Investigation of the Mechanism Behind Conditioning: Context, Simulation, Experiment

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CLIC Project Meeting #45, Tuesday 19th March 2024

A Short Notice…

Originally, this talk was scheduled to be a two-parter. Unfortunately, Victoria is not able to join us today, so I will attempt to present a few of her slides too.

For further results, please see the following MeVArc talks:

- **https://indico.cern.ch/event/1298949/contributions/5783849/**
- **https://indico.cern.ch/event/1298949/contributions/5783848/**
- **https://indico.cern.ch/event/1298949/contributions/5783864/**

Contents

High-Field Conditioning

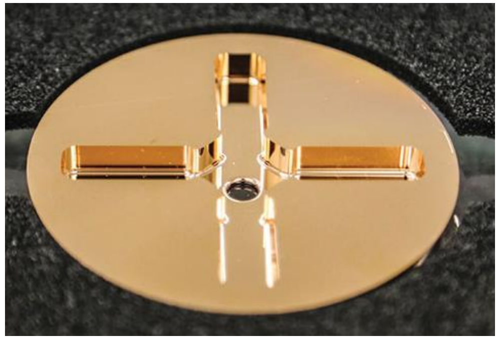
A few typical numbers for the CLIC RF cavities:

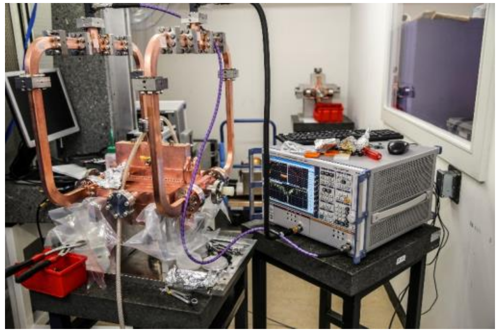
Peak surface E-field: ≈ 220MV/m

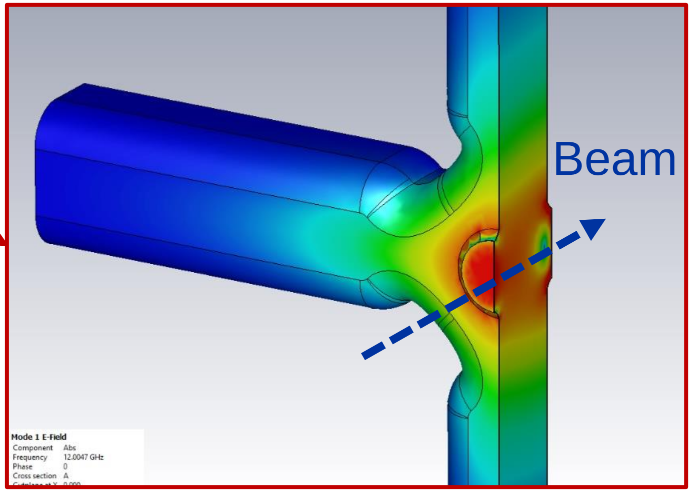
Peak input power: ≈ 40 MW.

RF pulse length: ≈ 200 ns (8 Joules per pulse).

Such structures (and other high-field components) cannot operate at this level immediately and are generally limited by breakdown.







Figures: Precision machined disc (top left), a VNA measurement of an assembled accelerating structure (top right), E-field distribution in a single cell (bottom left). And discs being stacked and aligned prior to bonding (bottom right).

High-Field Conditioning

To achieve stable high-power operation, they must first be conditioned.

However, conditioning is dynamic; the BDR evolves during measurements.

Additionally, we have data for a variety of devices, many of which were conditioned differently.

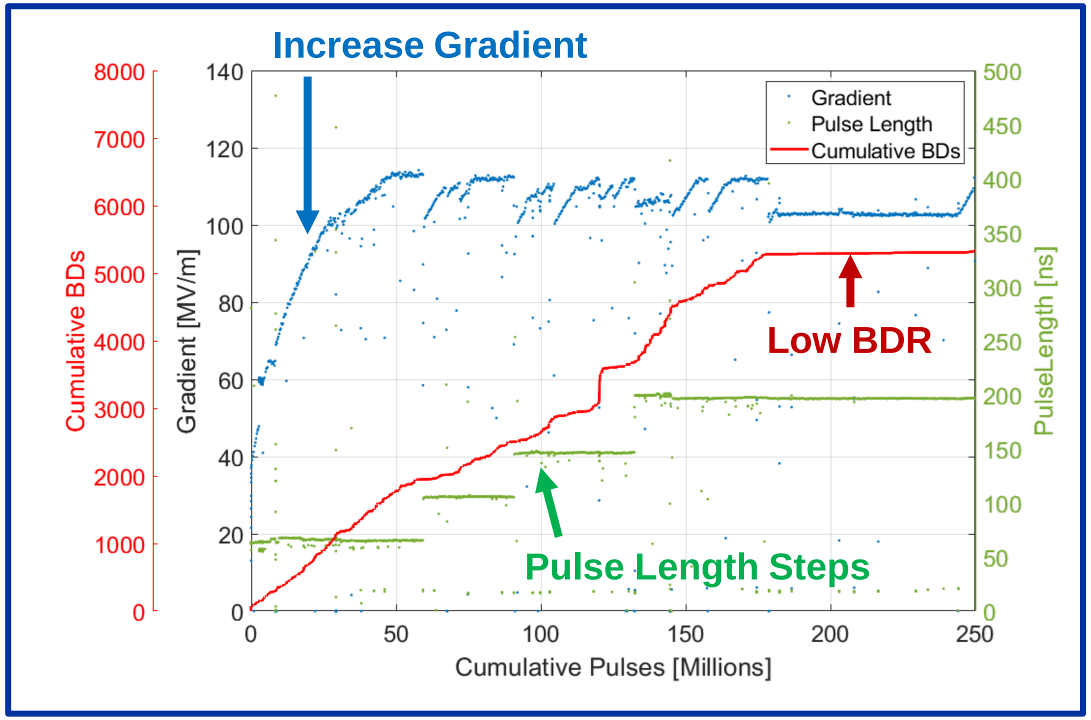


Figure: Typical conditioning procedure for a CERN accelerator cavity.

Why is Conditioning Important?

Although conditioning is commonplace (and necessary) in a variety of devices, neither it nor breakdown are fully understood.

The Practical Motivation:

- Conditioning requires time and electricity (expense) and comes with a risk of component damage. A better understanding facilitates optimisation of the procedure and risk reduction. In this sense, the procedure is still very much an open question for projects like CLIC.

The Theoretical Motivation:

- If we can better understand how the surface evolves (how/why the breakdown rate develops), we might consolidate existing theories and gain insight about the phenomena and the associated physics.

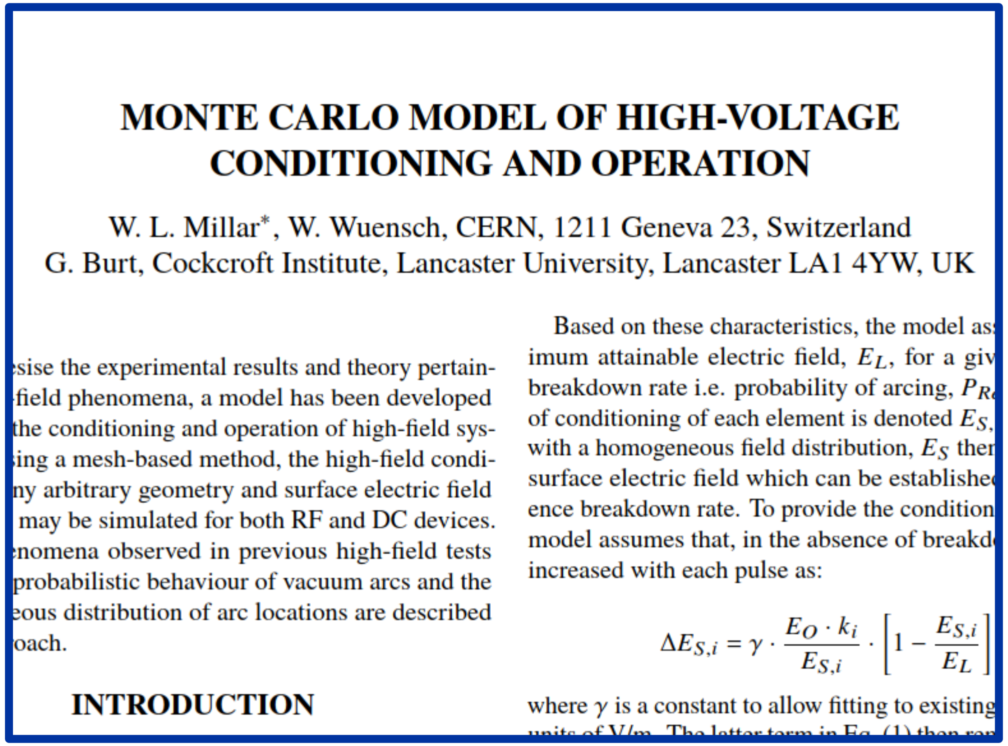
Contents

Overview of the Model

To help consolidate the experimental data, and quickly test our hypotheses, a model was developed at CERN.

In short, we assume that conditioning is not solely due to breakdowns, but a consequence of the applied field.

In other words, <u>we also condition on pulses</u>.



MONTE CARLO MODEL OF HIGH-VOLTAGE CONDITIONING AND OPERATION

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G. Burt, Cockcroft Institute, Lancaster University, Lancaster LA1 4YW, UK

ise the experimental results and theory pertain- field phenomena, a model has been developed the conditioning and operation of high-field sys- ing a mesh-based method, the high-field condi- ny arbitrary geometry and surface electric field may be simulated for both RF and DC devices. nomena observed in previous high-field tests probabilistic behaviour of vacuum arcs and the eous distribution of arc locations are described oach.

INTRODUCTION

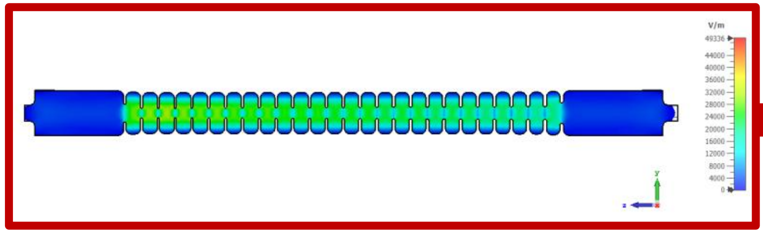
Based on these characteristics, the model as imum attainable electric field, E_L, for a giv breakdown rate i.e. probability of arcing, P_R of conditioning of each element is denoted E_S, with a homogeneous field distribution, E_S the surface electric field which can be establishe ence breakdown rate. To provide the condition model assumes that, in the absence of breakd increased with each pulse as:

$$\Delta E_{S,i} = \gamma \cdot \frac{E_O \cdot k_i}{E_{S,i}} \cdot \left[1 - \frac{E_{S,i}}{E_L}\right]$$

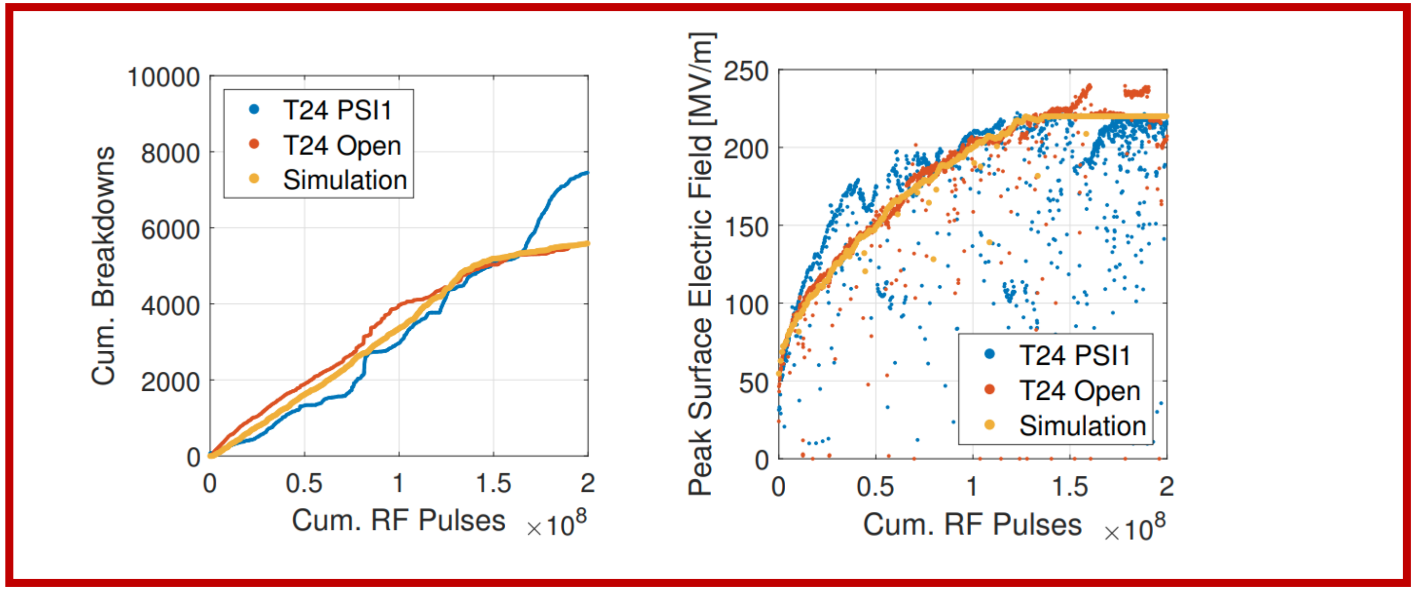
where γ is a constant to allow fitting to existing units of V/m. The latter term in Eq. (1) then re

Figure: Snippet of the relevant LINAC2022 conference paper (MOPORI24) [1].

Simulation Example – X-band LINAC



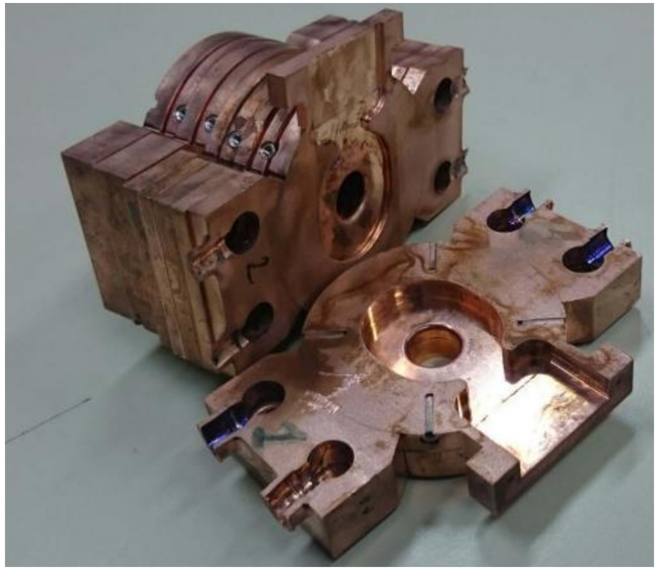
Cavity simulation (cell-to-cell).



Spatially resolved single-cell simulation [1].

Simulation Example - CLIC Crab Cavity Cell

Cavity after high-power test and cutting.



Face of a single cell.

Breakdown locations superimposed on electric field distribution.

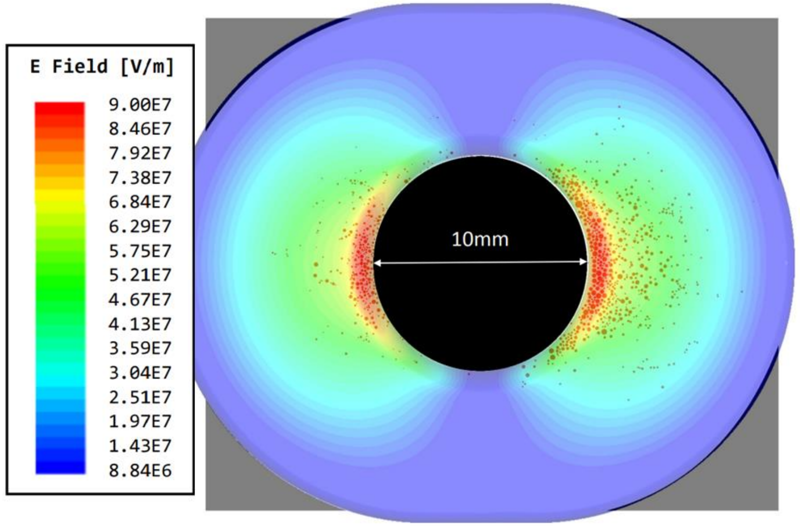
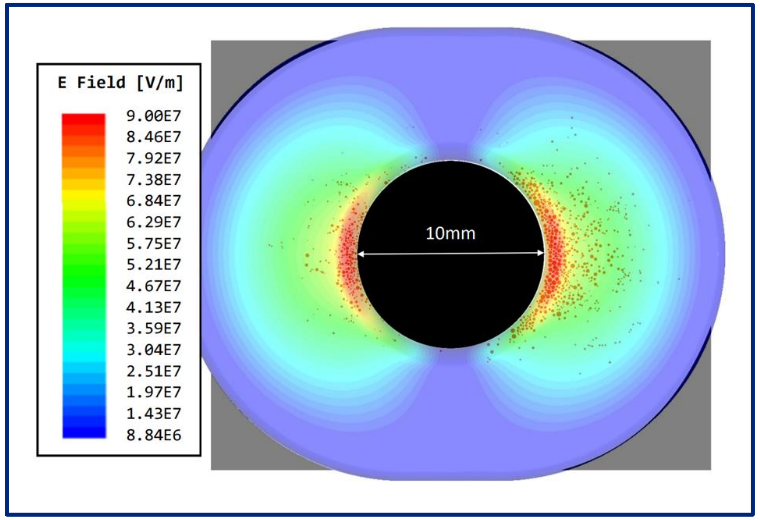


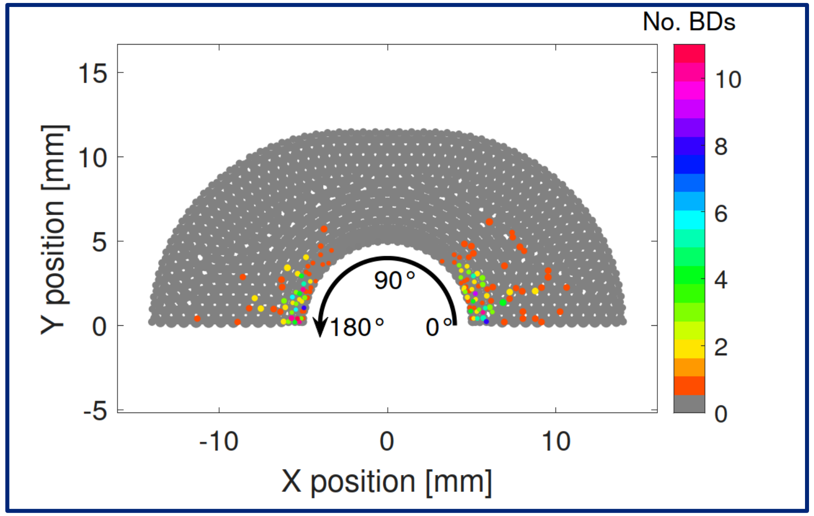
Figure: Images from the post-mortem examination of the CLIC crab cavity [2].

Simulation Example - CLIC Crab Cavity Cell

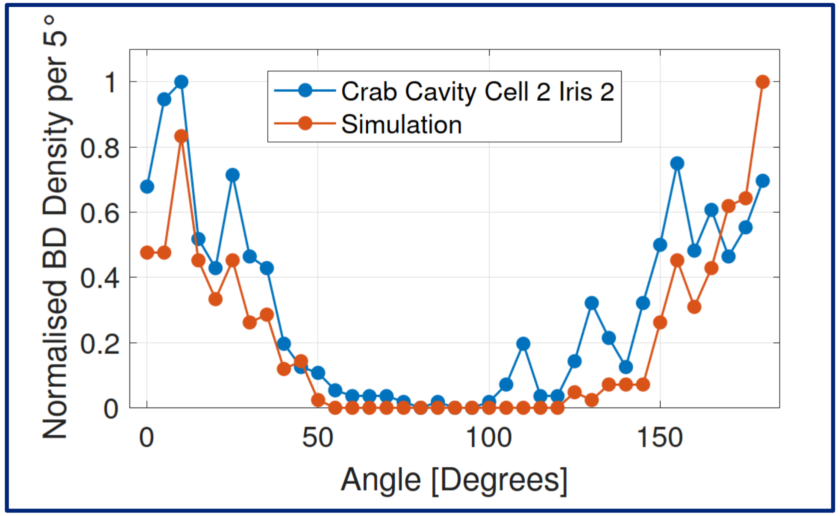
Real BD distribution.



Simulated BD distribution.

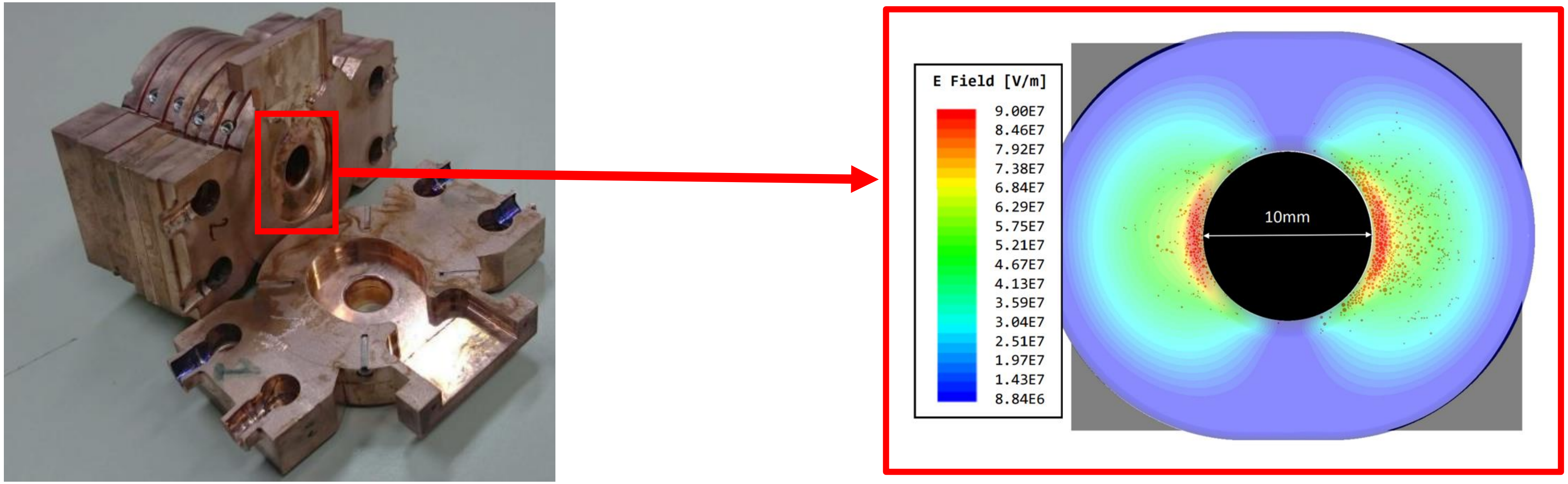


Comparison.



Field Dependence of Conditioning

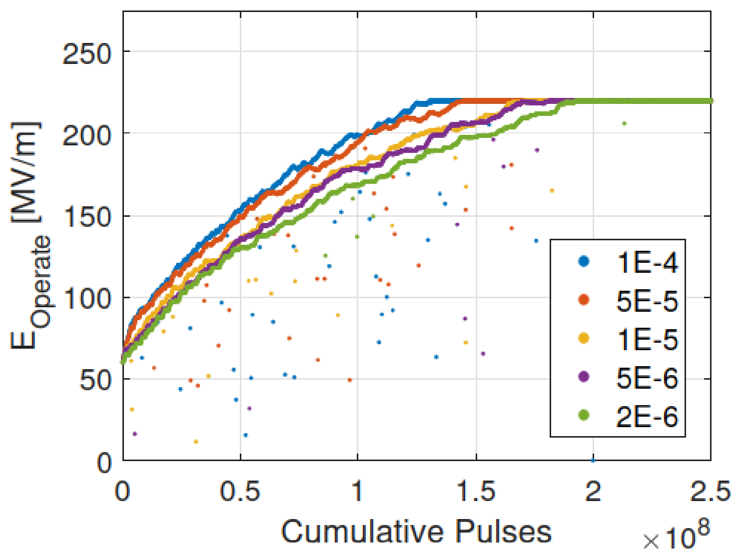
During tests, the global BDR usually scales strongly with the applied field (~$E^{10\text{-}30}$) but local BDRs rate scales differently.

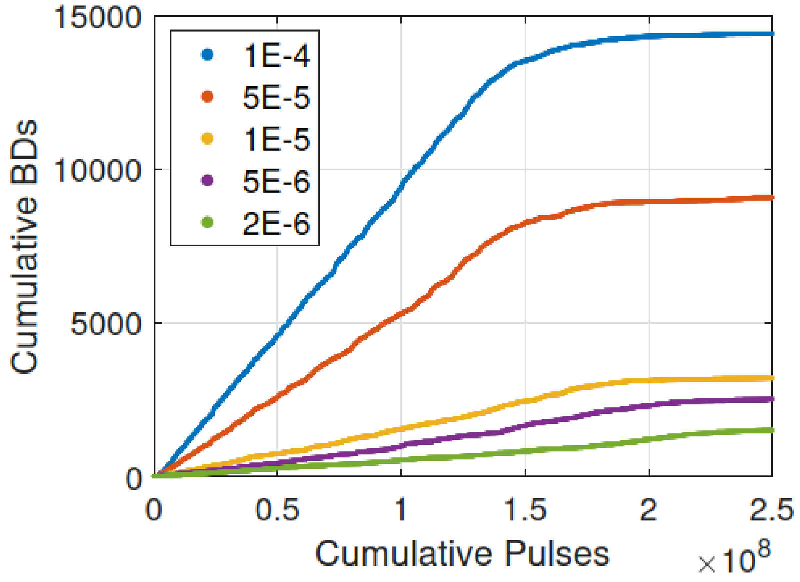


Figures: The CLIC crab cavity after testing (left) and the breakdown positions overlaid on the surface electric field distribution (right) [2].

Field Dependence of Conditioning

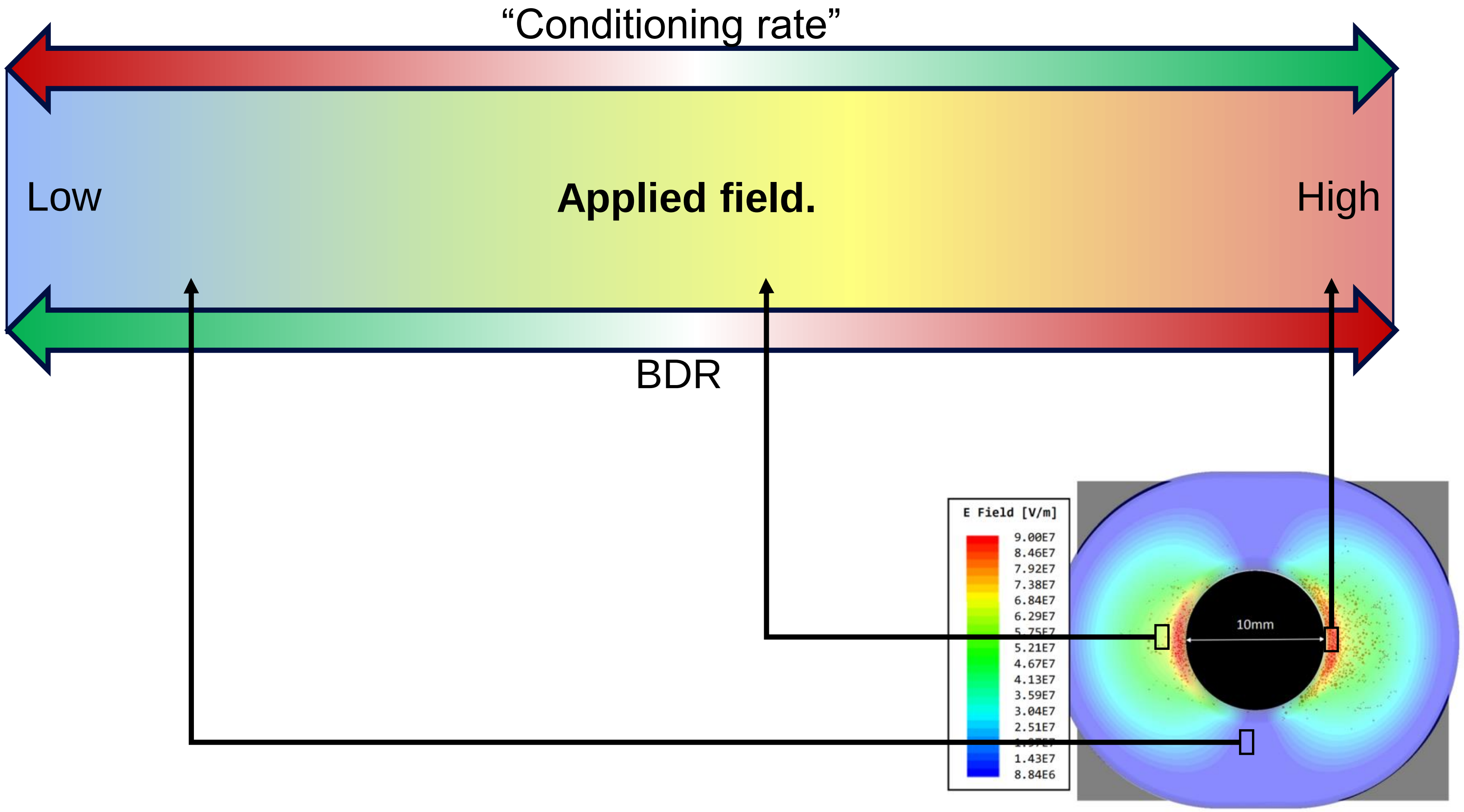
The process is dynamic → test results (and the model) both suggest a "field dependence" on conditioning. For example, see the simulation below:





Conditioning at different BDRs → Different no. of breakdowns accrued.

Field Dependence of Conditioning



Field Dependence of Conditioning

This points to several new questions:

- **To what extent are the breakdowns necessary?**
- **Can we regulate the field to prevent them and is there any benefit to doing so?**
- **By looking at different regions, can we relate the surface's propensity for high-field operation more concretely to a metallurgical quantity? If so, which one(s)?**

Contents

1. Introduction to Conditioning
2. Modelling Conditioning.
3. **The Electrode Experiment.**
4. Results.

Simulation and Design

Given its simplicity and comparatively low cost (relative to the RF test stands), the LES (Large Electrode System) is an attractive means of investigating this phenomenon.

Cameras allow the breakdown locations to be monitored during conditioning.

However, only flat, uniform electrodes have been studied so far (E-field is relatively homogeneous)…

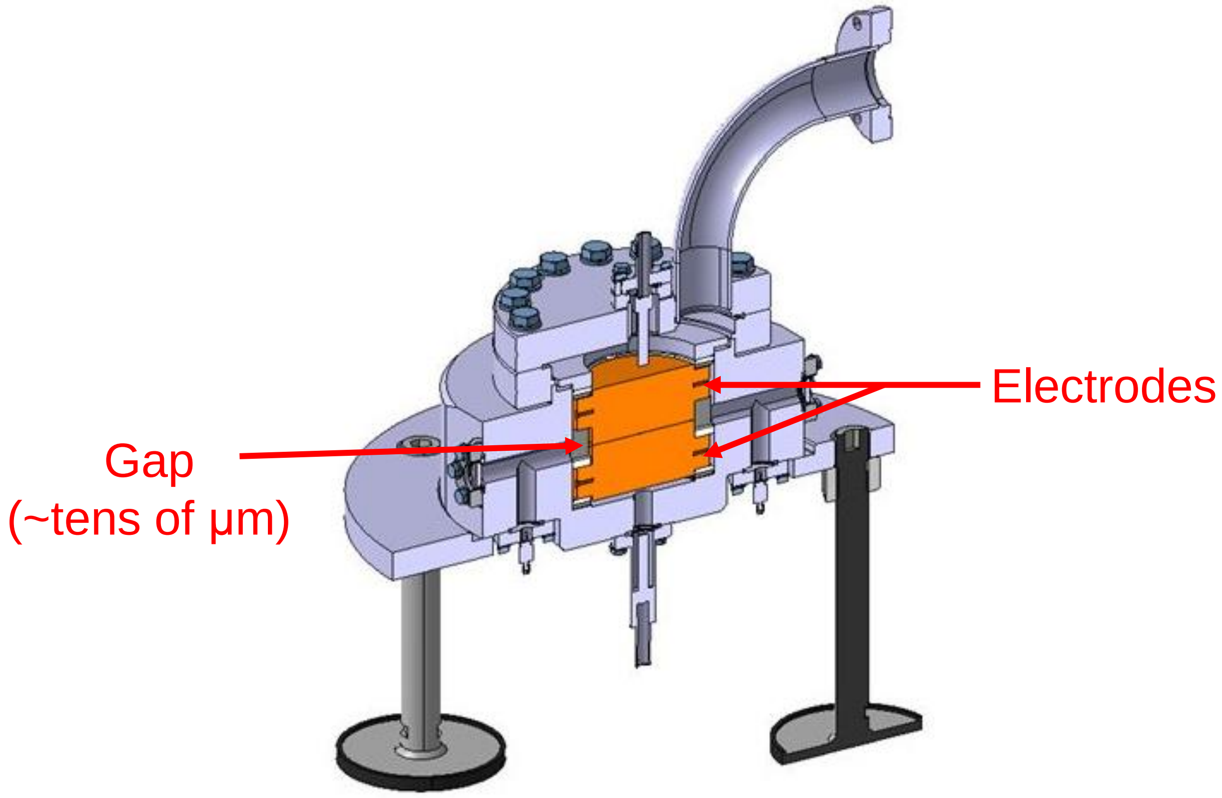
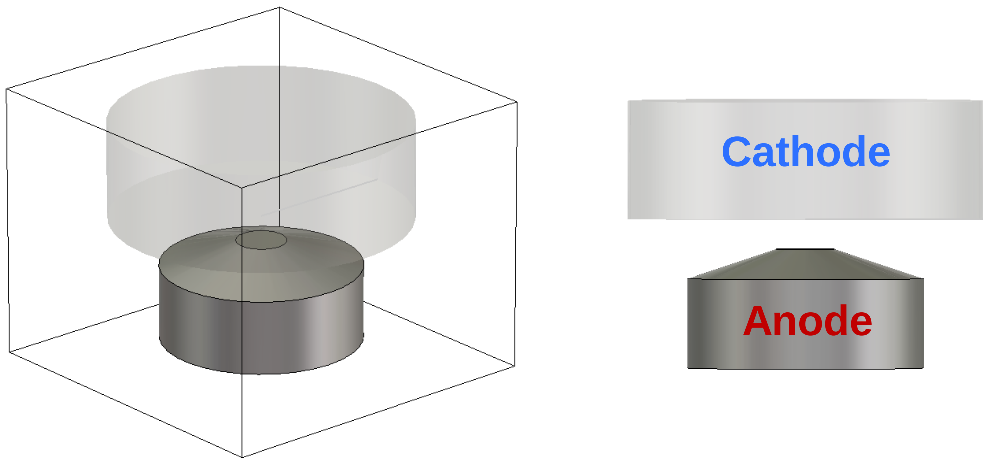


Figure: Rendering of CERN's LES [3].

Simulation and Design

Enter the frustum electrode – an electrode with a very gradual chamfer (~tens of microns).



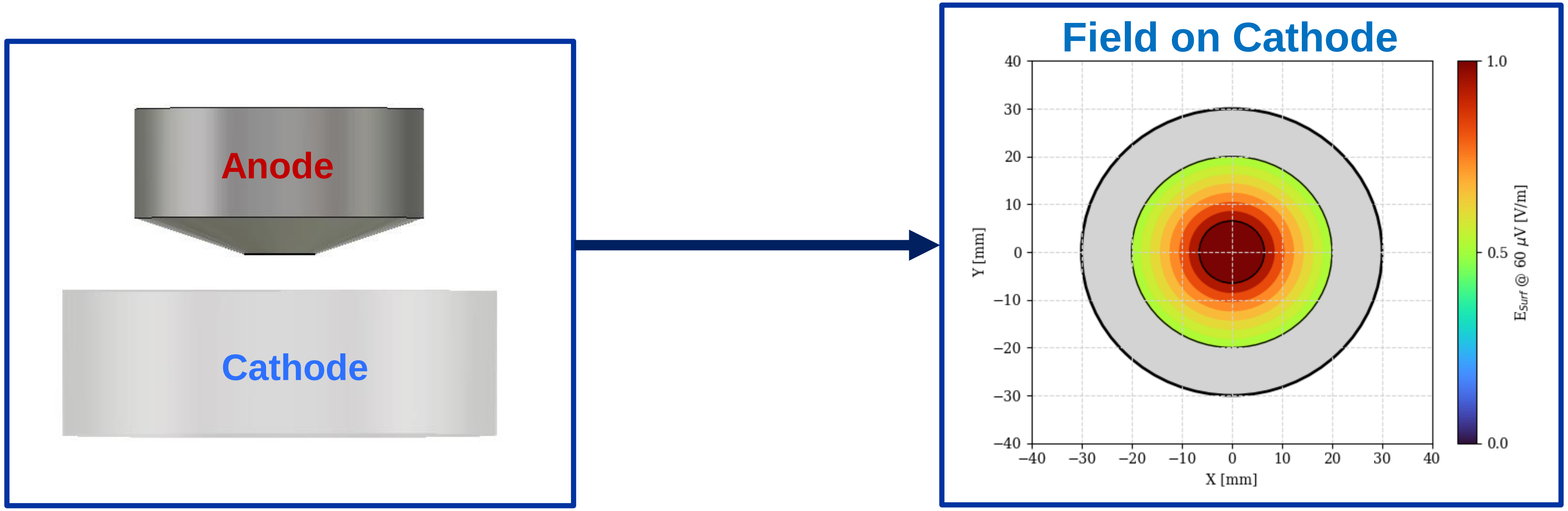
The Chamfered “Frustum” Anode

For illustrative purposes only, dimensions exaggerated!

Simulation and Design

- **Concentric sections are subjected to different conditioning procedures (ramping rate and BDR) – It's like multiple tests in one!**

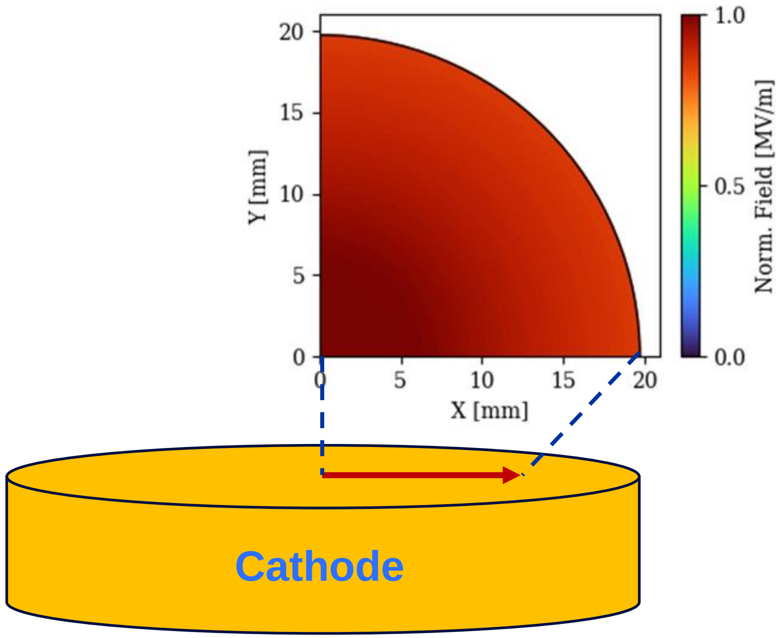
- **By monitoring the evolution of the breakdown distribution in real-time (via cameras), we can more directly observe the field dependence of conditioning.**



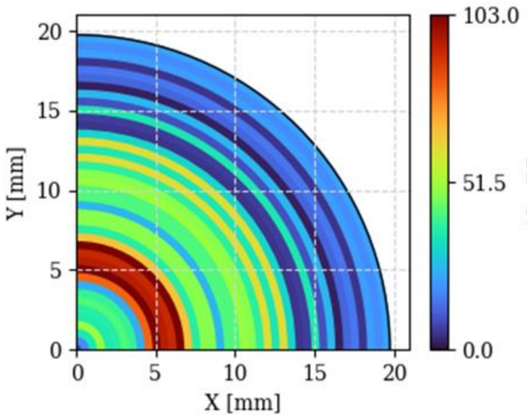
Simulation and Design

The electrode was roughly optimised in simulation using our conditioning model. The target – a decay in the density of the BD distribution (a lot of activity in the centre, less at the edge).

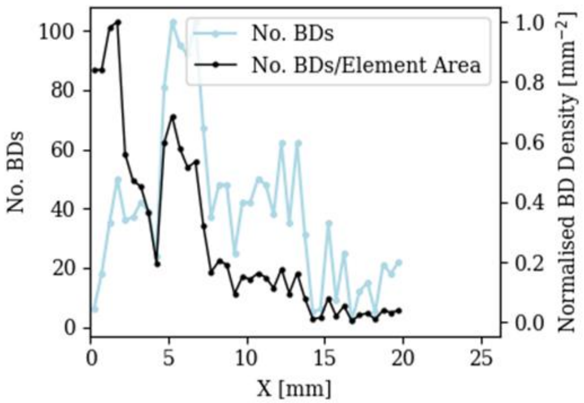
Surface E-Field



BDs per Mesh Element



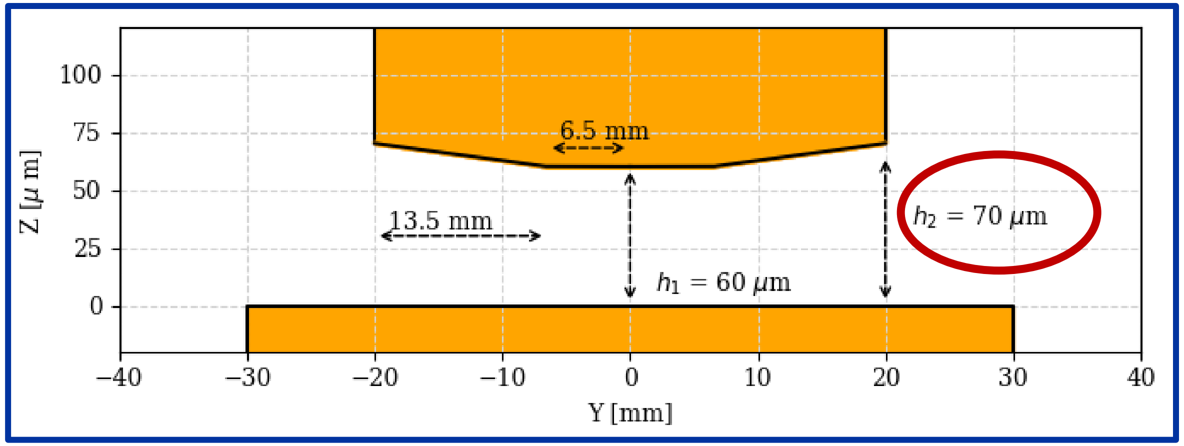
Radial BD Distribution



The “Frustum” Electrode

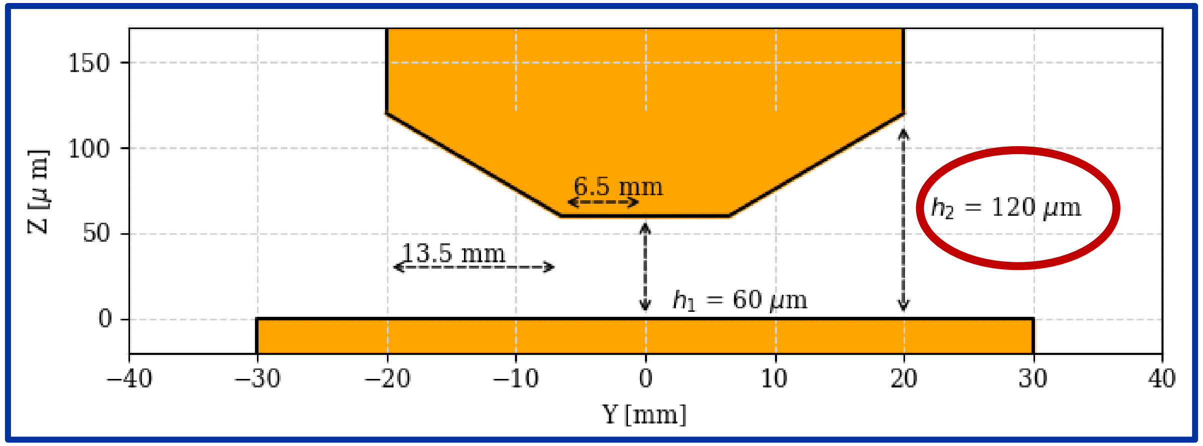
From simulation, two designs were selected and manufactured:

Design 1: Gap from 60 to 70 µm (gentle slope)



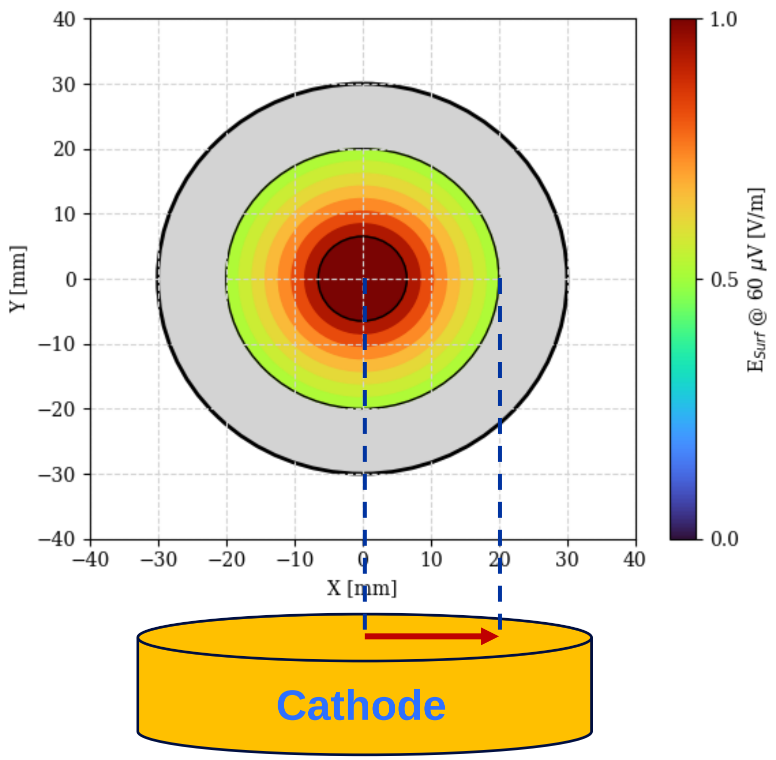
E-field reduction of **~14% (slope of only 10 µm!).**

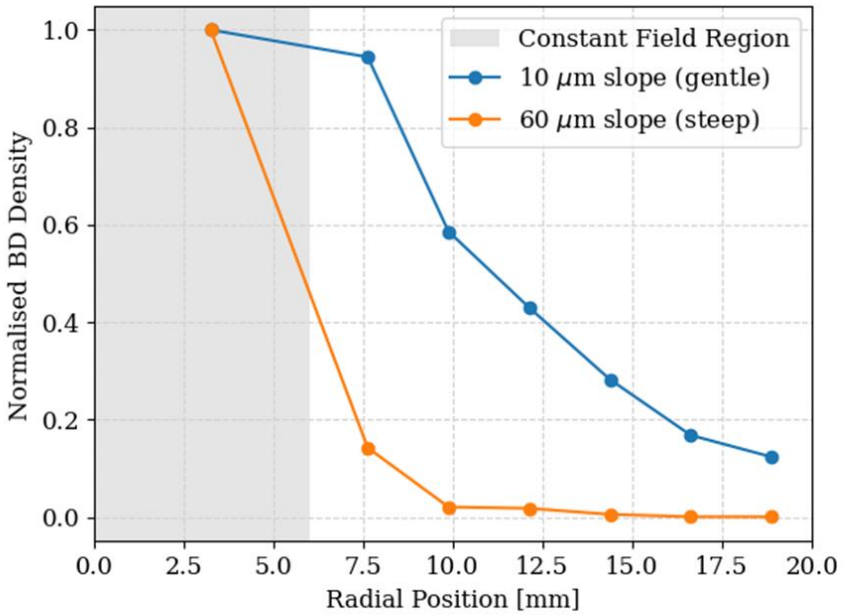
Design 2: Gap from 60 to 120 µm (steep slope)



E-field reduction of **~50% (slope of 60 µm!).**

Predicted Breakdown Distributions



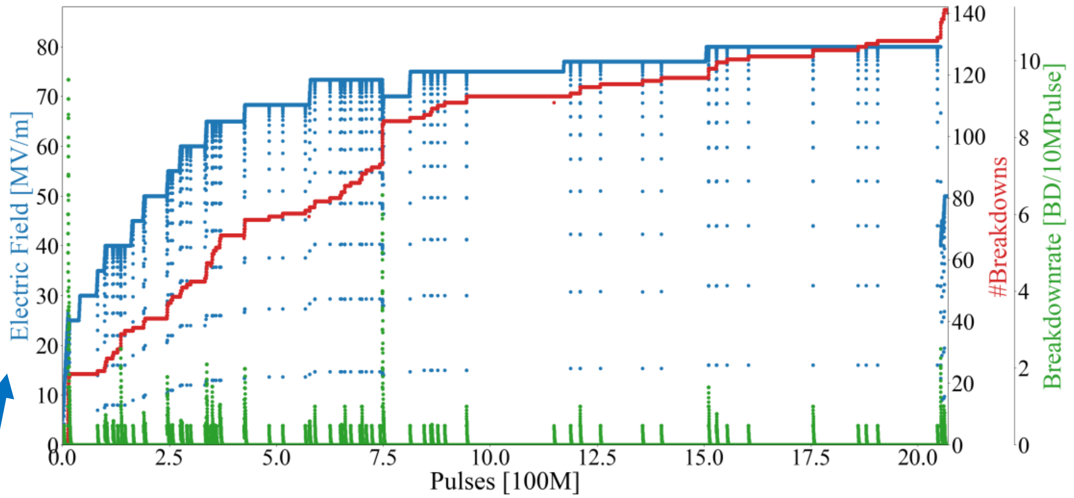


Note: Results shown are an average of 10 simulations (conditioned to 80 MV/m, ~3-400 breakdowns/sim).

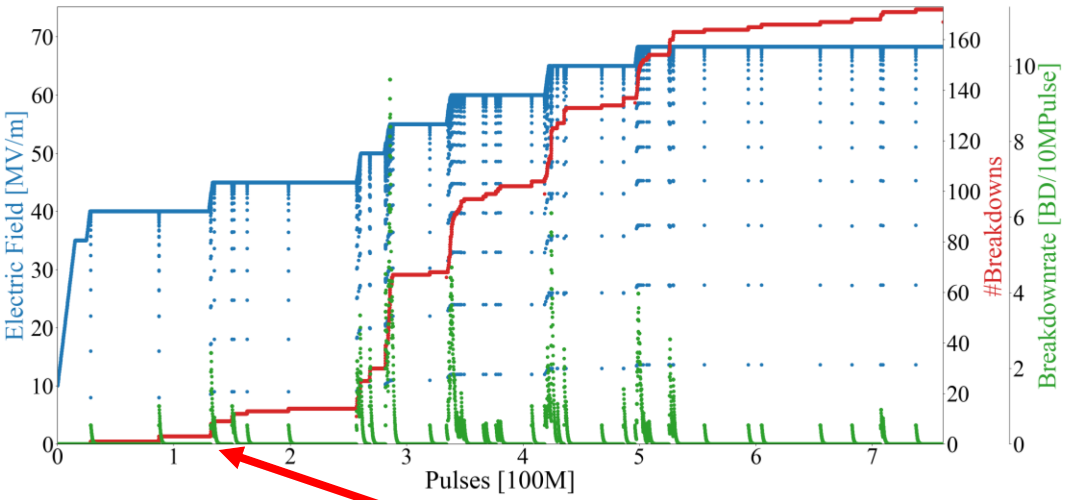
Contents

Conditioning History (1us pulse length @ 1kHz)

Design 1 (gentle slope)



Design 2 (steep slope)



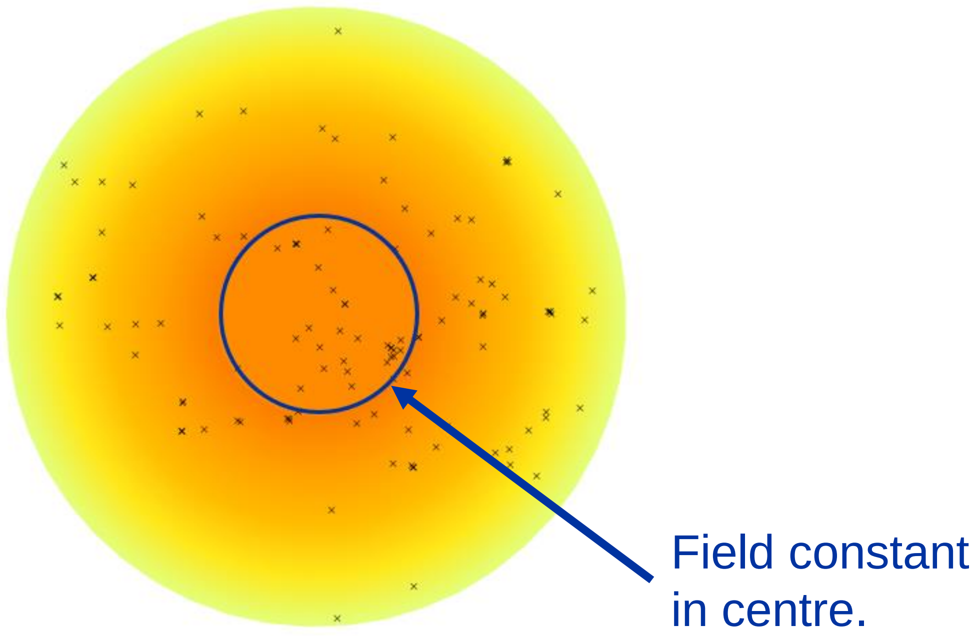
Peak field (at center of electrode).

DISCLAIMER!
Not entire conditioning history of this electrode!

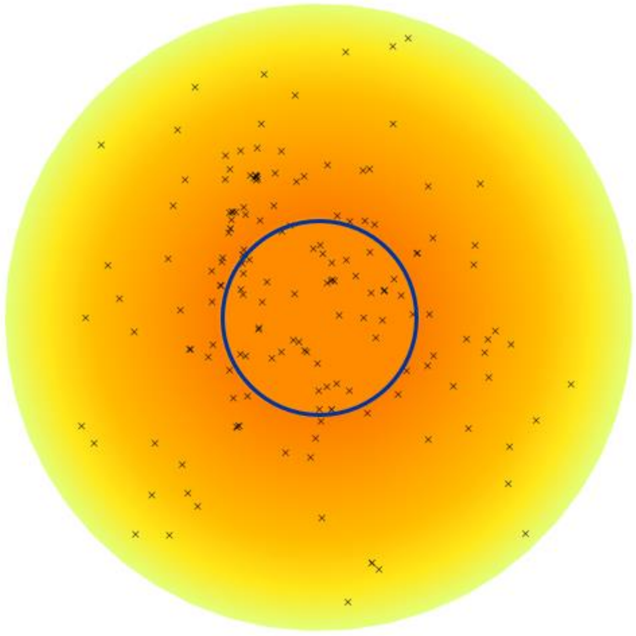
Figures taken from Victoria's MeVArc talk [4]!

Breakdown Locations

Design 1: Gap from 60 to 70 μm (gentle slope)



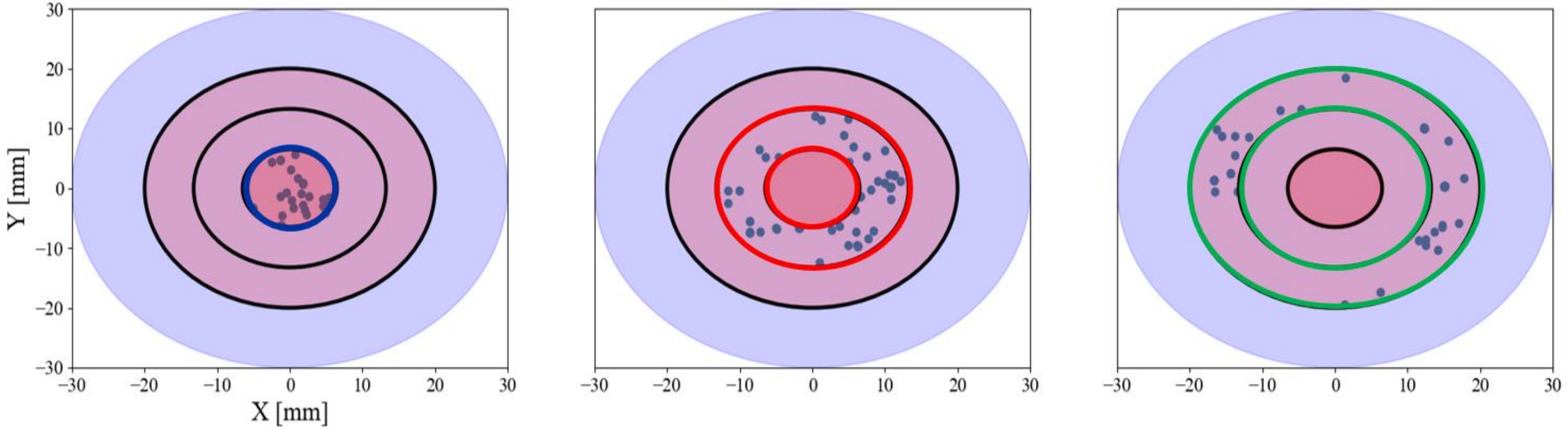
Design 2: Gap from 60 to 120 μm (steep slope)



Figures taken from Victoria's MeVArc talk [4]!

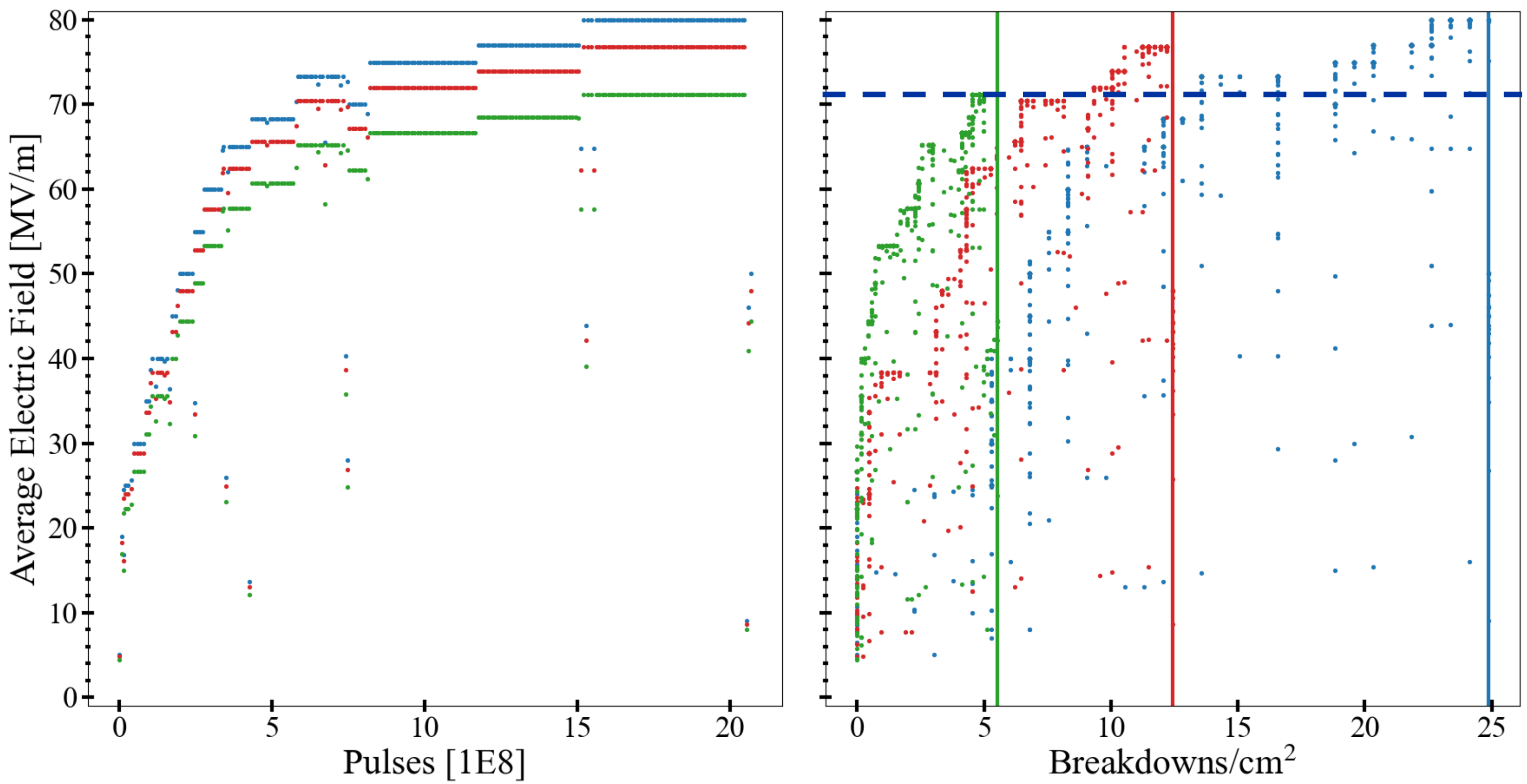
Breakdown Locations – Electrode 1 (gentle slope)

The electrodes may be divided into three sections – high, medium, and low field.



Figures taken from Victoria's MeVArc talk [4]!

Conditioning – Electrode 1 (gentle slope)

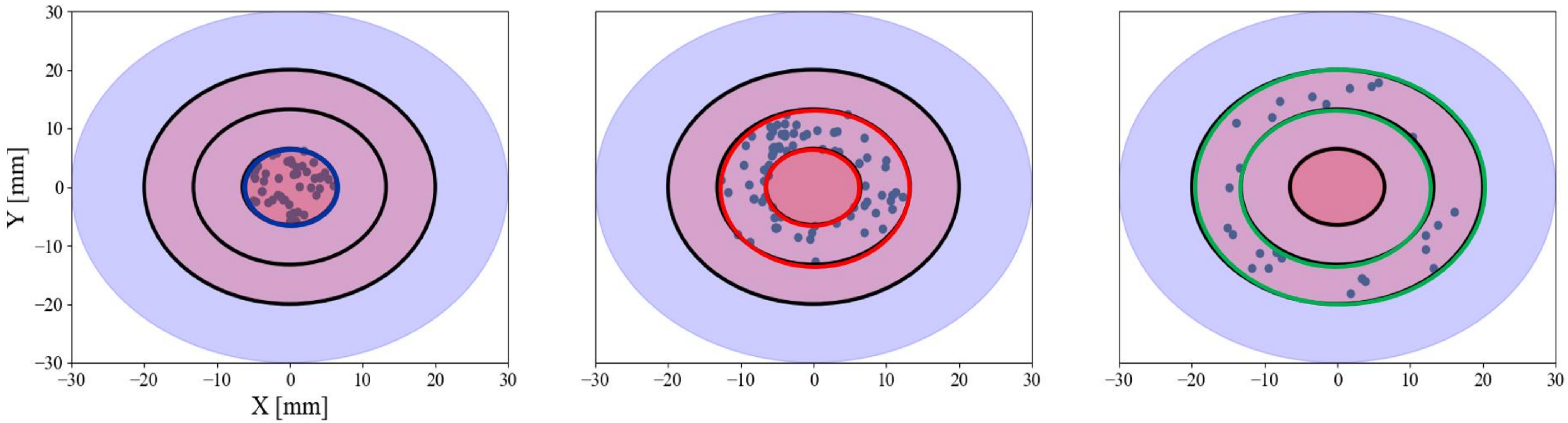


Dashed line at 71 MV/m – Sections reach this level with a different number of breakdowns/cm^2 !

Figures taken from Victoria's MeVArc talk [4]!

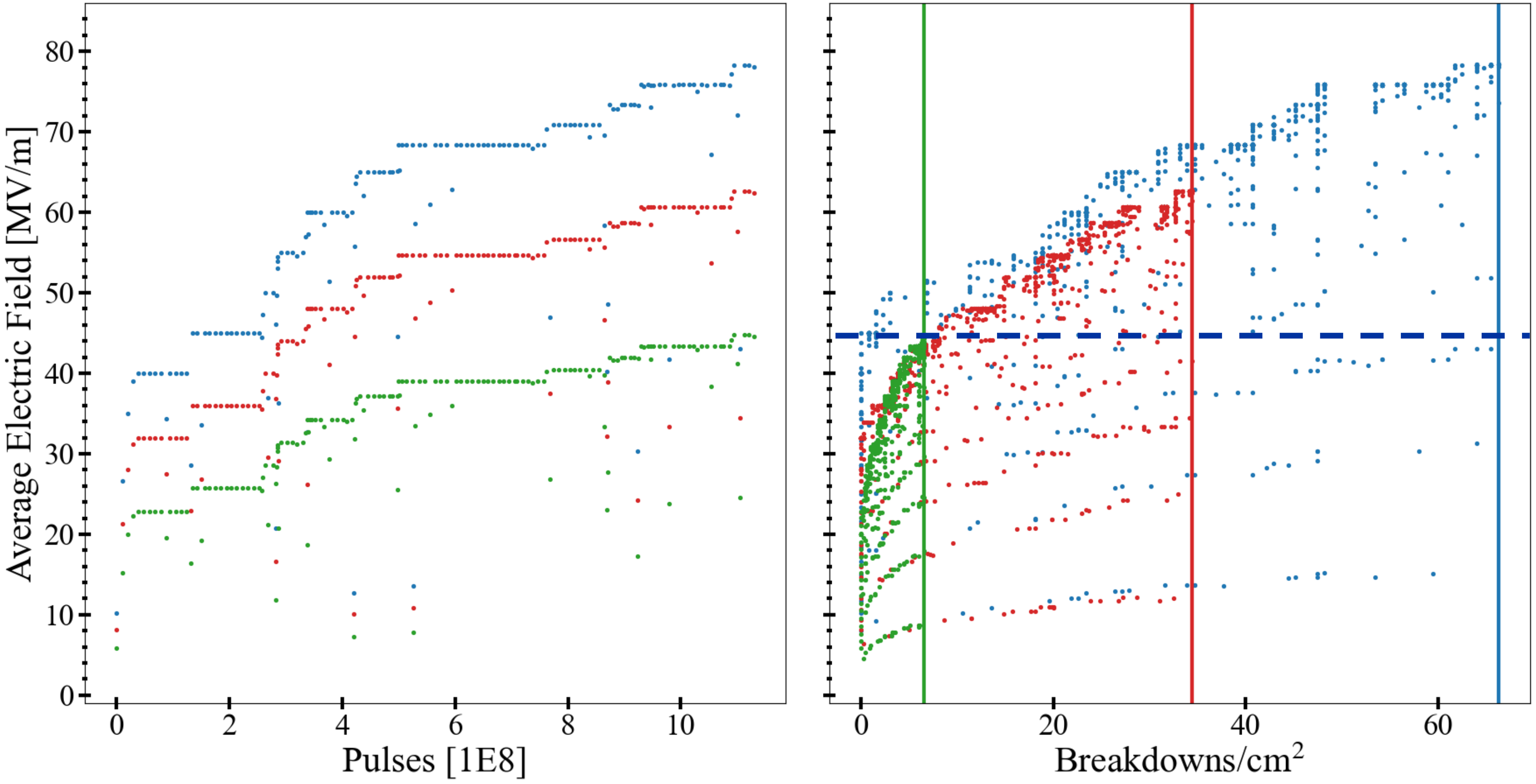
Breakdown Locations – Electrode 2 (steep slope)

The electrodes may be divided into three sections – high, medium, and low field.



Figures taken from Victoria's MeVArc talk [4]!

Conditioning – Electrode 2 (steep slope)



Dashed line at 45 MV/m. Result is more difficult to interpret.

<u>DISCLAIMER!</u>
Early breakdowns (at edge) were not recorded.
→ Blue and red data should be shifted further to the right.

Figures taken from Victoria's MeVArc talk [4]!

Comparison with Simulation

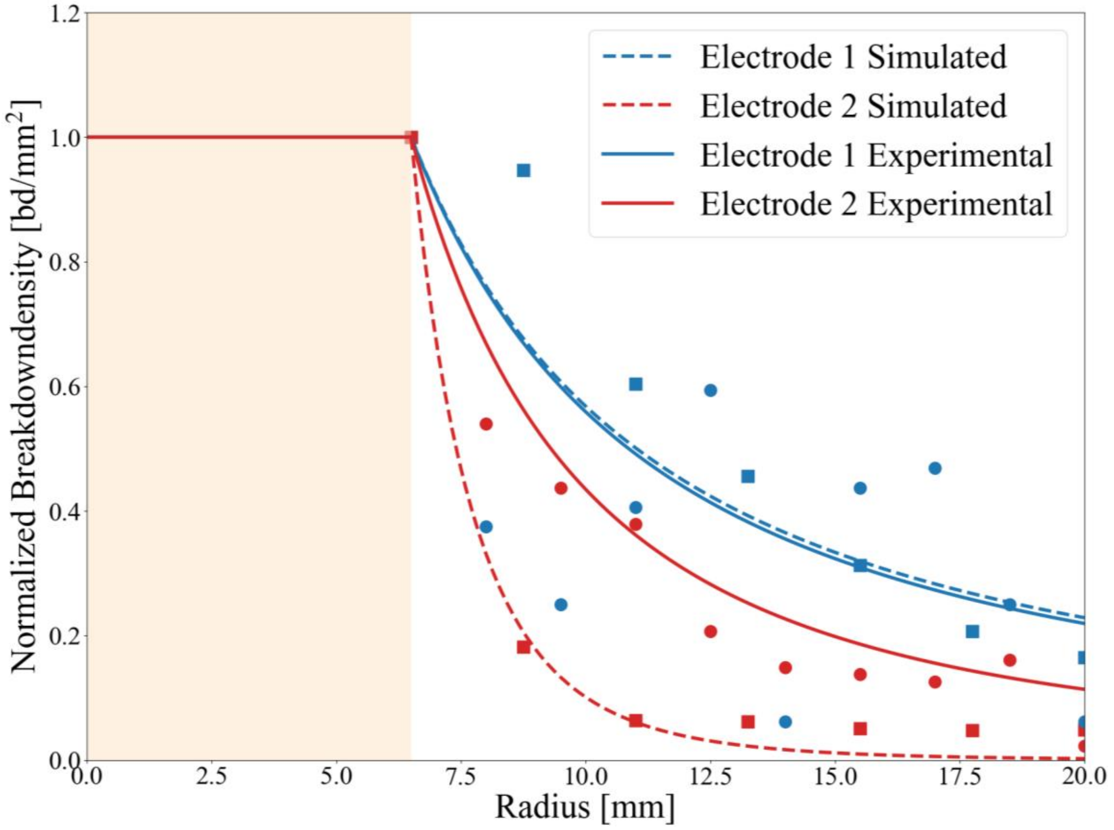
Fitting to $BDR = \alpha * r^{-\beta}$:

- Simulation 1: $\beta = 1.31$
- Electrode 1: $\beta = 1.35$

- Simulated 2: $\beta = 5.32$
- Electrode 2: $\beta = 1.93$

As expected, all results far from the usual $BDR \propto E^{30}$ which is observed for well conditioned devices.

<u>Reminder:</u> Breakdowns were missed during the start of the electrode 2 test → experimental curve should likely be depressed.



Figures taken from Victoria's MeVArc talk [4]!

Conclusions

For the first time, electrodes with an inhomogeneous E-field distribution have been tested in CERN's LES system.

- **The breakdown locations were monitored in real-time and show that different regions reach a given field level while having accrued different numbers of breakdowns (a field dependence of conditioning).**

- **The analysis is ongoing (e.g., gap dependence still to be investigated).**

- **Features are machined on the anode - they can be reused! More tests are planned to improve the statistics.**

Thank you. Questions?

References

[1] – W. Millar et al., “Monte Carlo Model of High-Voltage Conditioning and Operation”, Proceedings of the 31st Linear Accelerator Conference (LINAC22), Liverpool, UK, 2022, pp.283-286, **DOI:** 10.18429/JACoW-LINAC2022-MOPORI24

[2] – E. Castro, “CLIC Crab Cavity Post-Mortem analysis” (presentation), Available online: https://indico.cern.ch/event/449801/contributions/1945273/

[3] – A. Korsback, “CERN dc spark system capabilities” (presentation), Available online: https://indico.cern.ch/event/336335/contributions/788991/

[4] – V. Bjelland, “Field Dependence of Conditioning-Experimental Measurements” (presentation), Available online: https://indico.cern.ch/event/1298949/contributions/5783848/

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