Monte Carlo simulation of vacuum breakdown occurrence

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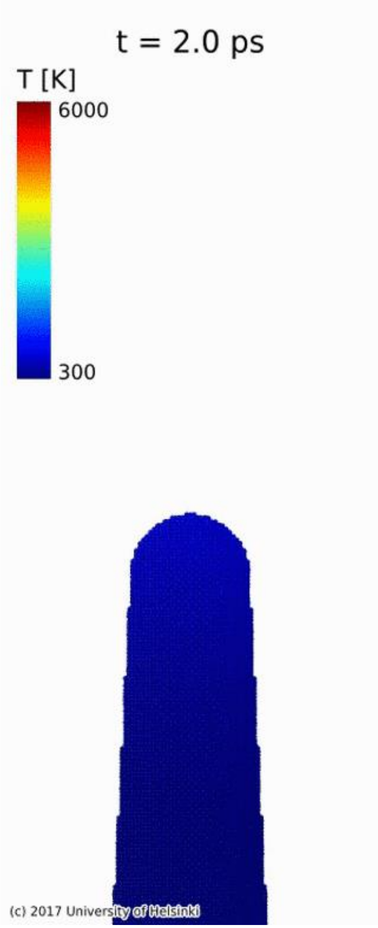
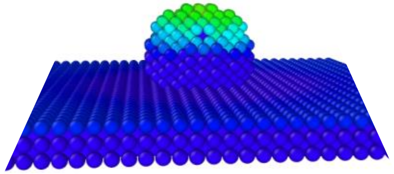
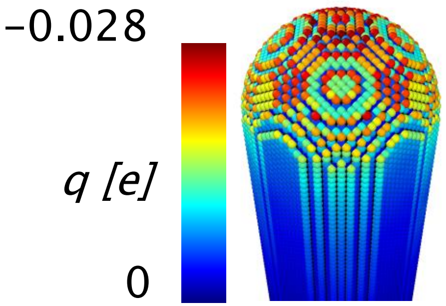
Experiment vs simulation scale mismatch

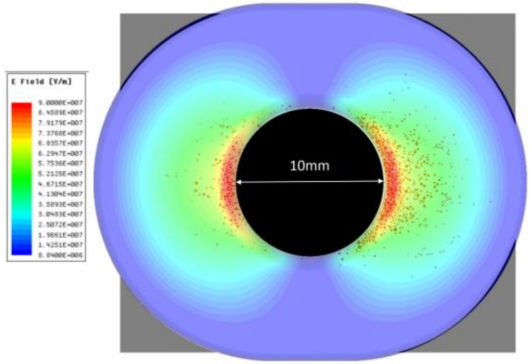
- Simulation: ns, nm, simple systems
- Experiment: sec, mm, complex systems

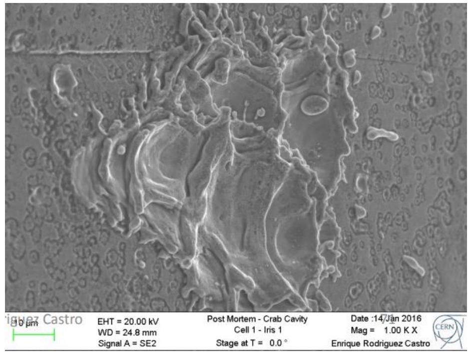






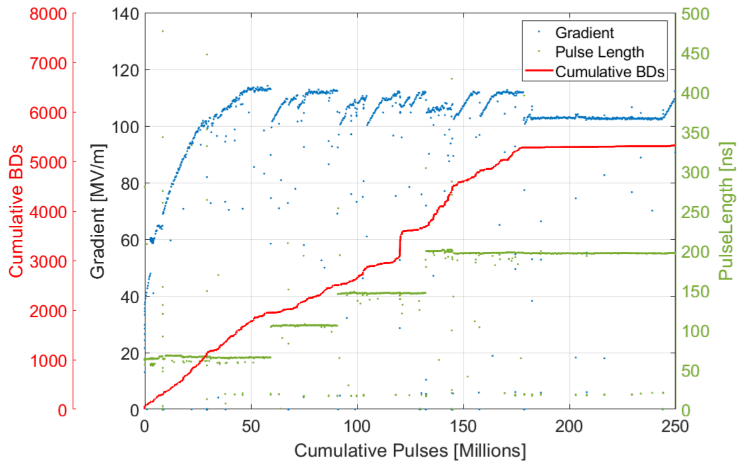
Post-mortem analysis





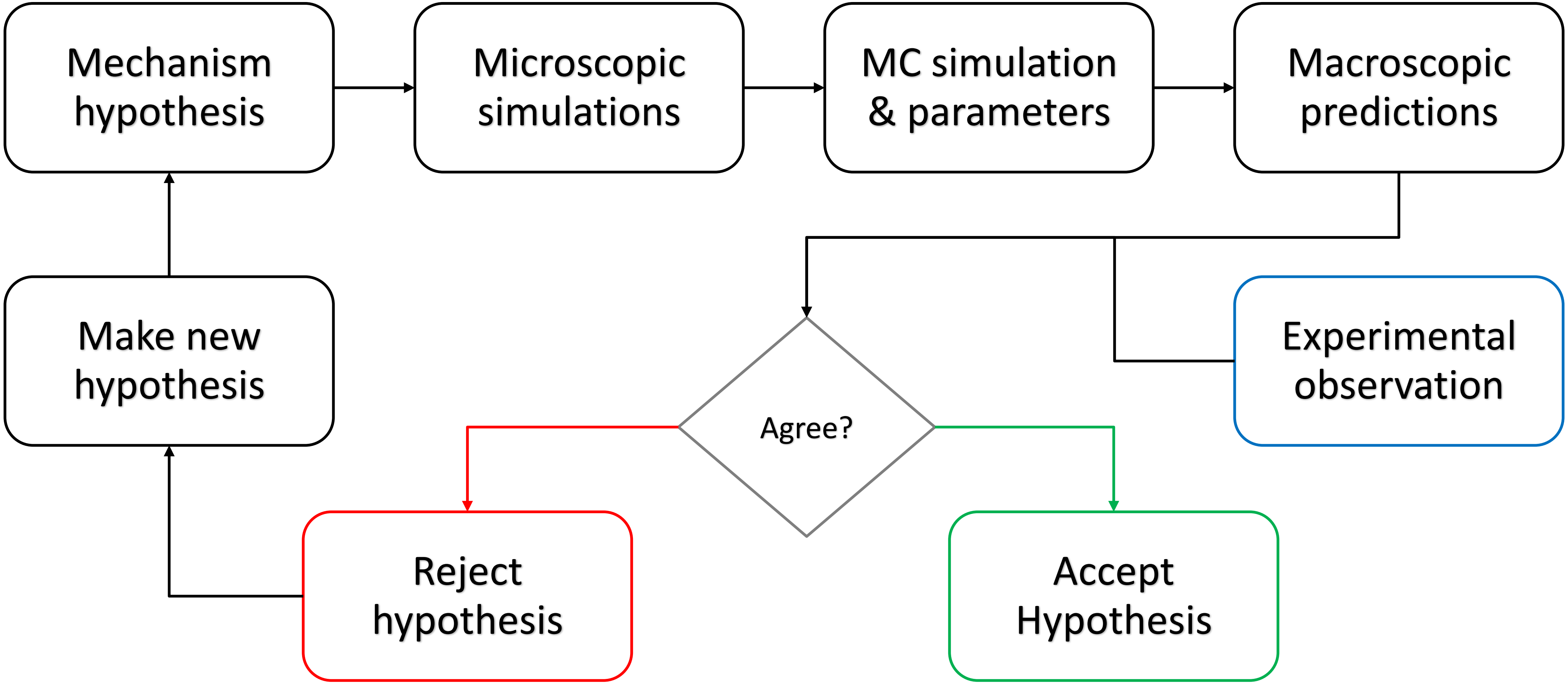
Connect?

Conditioning curves & history

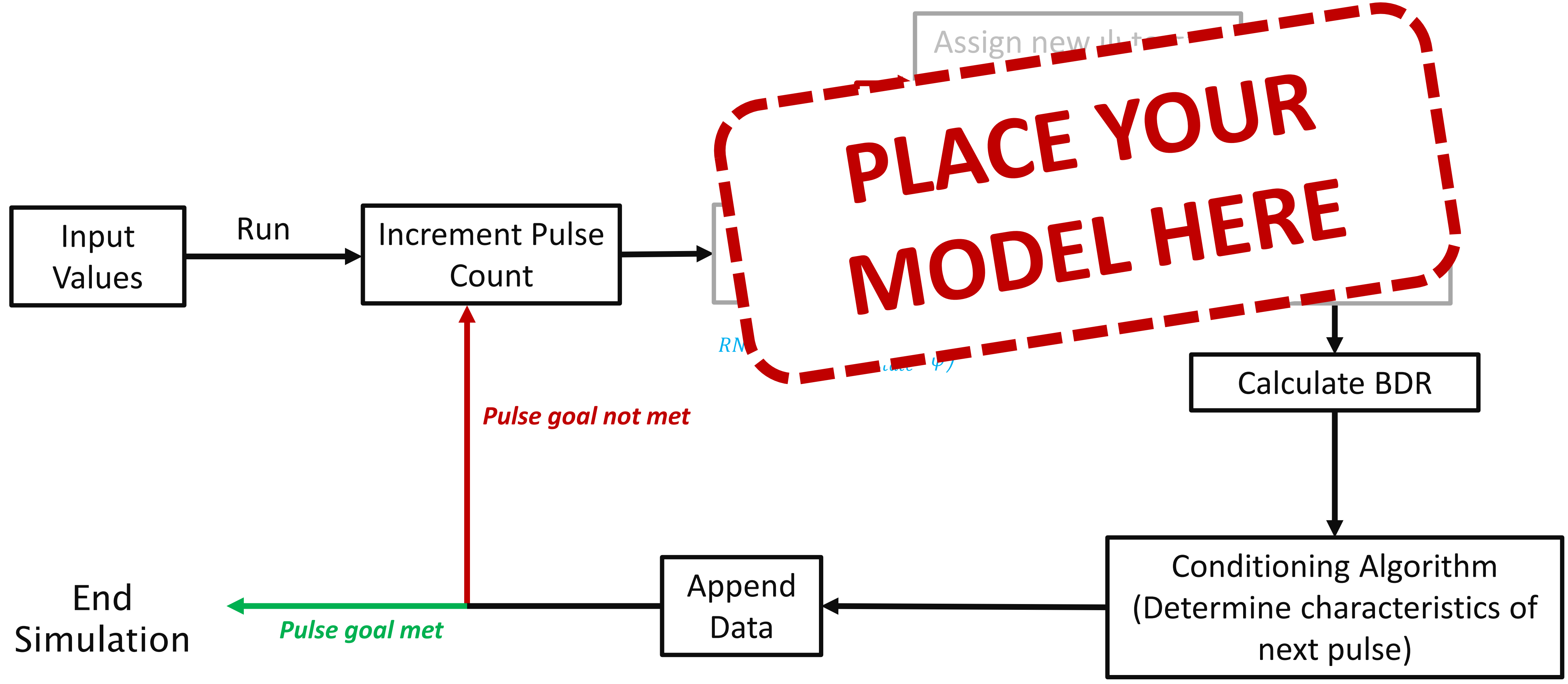


Figures: Lee Millar, MiniMeVArc

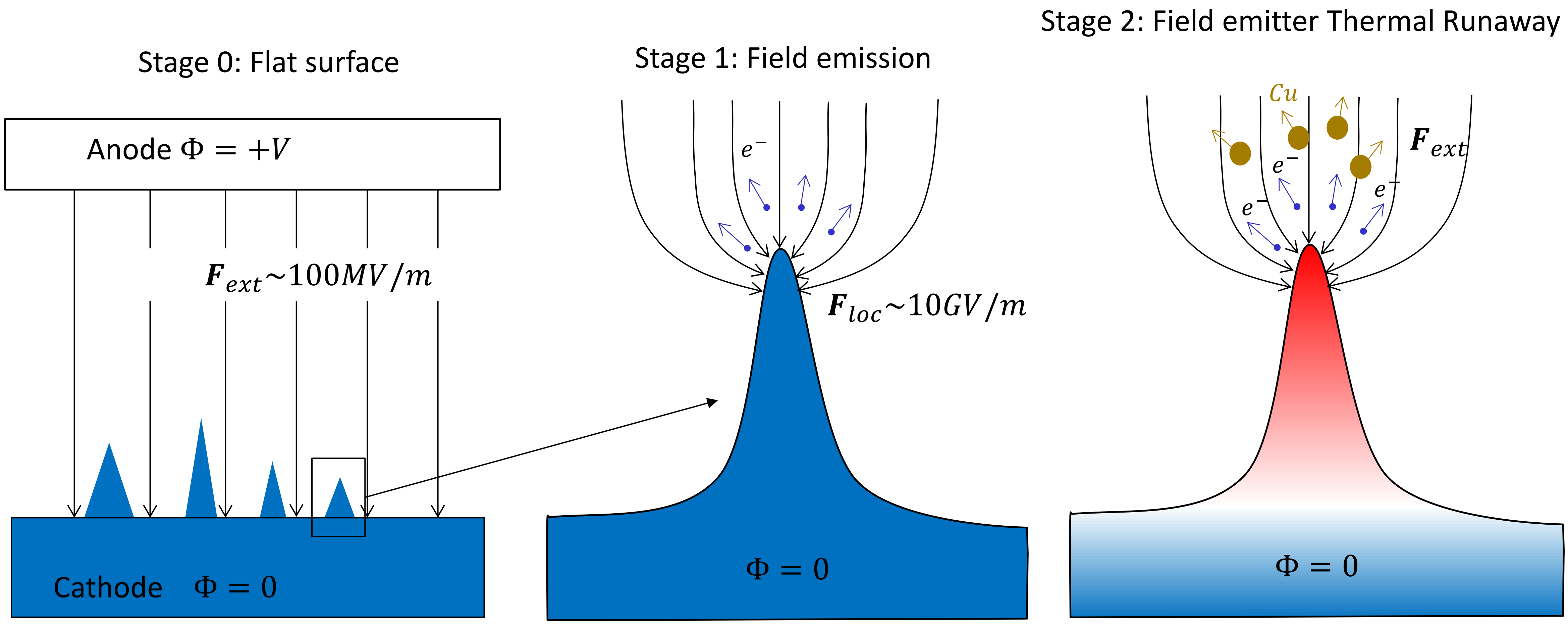
Connecting theory & experiment



Answering Lee’s call

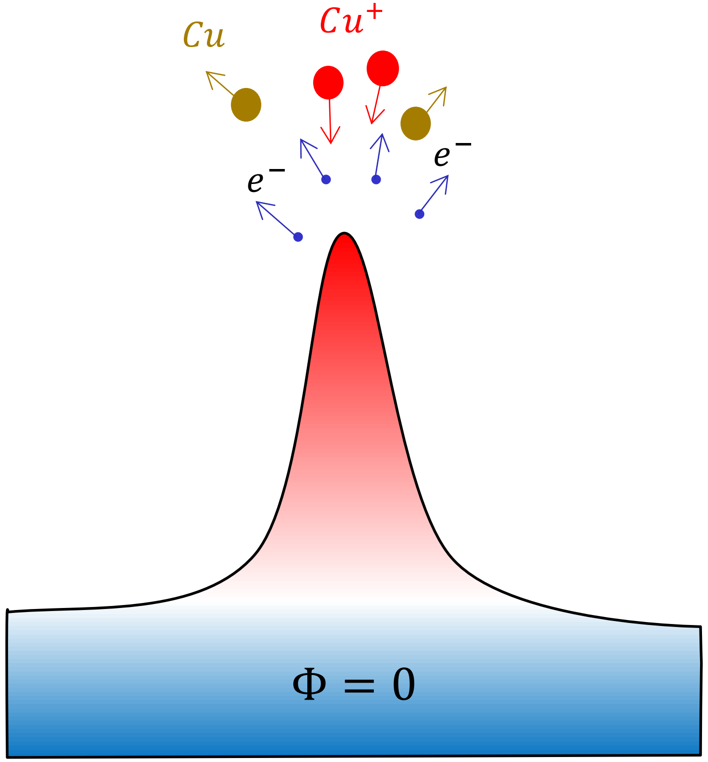


Conventional wisdom on VBD

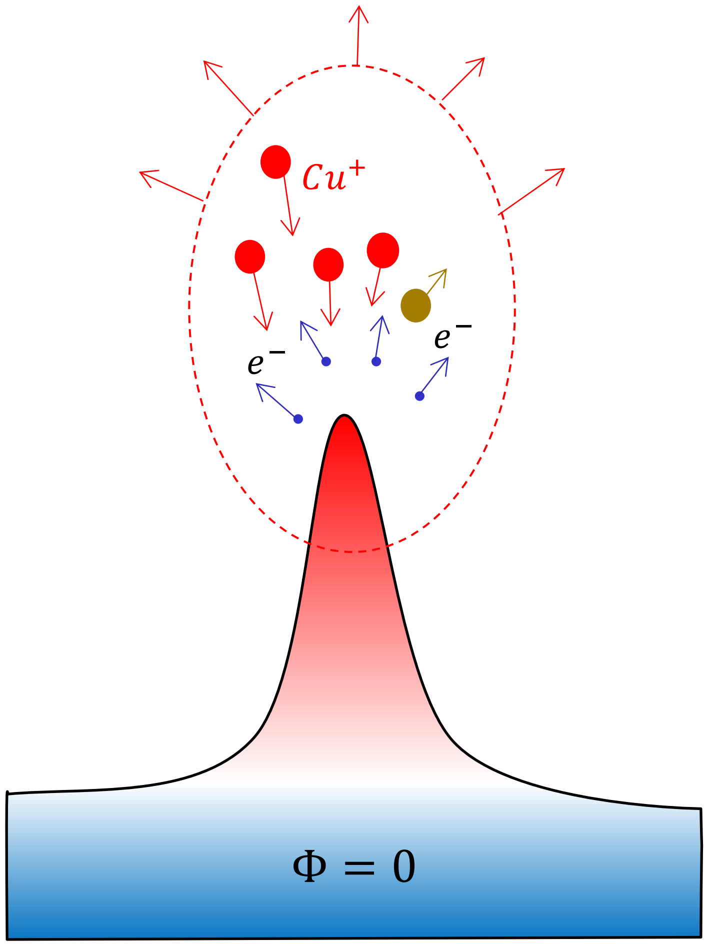


Vacuum breakdown stages

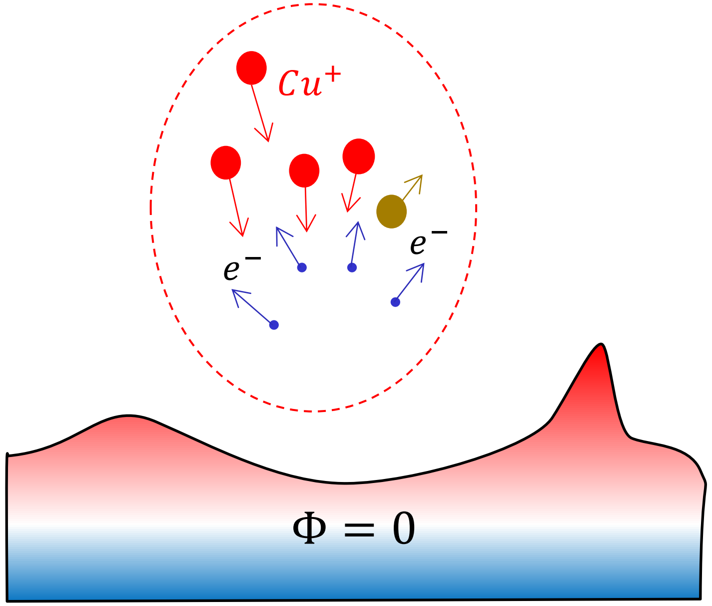
Stage 3: Ionization runaway & Plasma onset



Stage 4: Plasma expansion

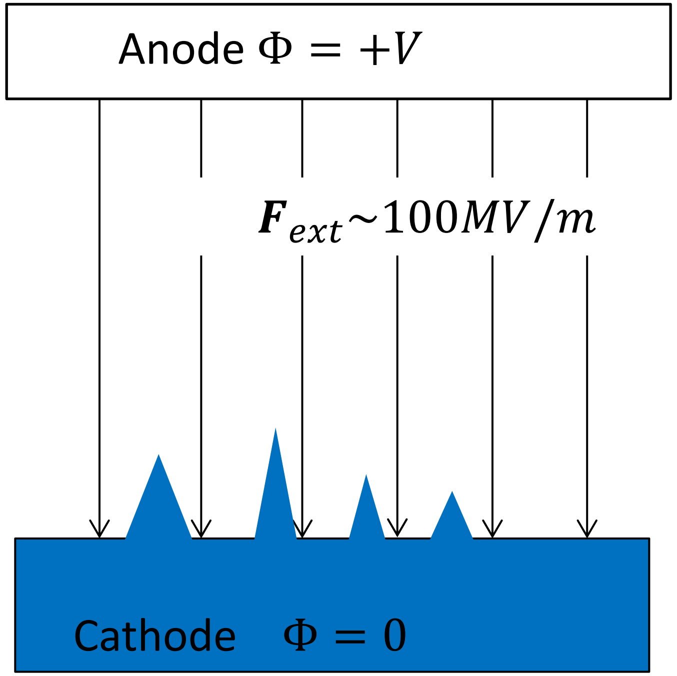


Stage 5: Burning arc, crater formation



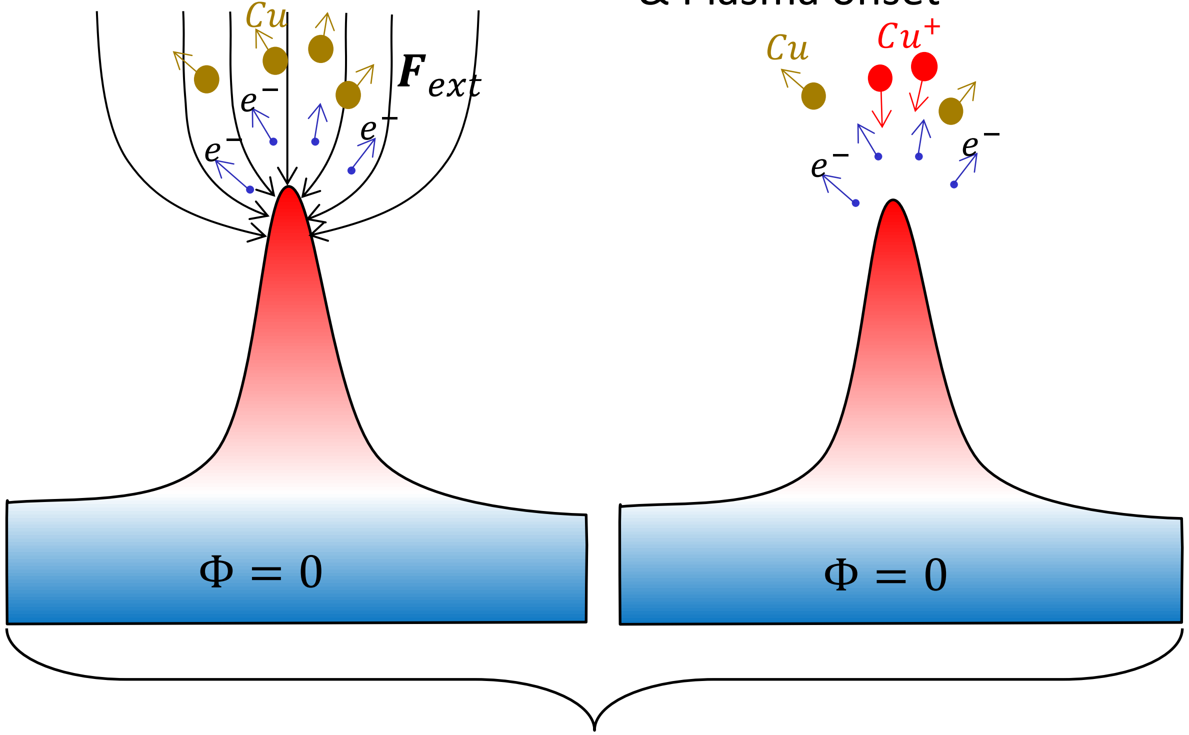
Crucial stages for VBD mitigation

Protrusion formation: Mitigate by material choice, conditioning, vacuum quality, etc



Stage 2: Field emitter Thermal Runaway

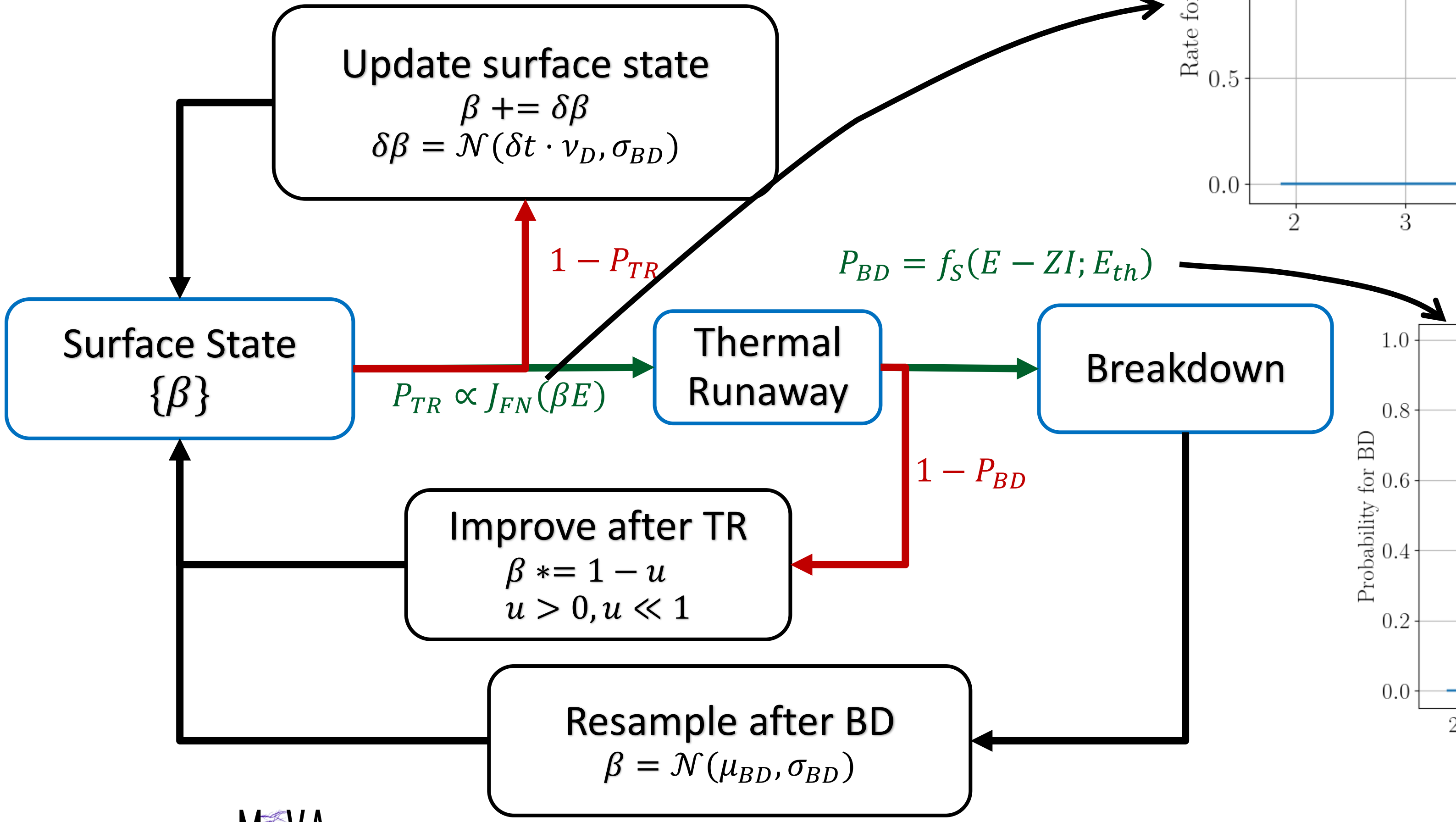
Stage 3: Ionization runaway & Plasma onset

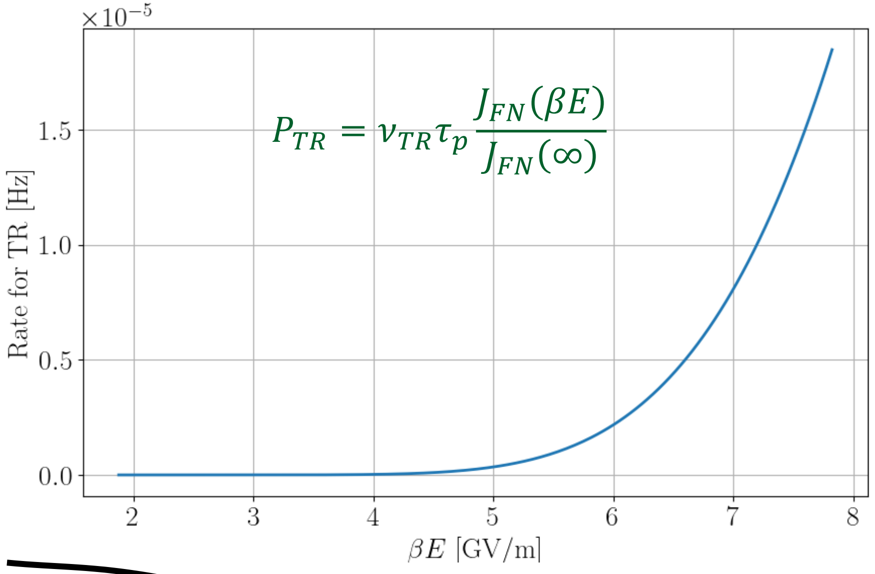


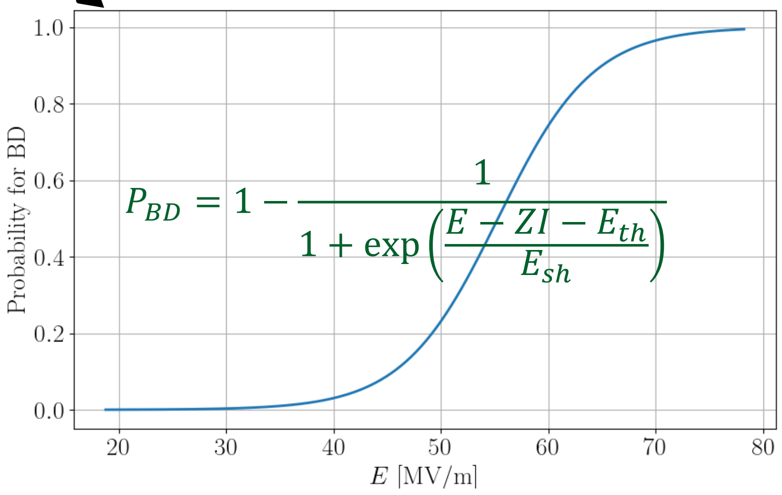
(Not really distinguishable): Mitigate by EM power coupling (RF design of structures)

The model

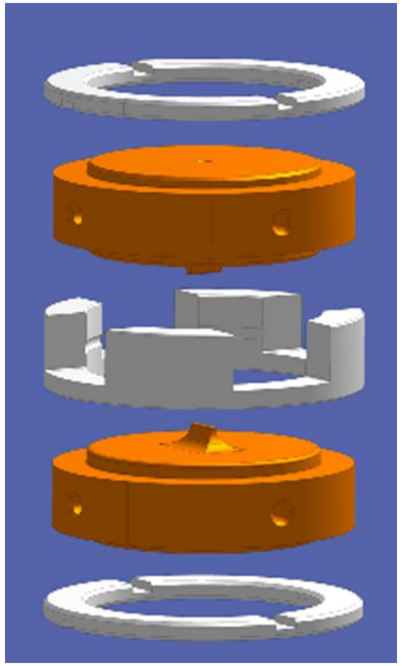
- Surface state deteriorates at constant rate (s^{-1})
- Thermal runway slightly improves the surface state
- Breakdown "cleans up" (resample)

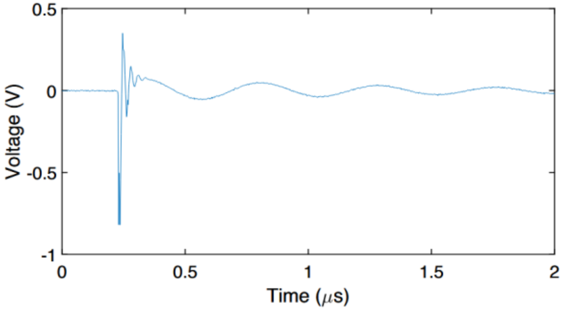


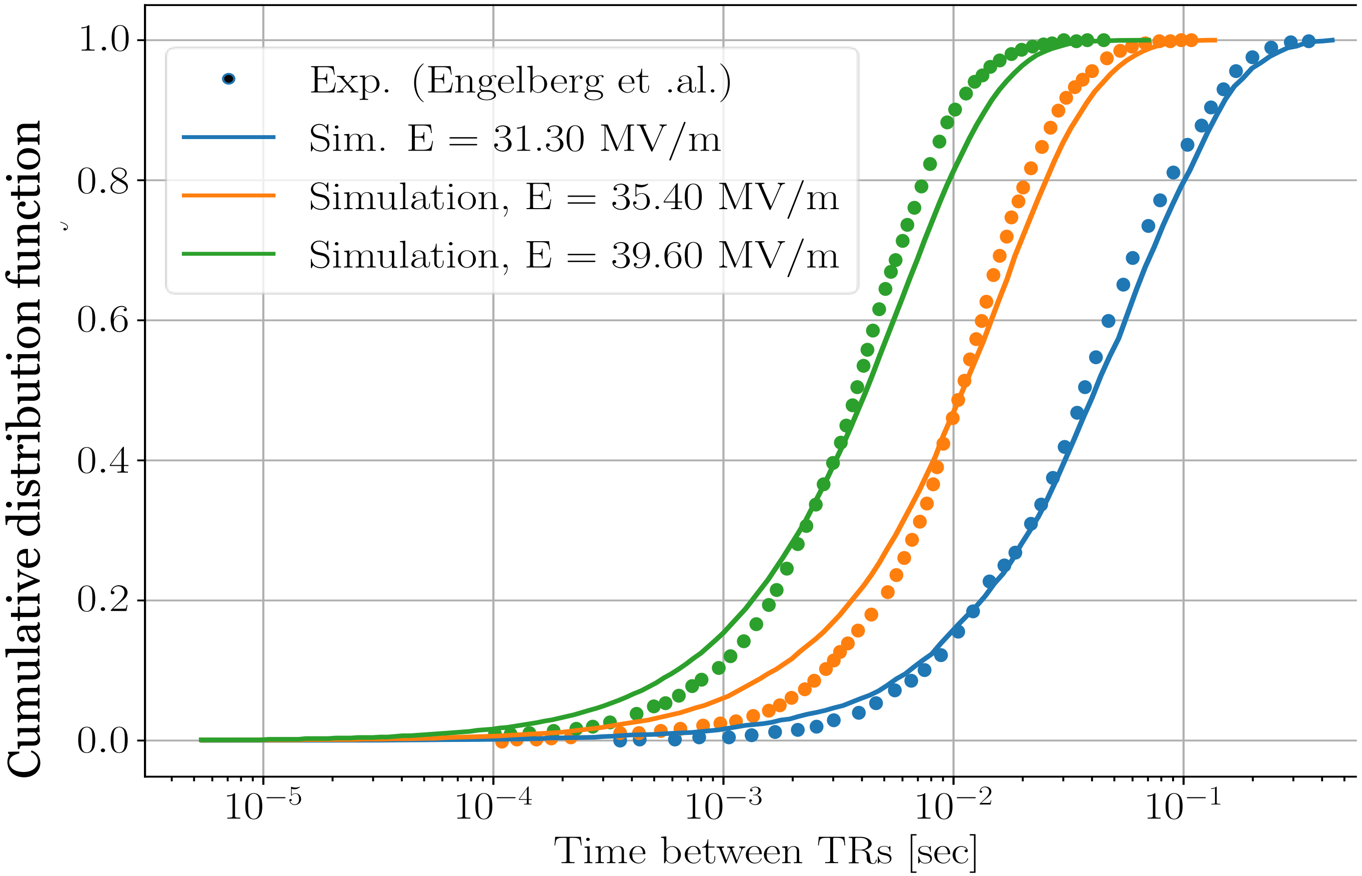




Thermal Runaway statistics



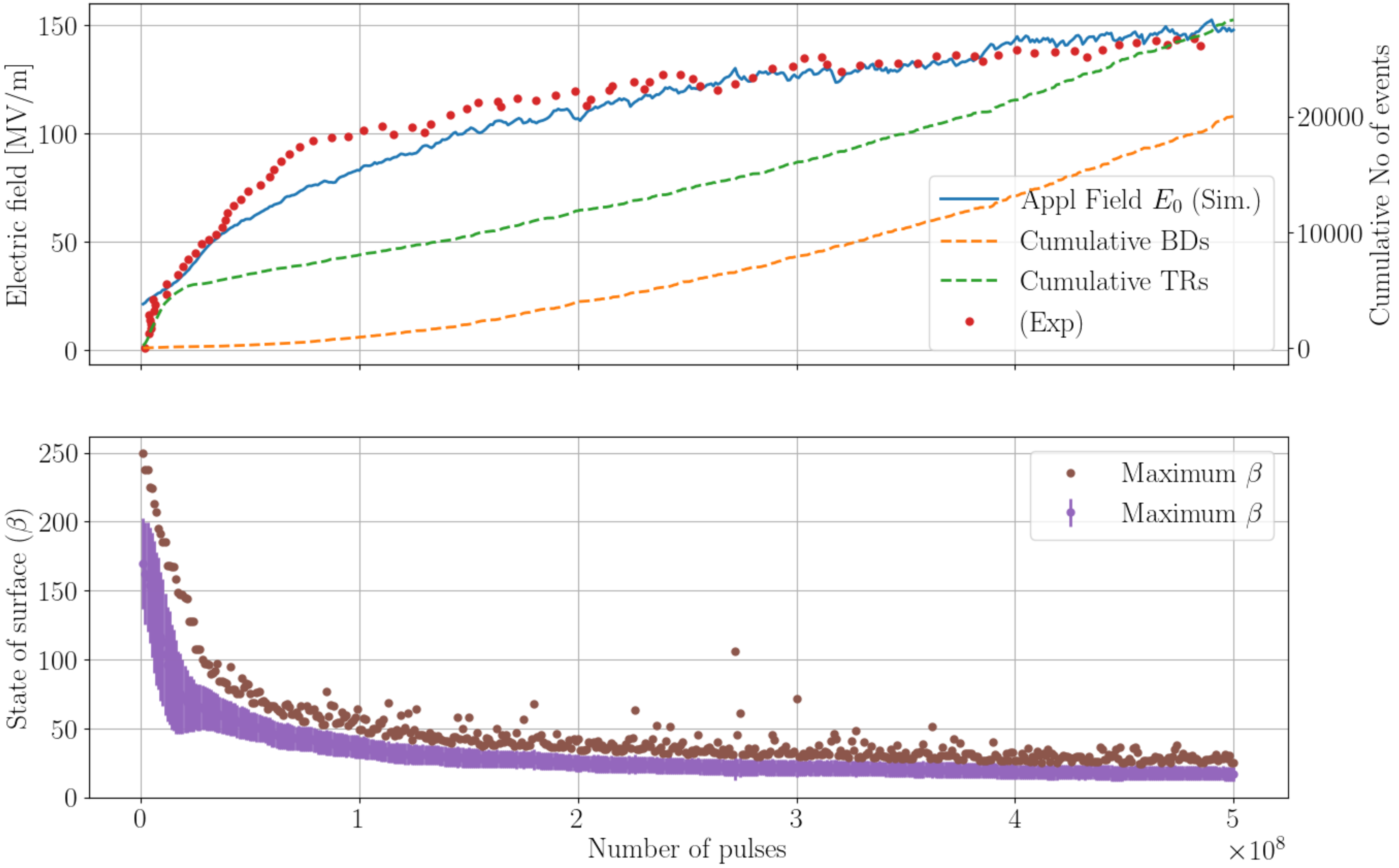


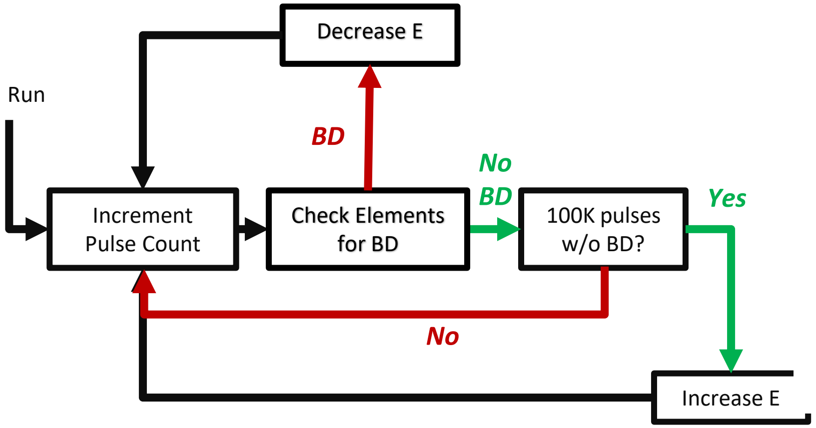


- Current spike event experiments: Engelberg et. al. PRSTAB 23, 123501 (2020):
- Interpret current spikes them as TR events and fit the TR loop parameters

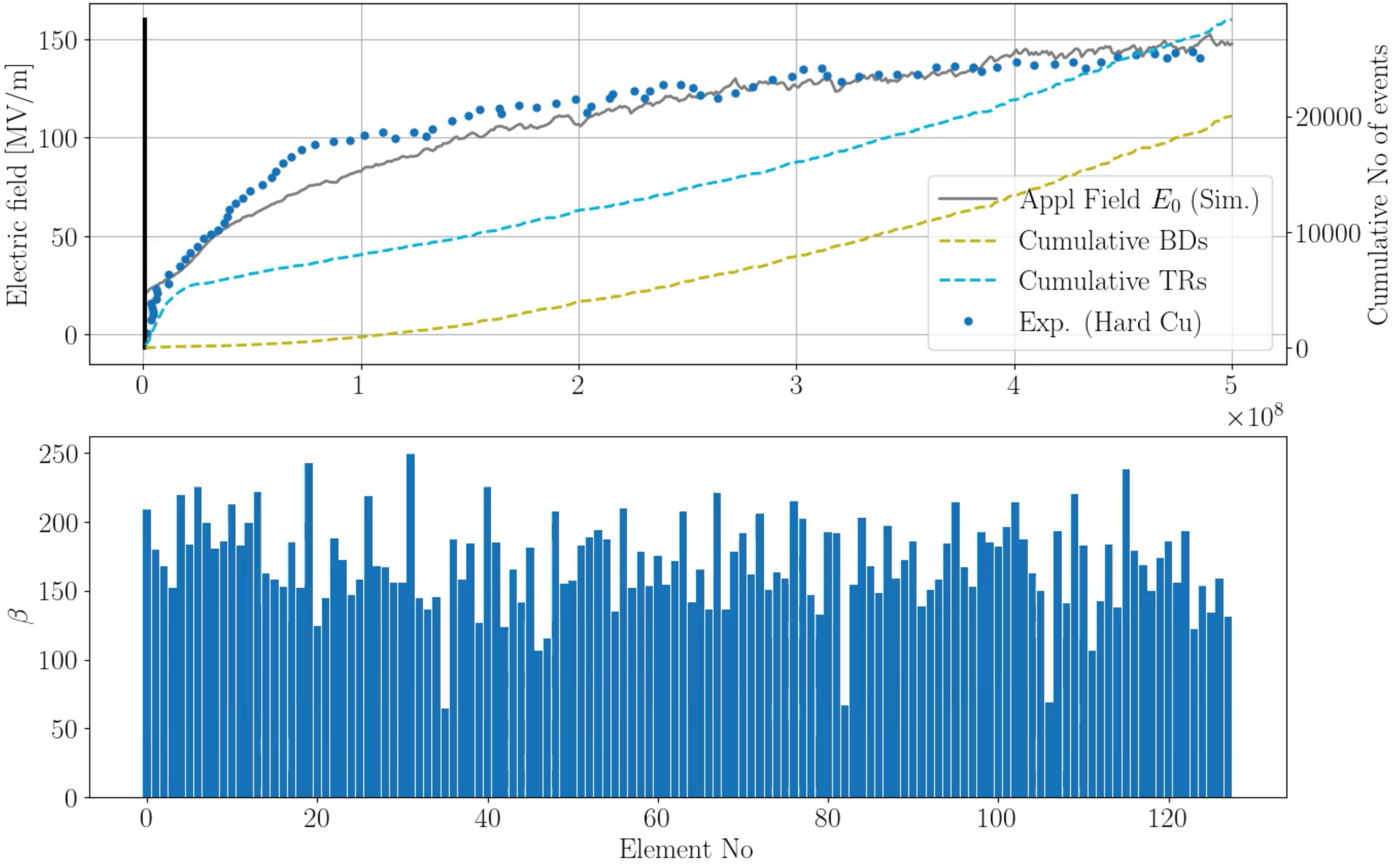
Conditioning

- Conditioning mechanism: gradual decrease of β due to TRs (burning tips out) and BDs
- BDs not necessary for condition. They might cause BDs de-conditioning
- Saturation: the rate of improving the surface by TRs equalizes the constant rate of surface deterioration.



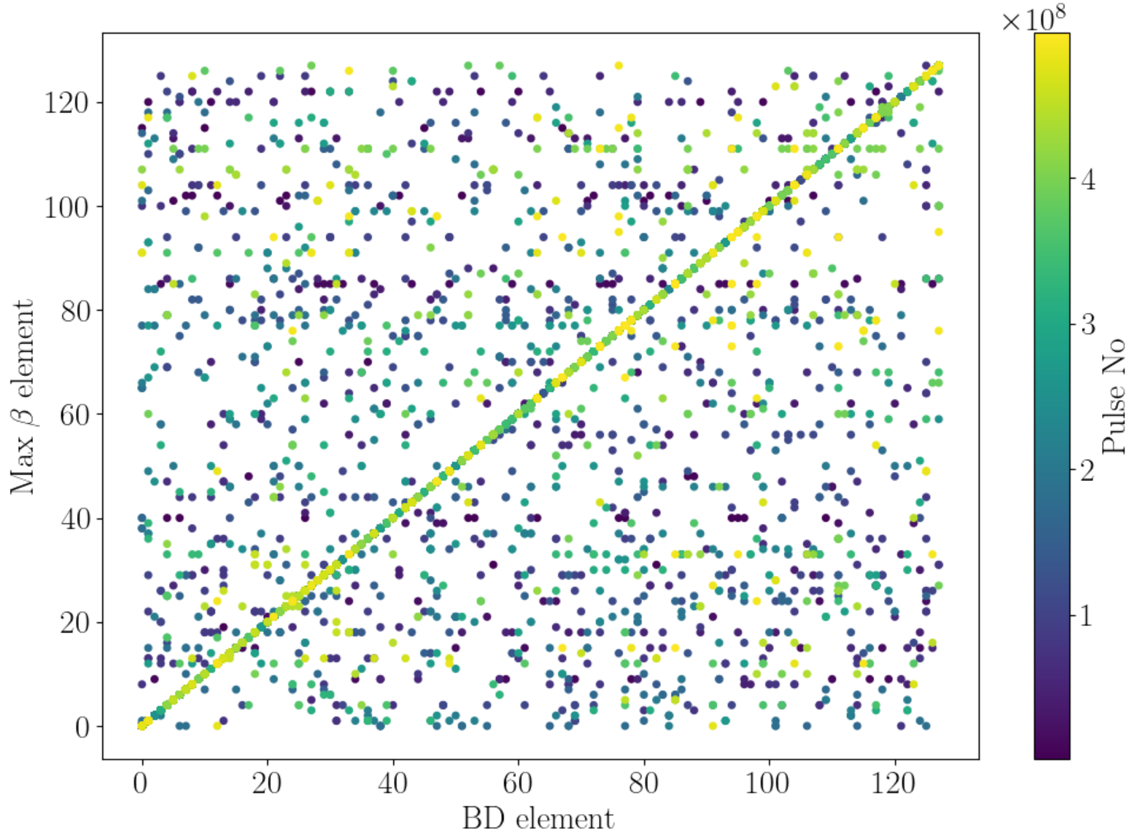


Conditioning (fancier)

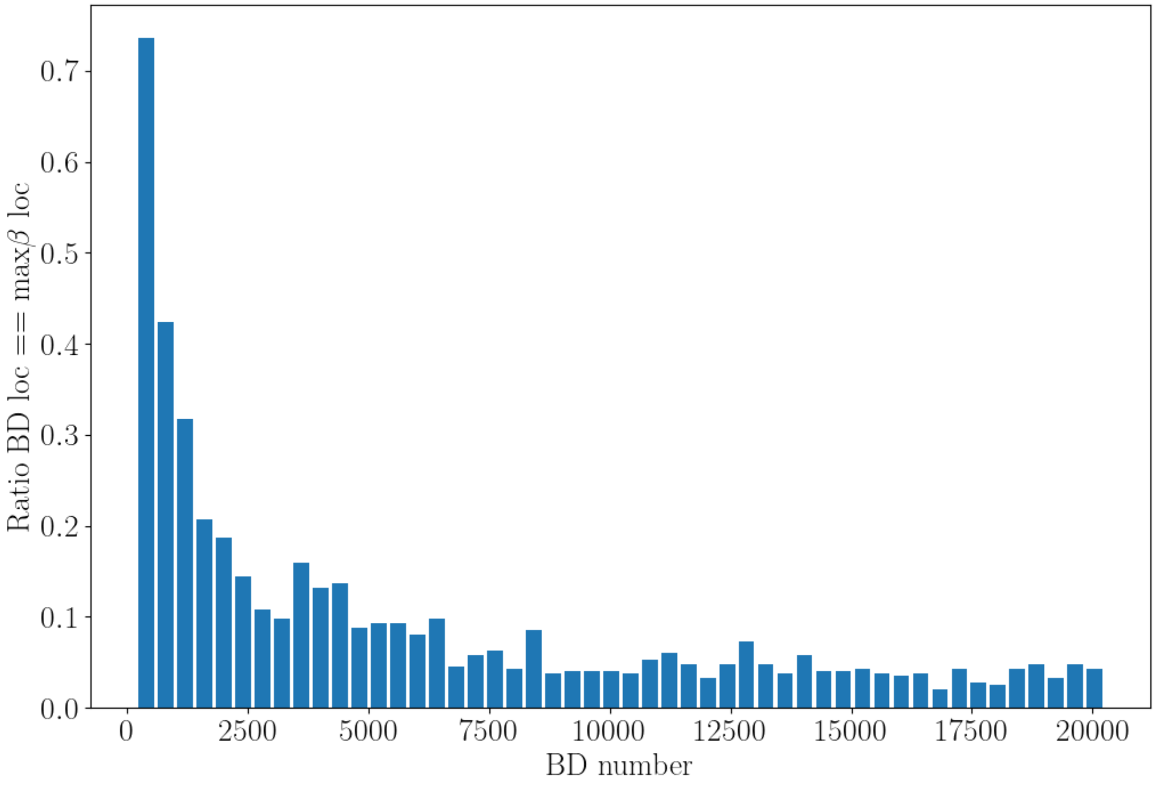


Dominant emitters vs BD

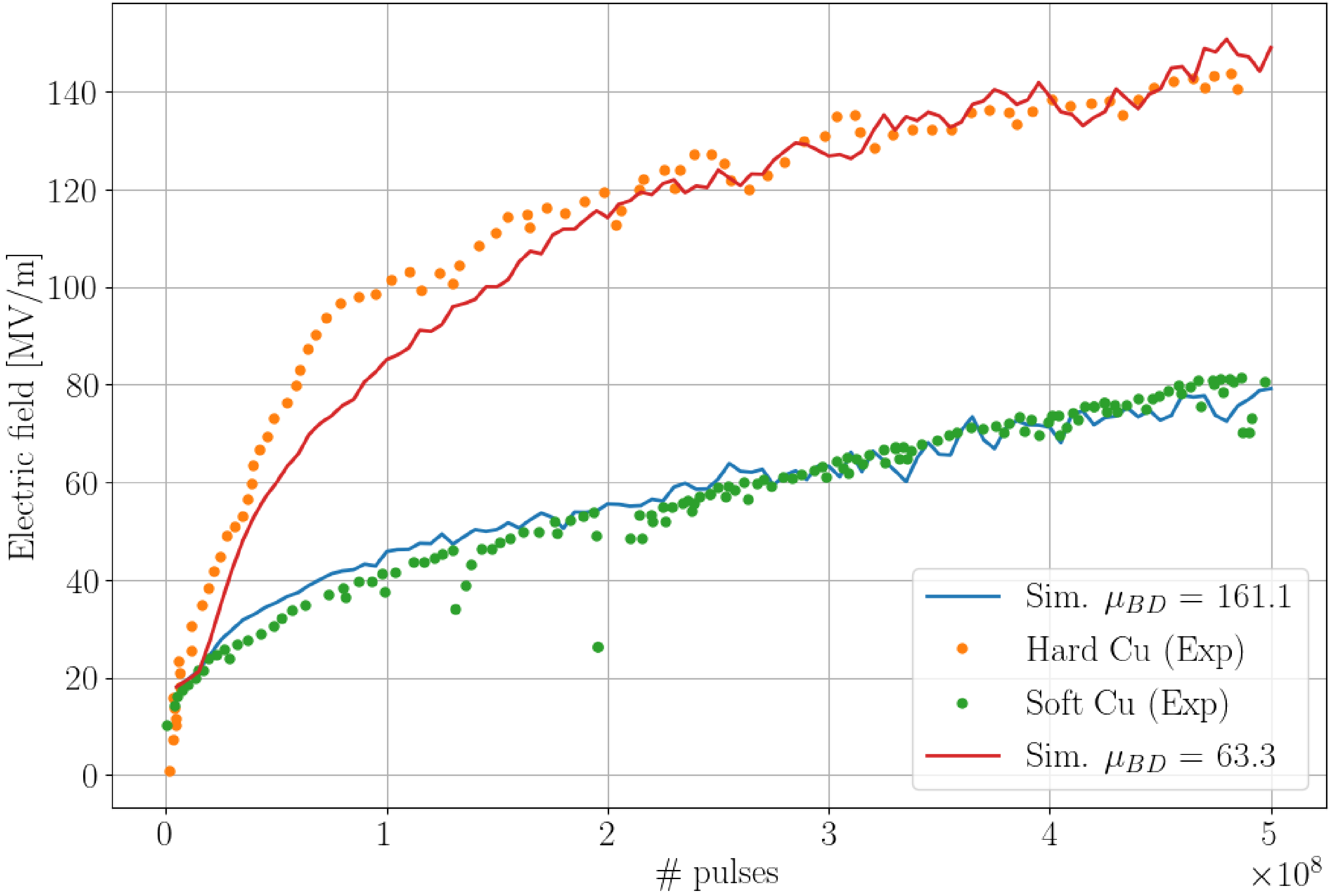
- 90% of BDs from dominant emitter



- But in the initial stages…



Soft vs Hard Cu

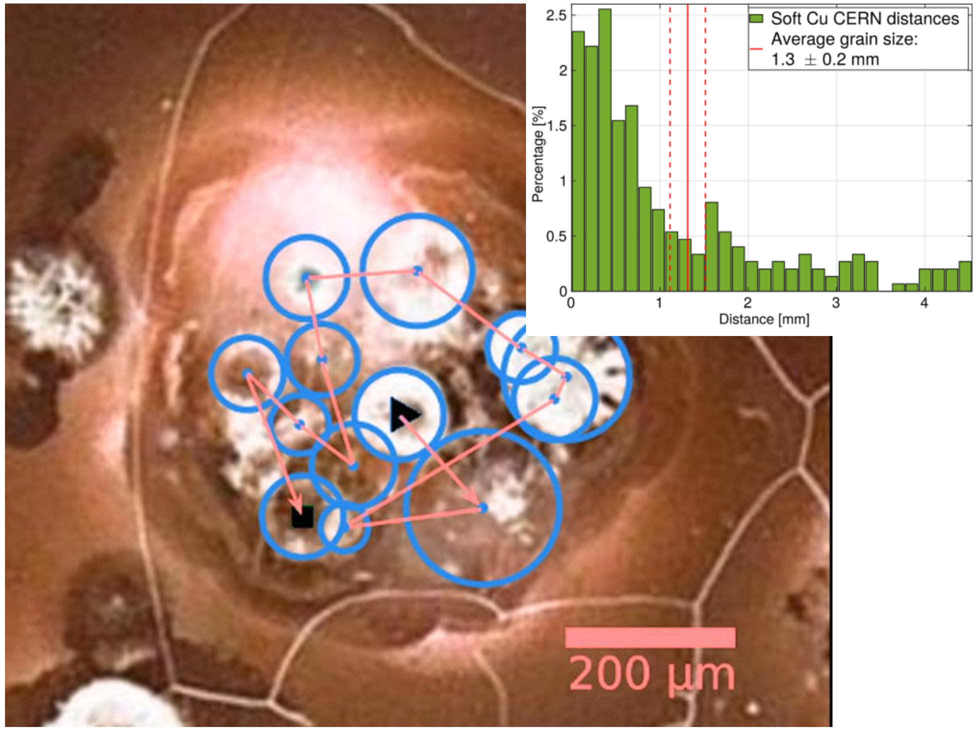


Exp. data: A. Saressalo et. al. J. Appl. Phys. 130, 143302 (2021)

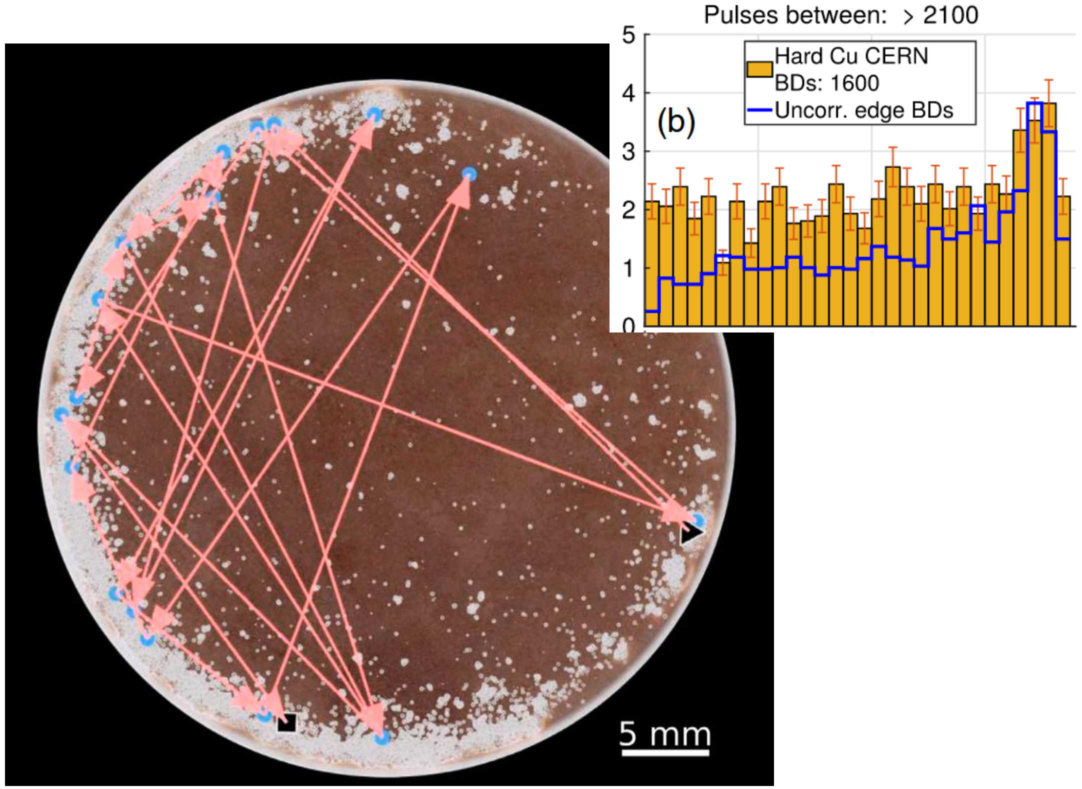
- Recurring MeVArc question: **What's so different between soft Cu and hard Cu?**
- The only parameter tweak that seemed to easily explain the difference is the damage a BD leaves behind
- Difference between soft and hard: grain size

A tentative possible explanation

- Soft Cu:
  - ➢ Consecutive BDs in the same grain
  - ➢ Plastic deformation caused **during a BD** propagates inside the grain



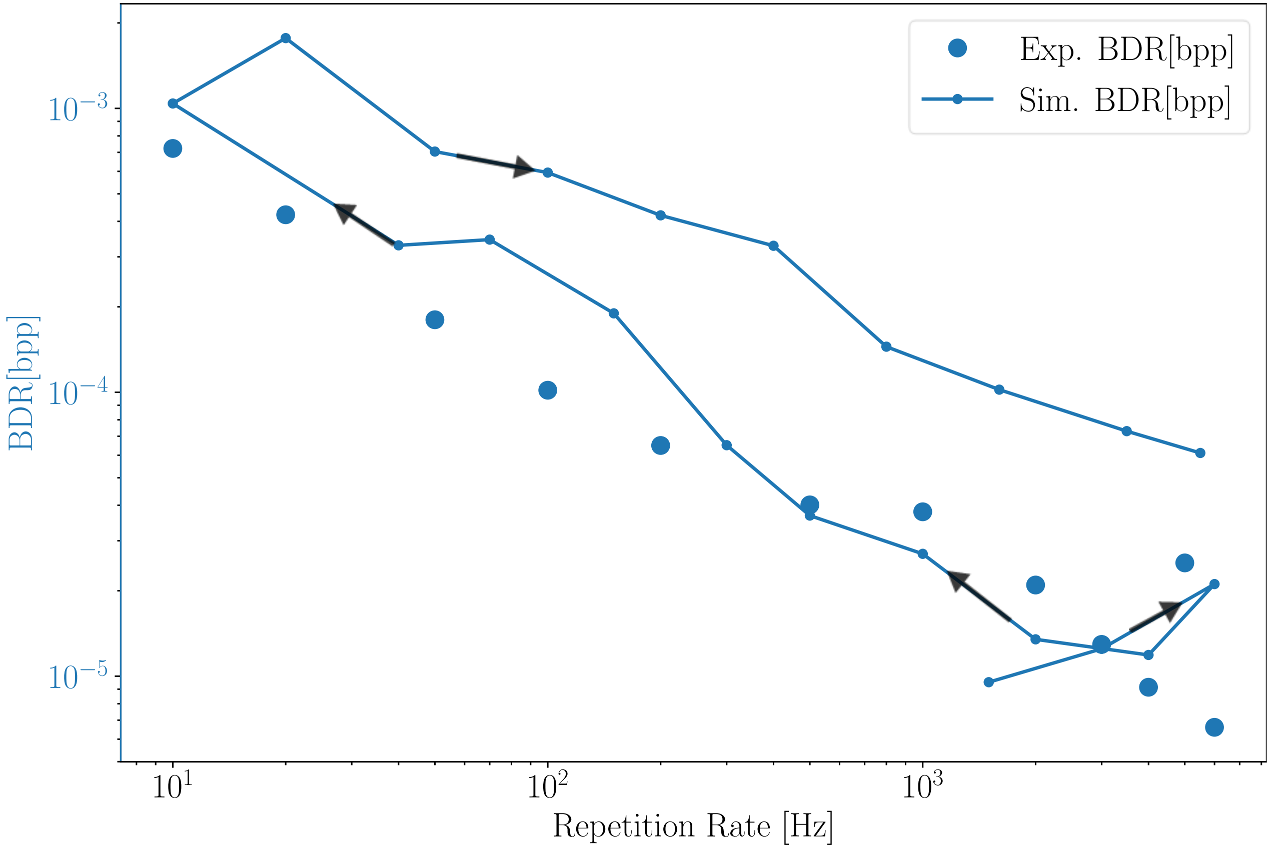
- Hard Cu:
  - ➢ Consecutive BDs uncorrelated
  - ➢ Plastic deformation pinned



Images: A. Saressalo et al. PRSTAB 23, 23, 023101 (2020)

Pulse frequency dependence

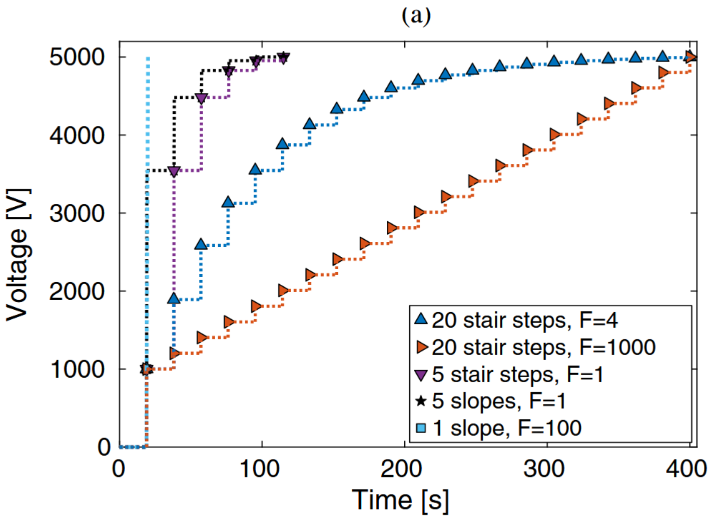
- Another curious finding has been the pulse frequency dependence
- Preliminary results show that the model reproduces it (at least qualitatively)
- Hysteresis: running at low repetition rates seems to be “deconditioning” the surface
- The dependence comes from the assumption that the surface state deteriorates at a constant rate (regardless of field application)

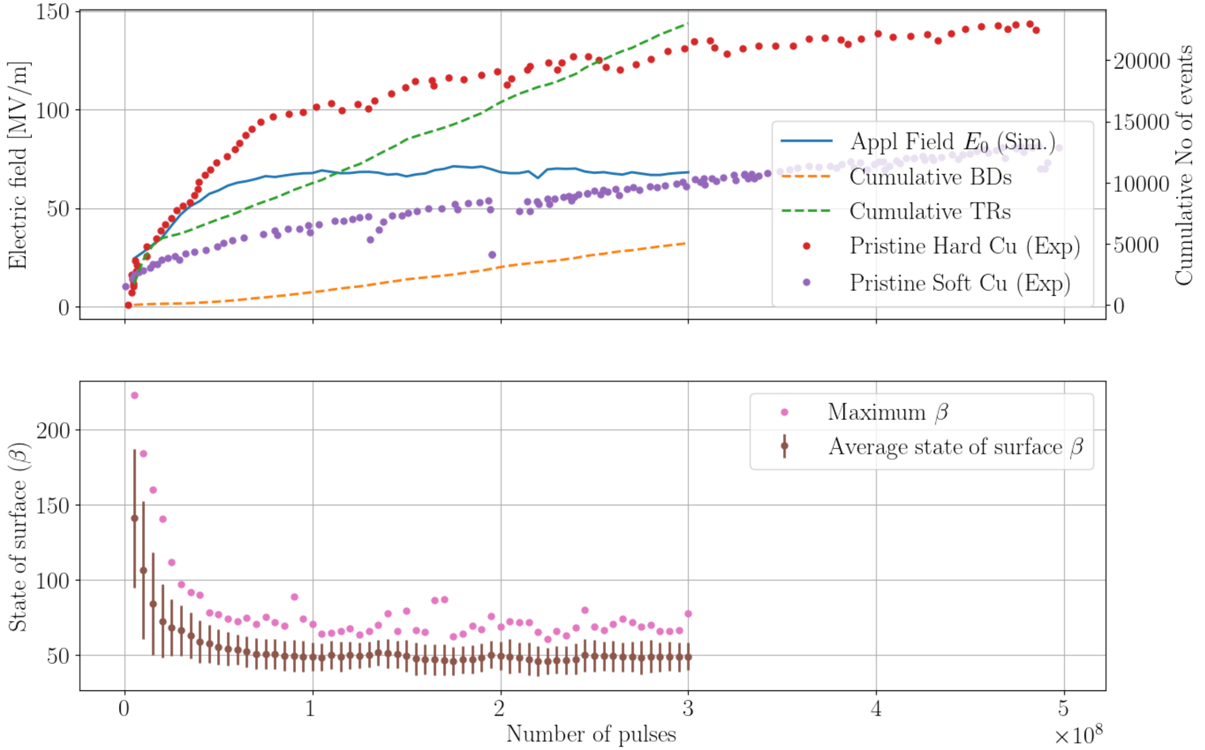


Exp. data: A. Saressalo et al. PRSTAB 23, 113101 (2020)

BUT… recovery algorithm?

- Current model disregards the recovery algorithm
- If implement the 400 sec idle time after each BD, the conditioning becomes really clamped





- Future efforts hopefully will understand this behavior
- Hint: The surface doesn't deteriorate constantly but most probably "converges" to some max ⟨β⟩ value

Summary and Outlook

Breakdown Occurrence Monte Carlo:

- Bridge the gap between theory and experiment
- Allow to reject hypotheses and make new ones

Current model:

✓Reproduce current spikes statistics (Engelberg et. al. Phys. Rev. AB (2020))
✓Reproduce conditioning curves hard Cu vs soft Cu
✓Reproduce pulse frequency dependence
✓**Preliminary explanation of hard vs soft**

Outlook :

✓Power flow dependence (see talk by Tauno Tiirats)
✓Simulate BD and FE distribution for varying field electrodes
✓Understand problems of recovery algorithm (more realistic surface deterioration model?)
✓Cryogenic behavior.

BD distance histograms