Simulation approach to investigate the influence of electromagnetic power in vacuum breakdown

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ERA Chair MATTER

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Outline

- **Introduction**
  - Motivation & Goal
  - Multiscale breakdown simulations & FEMOCS
- **Electromagnetic power supply**
  - Idea
  - Implementation
  - Preliminary results
    - R circuit
    - LES system
- **Conclusion**

Motivation

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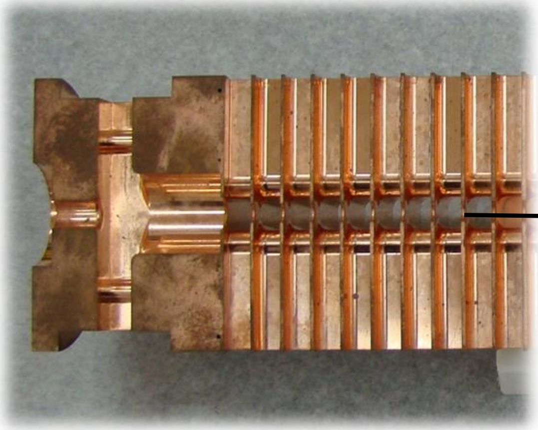
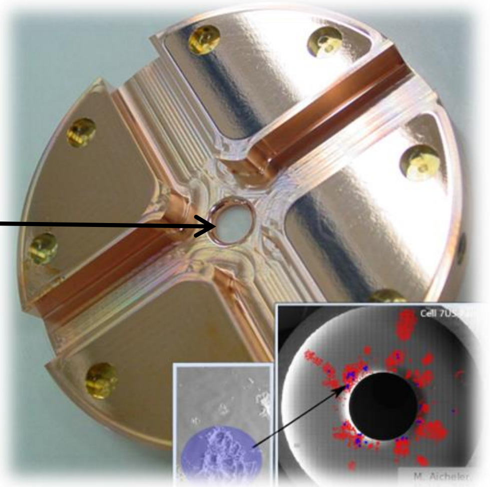
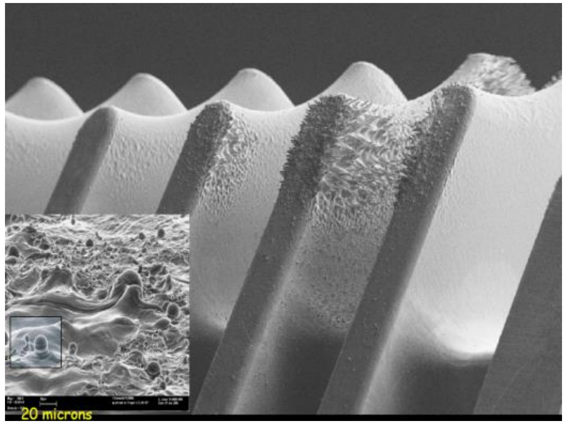
High electric field (>100 MV/m) → Vacuum Breakdown **(VBD)** → **Beam distorted and luminosity lost !**



Accelerating structure (CLIC)





Surface damage in CLIC accelerating structures after the breakdown

Images: Walter Wuensch, CERN

- **VBD mitigation techniques**:
  - Controlling relevant characteristics
    - electric field strength
    - surface roughness
    - contamination of material surface
  - **Limiting the available EM power** [1,2]

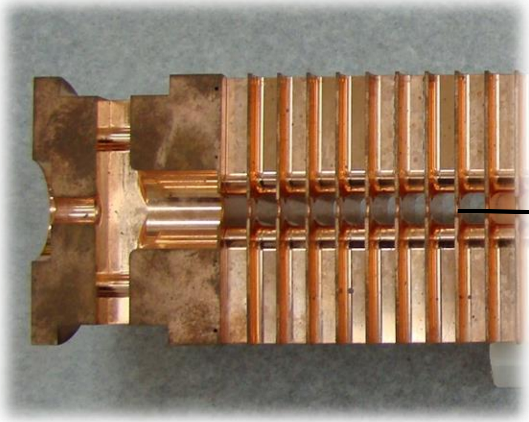
[1] W. Wuensch. The Scaling of the Traveling-Wave RF Breakdown Limit. Technical Report CERN-AB-2006-013. CLIC-Note-649, CERN, Geneva, Jan 2006.
[2] A. Grudiev, S. Calatroni, and W. Wuensch. New local field quantity describing the high gradient limit of accelerating structures. Phys. Rev. ST Accel. Beams, 12:102001, Oct 2009.

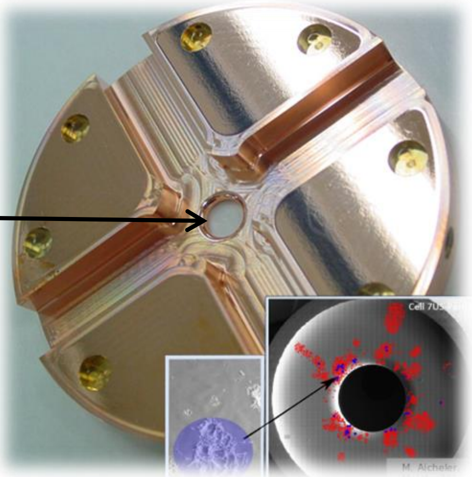
The project

- The hypotheses:
  - **The power supply limitation hinders the development of plasma exactly at the moment plasma initiates** (stage 2-3)
  - The VBD can be described by multi-scale simulations

- **The goal:**
  - Describe quantitatively the **EM power dependence of VBD initiation**

- **Dedicated Research project**
  - **Estonian Research Council**
  - Research grant nr. SJD66
  - Horizon 2020 ERA Chair MATTER





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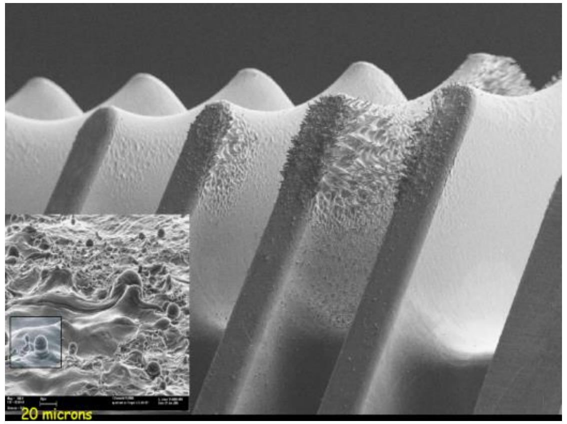

Surface damage in CLIC accelerating structures after the breakdown

Images: Walter Wuensch, CERN

Multiscale breakdown simulations

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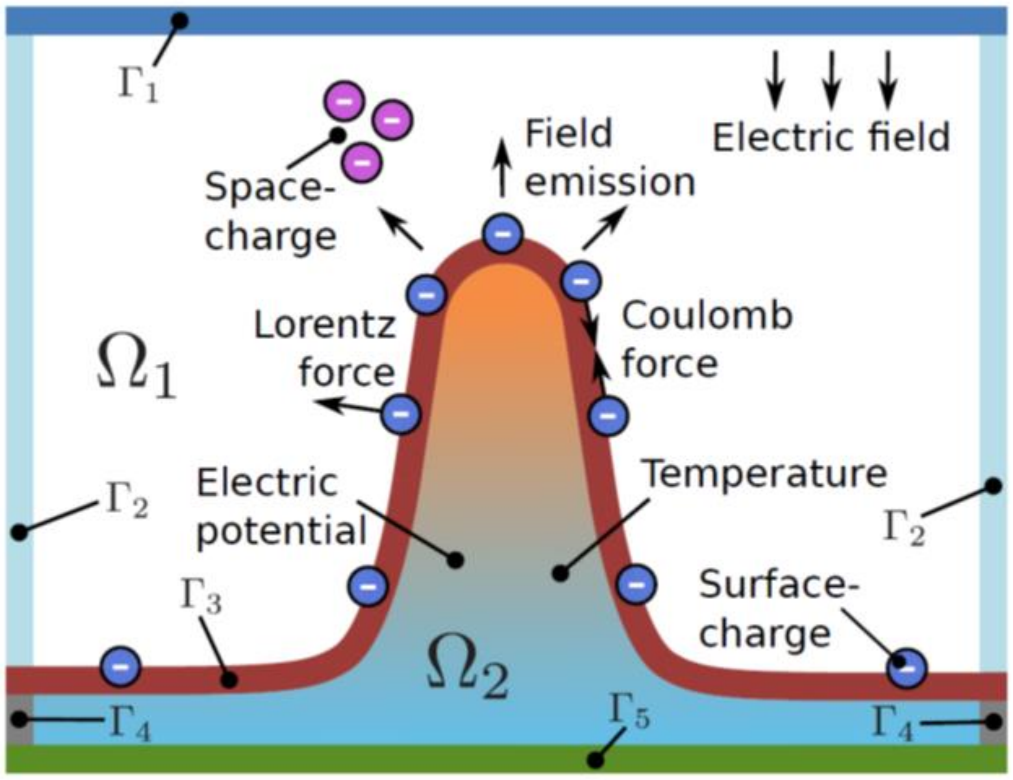
- VBD involves **various phenomena in various space scales**:
  - Emission spot formation
  - **Thermal runaway**
  - Field emission
  - **Plasma formation**
  - Surface damage

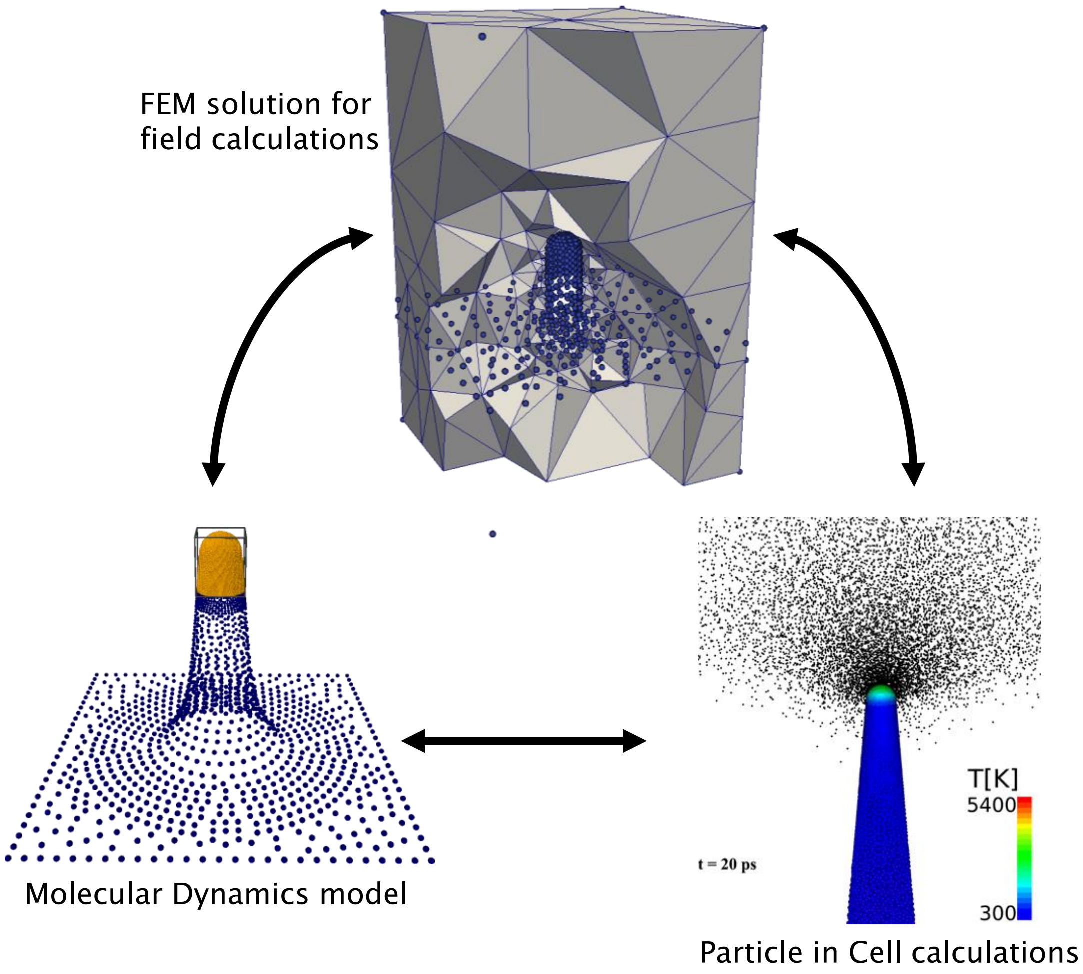
- Need for concurrent, **multi-scale, multi-physics simulations**
  - **Atomistic simulations**
    - Molecular Dynamics (MD)
    - Particle Dynamics (PIC)
  - **Continuum simulations**
    - Thermomechanics (FEM)
    - Electromagnetics (FEM)

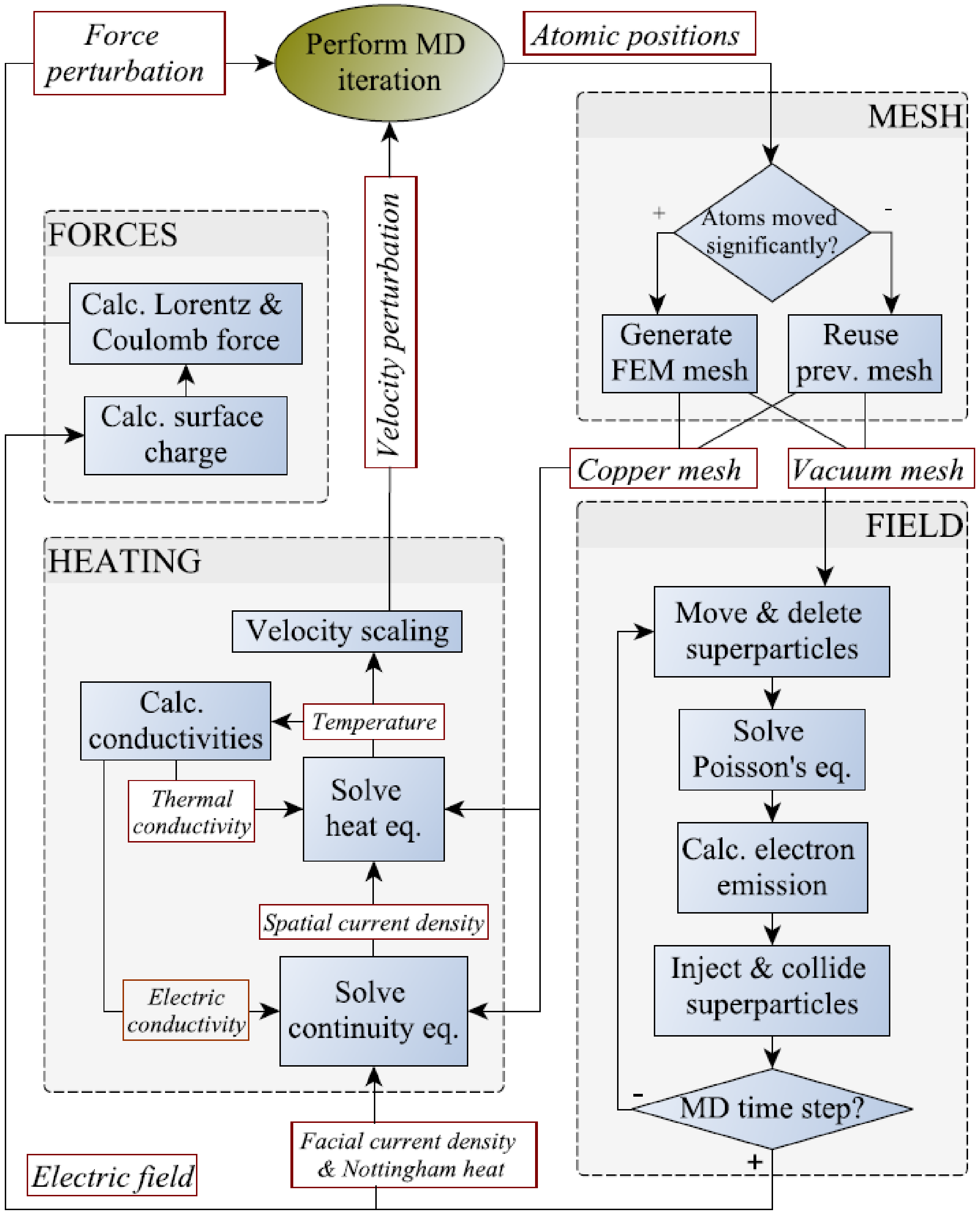


Scheme of considered physics in VBD simulation

Images: Mihkel Veske, UH&UT

FEMOCS



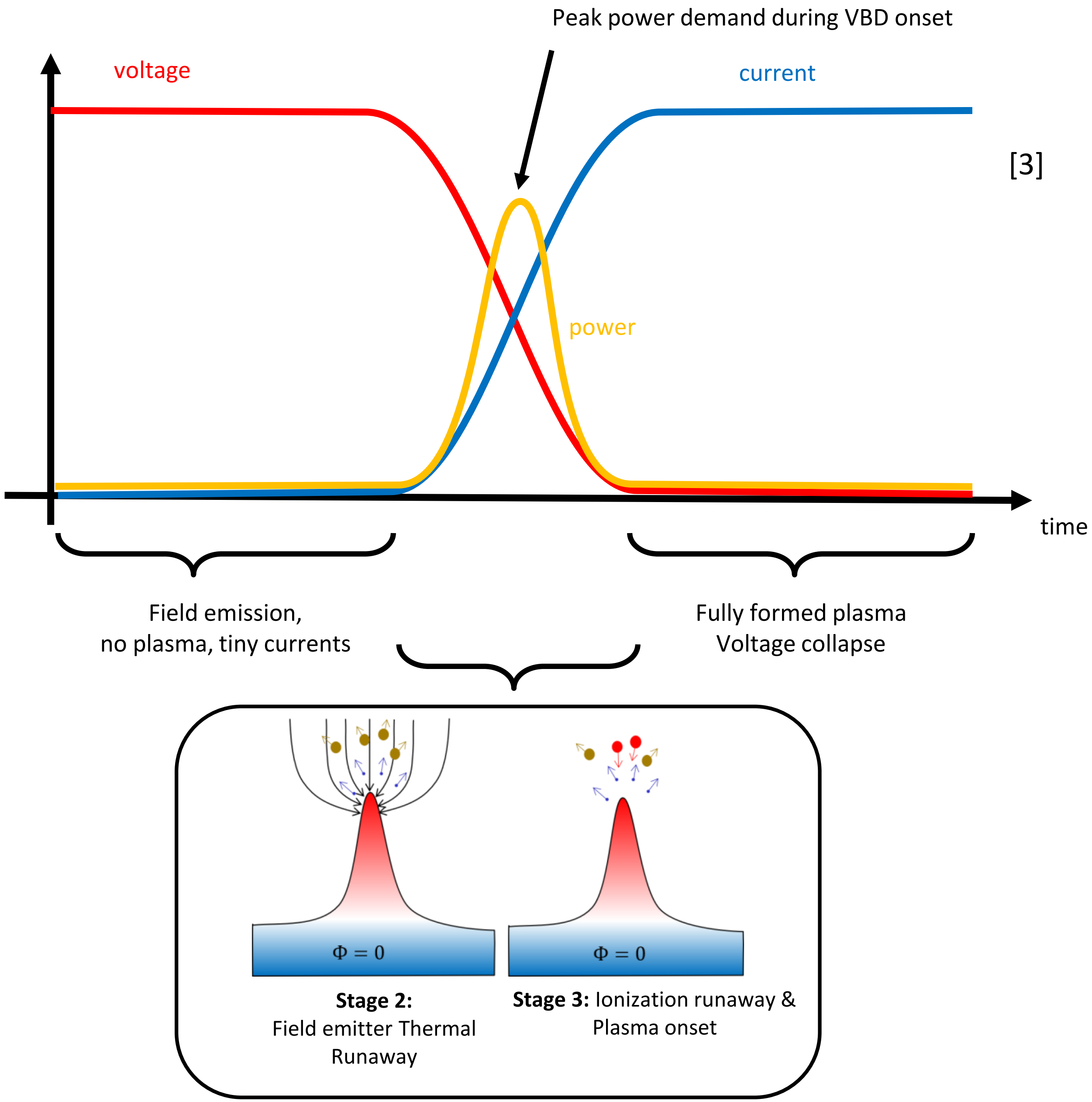


Images: Mihkel Veske, UH&UT

Electromagnetic power supply

- *„Experimental data (CERN, SLAC and KEK) suggests <u>High-Gradient limit depends on power flow</u>, not only E field“ [3]*
  - **Plasma initiation requires a large influx of power**

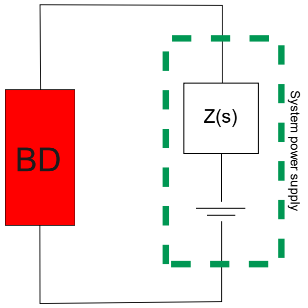
- Ultimate VBD limit is **a function of available power**
  - During VBD onset, <u>not before</u>!
  - **Local power flow**
    - Local surface E field decreases under VBD loading



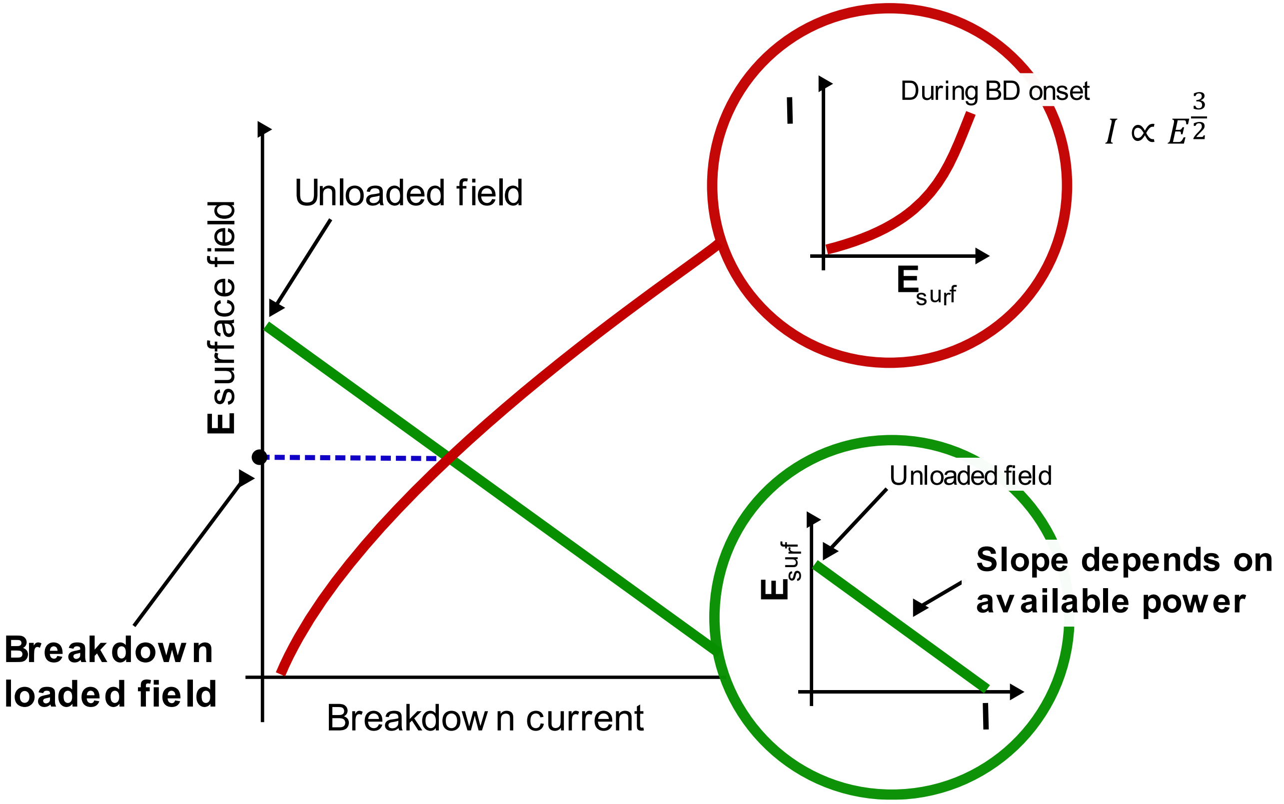
[3] **J. Paszkiewicz**, A. Grudiev, and W. Wuensch. Breakdown-loaded electric field as a high gradient limit. *2019 International Workshop on Mechanisms of Vacuum Arcs (MeVAarc)*, 2019.

Inclusion strategy

- **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.

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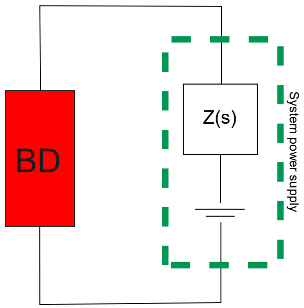

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  - For **any point** in the domain evaluate:
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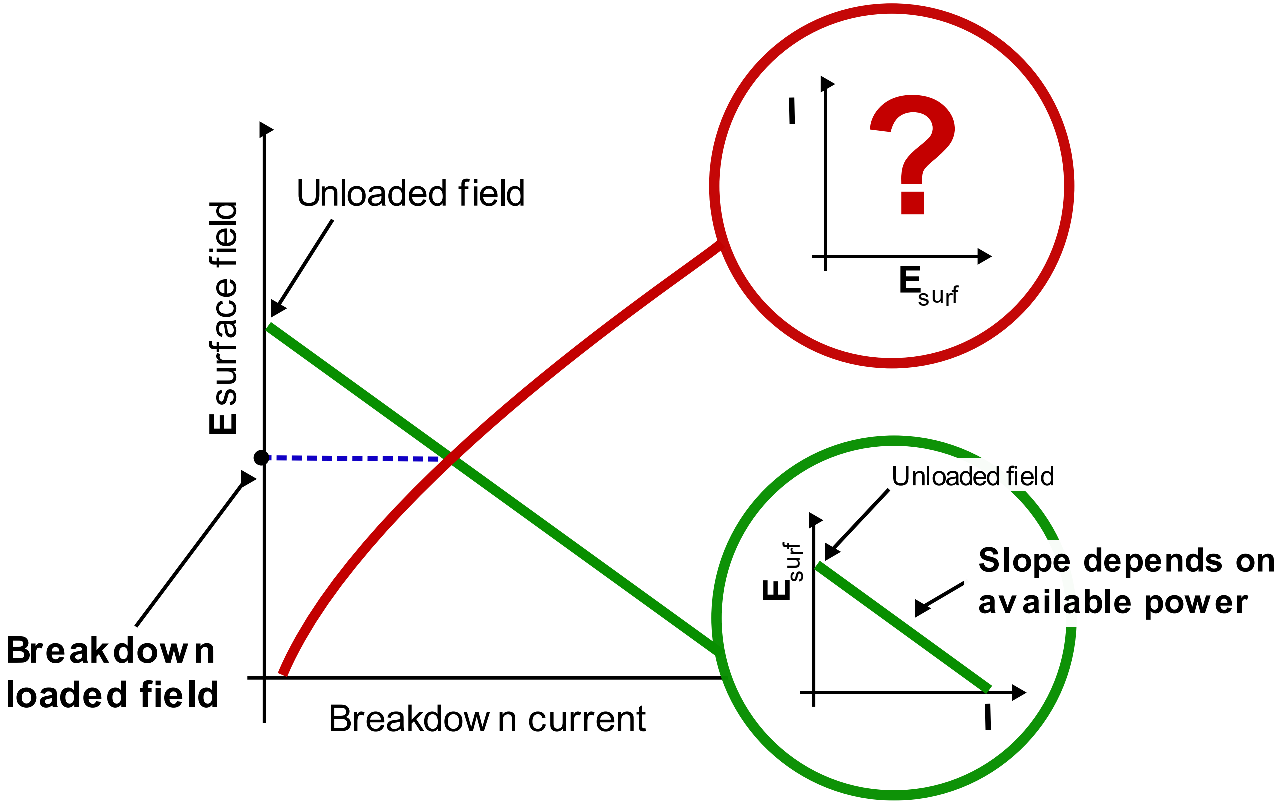
    - Find quasi-equilibrium point
- **DOES NOT ACCOUNT FOR THE FULL PHYSICS OF VBD!!!**



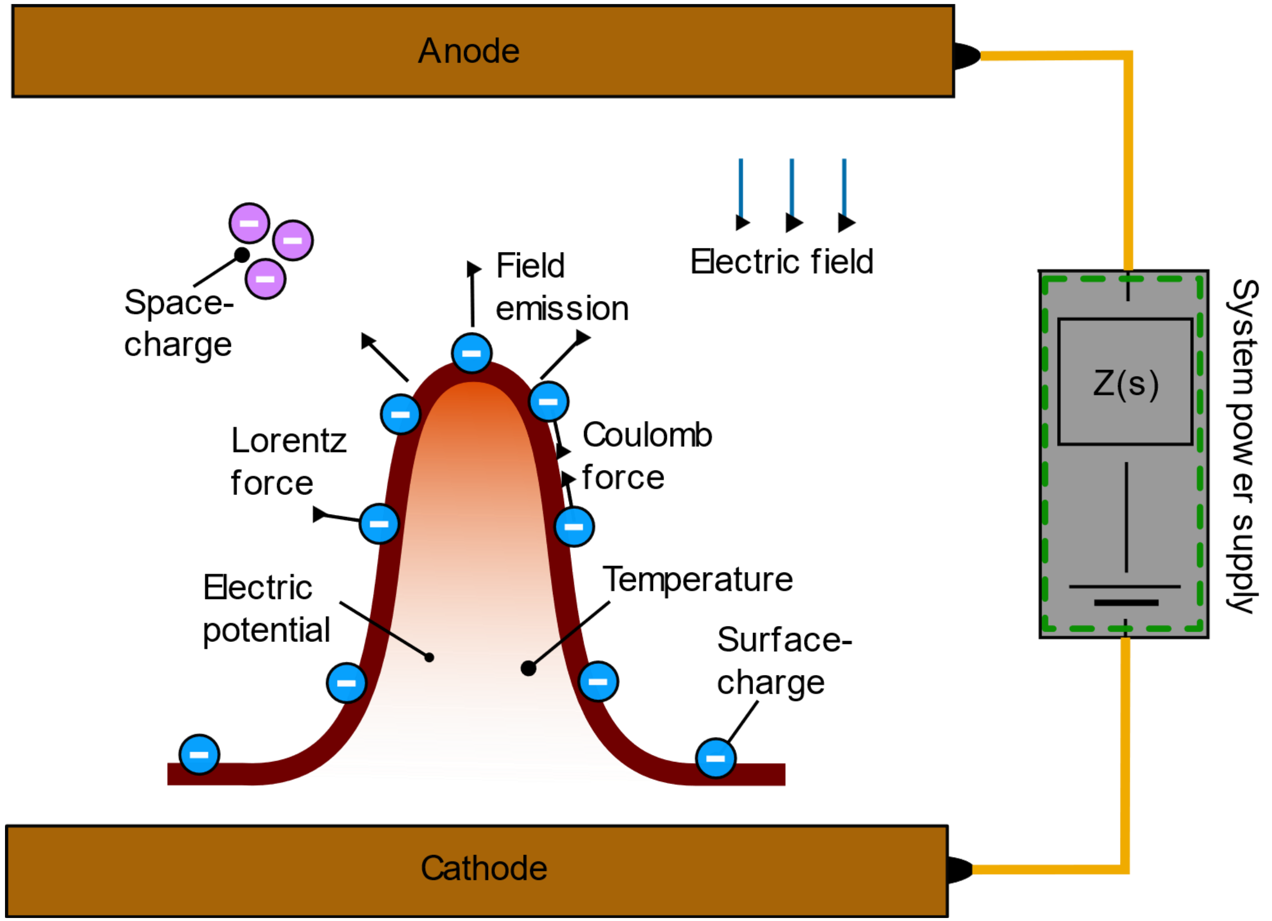
Implementation

- **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

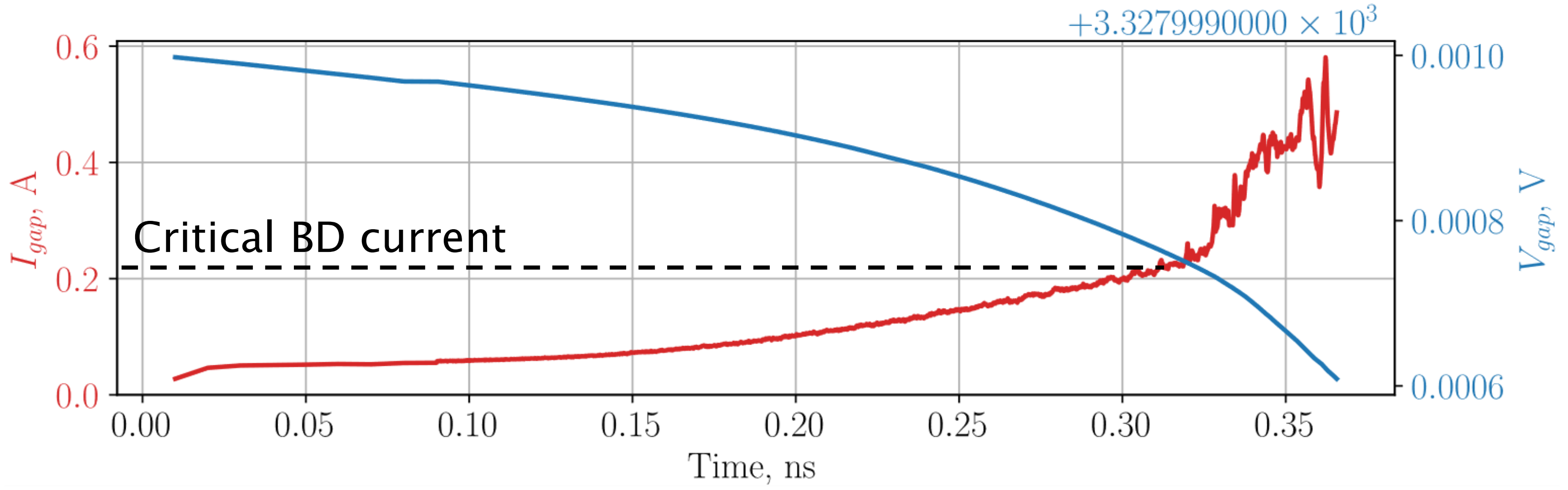


Project direction

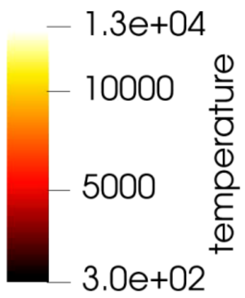
- **The goal:**
  - To determine the **critical quantities** related to the EM power limitation in VBD initiation
  - Consider RF structures (accelerator)

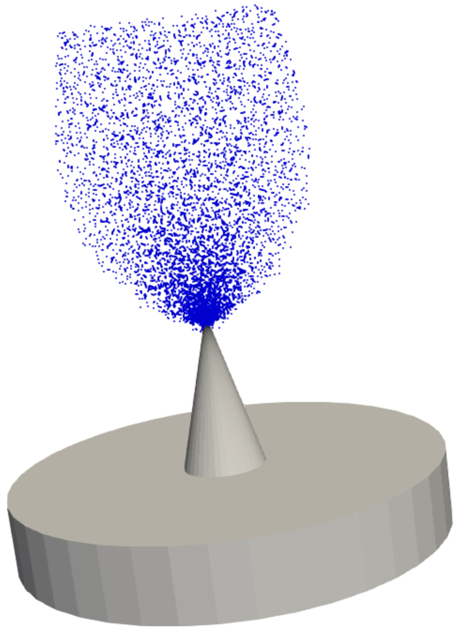
- **Pulse DC system (LES)**
  - **Two models:**
    - Static model
    - Dynamic model
  - **Data:**
    - Impedance values from existing data (CST/EM calculations)
    - **Tip shapes + impedance** + applied field + material parameters <- Sensitivity analysis
    - <u>**Comparison to conducted tests - statistics!**</u>
      - BD location (local Z)
      - <u>Saturated field & applied field</u>

VBD initiation example

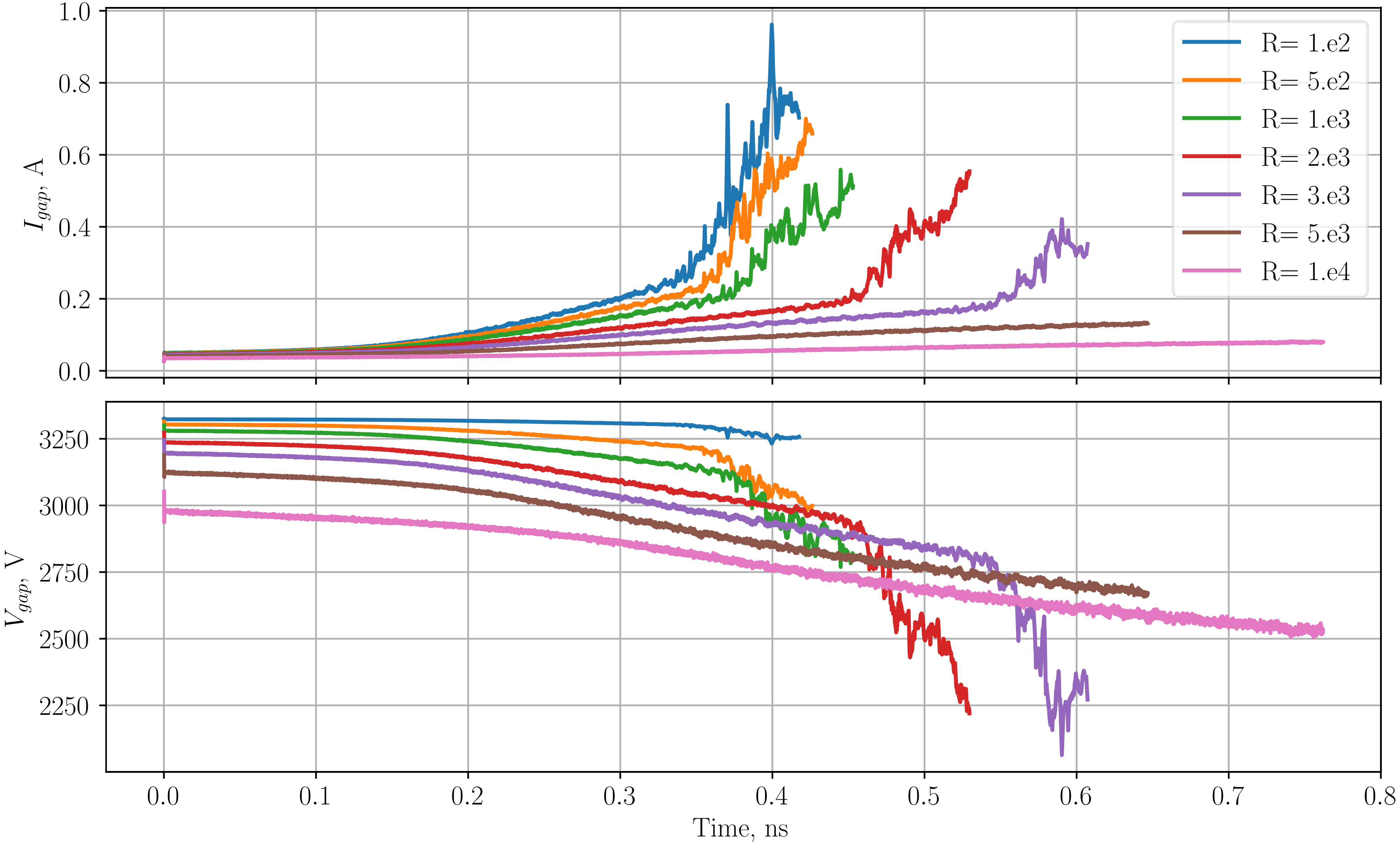


- Electrons
- Neutrals
- Ions

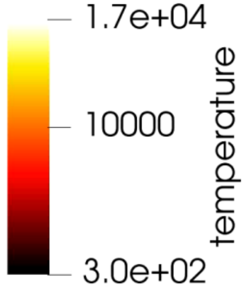


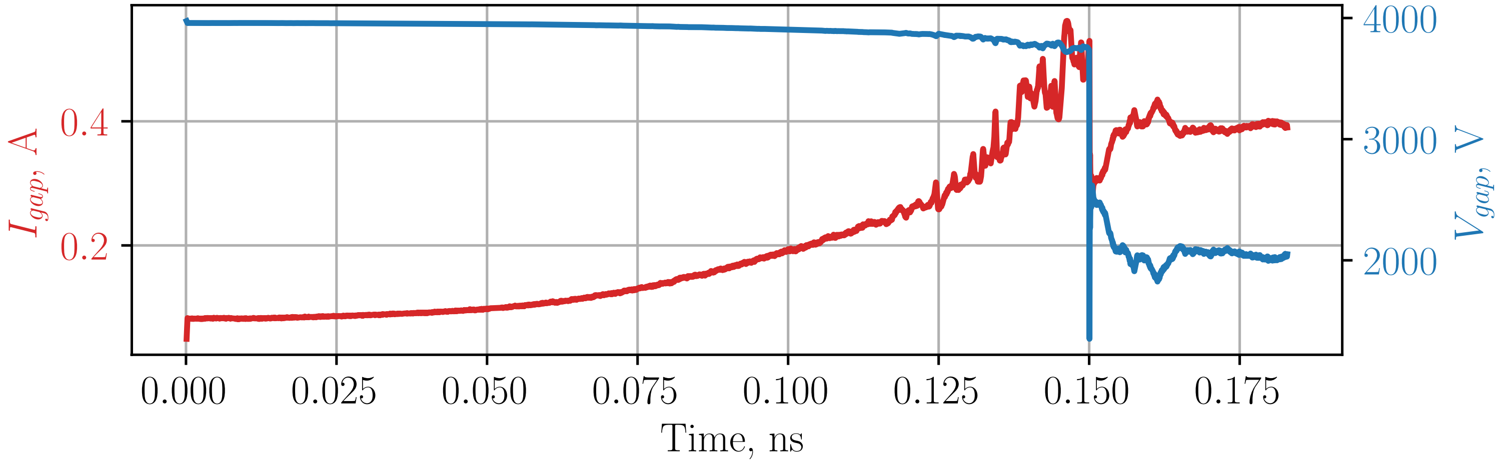


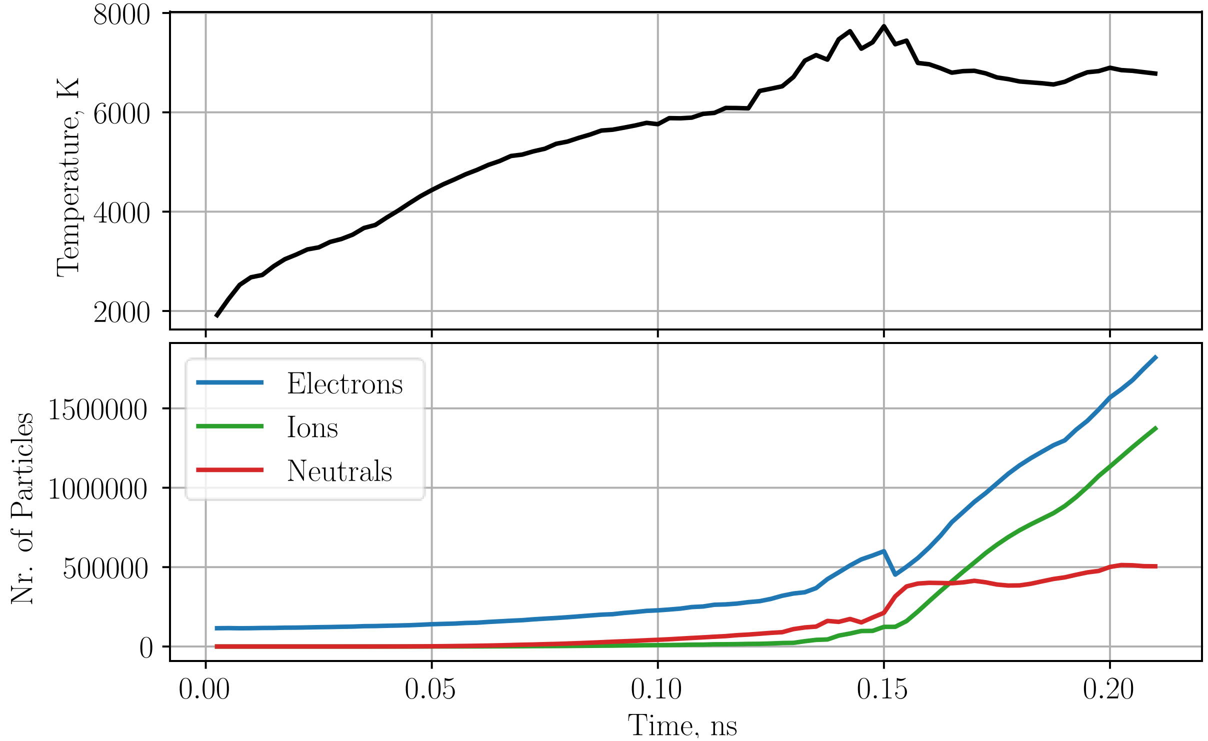
R circuit case study



Voltage drop







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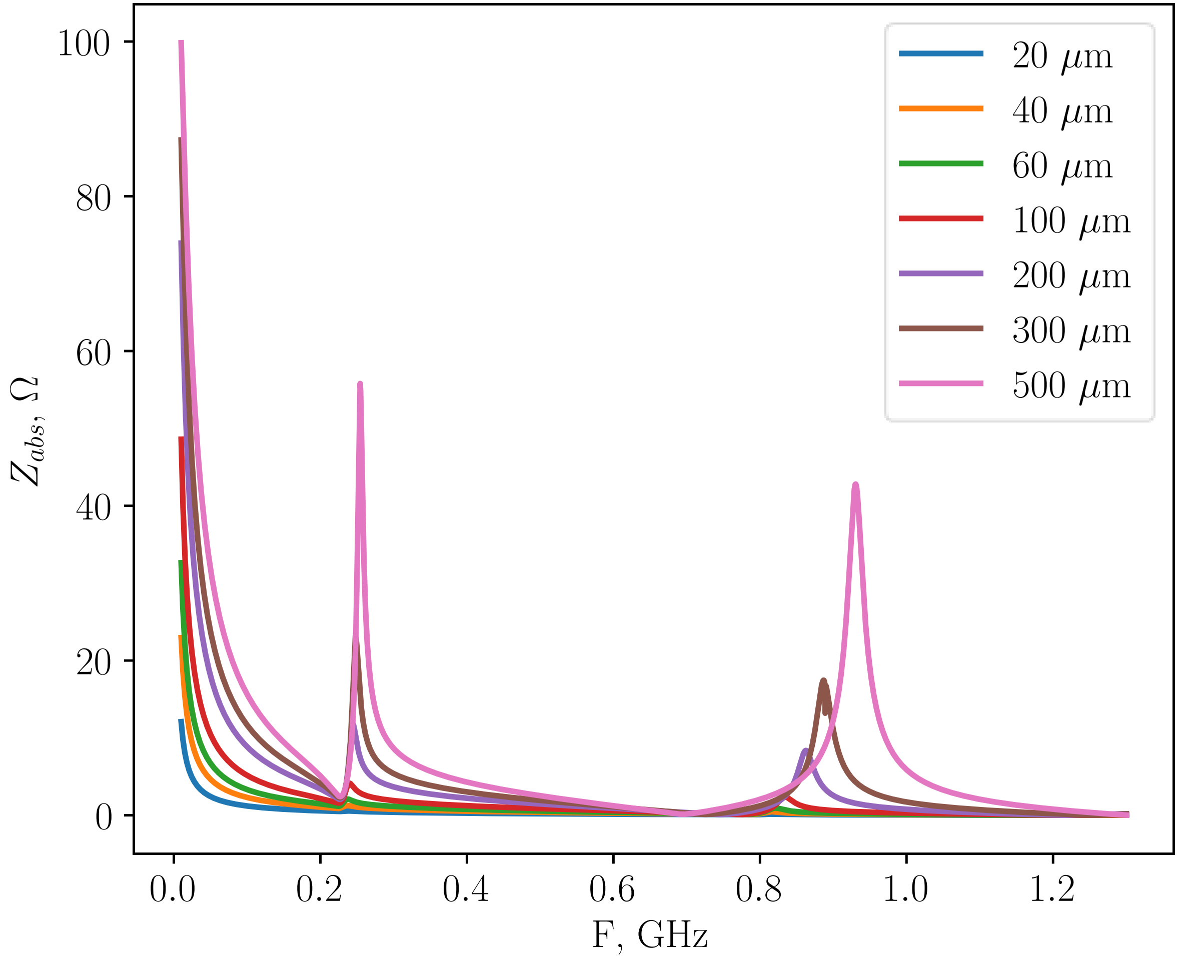
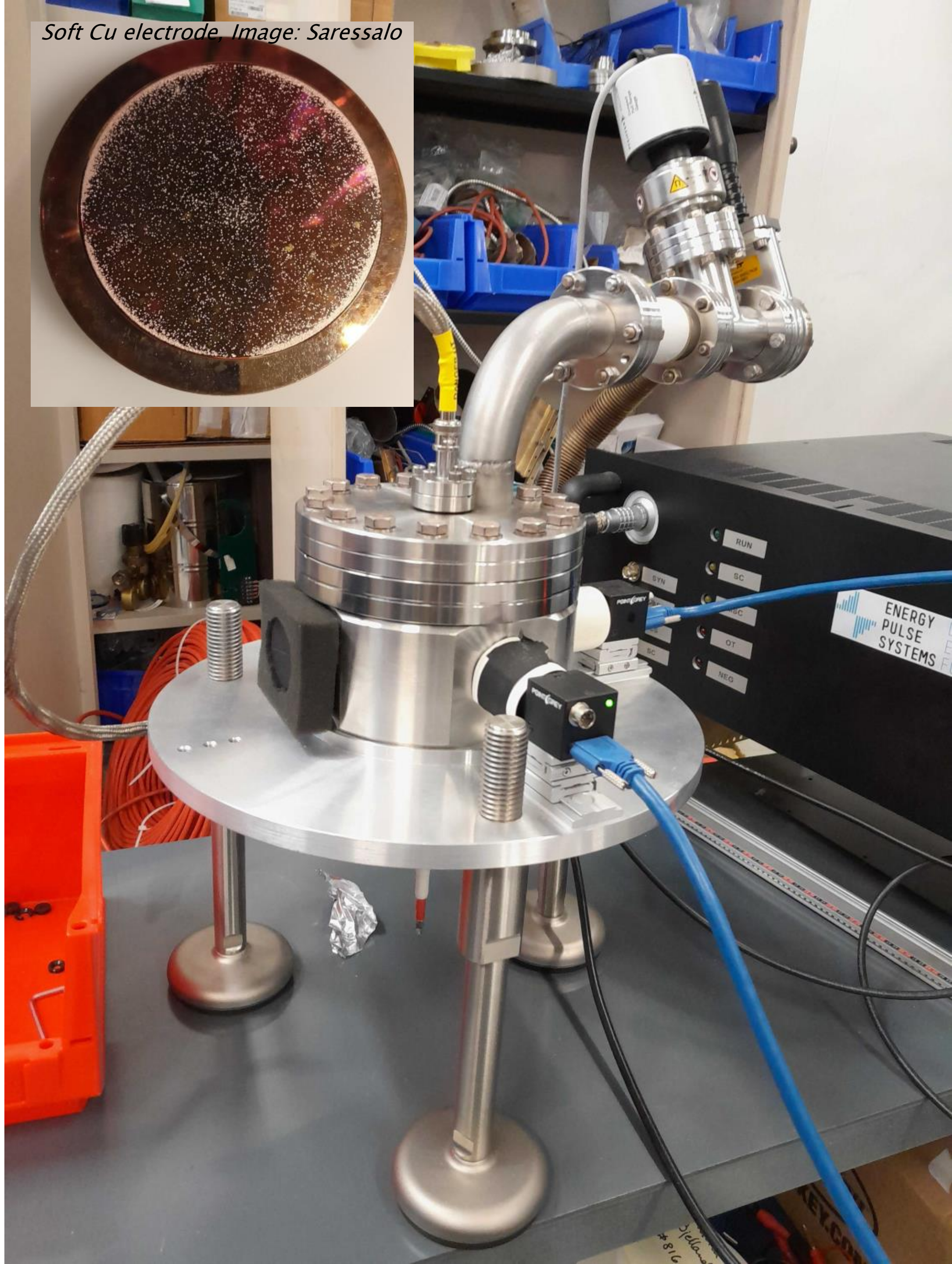
DC Large Electrode system [5]

Data provided by: Paszkiewicz

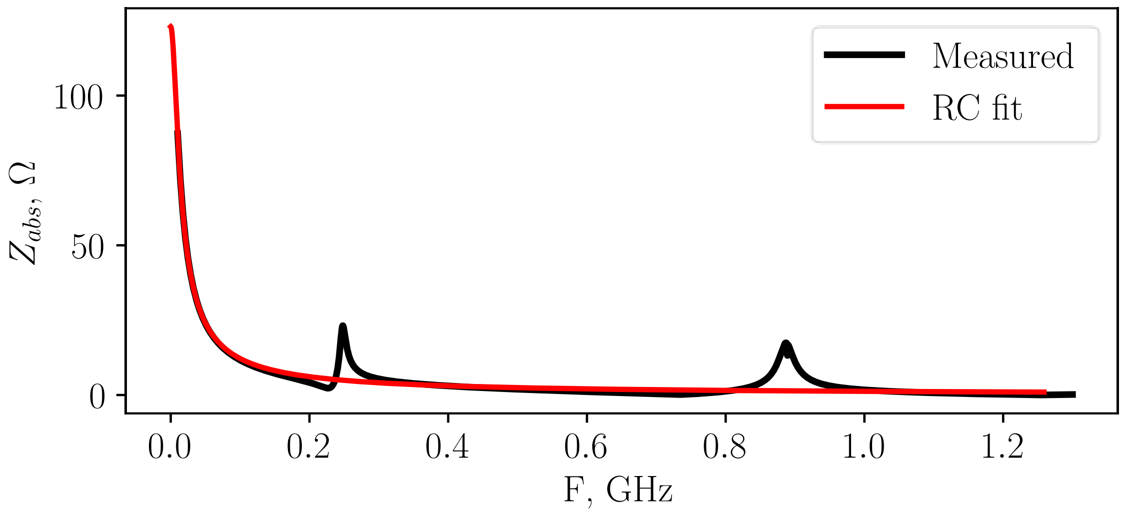


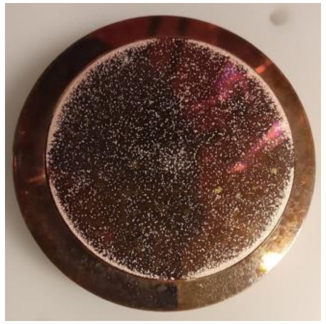


[5] I. Profatilova, Recent progress at pulsed DC systems, in 8th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2019) (Padova, Italy, 2019).

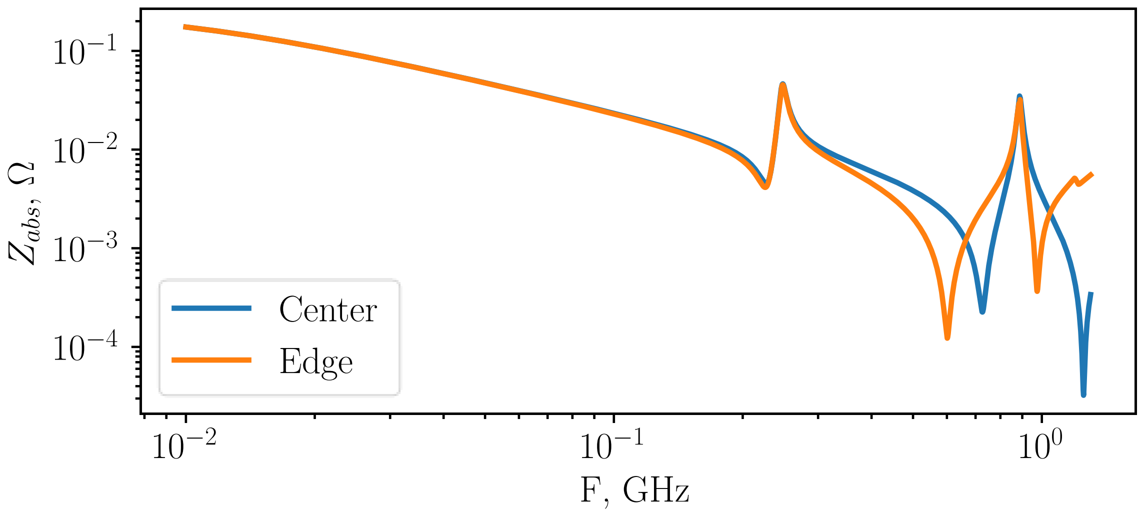
Qualitative nature of results

- Z response *(from J.Paszkiewicz)*
  - 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

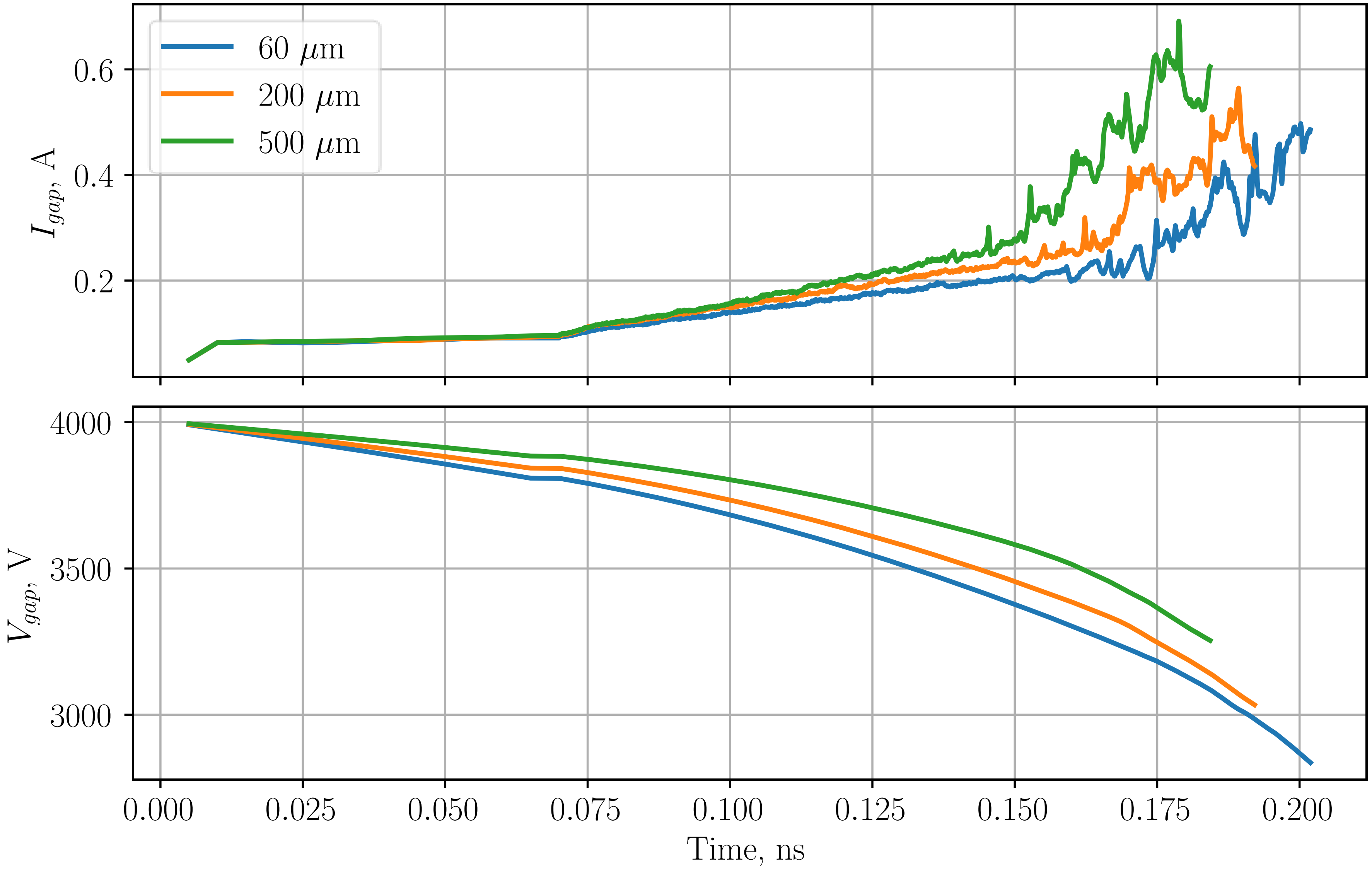




Soft Cu electrode,
Image: Saressalo



Preliminary LES simulation results



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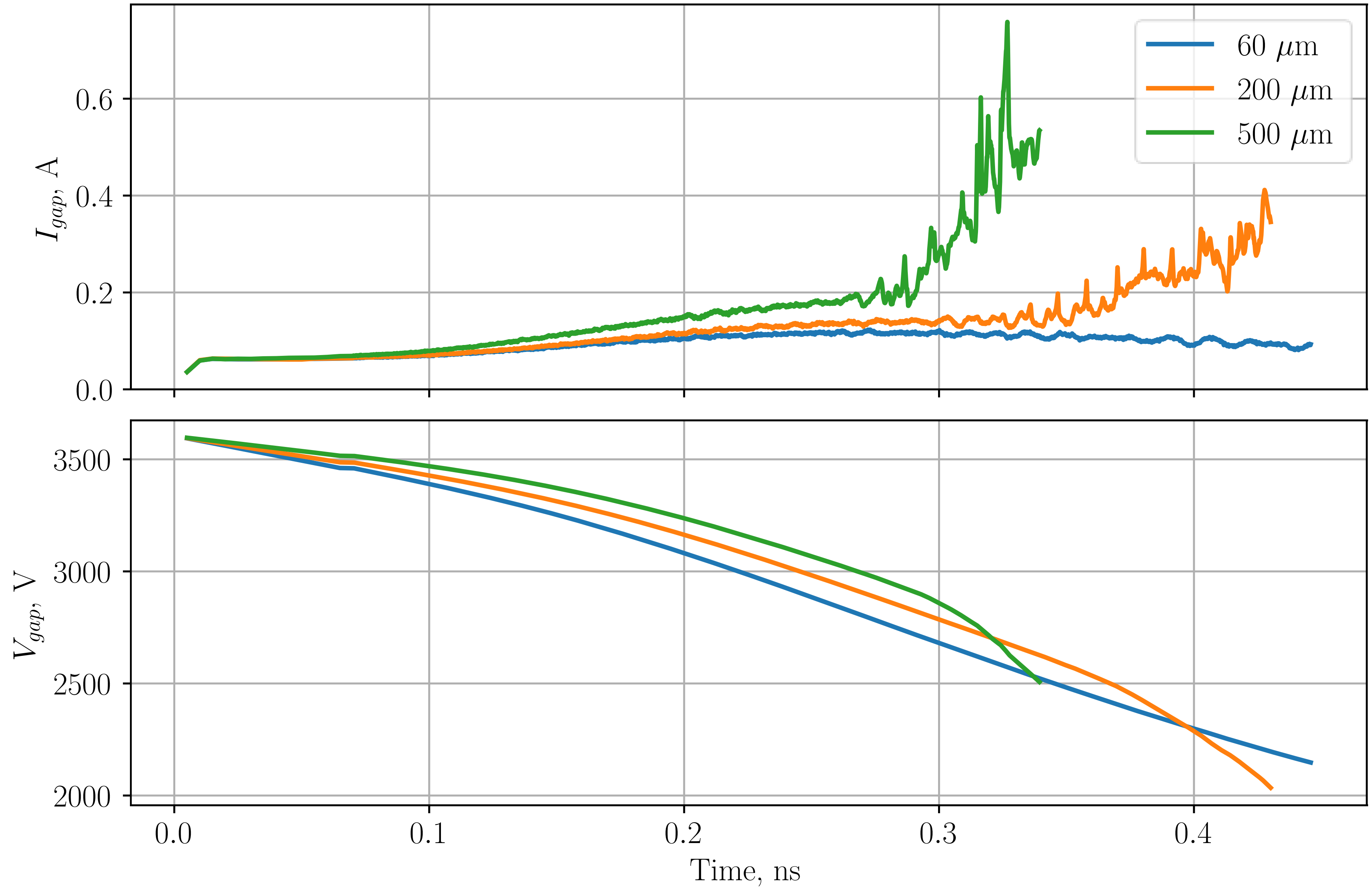


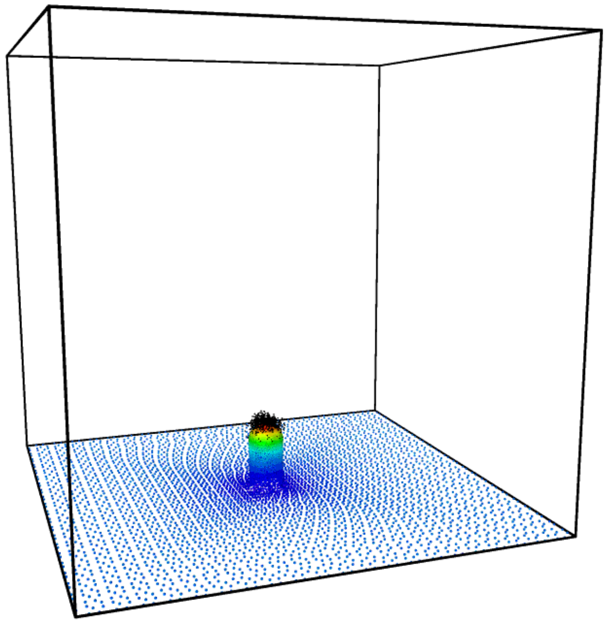
Conclusion & Next steps

- **FEMOCS with the „full circuit system“**
  - Allows investigation of the VBD dependence on system power flow

- Conclusions (preliminary)
  - **Indications of critical BD current**
  - **„High“ impedance can prevent reaching runaway state**

- Next steps
  - **Tip geometry influence**
    - **Critical current** (or relevant limit measure)
    - β & T
  - In-dept investigation into Pulse DC system (LES)
    - Static tip
    - **Z data!!!**
  - Surface/tip morphology
    - MD coupling & 3D *[R. Koitermaa]*

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).