



Coupled electromagnetic–thermal–circuit modelling of quench-back in a co-wound Nb-Ti solenoid – simulation & experiment

Eino Tiirinen^{*1,2}, Benoit Cure¹, Hans Danielsson¹, Alexey Dudarev¹, Gerrit Daan Flier^{1,3}, Francois Garnier¹, Anna Kario^{1,3}, Matthias Mentink¹, Shuvay Singh^{1,4}, Jan Hein Verhoeff^{1,3}, Jasper van der Werf¹

^{*}Presenting author

¹CERN, Geneva, Switzerland ; ²University of Tartu, Tartu, Estonia

³University of Twente, Enschede, The Netherlands ; ⁴Astral Systems, Bristol, The United Kingdom.

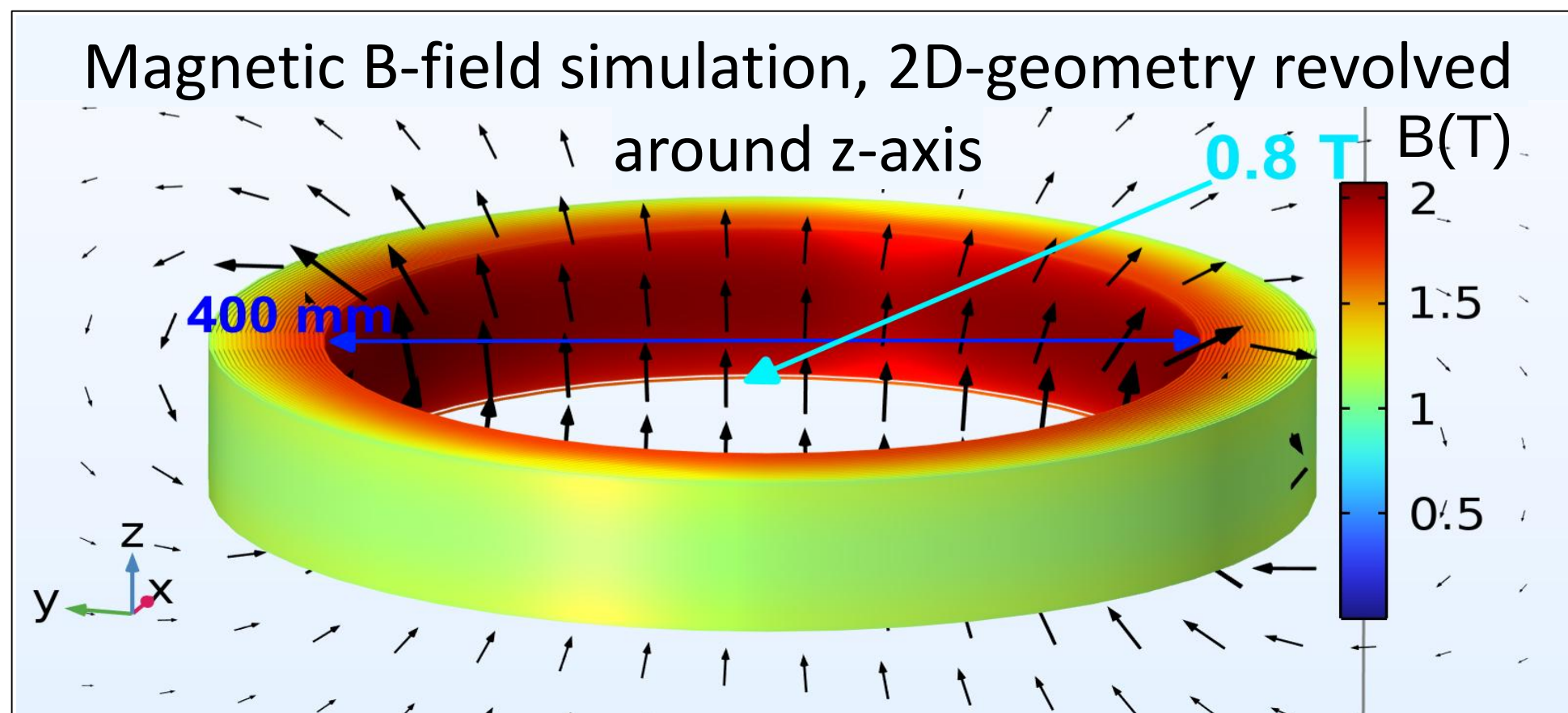
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Motivation and goal

- Quench-back through a co-wound normal-conducting secondary [1] couples electromagnetics, heat transfer and an external circuit on millisecond time scales.
- The goal of this work is a predictive COMSOL model that reproduces a measured fast discharge without free fit parameters, using geometry, material properties from literature and the measured circuit constants.
- Experimental validation was done on a co-wound Nb-Ti and Cu demonstrator solenoid [2].

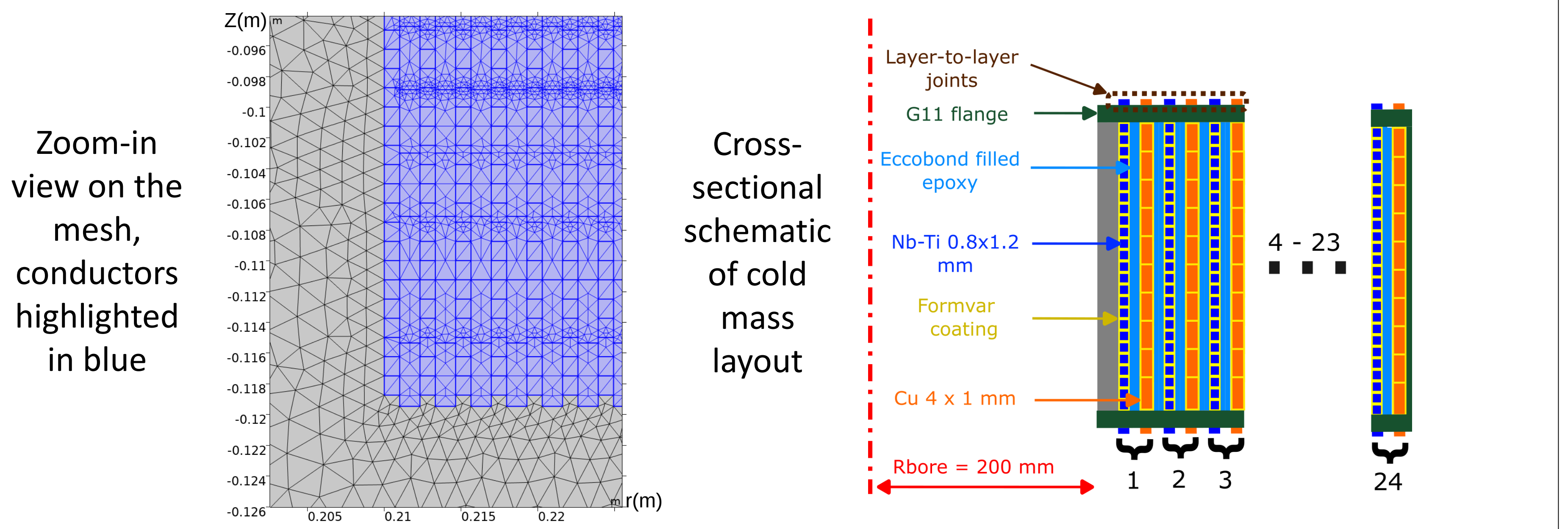


Material properties, scaling law

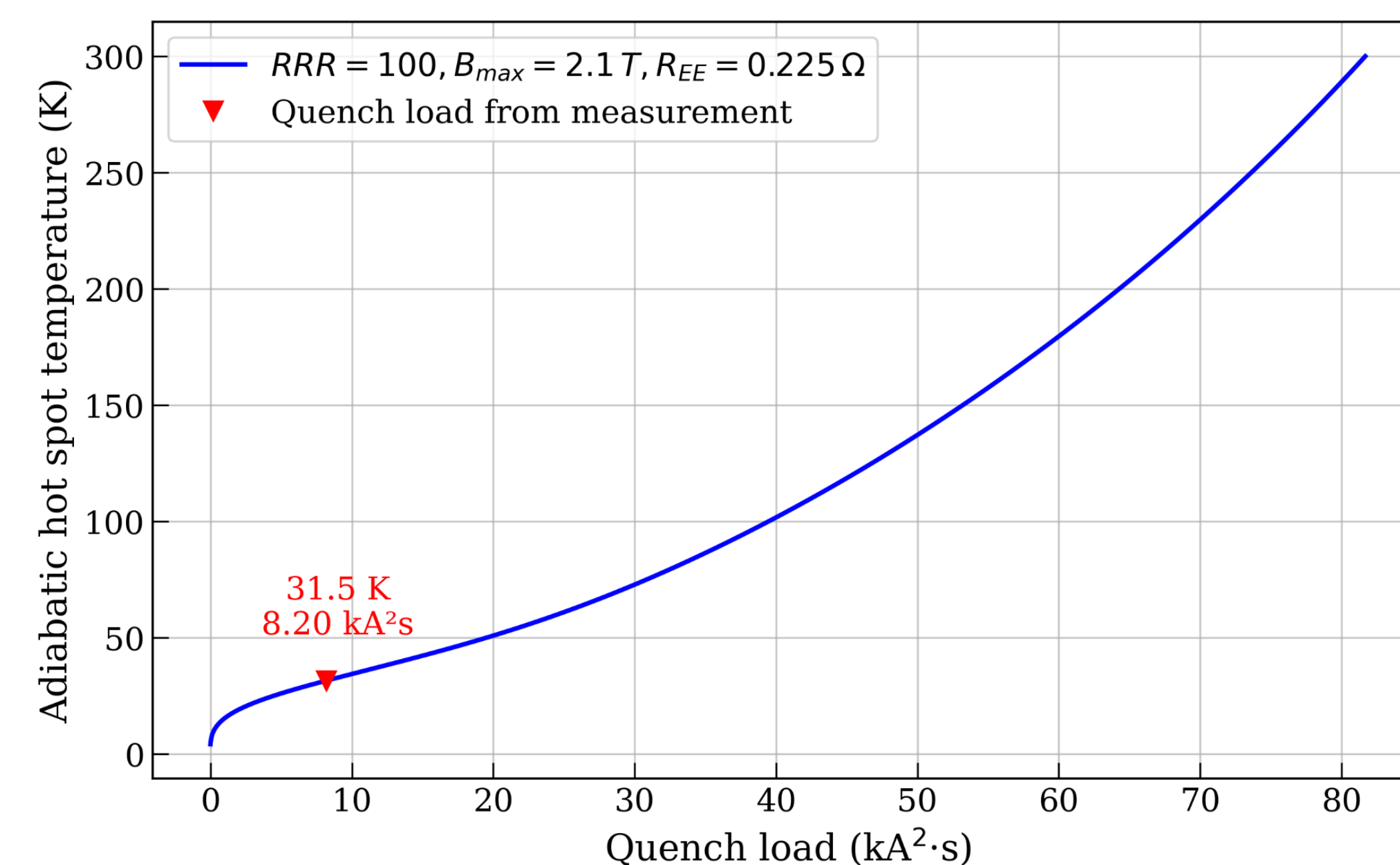
- $\rho(B,T)$ from Wiedemann-Franz relation, using k for Oxygen-free high conductivity (OFHC) copper [3], including magnetoresistance.
- Temperature dependent specific heat of conductor unit cells found using area fraction. Data for OFCE Cu and G-10 (approximated for all insulation) from [3], Nb-Ti 49 wt% Ti from Cryocomp.
- Critical surface [4-5]: determines temperature margin, when and where the primary transitions to normal-conducting state, which drives the quench-back.

Coil geometry and model definition

- 2D axisymmetric geometry, free triangular mesh with 34k elements with 150k DOF.
- Every turn resolved individually: 24 layers $\times$ 64 Nb-Ti turns and 24 $\times$ 20 Cu turns, adiabatic external boundaries.
- Conductor unit cells meshed individually; inter-turn insulation is not meshed but imposed as thermally thin layers, insulation inside the cell is homogenised by area fraction.
- Magnetic Fields (mf) A_ϕ with $\sigma = 0$ in all domains, currents imposed as External Current Density
- Heat Transfer in Solids (ht) for T, Joule heating source $Q = \rho(I/A)^2$.



Adiabatic hotspot as a function of quench load



Simulation outputs

- Effect of Energy-extraction circuit resistance and diode forward voltage on adiabatic hotspot temperature T_{max}

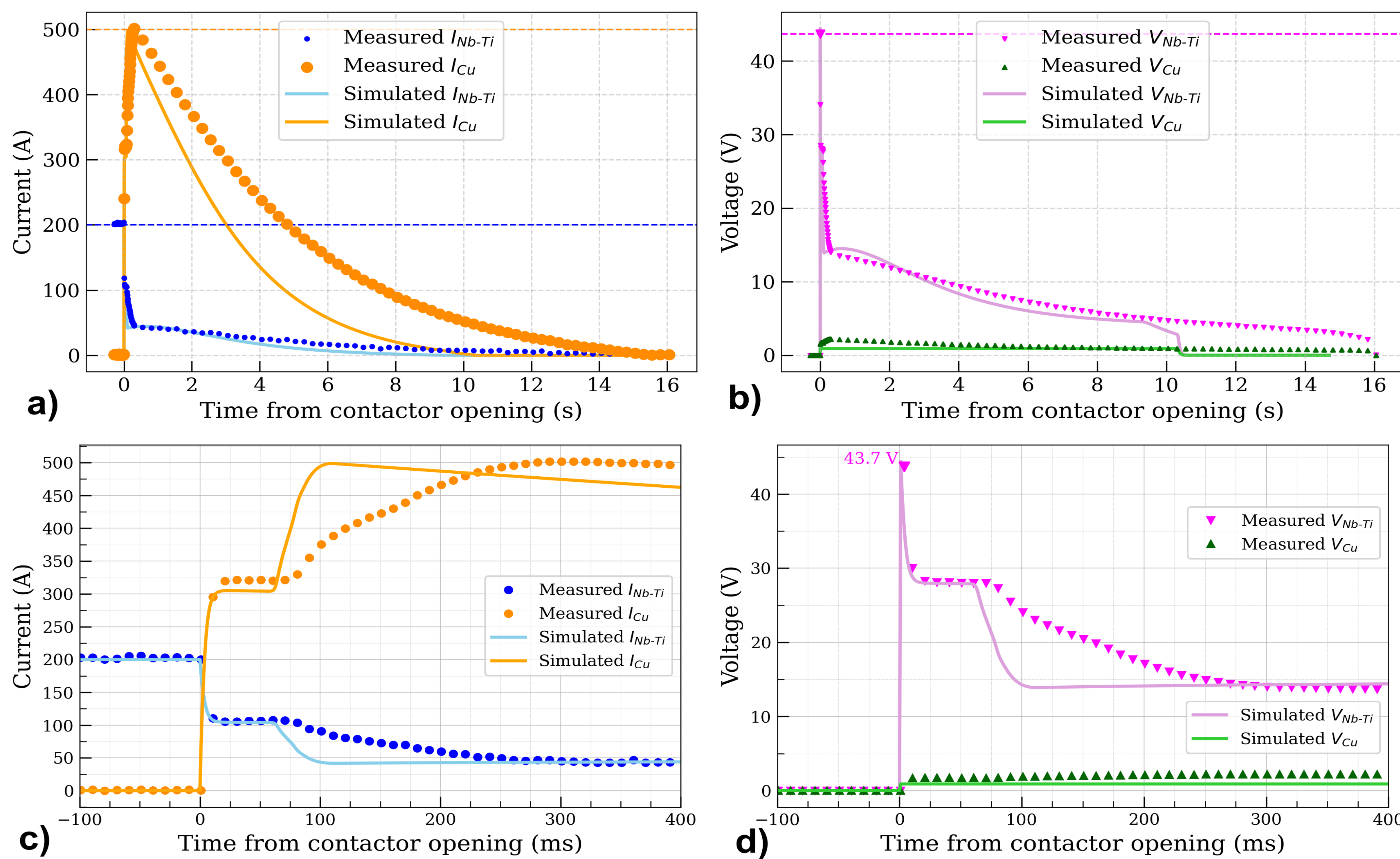
$$\int_0^\infty J^2(t) dt = \int_{T_0}^{T_{max}} \frac{\gamma C(T)}{\rho(B, T)} dT$$

- Voltagess obtained by integrating B-field solution, Currents fed back as external current densities

$$V_{prim} = \frac{I_1}{A_{prim}^2} \int_{prim} \rho dV + \frac{1}{A_{prim}} \int_{prim} \frac{\partial A_\phi}{\partial t} dV$$

- Efficiency of quench-back: Keeping quench load fixed, and comparing to simple discharge over an external dump resistor: Peak extraction voltage 43.7 V instead of 713 V — **A factor 16 lower.**

Coil discharge behavior - Current and voltage over time



Fast discharge – simulation & measurement

- Fast discharge from $I_0 = 200$ A. Long (a,b) and short time-scales (c,d)
- Measured and simulated curves agree on peak current, peak voltage and the onset of quench-back at $t \approx 100$ ms.
- c) Nb-Ti current falls to 100 A within 100 ms and to a quarter of nominal by 300 ms, then decays to zero over 15 s.
- d) Peak voltage across the extraction system 44 V

Conclusions and Outlook

- A COMSOL-based multiphysics quench simulation model is presented and compared to experimental observations on a demonstrator solenoid.
- The method gives a favorable adiabatic hotspot temperature (32 K) and a low peak discharge voltage (44 V).
- Next steps: Conduction-cooled operation of magnet using a GM-cryocooler, including implementing REBCO-hybrid current leads for magnet powering.

References

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