



Simulation based investigation on the influence of electromagnetic power in VBD initiation process

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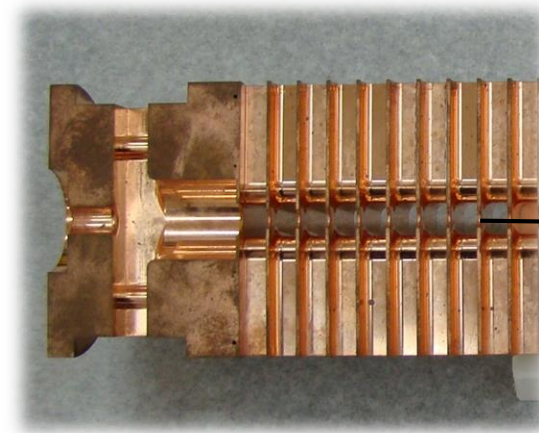


Outline

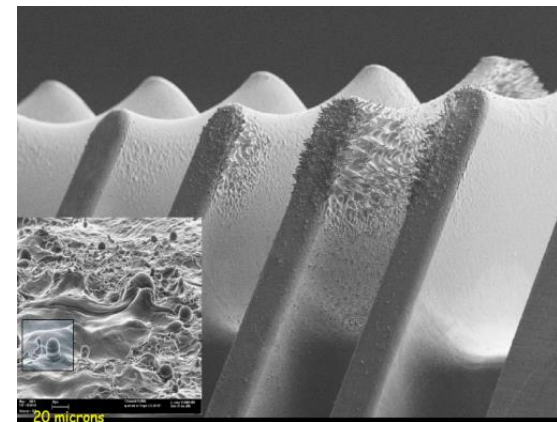
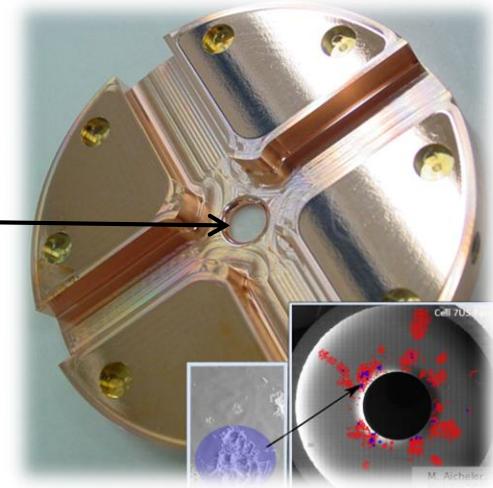
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- **Introduction**
- **Electromagnetic power flow & simulations**
 - Idea
 - Implementation
 - FEMOCS
 - BDMC
 - Preliminary results
- **Conclusion**

- **VBD mitigation techniques:**
 - Controlling relevant characteristics
 - (electric field, surface roughness, contamination)
 - **Limiting the available EM power** [1,2]
- The hypotheses:
 - **The power supply limitation hinders the development of plasma exactly at the moment plasma initiates** (stage 2-3)
- **The goal:**
 - Describe quantitatively the **EM power dependence of VBD initiation**



Accelerating structure (CLIC)



Surface damage in CLIC accelerating structures after the breakdown

Images: Walter Wuensch, CERN

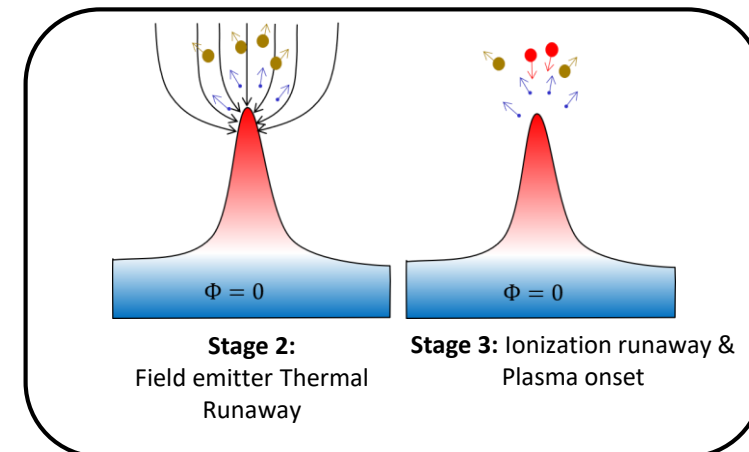
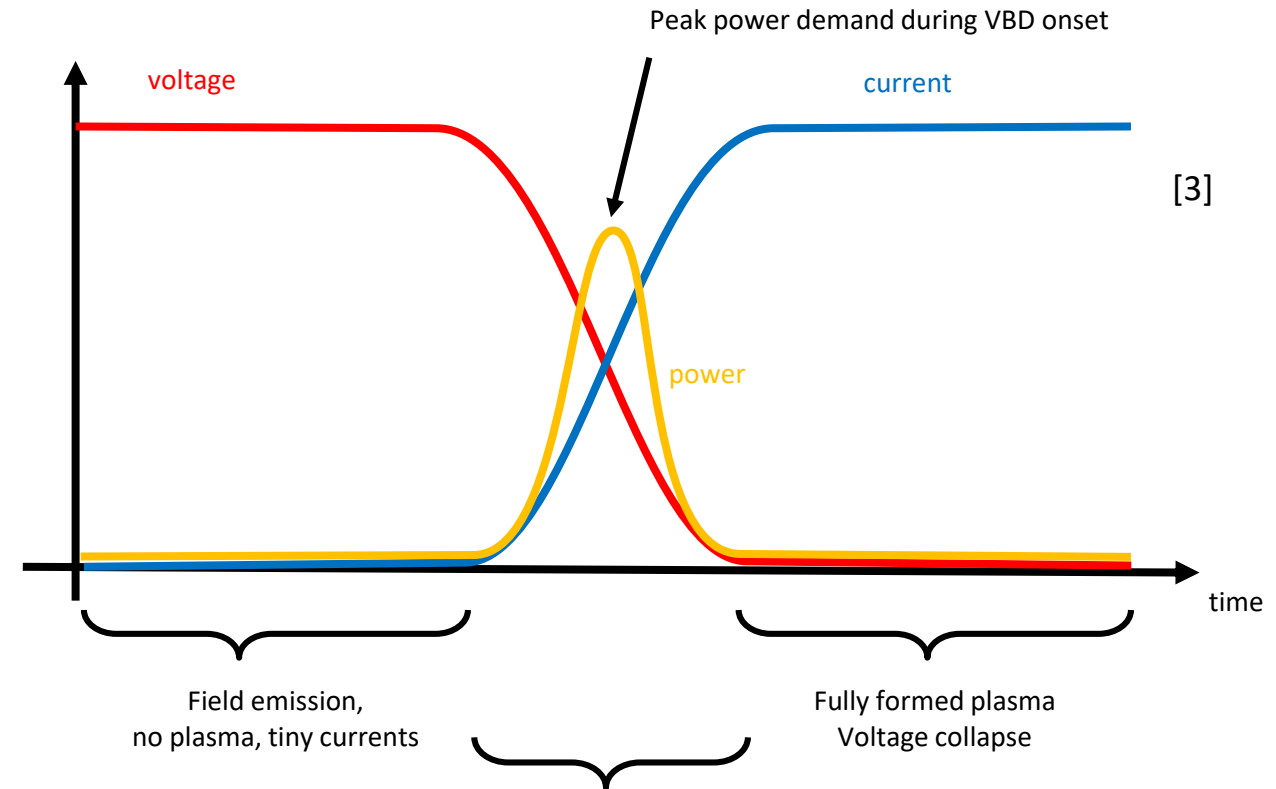
[1] W. Wuensch. The Scaling of the Traveling-Wave RF Breakdown Limit. Technical Report CERN-AB-2006-013. CLIC-Note-649, CERN, Geneva, Jan 2006.

[2] A. Grudiev, S. Calatroni, and W. Wuensch. New local field quantity describing the high gradient limit of accelerating structures. Phys. Rev. ST Accel. Beams, 12:102001, Oct 2009.

Electromagnetic power supply

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- „Experimental data (CERN, SLAC and KEK) suggests High-Gradient limit depends on power flow, not only E field“ [3]
 - **Plasma initiation requires a large influx of power**
- **Ultimate VBD limit is a function of available power**
 - During VBD onset!
 - **Local power flow**
 - Local surface E field decreases under VBD loading



[3] J. Paszkiewicz, A. Grudiev, and W. Wuensch. Breakdown-loaded electric field as a high gradient limit. 2019 International Workshop on Mechanisms of Vacuum Arcs (MeVAarc), 2019.

Investigation strategy

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Multi-scale physics
FEMOCS

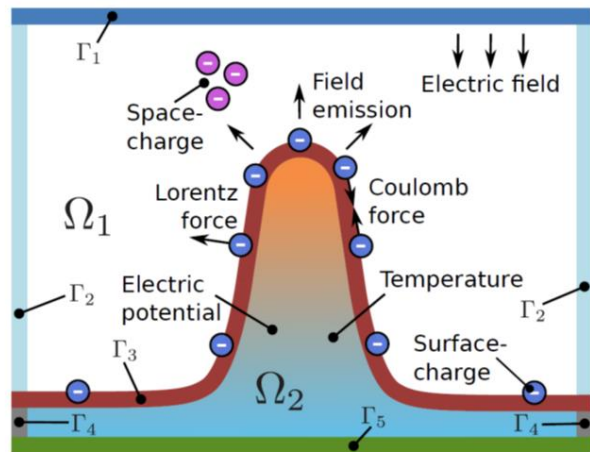


Image: Mihkel Veske, UH&UT

Real measurements & statistics
BDMC

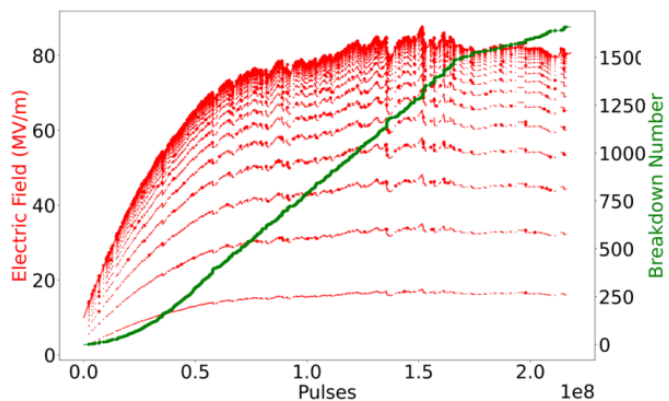


Image: Victoria M. Bjelland, CERN





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Multi-scale simulations

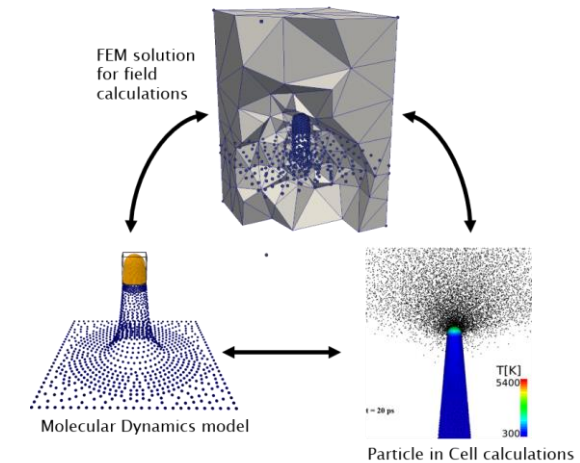
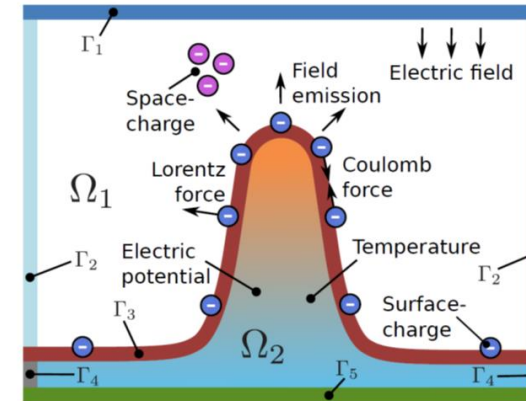
FEMOCS

Multiscale breakdown simulations

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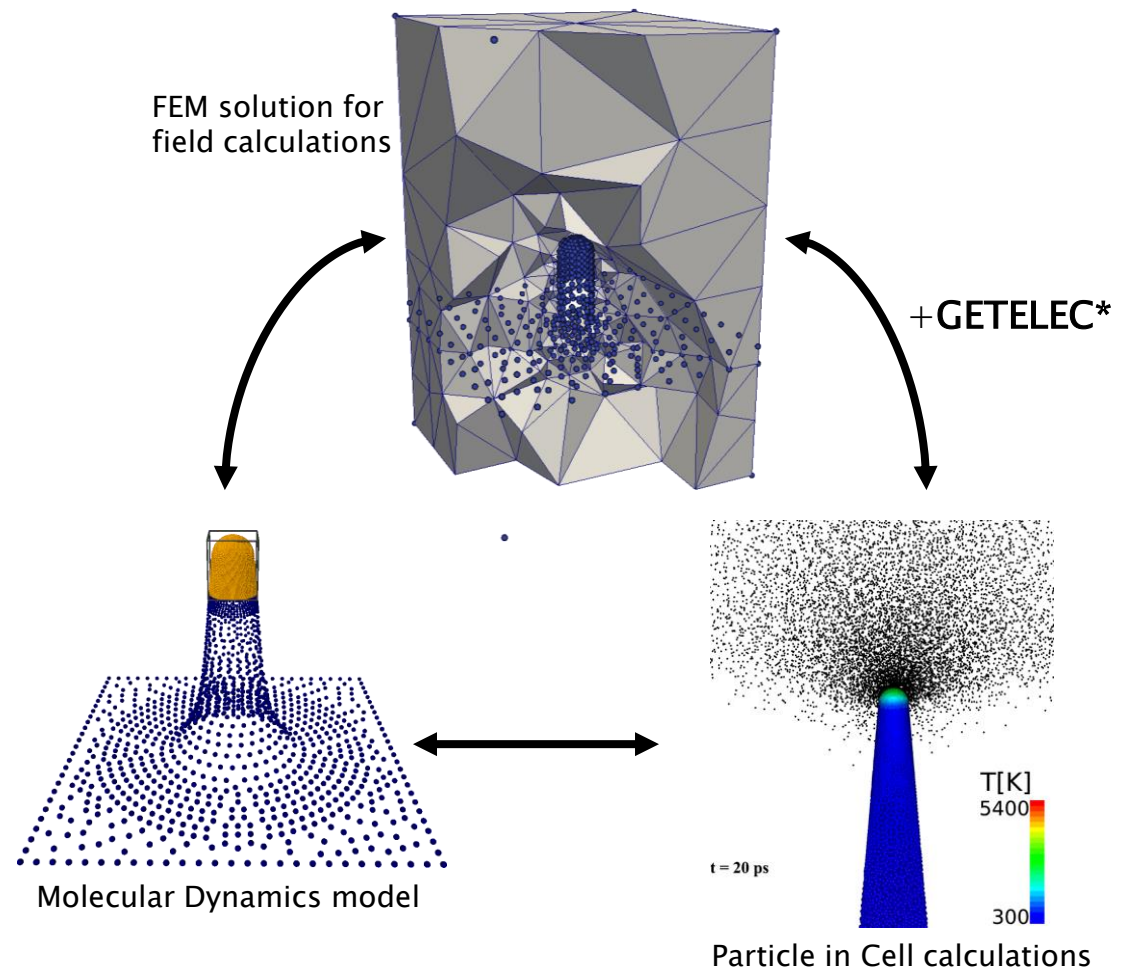
- VBD involves **various phenomena in various space scales**:
 - Emission spot formation
 - **Thermal runaway**
 - **Field emission**
 - **Plasma formation**
 - Surface damage

- Need for concurrent, **multi-scale, multi-physics simulations**
 - **Atomistic simulations**
 - Molecular Dynamics (MD)
 - Particle Dynamics (PIC)
 - **Continuum simulations**
 - Thermomechanics (FEM)
 - Electromagnetics (FEM)

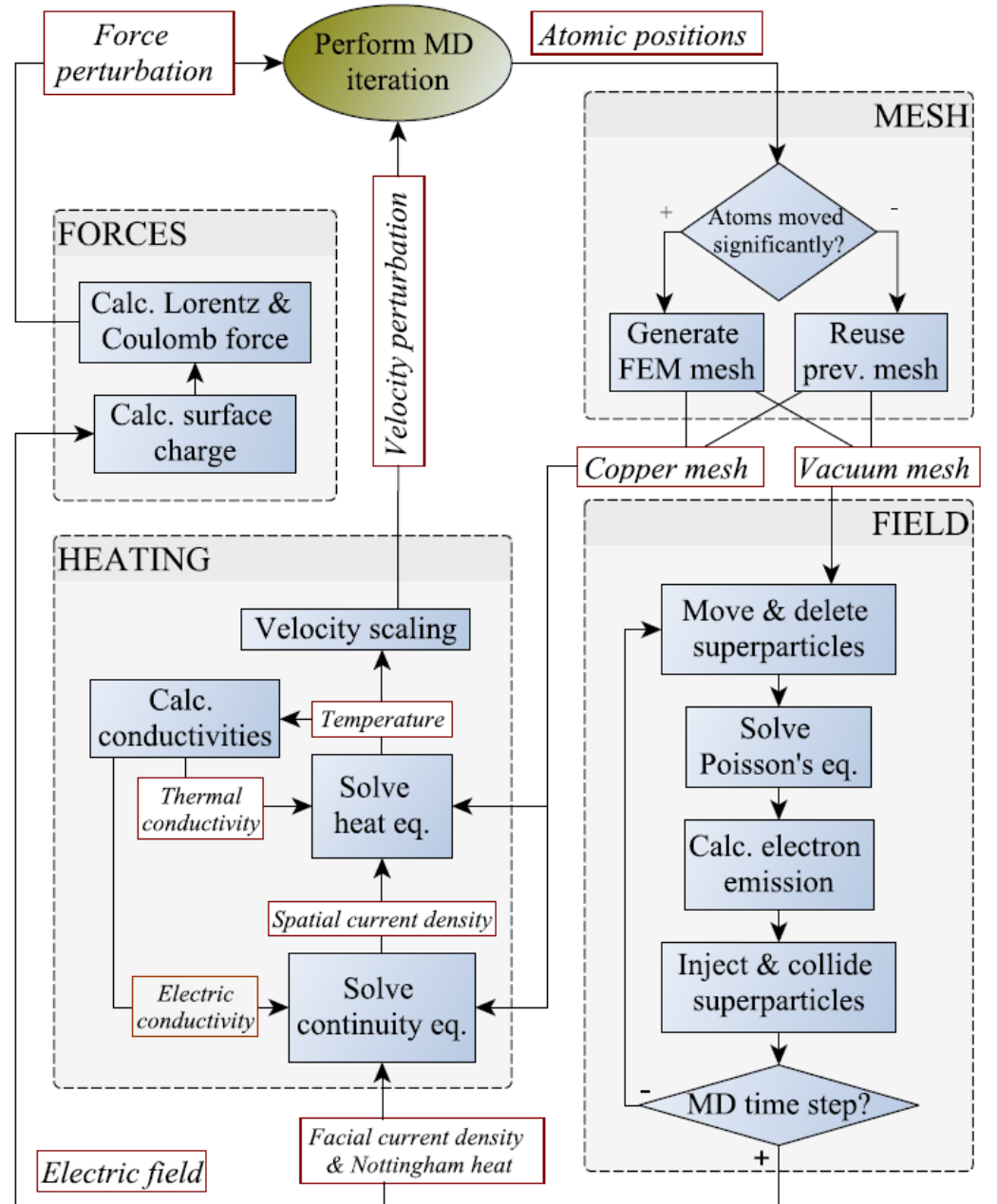


FEMOCS (gitlab.ut.ee/matter/femocs)

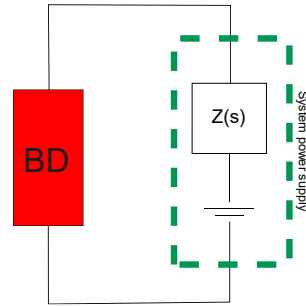
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* Version 3 soon to be published: gitlab.ut.ee/matter/getelec

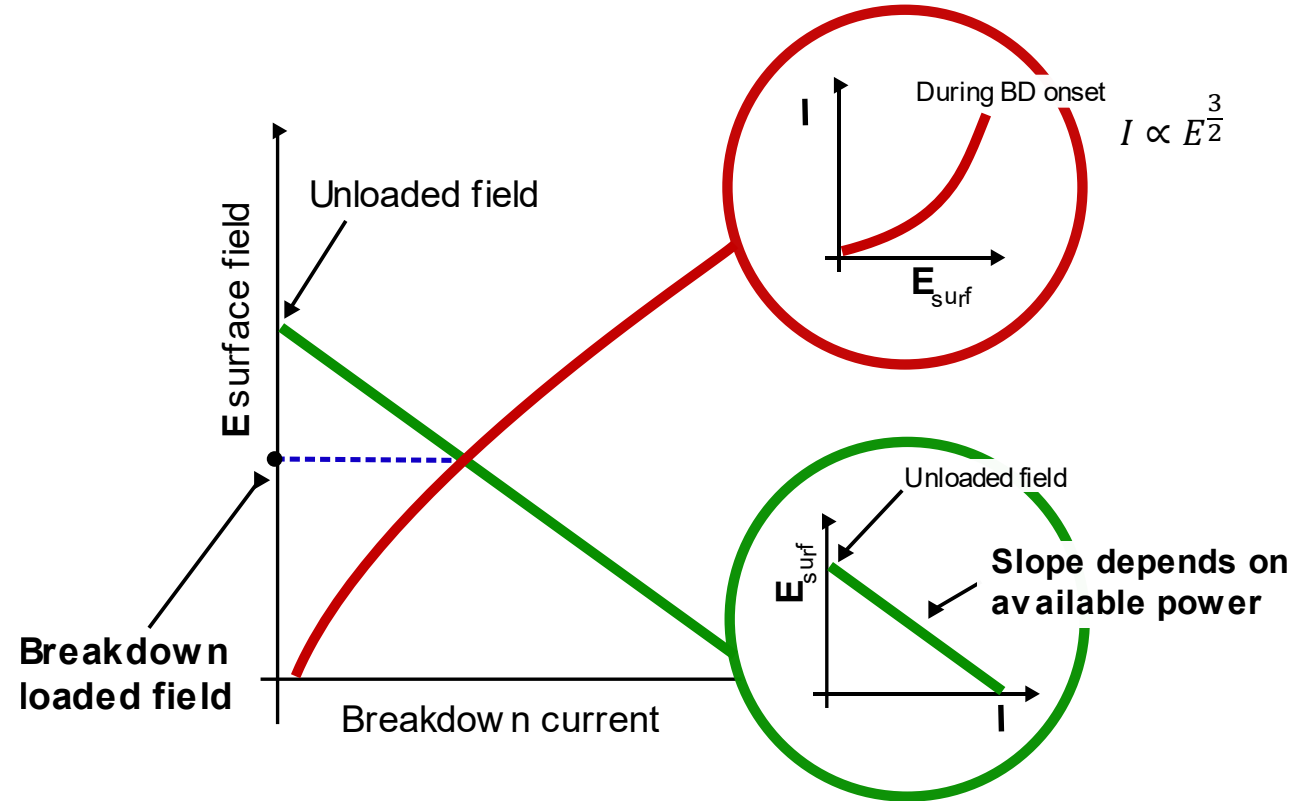


- **Jan Paszkiewicz's solution** [4]:



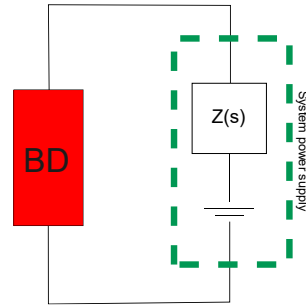
- Simplified circuit
- VBD dynamics approximated by a "simple" non-linear circuit element (*Child-Langmuir law*)
- For **any point** in the domain evaluate:
 - **dependence of local field on test current**
 - **assumed function** for VBD site emitted current
 - Find quasi-equilibrium point

- **Elegant, but ...**



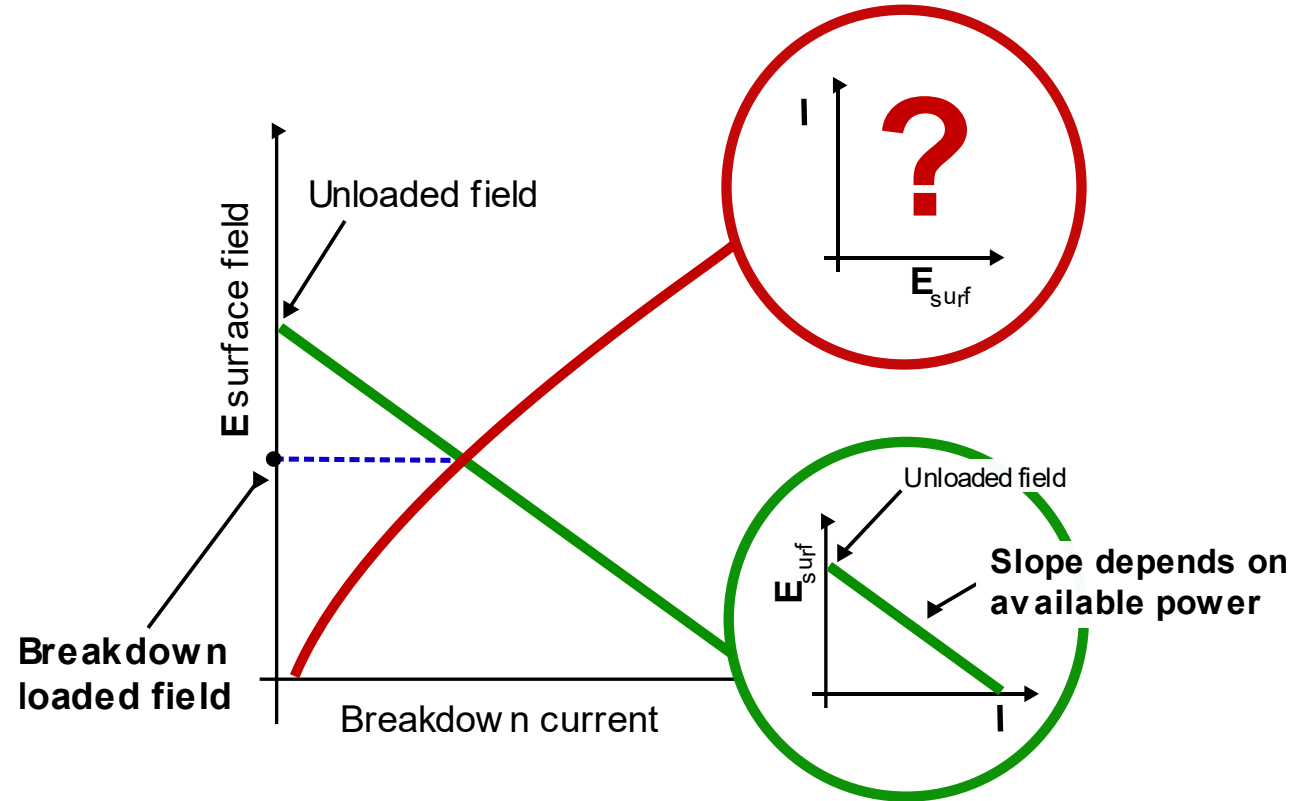
[4] Paszkiewicz, Jan. *Studies of breakdown and pre-breakdown phenomena in high-gradient accelerating structures*. Diss. University of Oxford, 2020.

- **Jan Paszkiewicz's solution:**

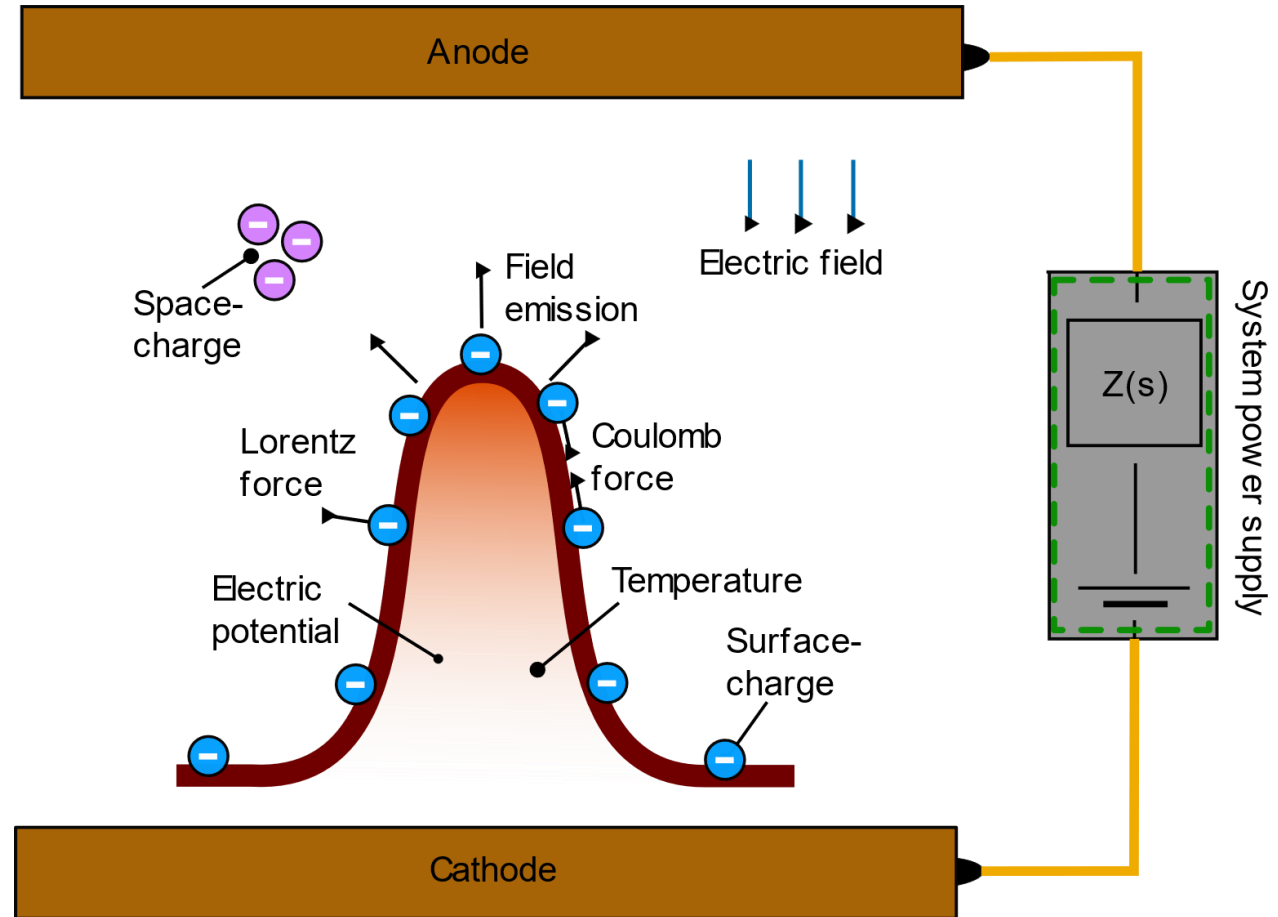


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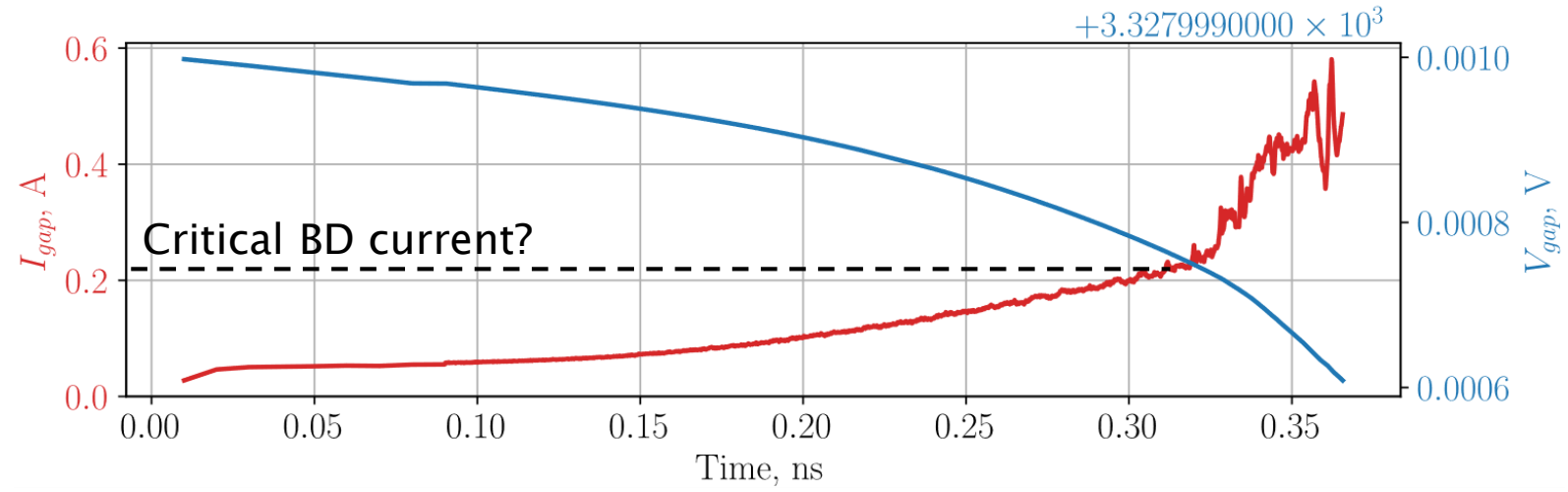
- **DOES NOT ACCOUNT FOR THE FULL PHYSICS OF VBD!!!**



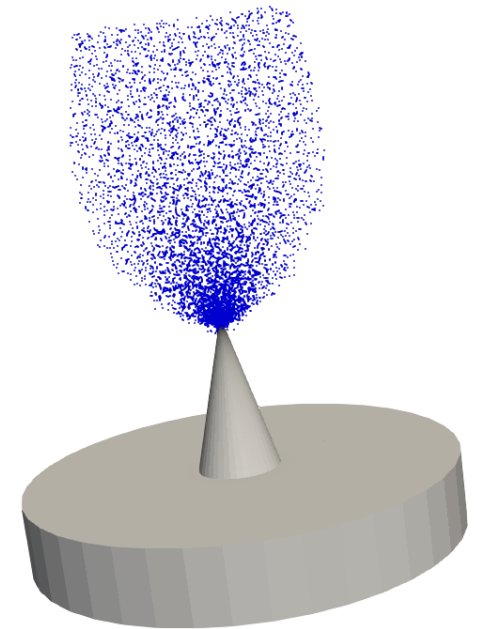
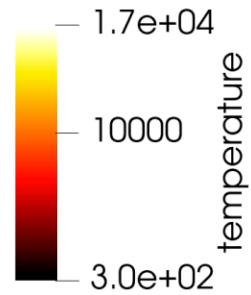
- **FEMOCS to the rescue**
 - Evaluate the local VBD physics accurately
- **Couple the whole system to the VBD**
 - Via impedance $Z(s)$ (*Thevenin theorem*)
 - At any point in the system
- V_{sim} as the coupling link:
 - $V_{sim}(s) = V(s) - I(s)Z(s)$
with Reverse Laplace transform:
 $v_{sim}(t) = v(t) - i(t) * \zeta(t)$ *Impulse response*
- $Z(s)$ as the **system design parameter**
 - Each point has an unique impulse response



VBD initiation example

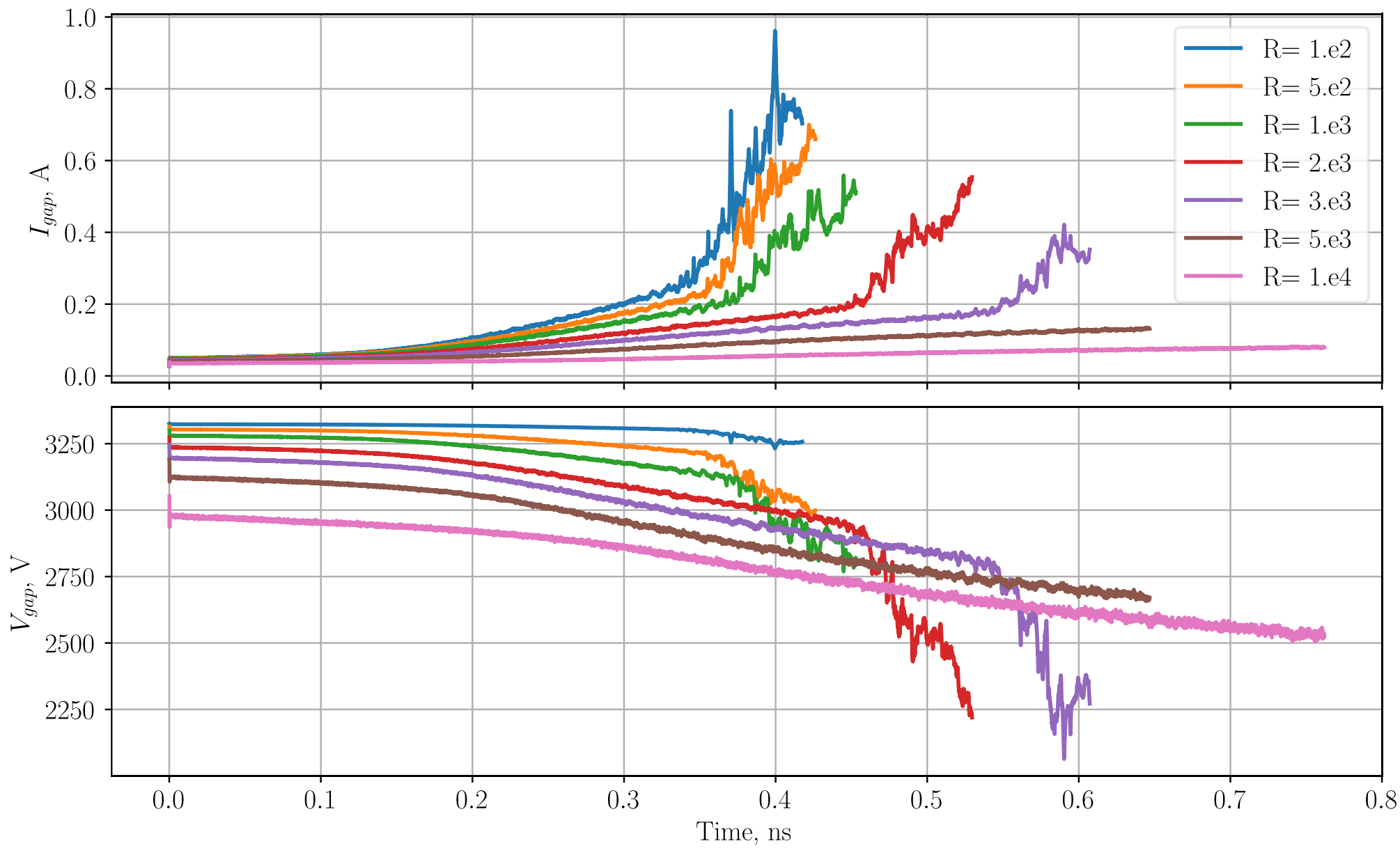


- Electrons
- Neutrals
- Ions



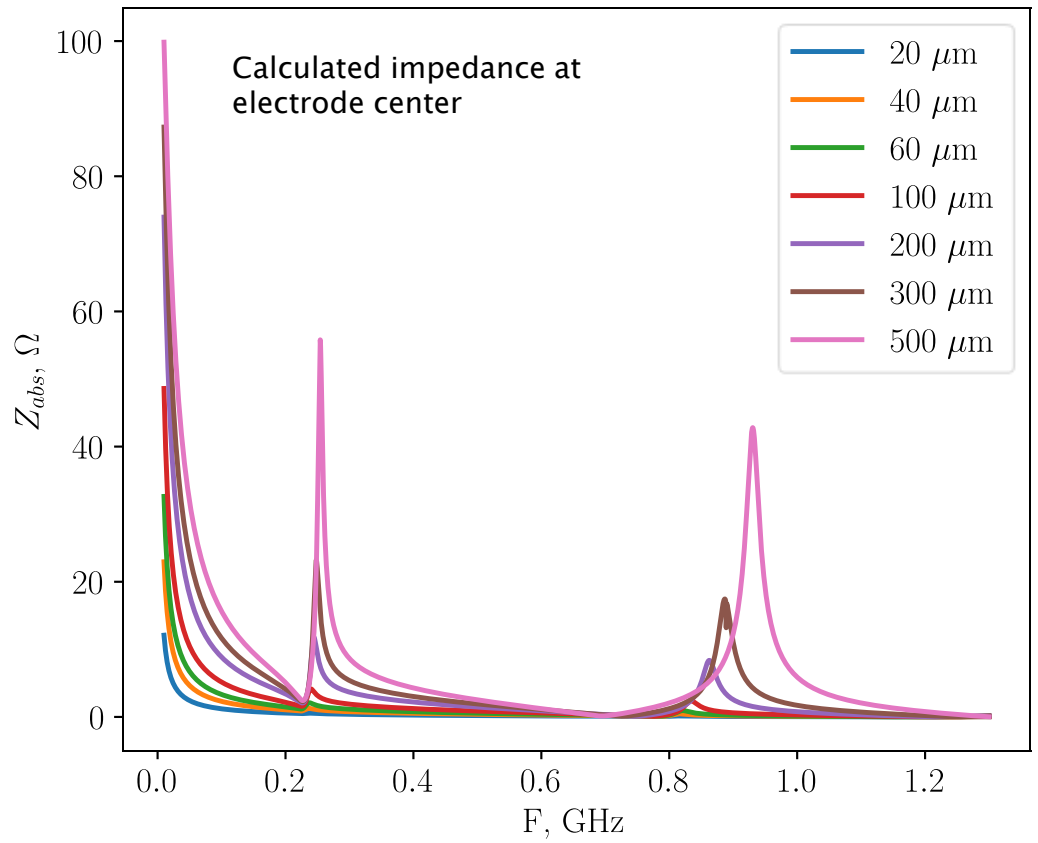
R circuit case study

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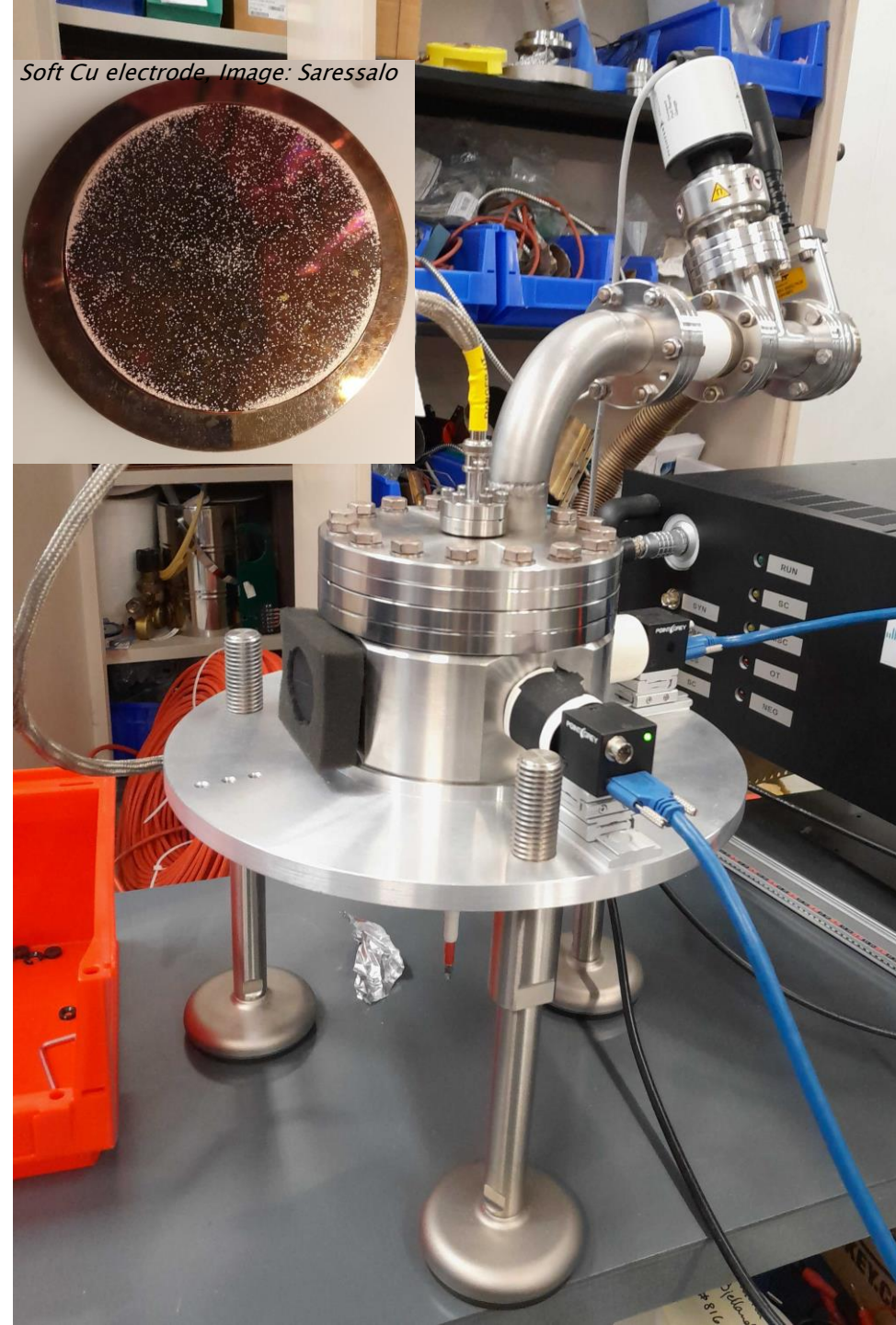
DC Large Electrode system

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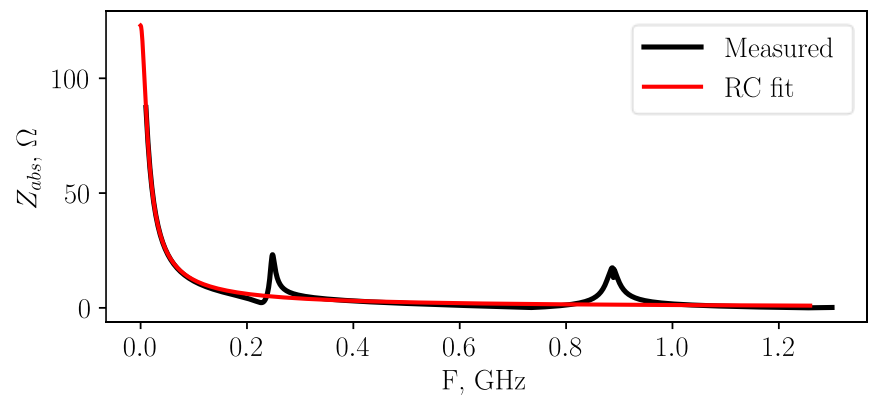
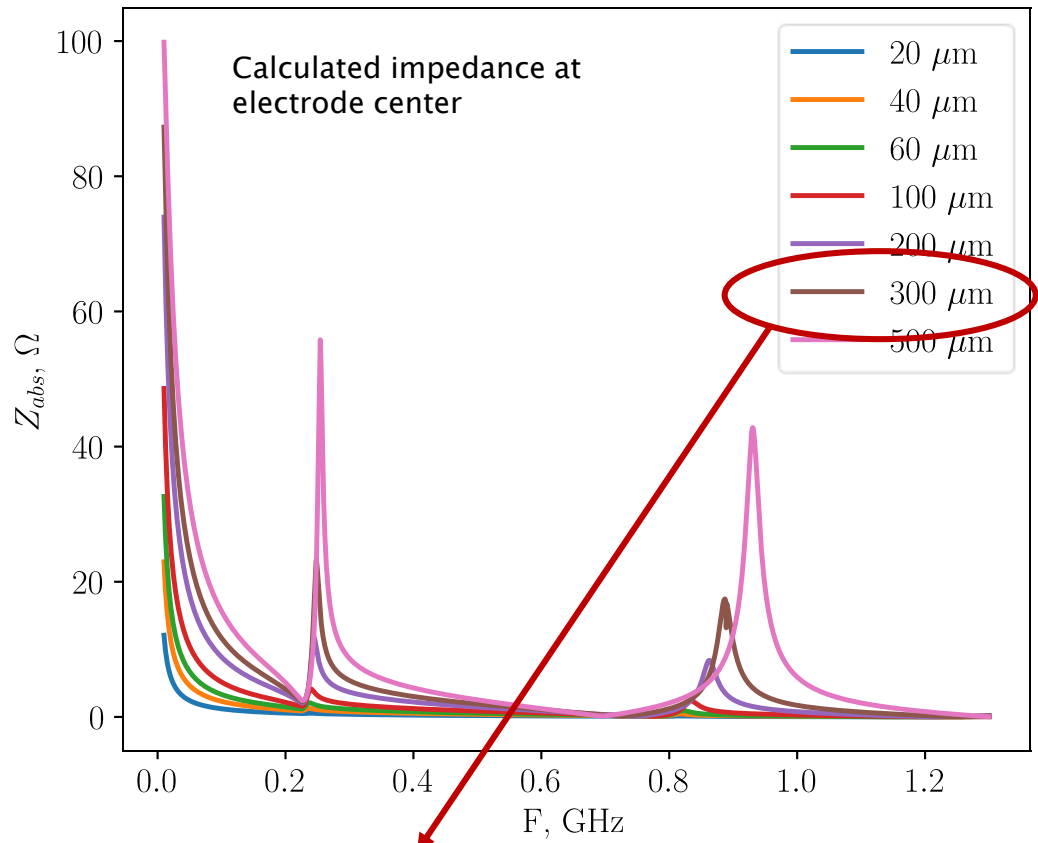
Data by: Jan Paszkiewicz, CERN

Soft Cu electrode. Image: Saressalo



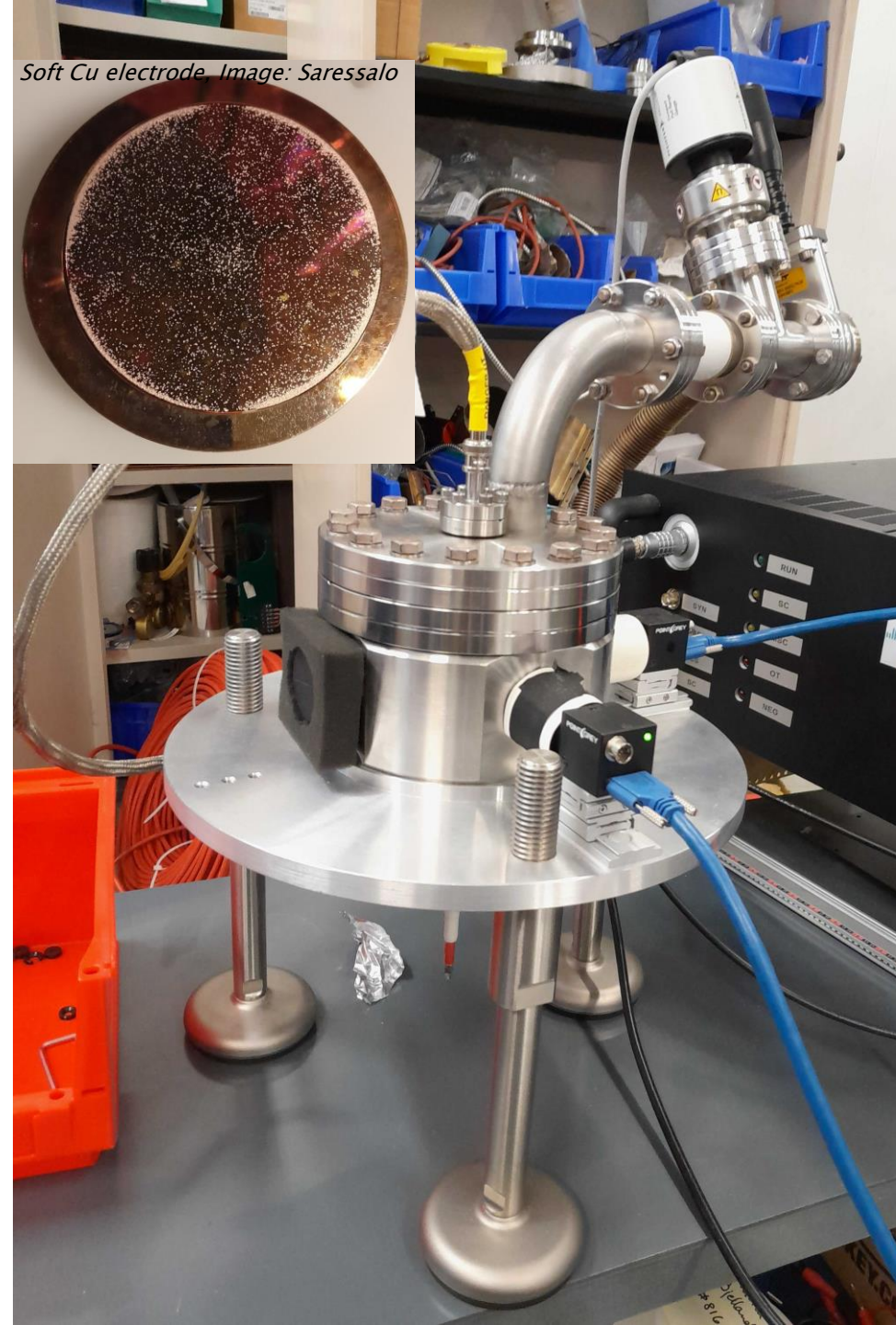
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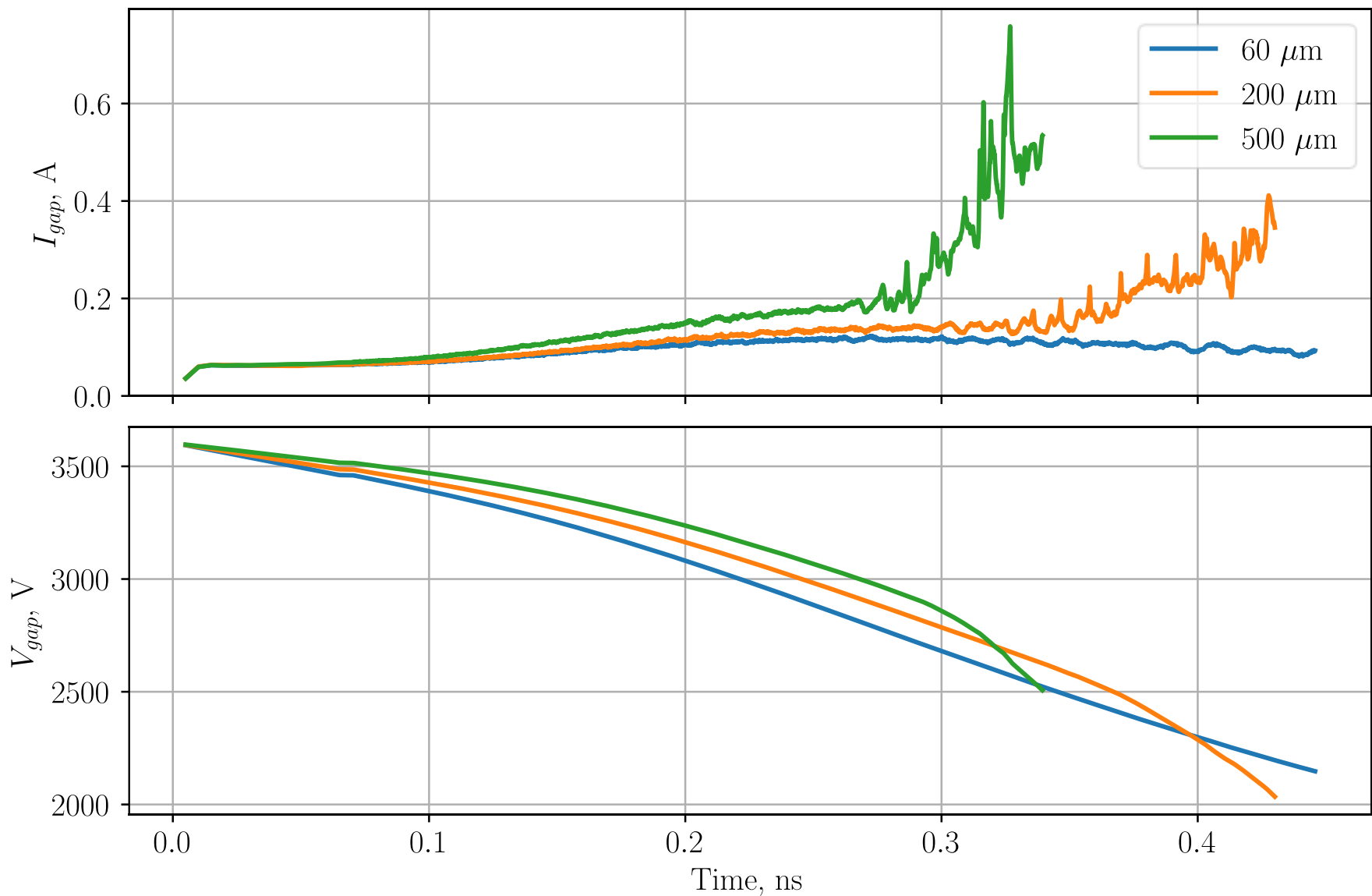
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Soft Cu electrode. Image: Saressalo



Preliminary LES simulation results $\leftarrow H = 2.5 \mu\text{m}$

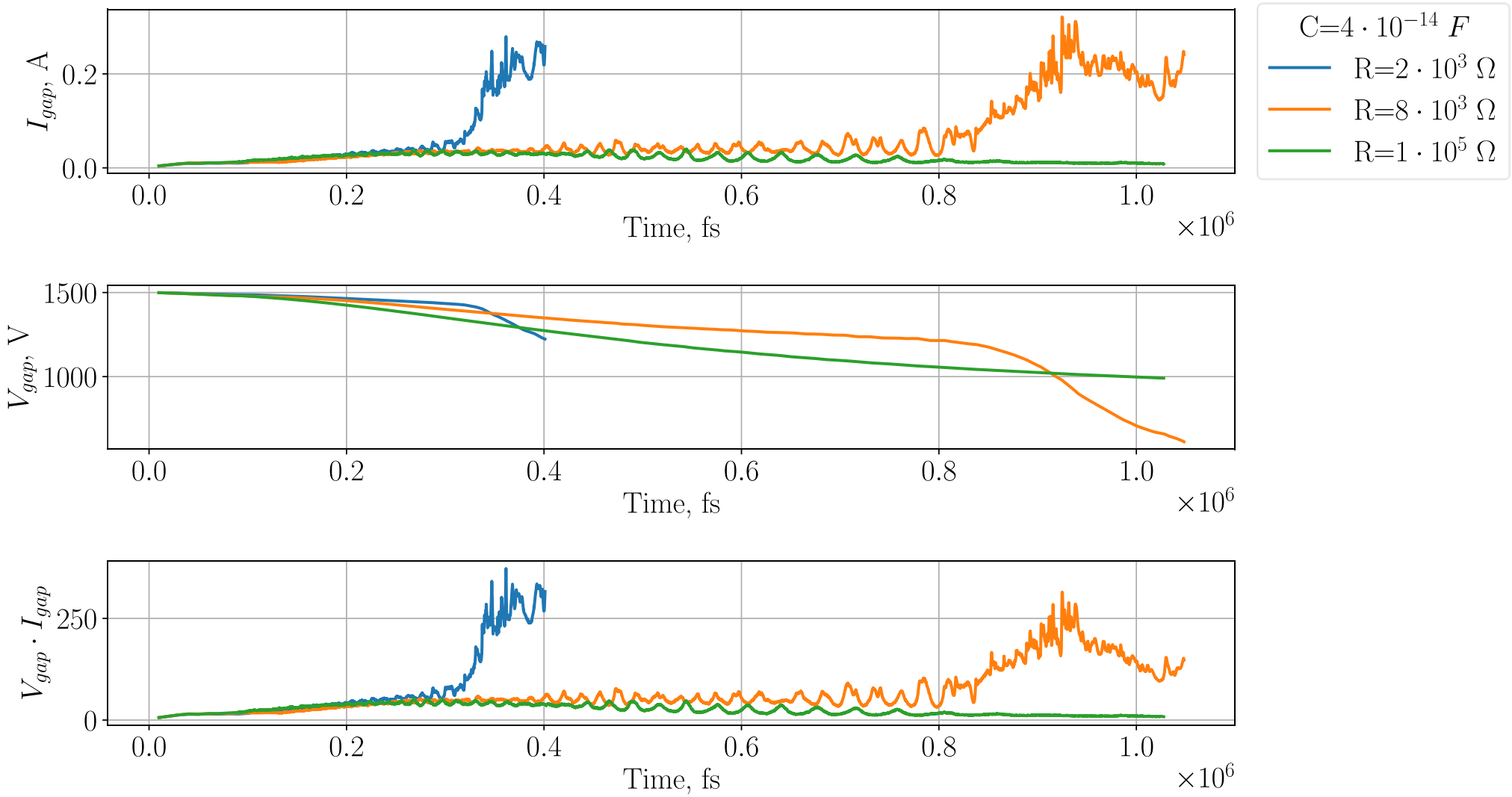
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* Intentionally modified applied field !!

RC circuit case study -> $H = 2.5 \mu\text{m}$

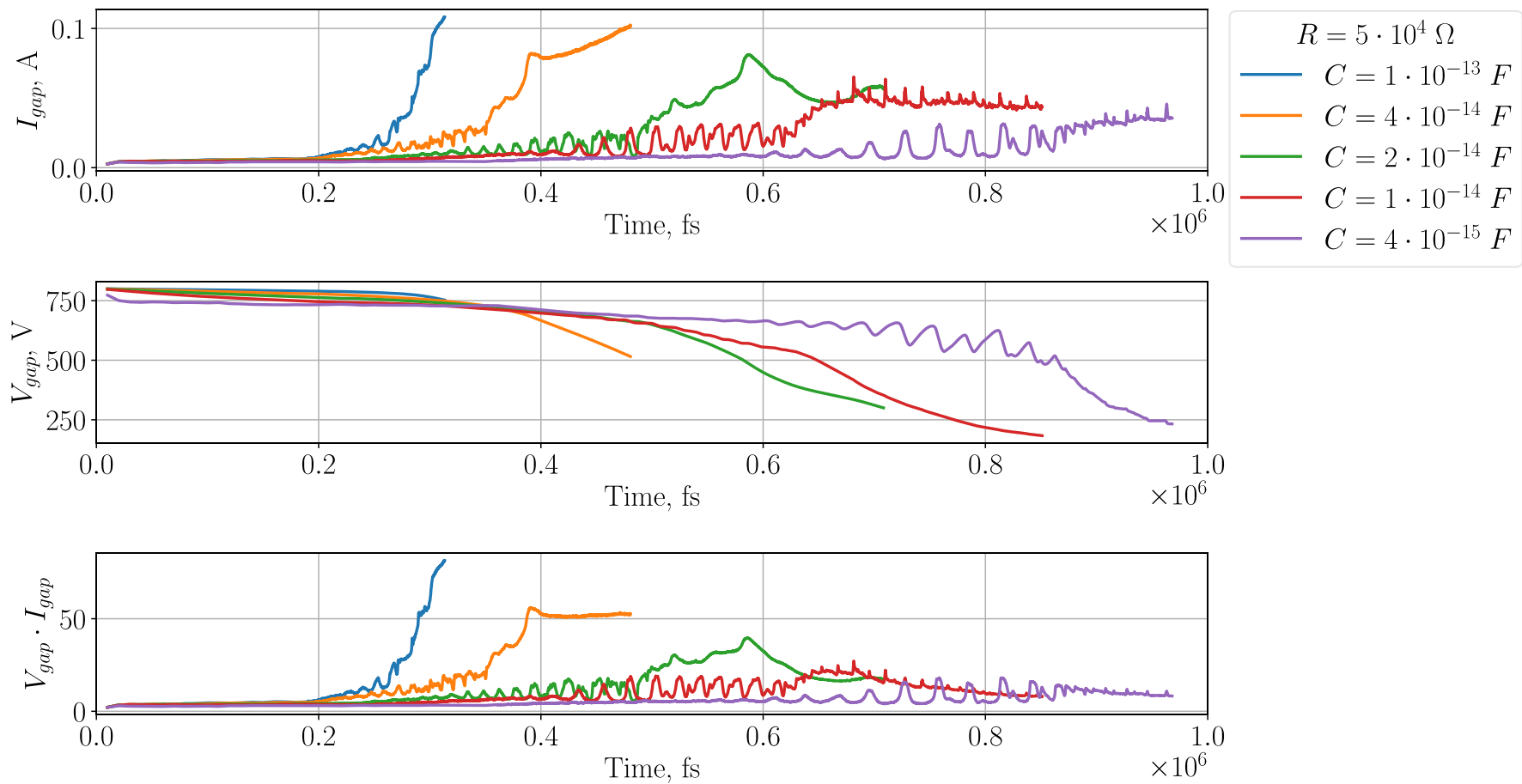
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RC circuit case study -> $H = 1 \mu\text{m}$

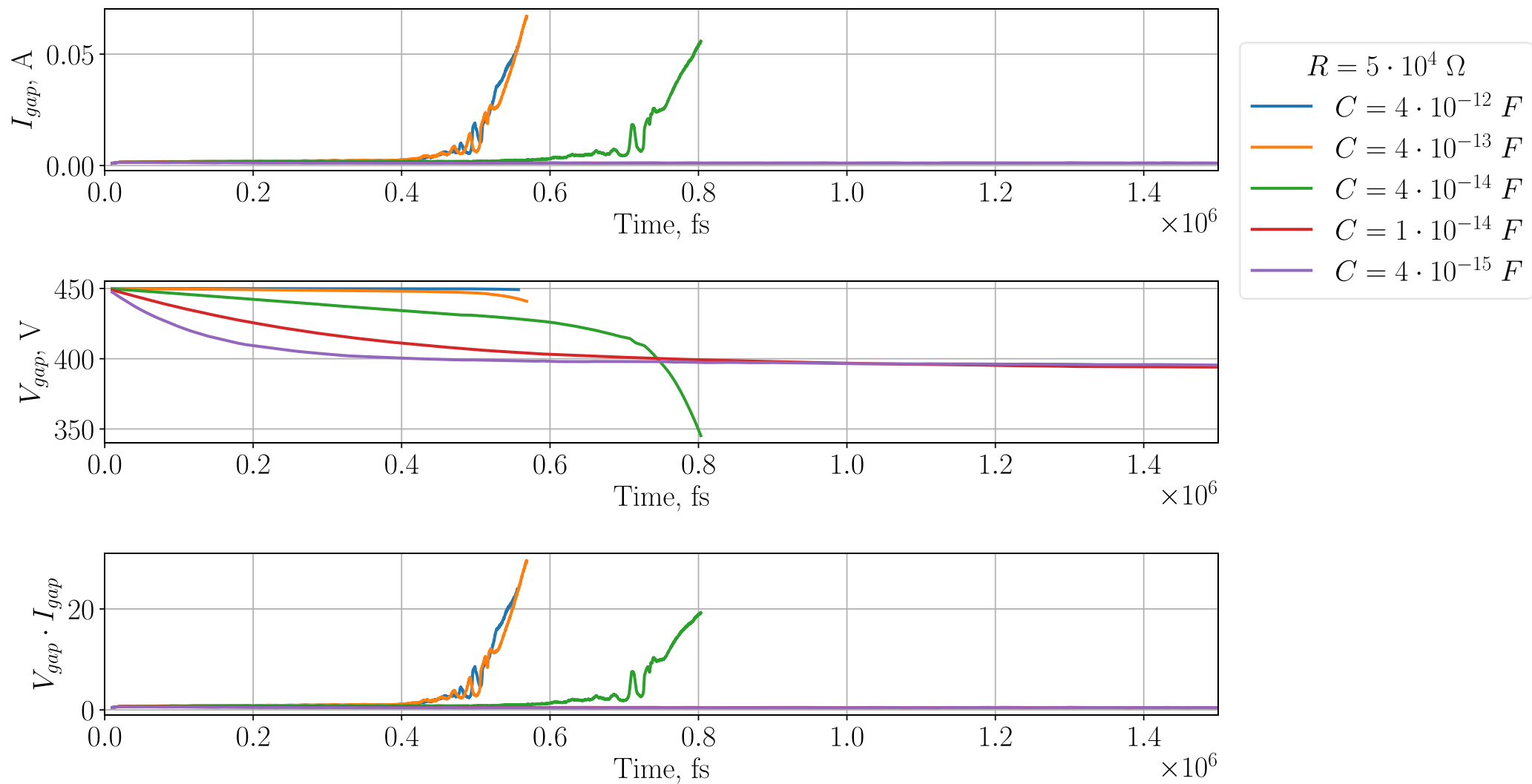
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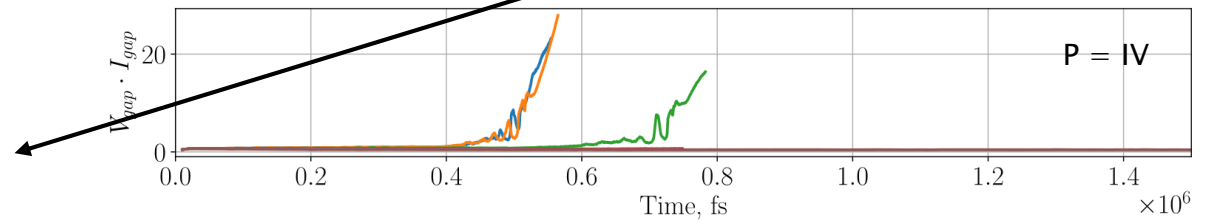
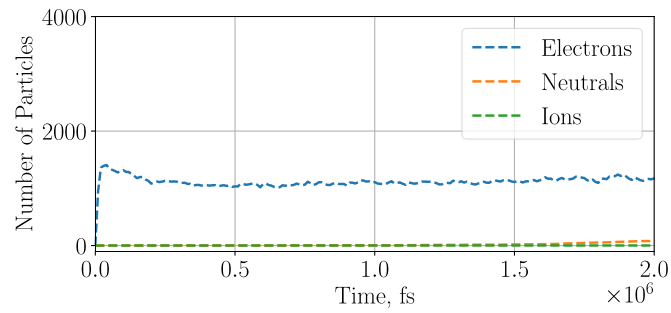
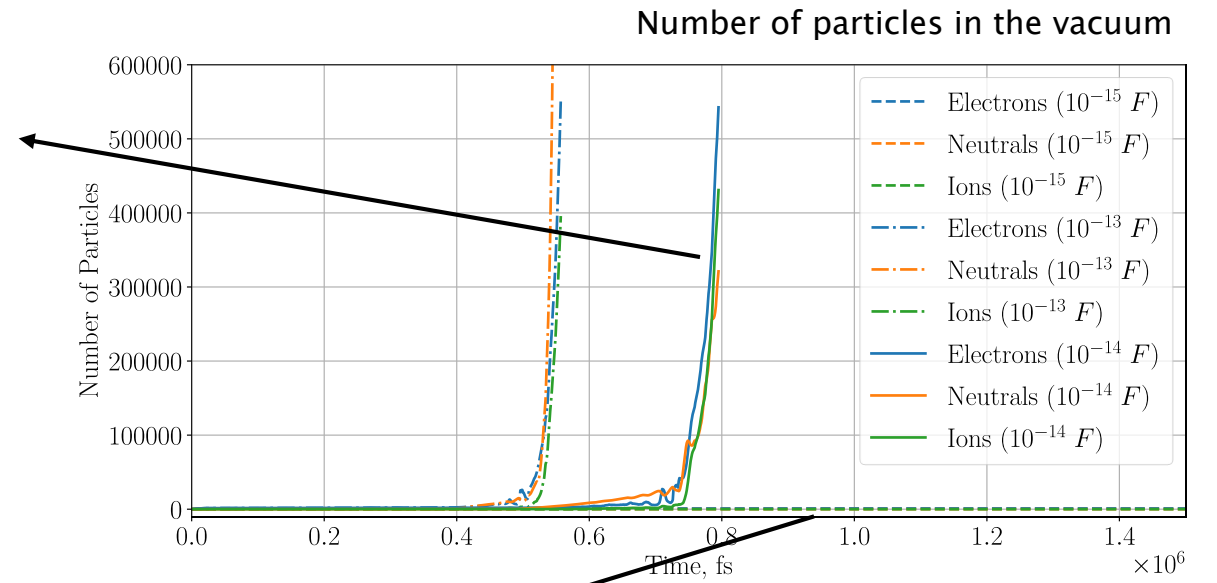
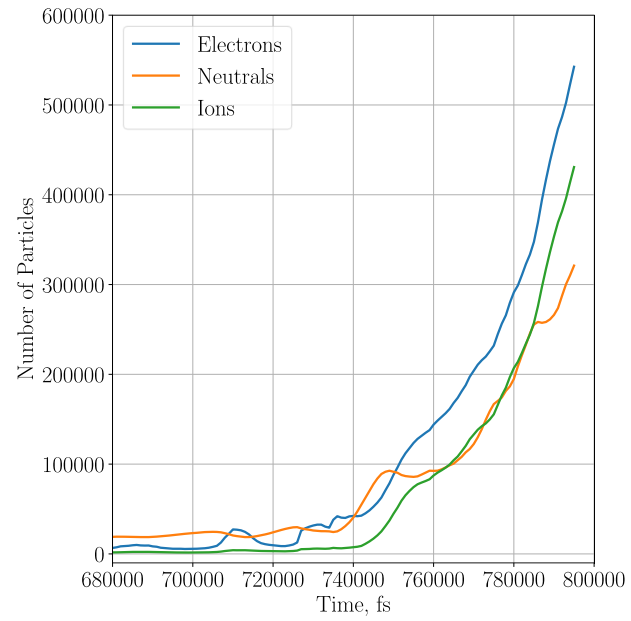
- Electrons
- Neutrals
- Ions



RC circuit case study -> $H = 0.6 \mu\text{m}$

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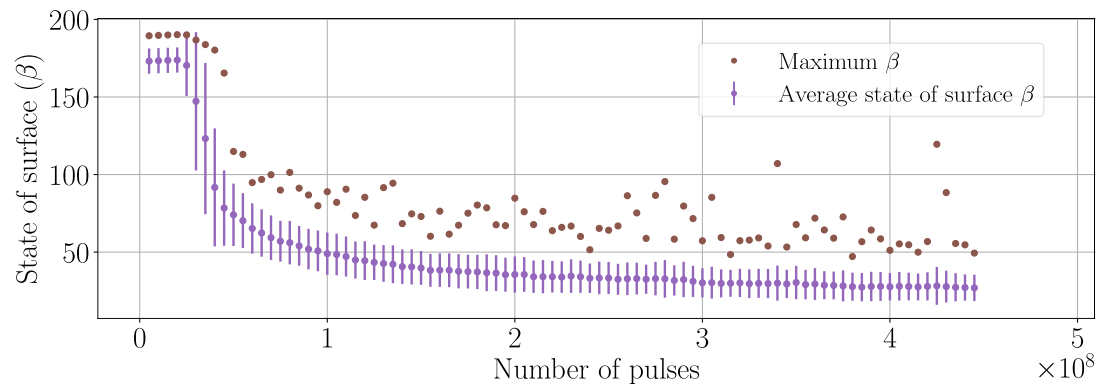
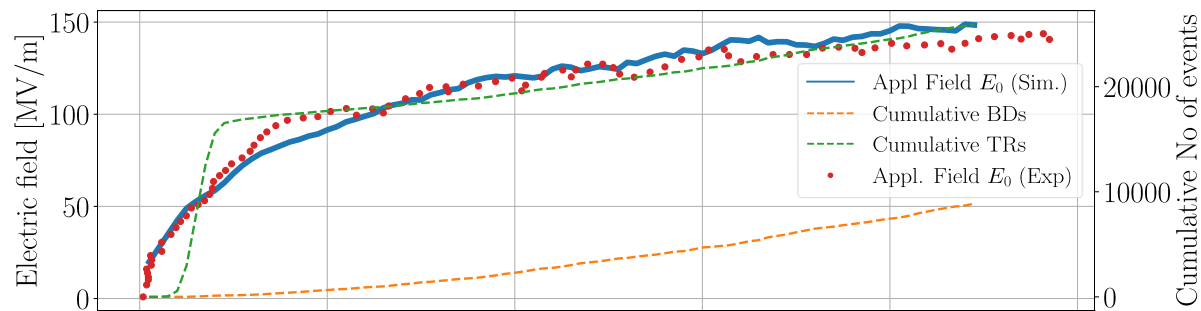
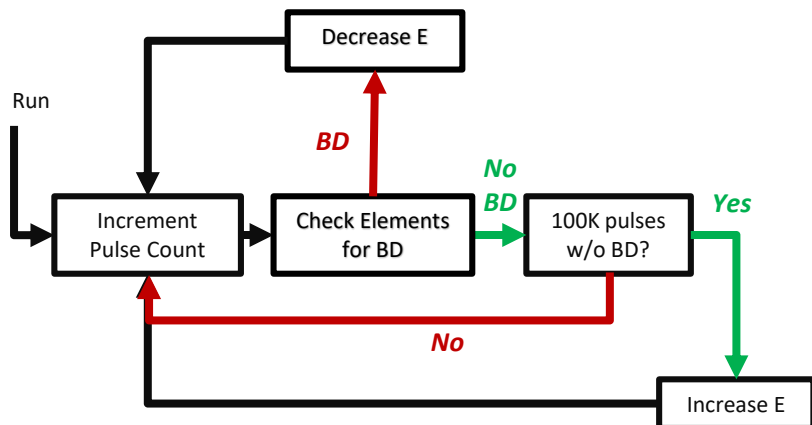


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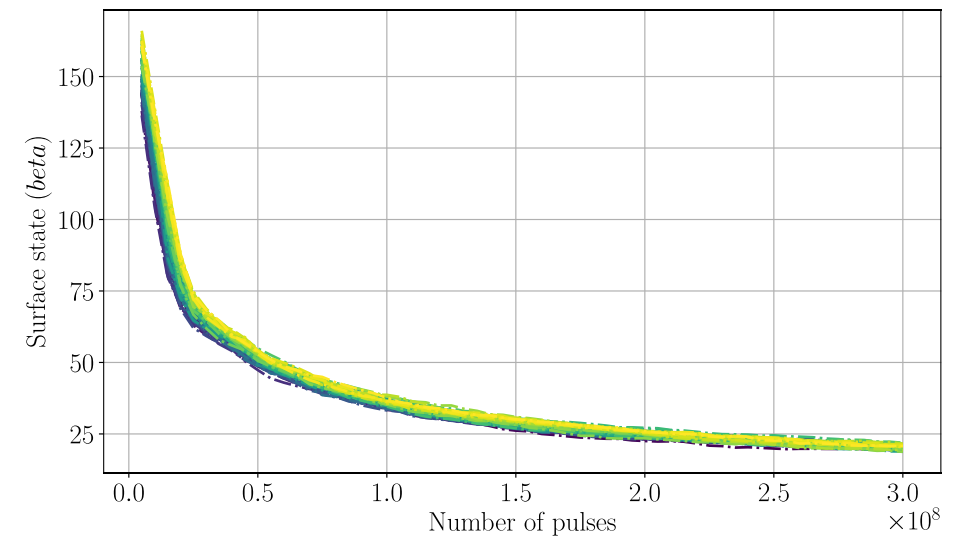
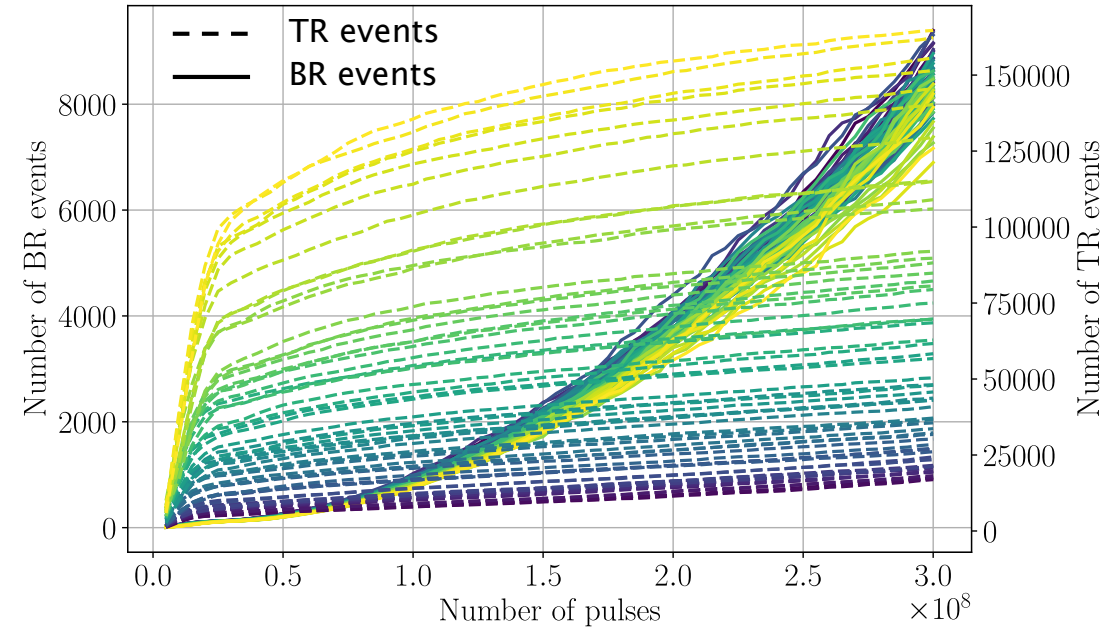
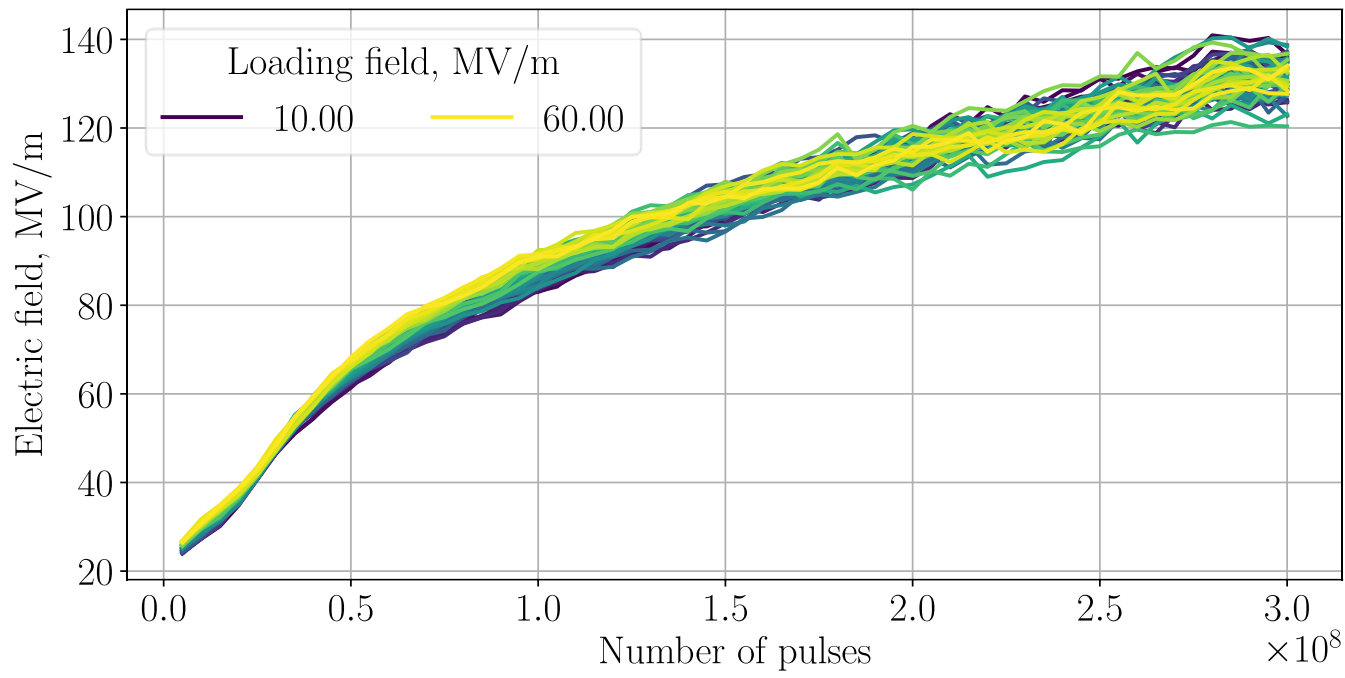
Breakdown Monte-Carlo simulation

BDMC

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

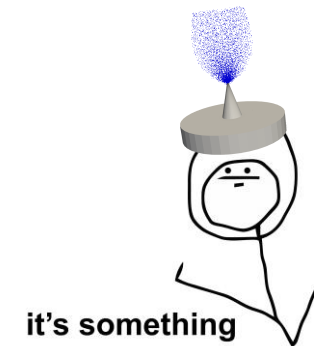


Model details: A. Kyritsakis, MeVArc 2025 talk: Monte Carlo simulations of vacuum breakdown occurrence dynamics and statistics

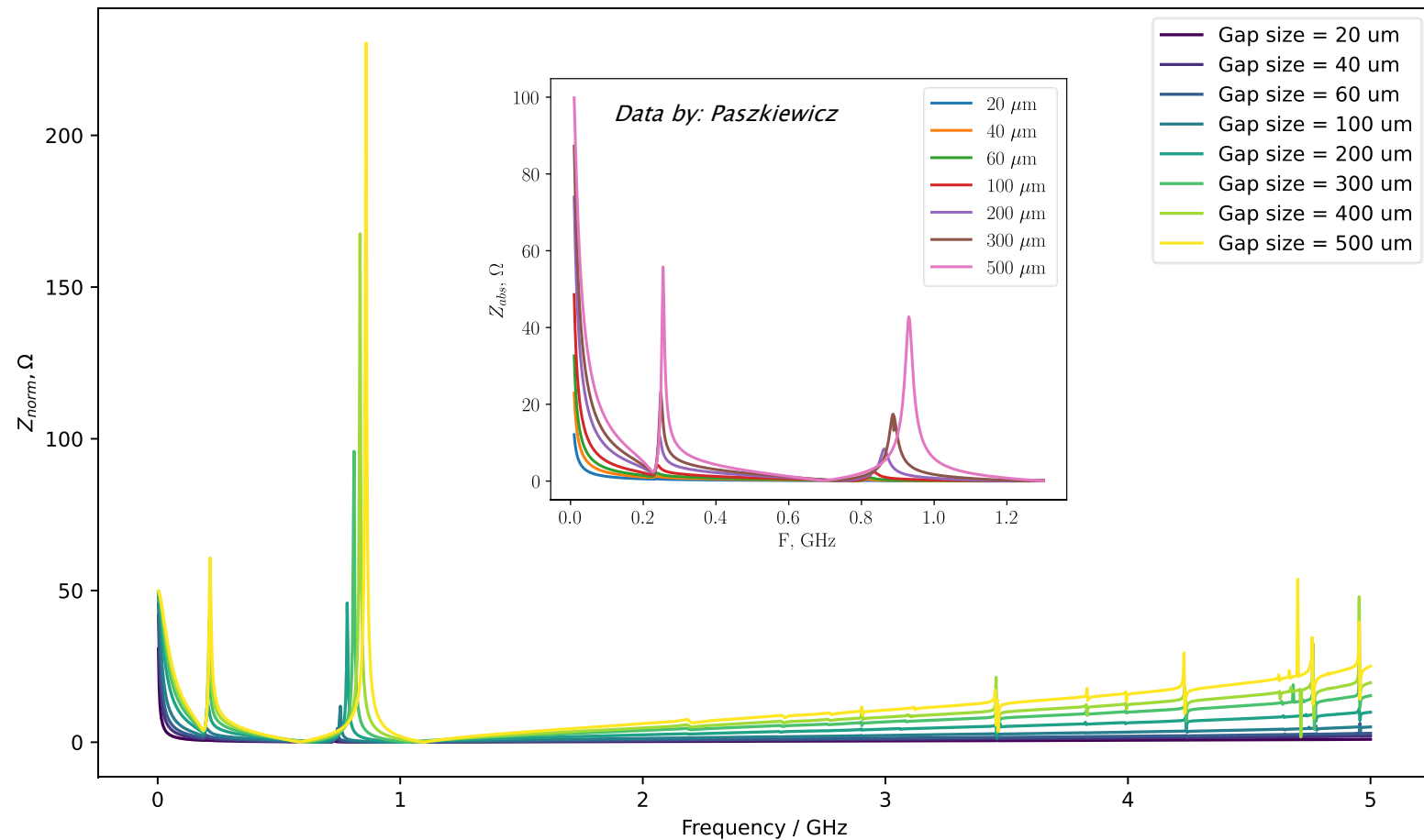


- „POC“: The impedance value plays a significant role in breakdown initiation process!
 - Evidence of strong dependence on system's power flow
 - Mitigation? (burning the asperities and current „choking“)
- Further work
 - *Existence of critical limit thresholds?*
 - Surface/tip morphology
 - **MD coupling & 3D [R. Koitermaa]**
 - *Continuum approach?*
 - Numerical investigation of the Pulse DC system (LES)
 - **FEMOCS** ← **Improved Impedance input**
 - BDMC

← **VALIDITY OF SHOWN RESULTS?**

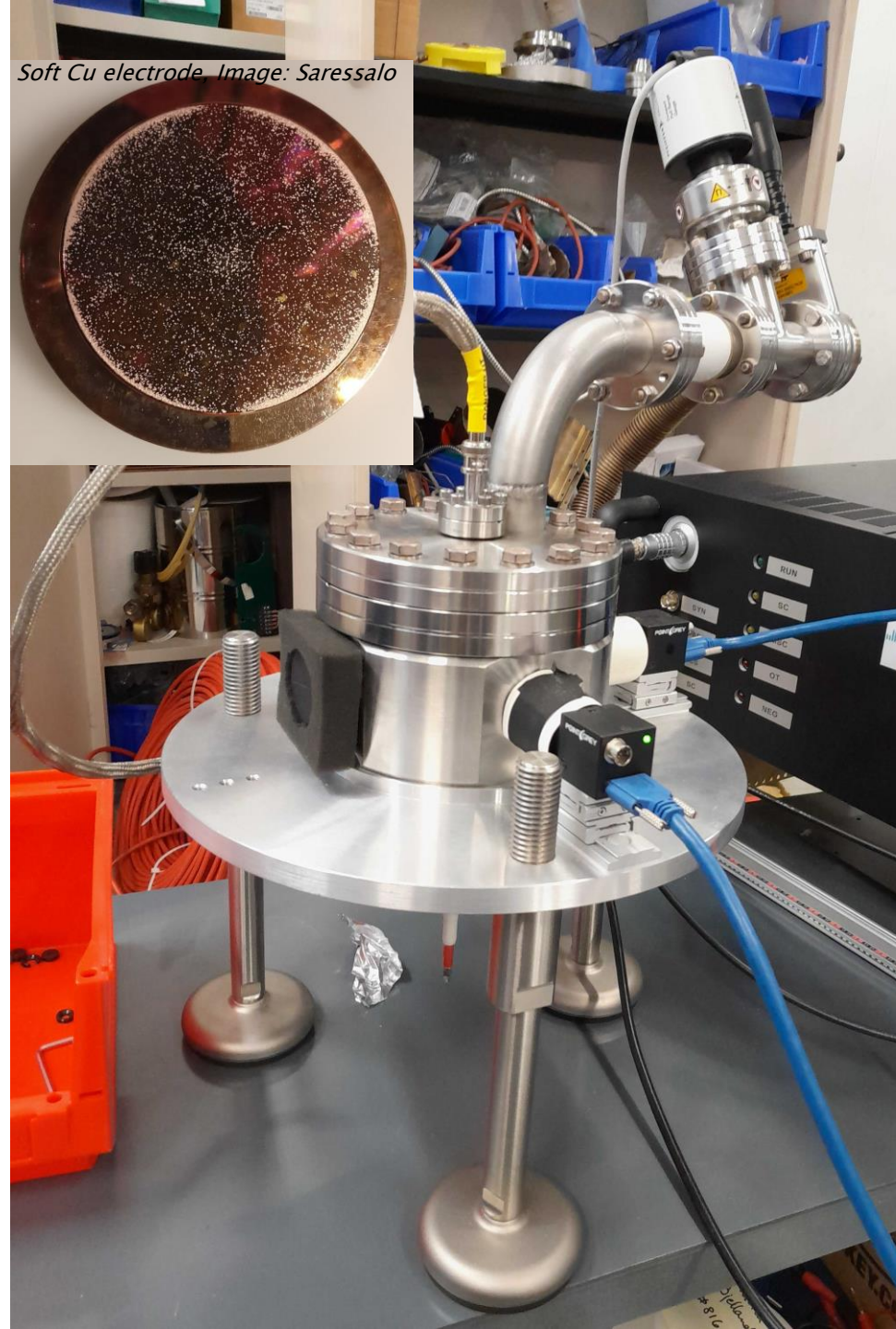


Calculated impedance at electrode center



Data provided by: Lee Millar, CERN

Soft Cu electrode. Image: Saressalo

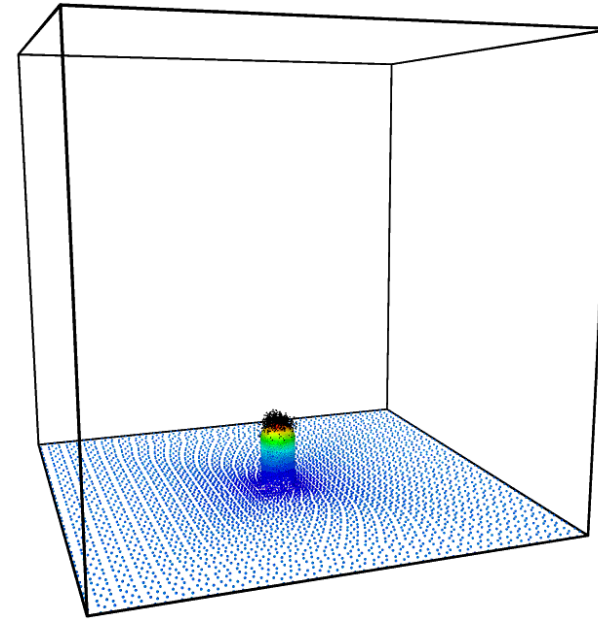


Thank you for your time!

This work is funded by:

Estonian Research Grant nr SJD66

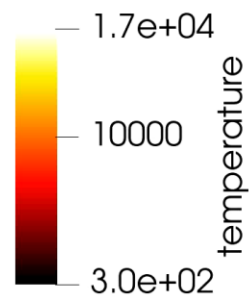
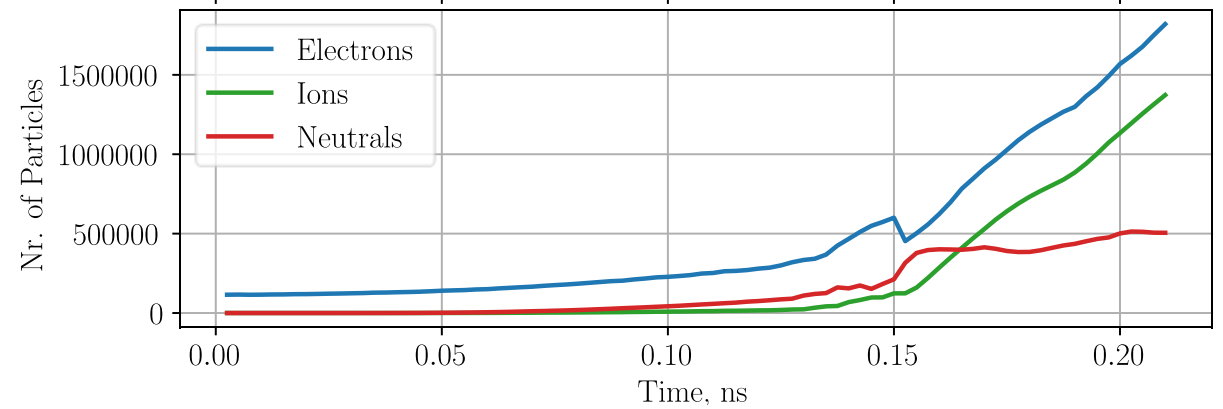
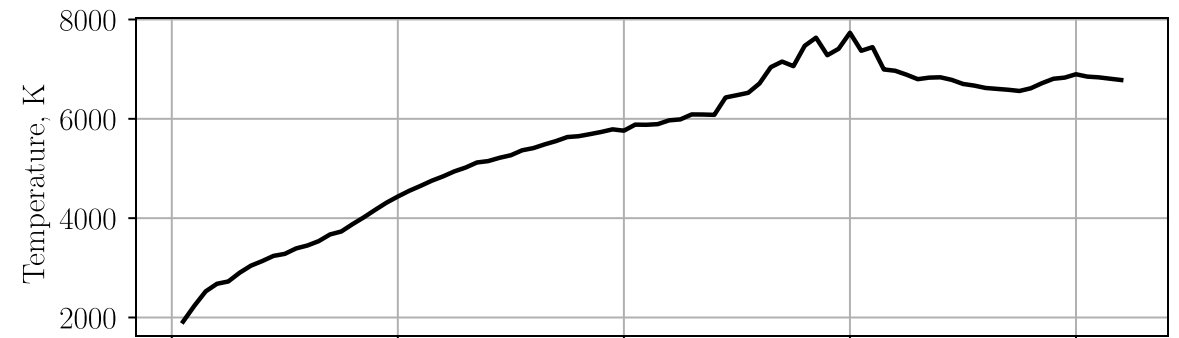
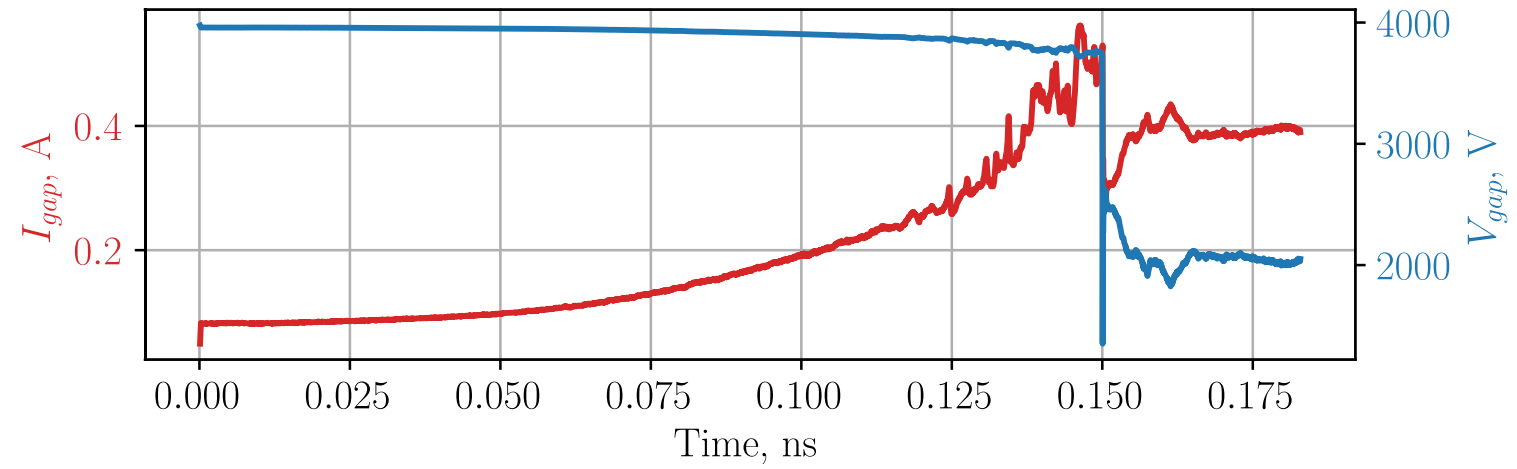
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Selection of FEMOCS Publications:

- Koitermaa, Roni, et al. "Simulating vacuum arc initiation by coupling emission, heating and plasma processes." *arXiv preprint arXiv:2402.08404* (2024).
- M. Veske, A. Kyritsakis, F. Djurabekova, K. N. Sjobak, A. Aabloo, and V. Zadin. Dynamic coupling between particle-in-cell and atomistic simulations. *Phys. Rev. E*, 101:053307, May 2020.
- M. Veske, A. Kyritsakis, K. Eimre, V. Zadin, A. Aabloo, and F. Djurabekova. Dynamic coupling of a finite element solver to large-scale atomistic simulations. *Journal of Computational physics*, 367:279 – 294, 2018.
- M. Veske, "Multiscale-multiphysics modelling of metal surfaces." *Report Series in Physics, PhD thesis* (2019).

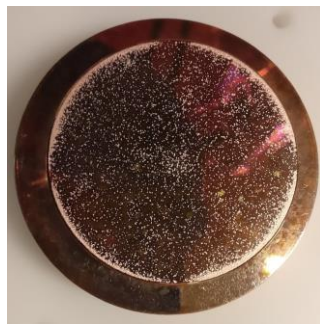
Voltage drop



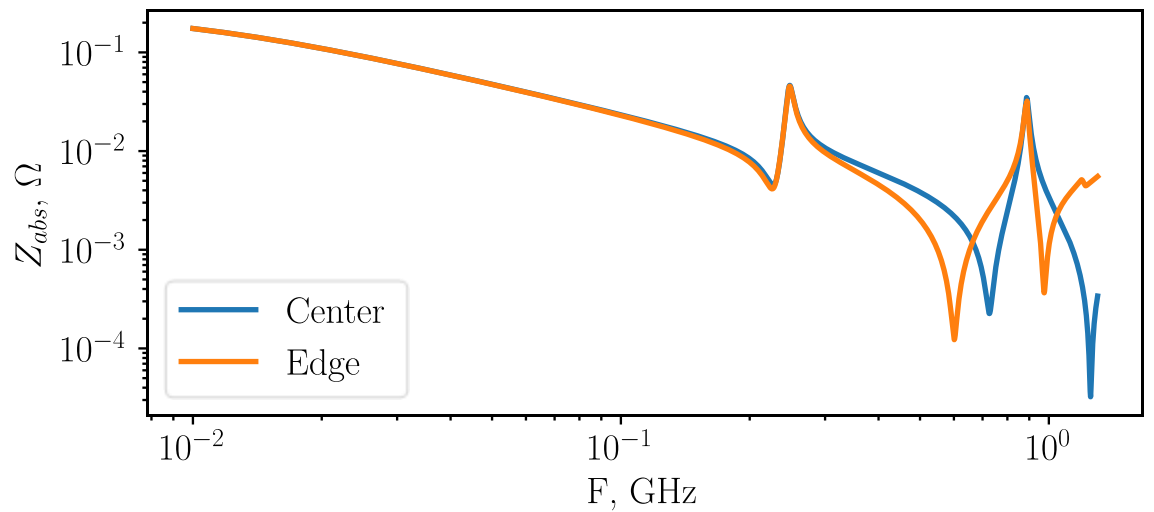
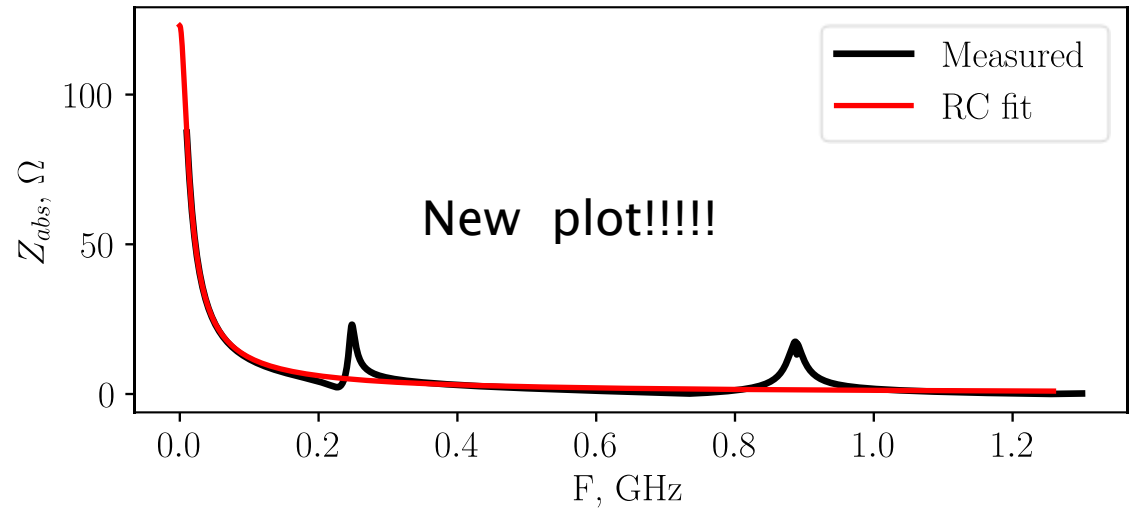
Qualitative nature of results

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- Z response (from J.Paszkievicz)
 - 1 MHz ... 1.3 GHz (>10 GHz)
 - RC fit for Z
- Tip geometry dependency (future work)
 - Static tip!
 - β & T
- Surface position indifference
 - center & edge

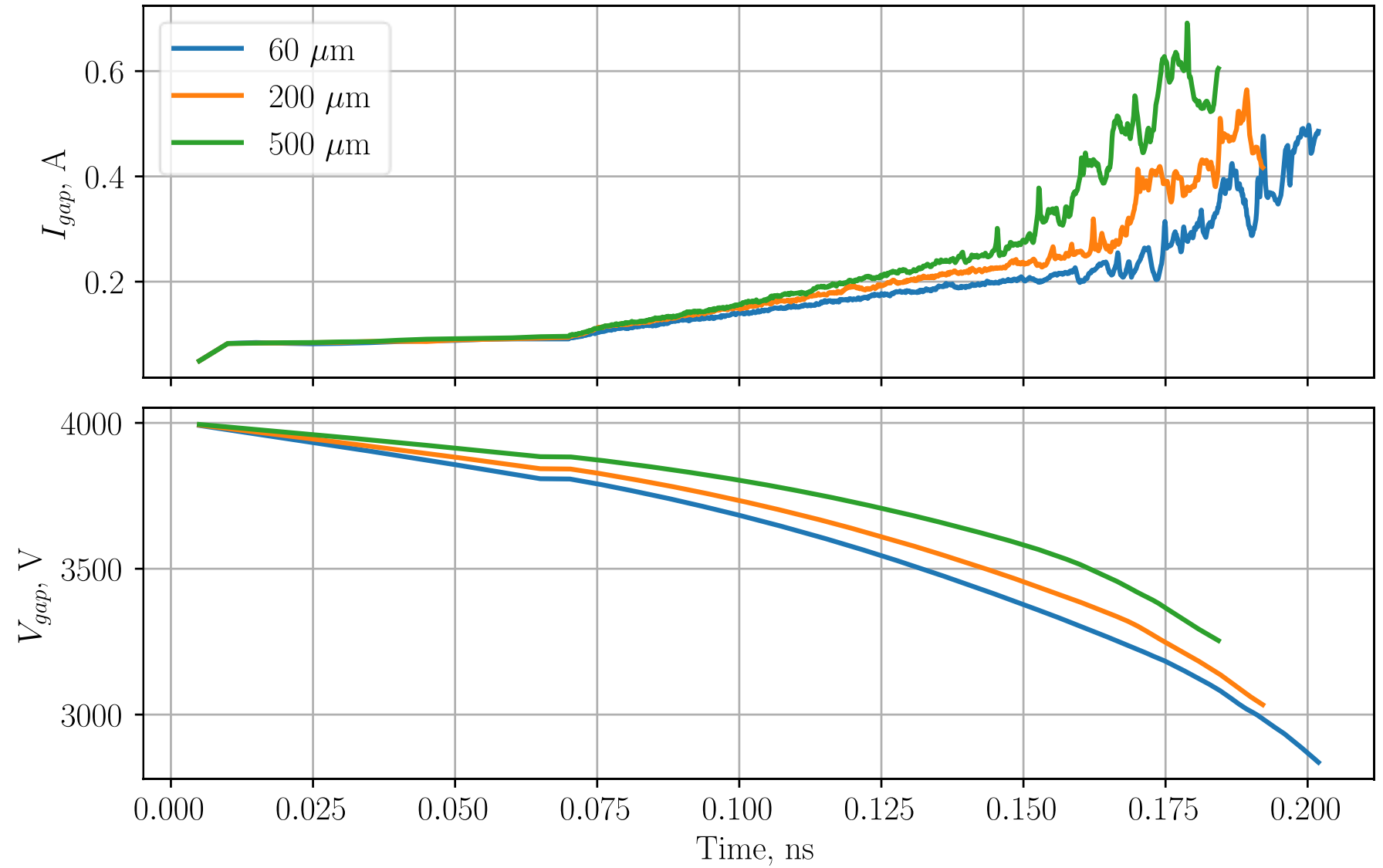


Soft Cu electrode, Image: Saessalo



Preliminary LES simulation results

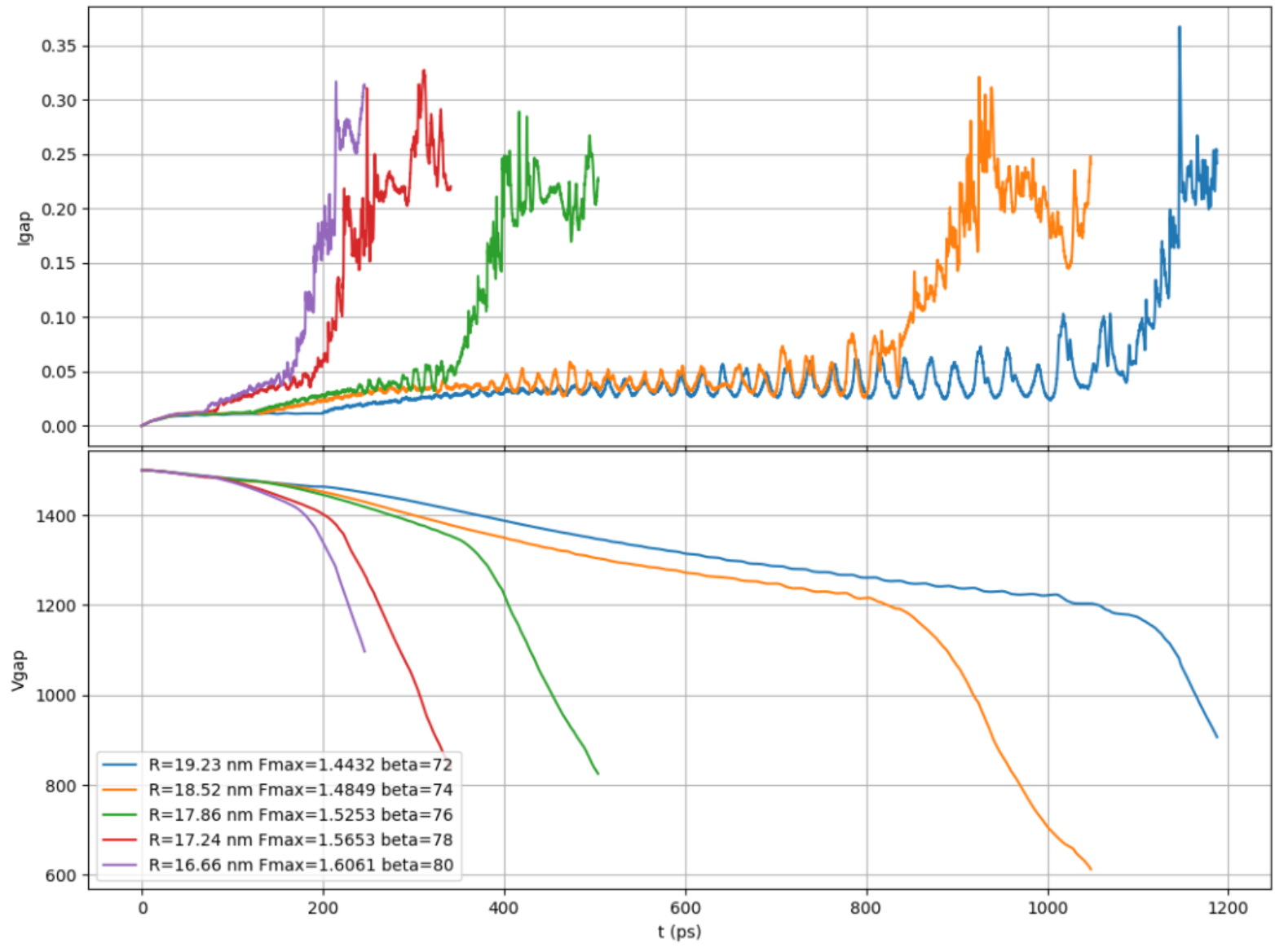
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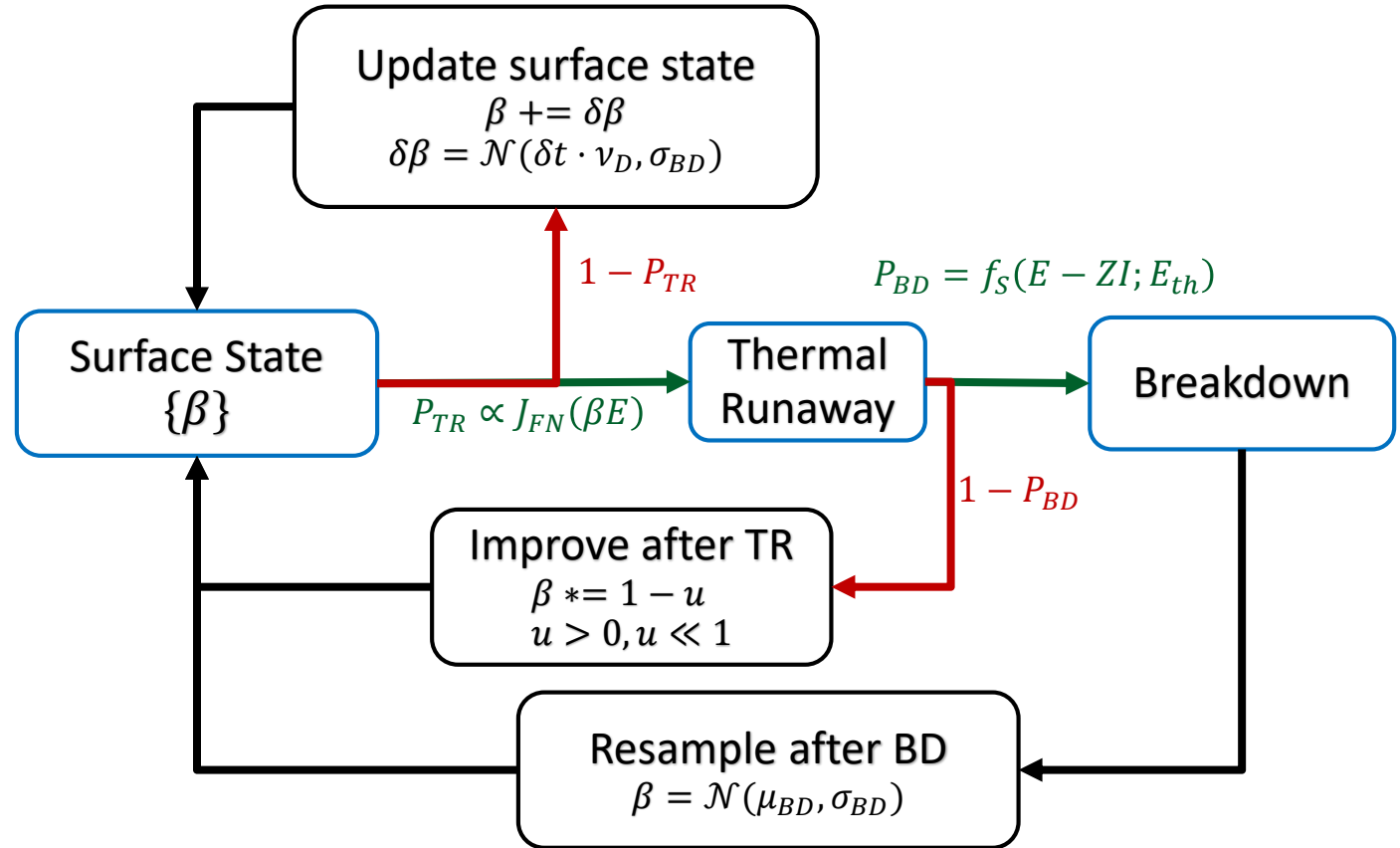


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gap current and voltage for tips with different H/R. For all cases, H=2500 nm, Voltage was 1500 V. Varying R



- Surface state deteriorates at constant rate (s^{-1})
- Thermal runaway slightly improves the surface state
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Model details: A. Kyritsakis, MeVArc talk: Monte Carlo simulations of vacuum breakdown occurrence dynamics and statistics

BDMC example study

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