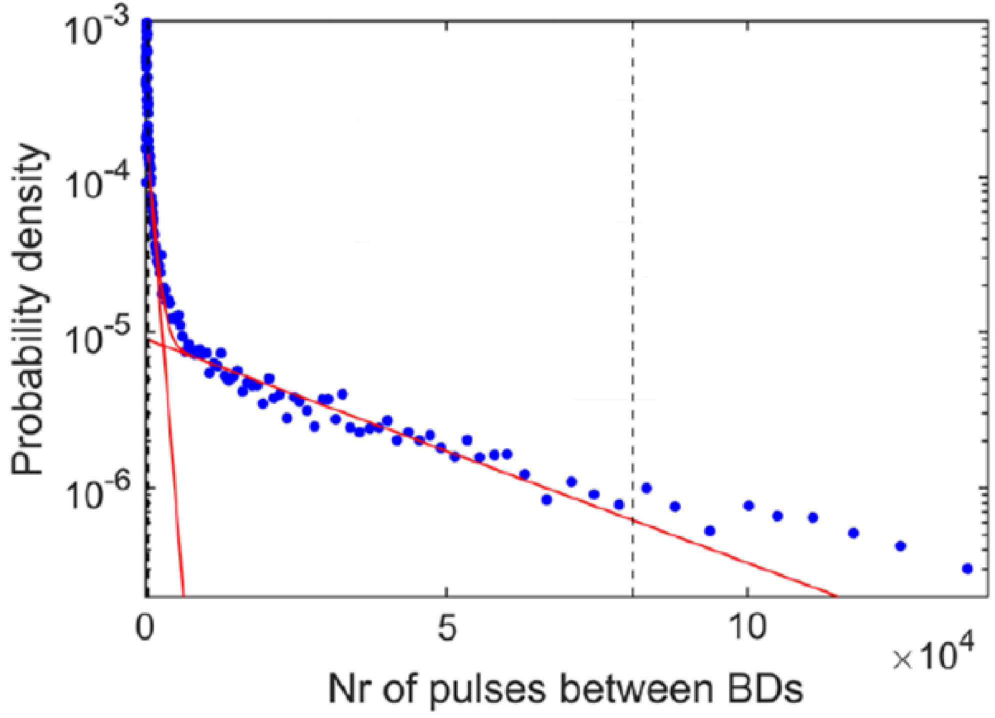
Simulated conditioning in red



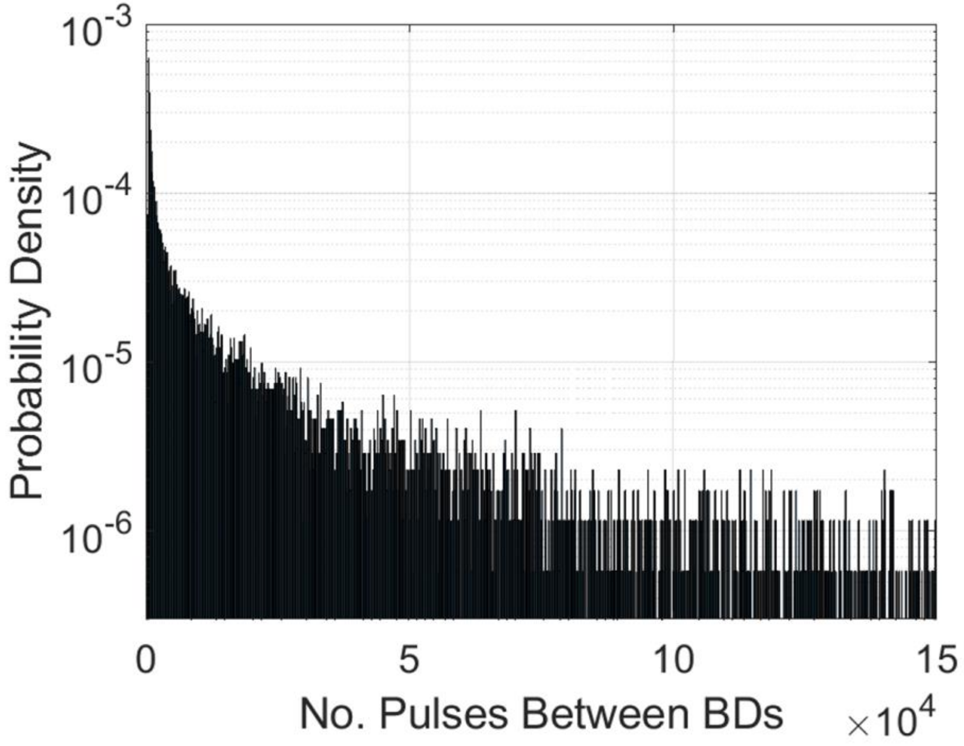


Comparison with Real Data

Real data with “two-rate” fit [5].



Simulation results.



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Conclusion and Future Plans

A **lumped model framework based on a pulse-to-pulse modification of the surface** has been created and demonstrates reasonable agreement with experimental data.

Future plans include:

- Investigate optimised (efficient, low risk) methods of conditioning and trial the results in the test stands at CERN.
- Trial other empirical scaling/probability distributions within the framework.

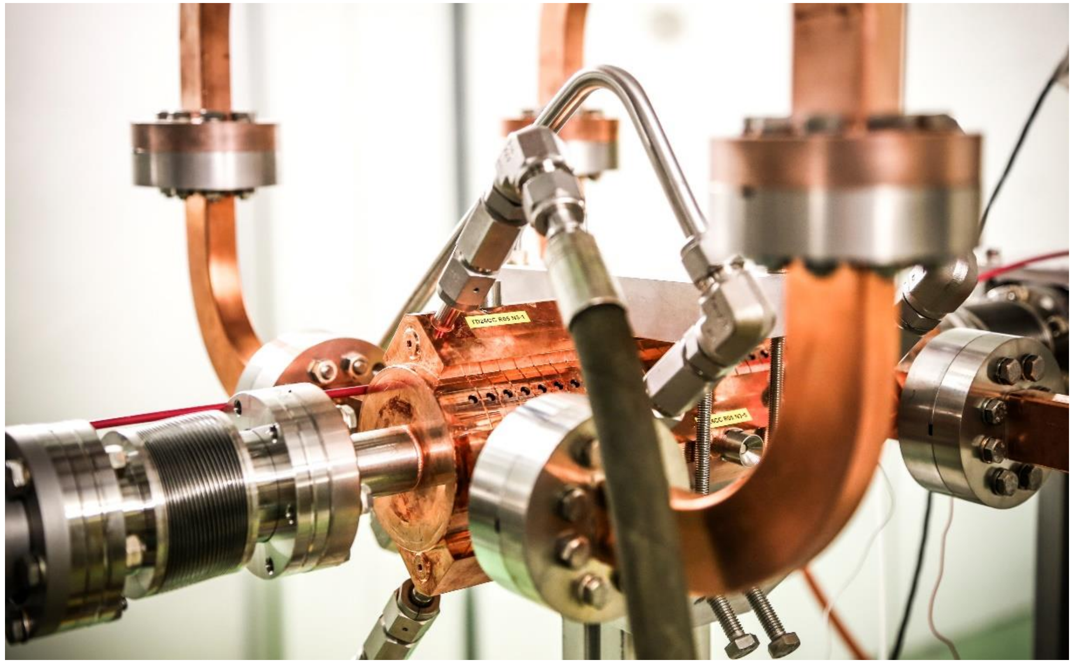

Figure: A TD26 accelerating structure installed in CERN's test stand for conditioning. Future algorithms may be trialed on an identical structure.

Thank you. Questions?

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