Monte Carlo simulation of vacuum breakdown occurrence

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Abstract

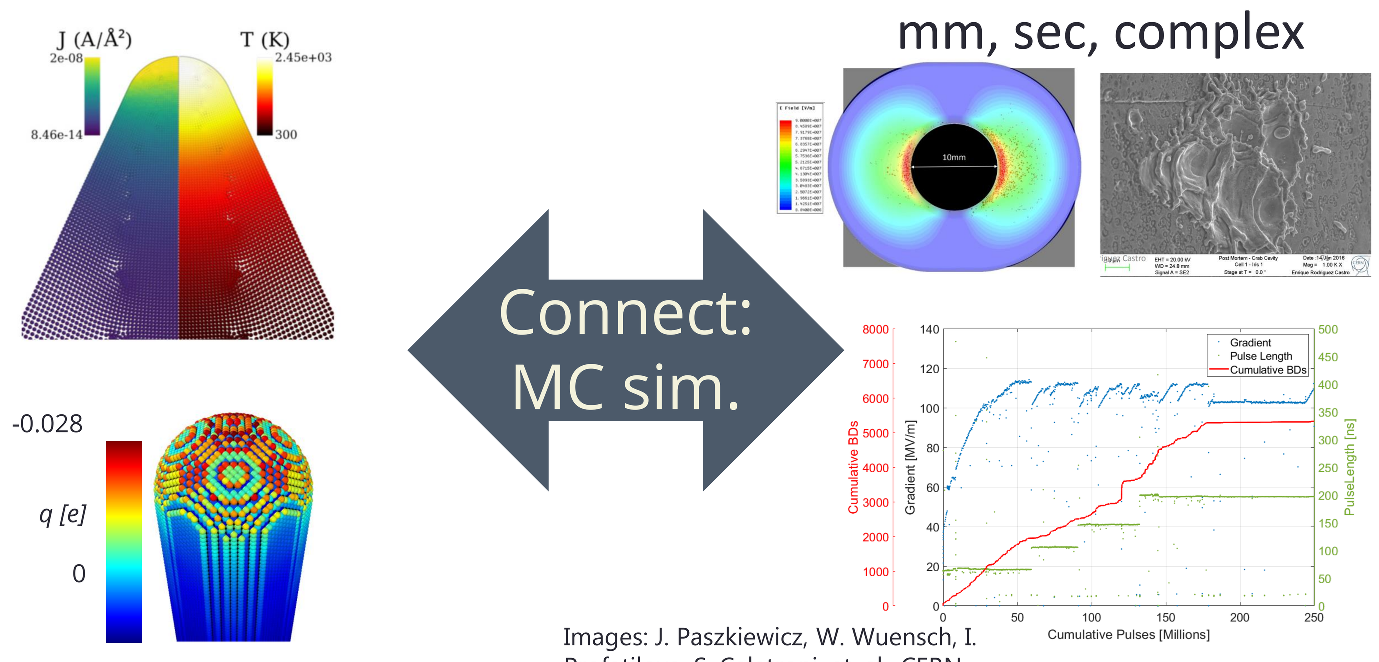
Despite abundant experimental data on Vacuum BreakDown (VBD) occurrence statistics, drawing conclusions on the underlying physical processes is challenging due to the low-level focus of most VBD models that cannot make quantitatively comparable predictions. Here we attempt to bridge this gap by modelling VBD occurrence as a **chain of random events simulated by Monte Carlo**. The metal surface is separated into 128 small elements described by a local field E, a power coupling impedance Z, and a surface state parameter β. On each pulse, surface elements are randomly tested for the occurrence of thermal runaway, with a probability proportional to the field emitted current density $\Gamma \propto f_{FN}(\beta E)$. Then elements where TR occurred are then tested for VBD, depending on E and the power coupling parameter Z of each point. β is updated after each pulse in a different manner, depending on whether nothing, TR, or VBD occurred. Our model gives predictions in good agreement with the experimental statistics of current spike events, as well as the conditioning curves of large electrode VBD systems.

Motivation

- Extensive experimental data on VBD occurrence not being able to connect with microscopic simulations

VBD Simulations
ns, nm, simple systems

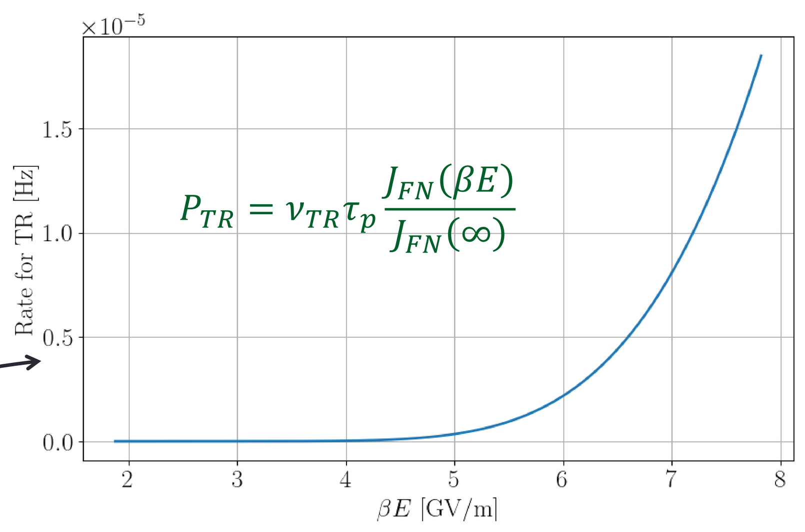
VBD Experiment (CERN)
mm, sec, complex

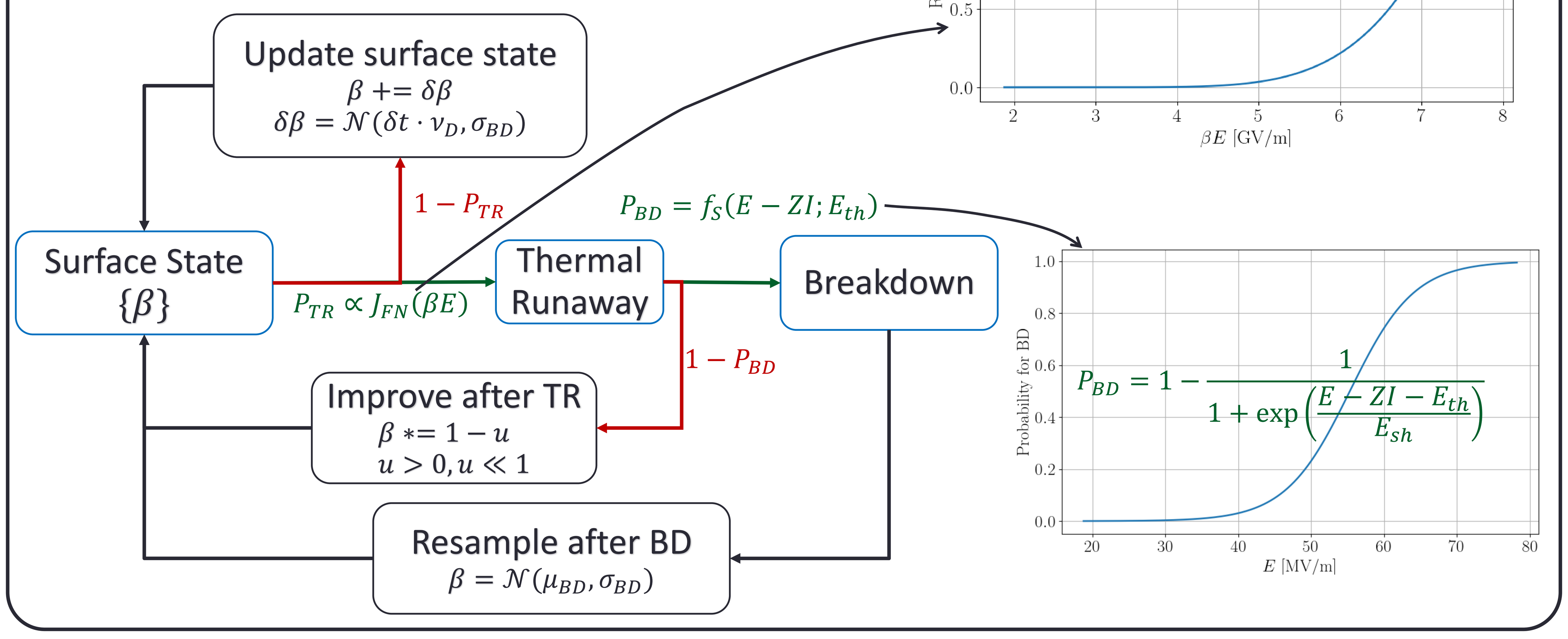


Images: J. Paszkiewicz, W. Wuensch, I. Profatilova, S. Calatroni, et. al., CERN

The model

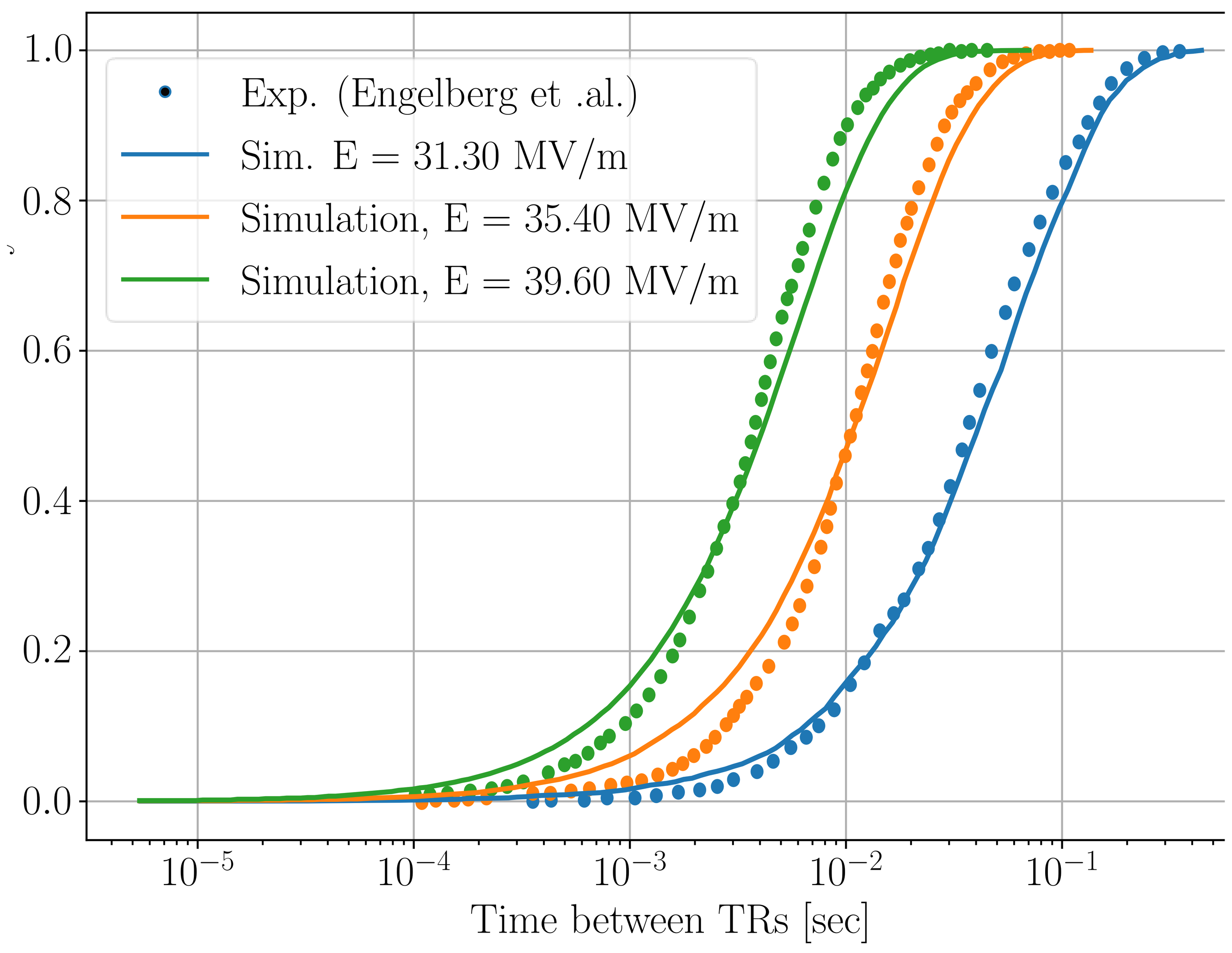
- Surface state deteriorates at constant rate (s[-1])
- Thermal runway slightly improves the surface state
- Breakdown "cleans up" (resample)



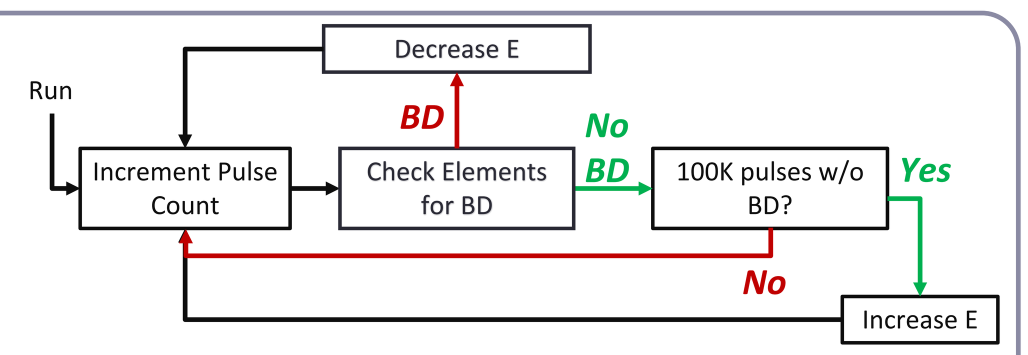


Thermal Runaway statistics

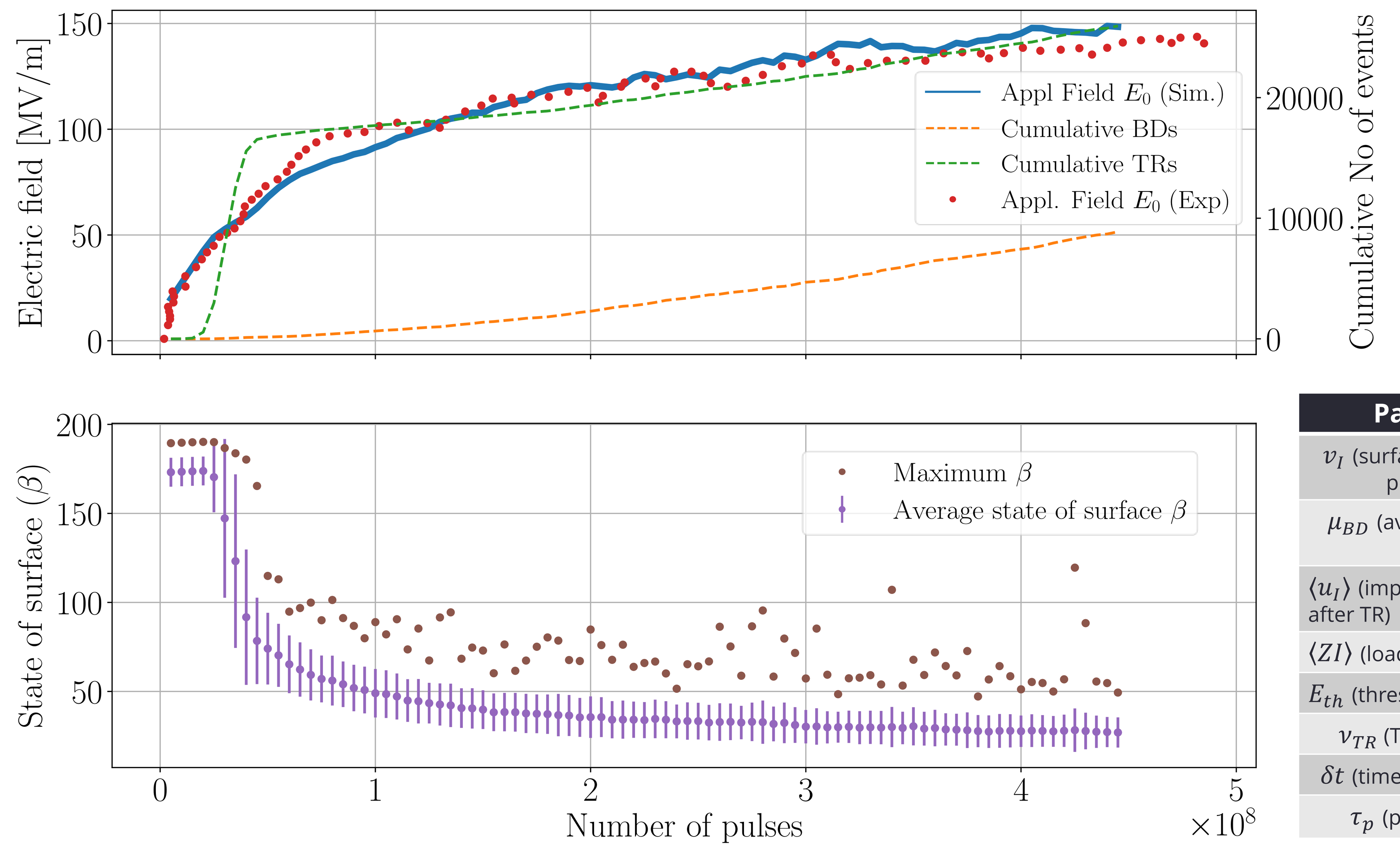
- TR events does not always lead to BD. For BD, the right amount of power flow is needed
- Experiments by Engelberg et. al, (PRSTB 2020) have shown that current spike events appear regularly under constant (low) field without causing BD. Here we interpret such events as TRs
- Our model predicts the statistical distribution of the time between TR events in good agreement with the experimental distribution of current spike events



Conditioning



- Experimental conditioning curves are reproduced by the model with a very good agreement
- The conditioning mechanism is mainly the gradual decrease of the average state of the surface due to TRs (burning tips out) and BDs
- BDs are not necessary for conditioning! In fact, after a certain level, BDs de-condition
- Saturation comes when the rate of improving the surface by TRs equalizes the constant rate of surface deterioration. This can explain the observed pulse frequency dependence!



• Exp. Conditioning curve from Saressalo et. al. J. Appl. Phys. 130, 143302 (2021), Fig. 7a (pristine Hard Cu)

Parameter	Value
ν_l (surface deterioration per second)	0.1mHz
μ_{BD} (average field after BD)	80 ± 24 MV/m
$\langle u_l \rangle$ (improvement rate after TR)	4×10^{-5}
$\langle ZI \rangle$ (loading field)	10 MV/m
E_{th} (threshold E for BD)	70 MV/m
ν_{TR} (TR attempt rate)	5.4 MHz
δt (time between pulses)	0.5 ms
τ_p (pulse duration)	1μs

Conclusions & Outlook

- MC simulations are promising to bridge the simulation - experiment gap for understanding VBD
- Our model reproduces the occurrence statistics of current spikes interpreted as thermal runaway events
- Our model reproduces qualitatively the conditioning curves, without imposing a pre-defined conditioning evolution. The conditioning behavior emerges naturally from the gradual improvement of the surface state
- Outlook: Predict dependence of pulse frequency; Automatic optimization algorithms to investigate the different parameters on different measurements; Implement accurate value of Z_{bd} at each point

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