$\mathbf{H} - \phi$ Simulations for Pre-Quench Modelling in HTS Tapes

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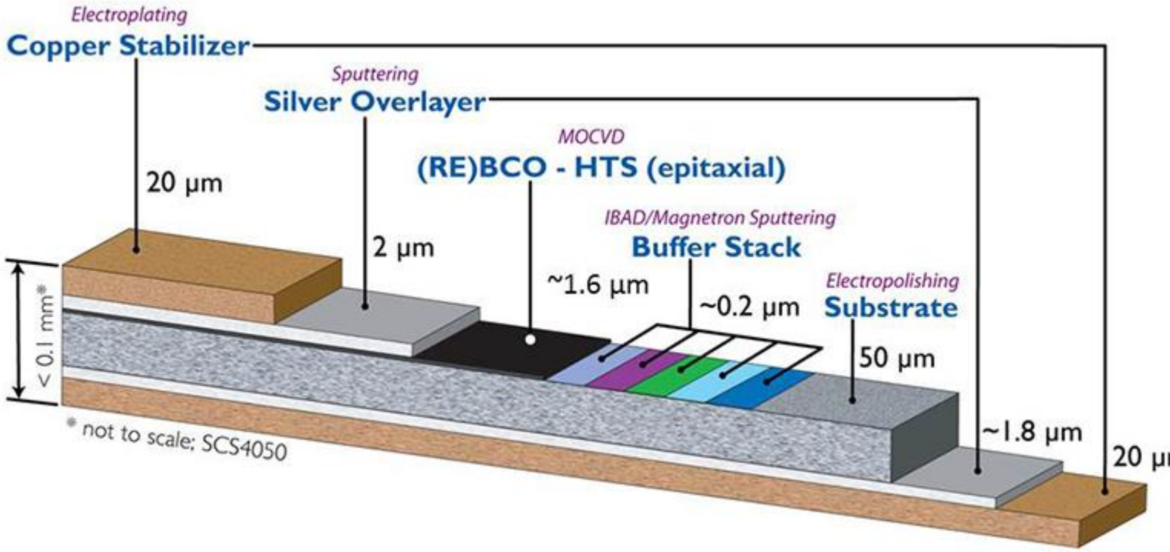
INTRODUCTION

HTS modelling can be extremely challenging

- Multiphysics often required
- Highly **non-linear** and **inter-dependent** material laws
- High-aspect ratio mesh

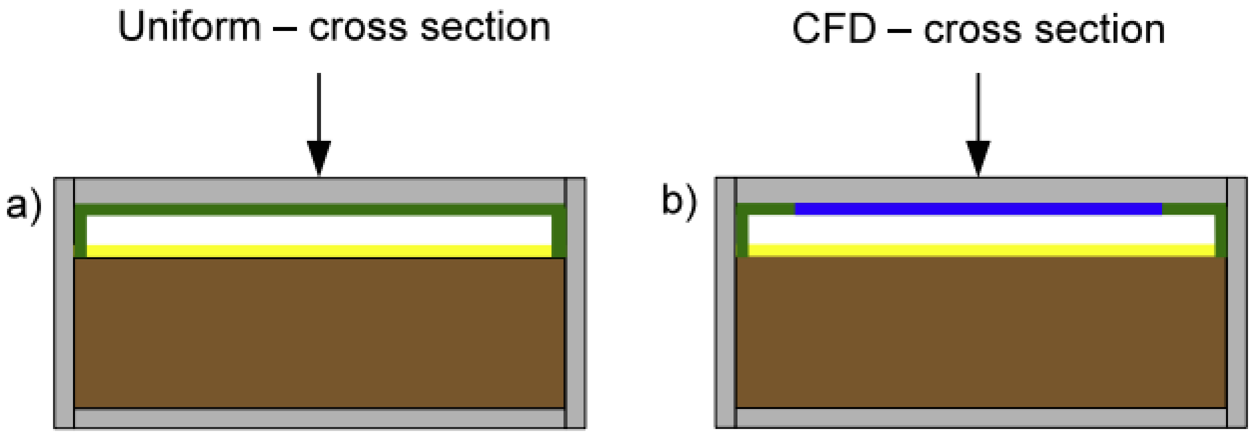
➔ lead to sensitive simulations when it comes to predicting quench nucleation and propagation



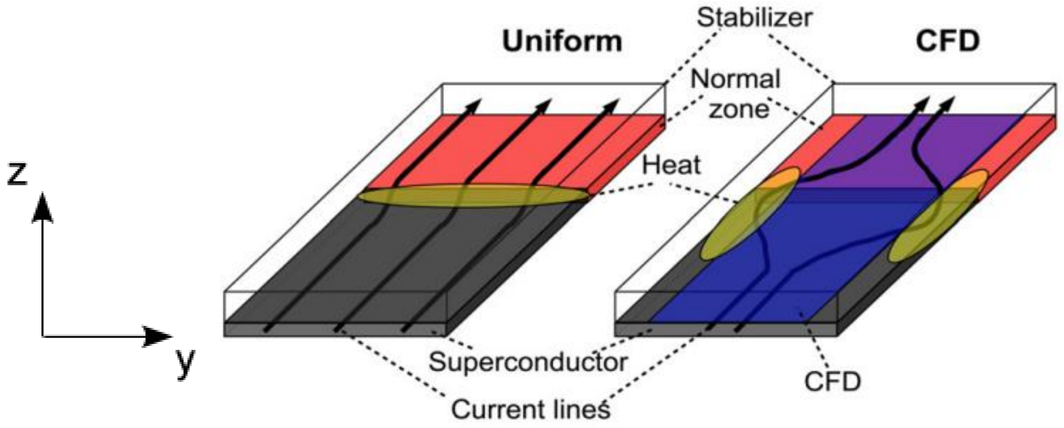
INTRODUCTION

Our goals in this work are to accurately:

- Compare different electromagnetic formulations, E-J characteristics and tape architectures, especially the Current Flow Diverter (CFD) tapes (3-D problems)
- Predict the hot-spot nucleation and propagation with temperature and voltage
- Investigate the “pre-quench” regime



NZPV enhancement
(6-7 times faster!)



C. Lacroix and F. Sirois, SuST. 27(3), 035003 (2014)

OVERVIEW

- Introduction
- **Electromagnetic Formulations**
- E-J Characteristic in HTS
- Simulation results
- Summary and Outlook

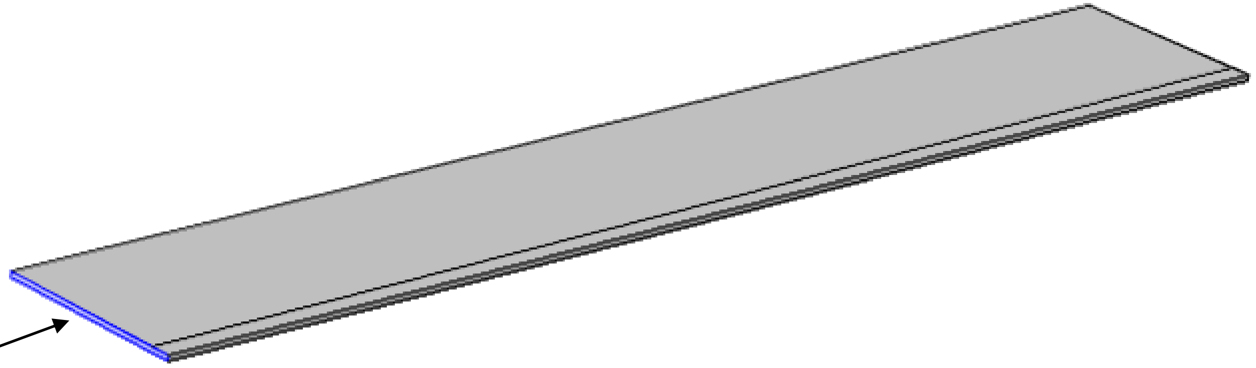
V formulation (electro-thermal)

- Describes a **current continuity** (flow) equation:

$$\nabla \cdot (\sigma \nabla V) = 0$$

- The current injection is imposed as a weak constraint:

$$\int_{\partial\Omega} \mathbf{n} \cdot \mathbf{J} \, dS = I$$



- **Numerically efficient simulations!**

Solving variable: V

Current density: $J = -\sigma \nabla V$

Magnetic Field: ?

H($-\phi$) formulation (magneto-thermal)

- Uses the strong equation

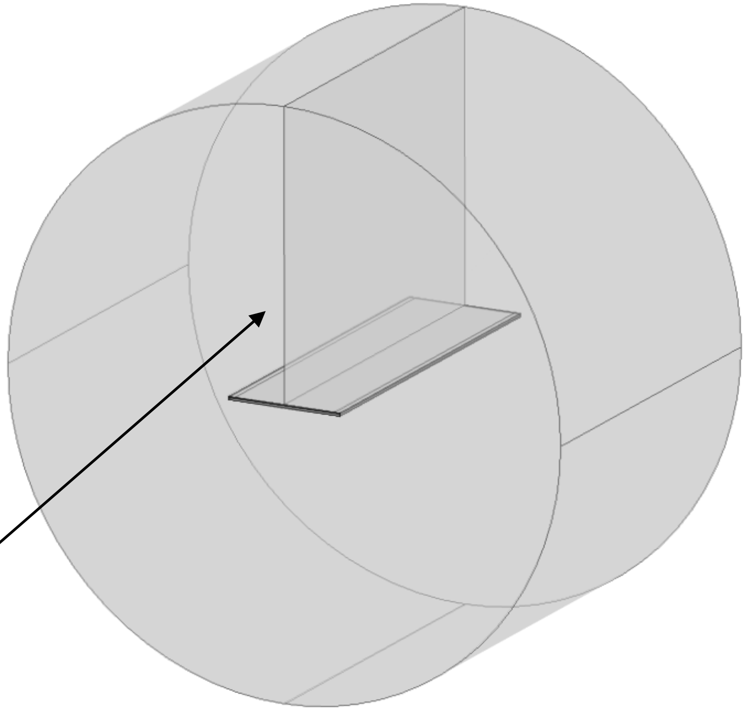
$$\nabla \times (\rho \nabla \times \mathbf{H}) + \partial_t(\mu \mathbf{H}) = 0$$

- In a **non-conducting region**:

$$\mathbf{H} = -\nabla\phi$$

- The current is imposed with a **"cut"**

- **Physically accurate simulations!**



Solving variable: $\mathbf{H}$ (or ϕ)

Current density: $J = \nabla \times \mathbf{H}$ (or 0)

Magnetic Field: $\mathbf{H}$ (or $\nabla\phi$)

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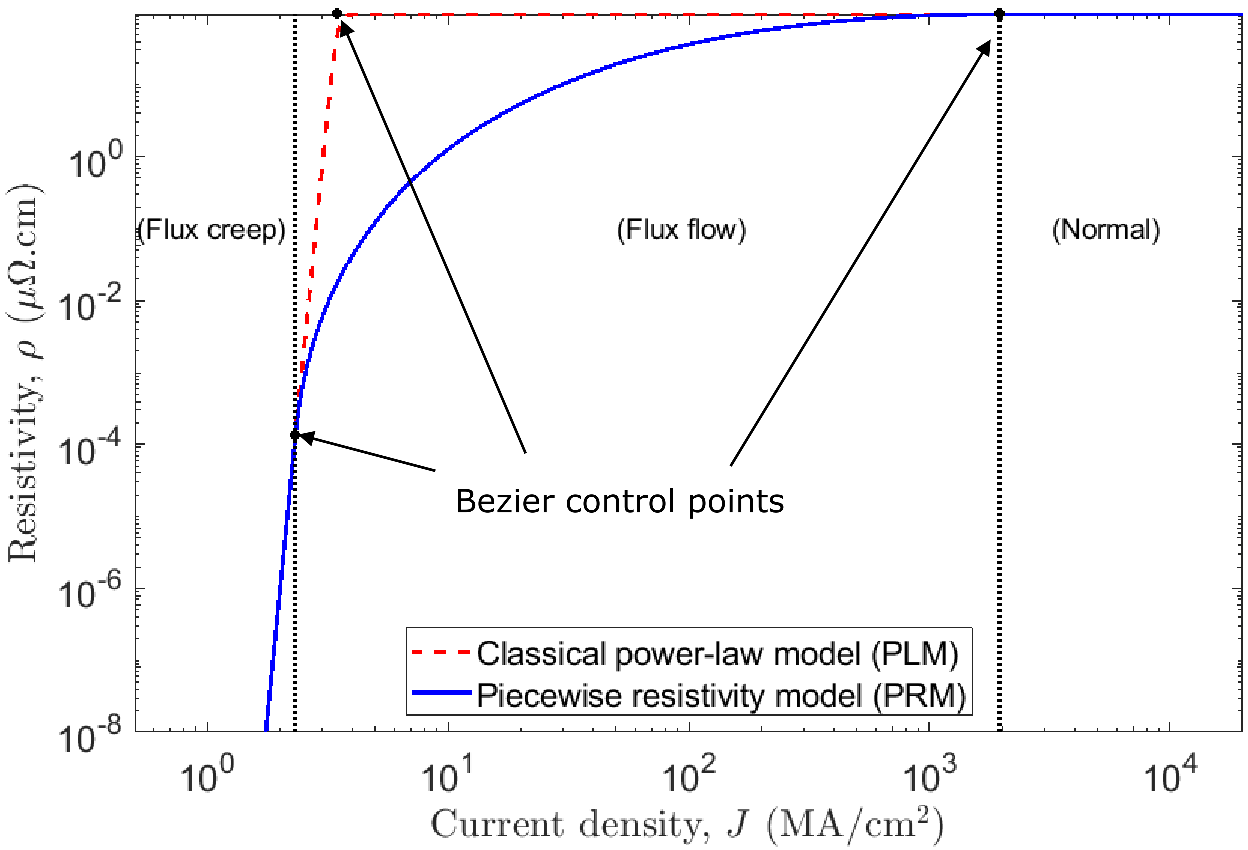
E-J CHARACTERISTIC

Very often, we observe that the classical power-law generates a hot-spot too early in simulations (*N. Riva, et al., SuST. 33(11), 27, 114008, 2020*)

Power-law model (PLM) vs. piecewise resistivity model (PRM)

- **PLM:** Simple, but overshoots the voltage during flux flow
- **PRM:** Better represents experimental results



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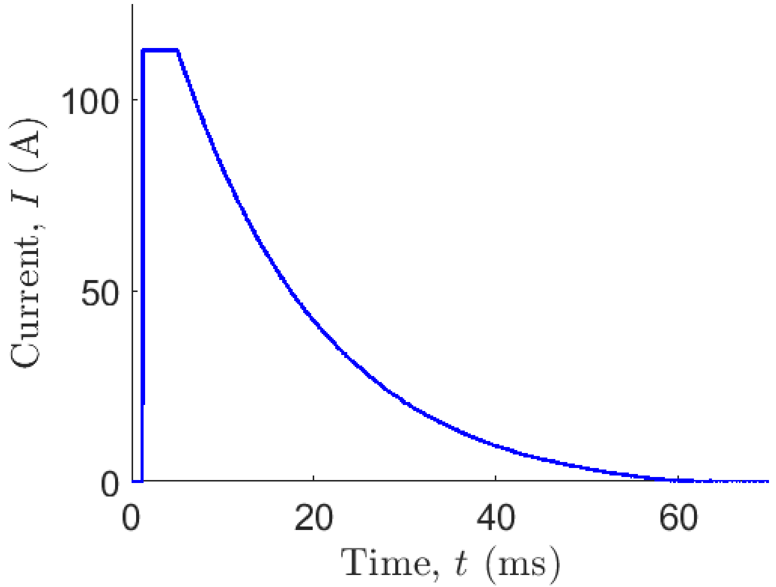
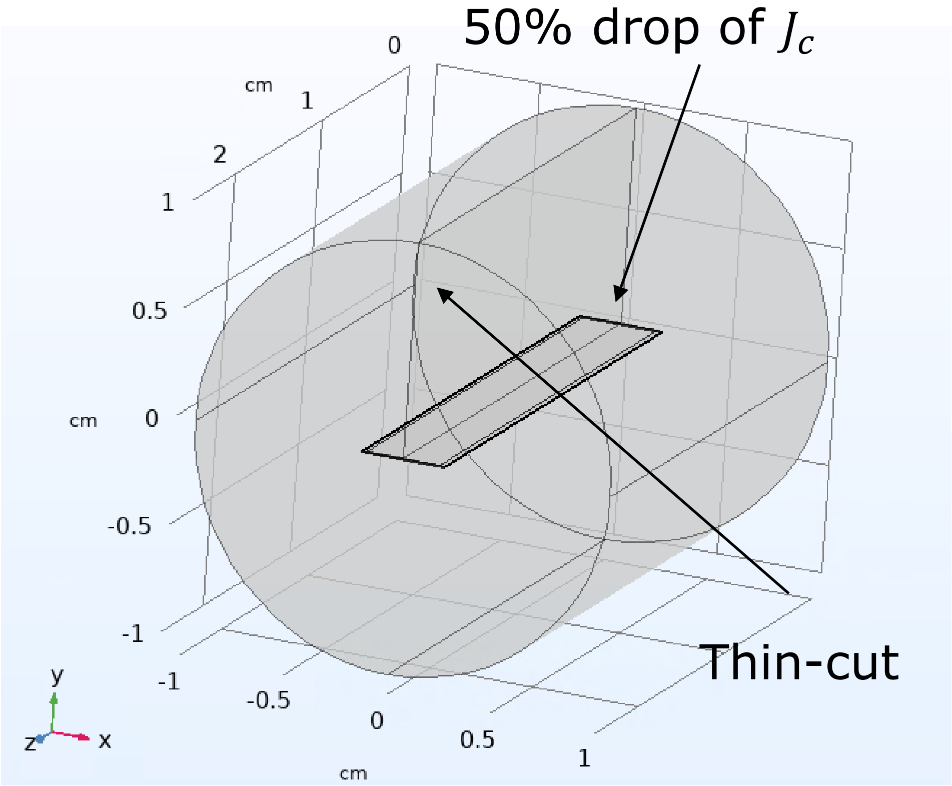
Simulated benchmark (COMSOL, 3-D)

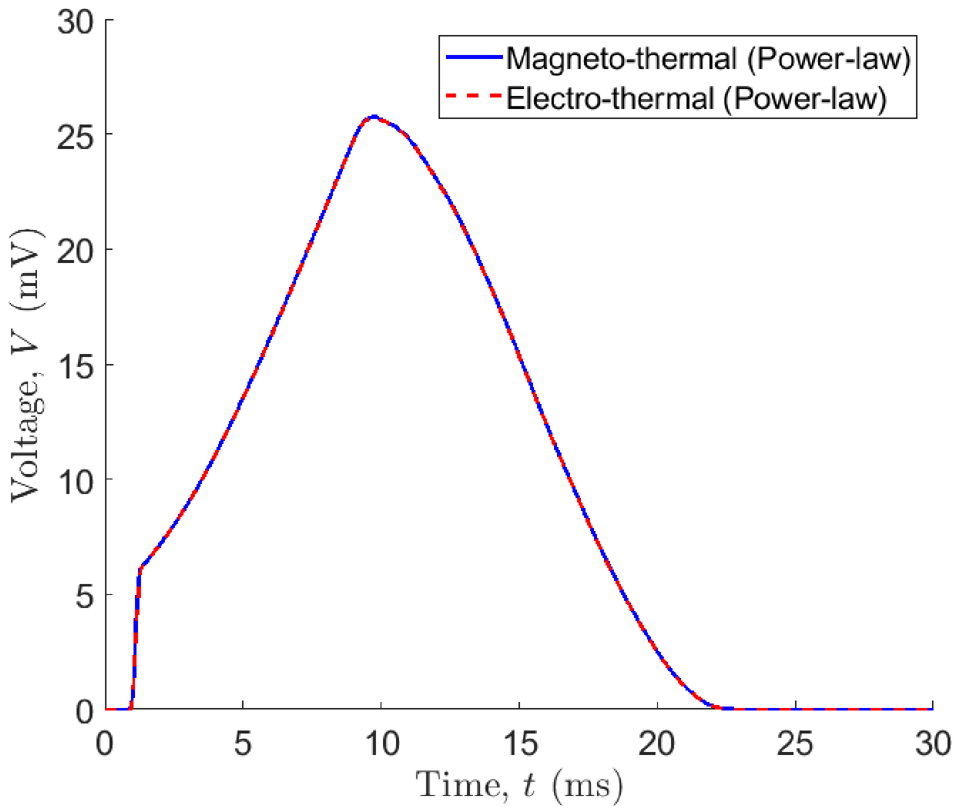
- Multilayered tapes (silver, interface, REBCO, buffer, Hastelloy and copper)
- Quench generated by a magnet (local drop of I_c)
- Experimental data available

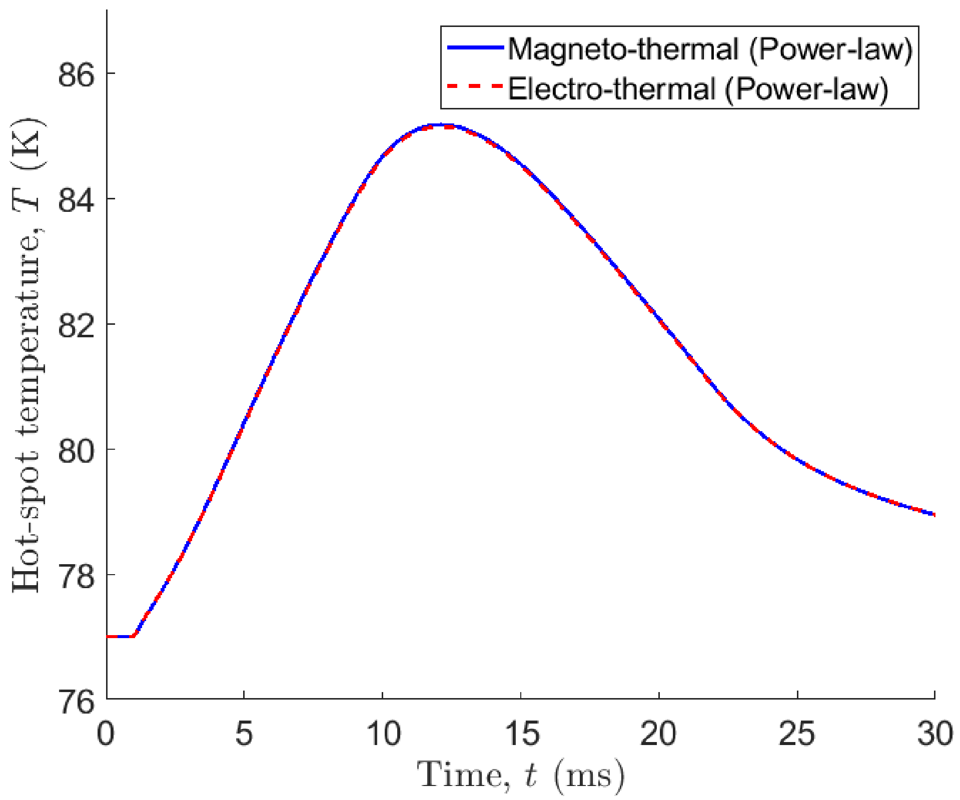




RESULTS

<u>Commercial tape:</u>
Electro-thermal simulations vs. Magneto-thermal simulations (power-law)

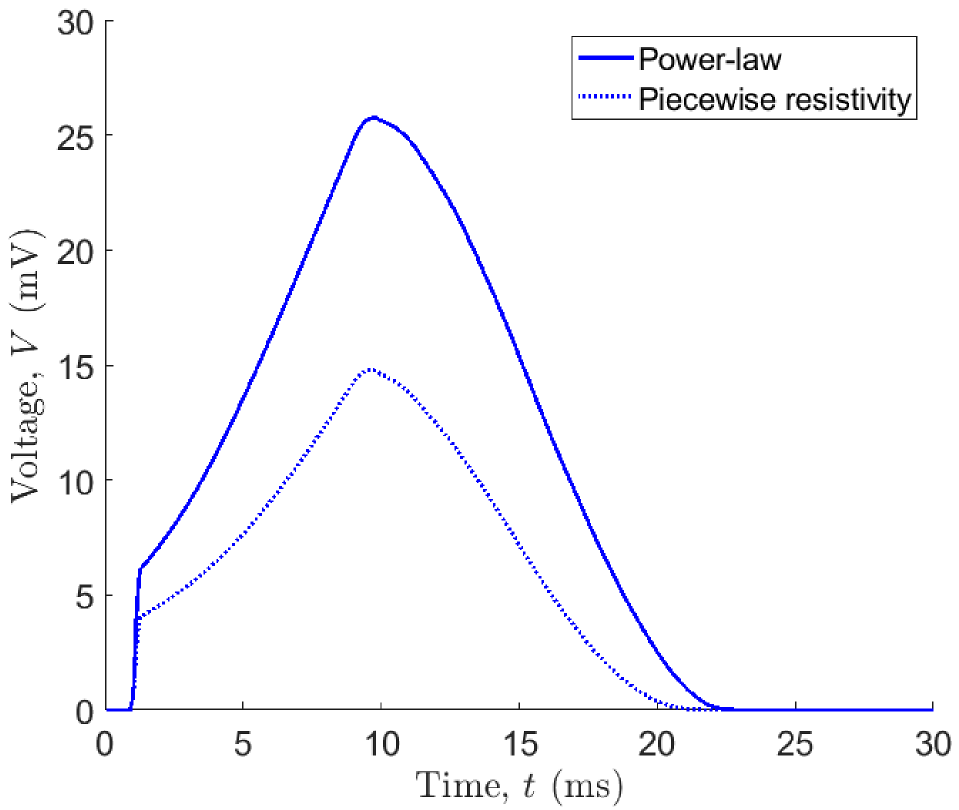


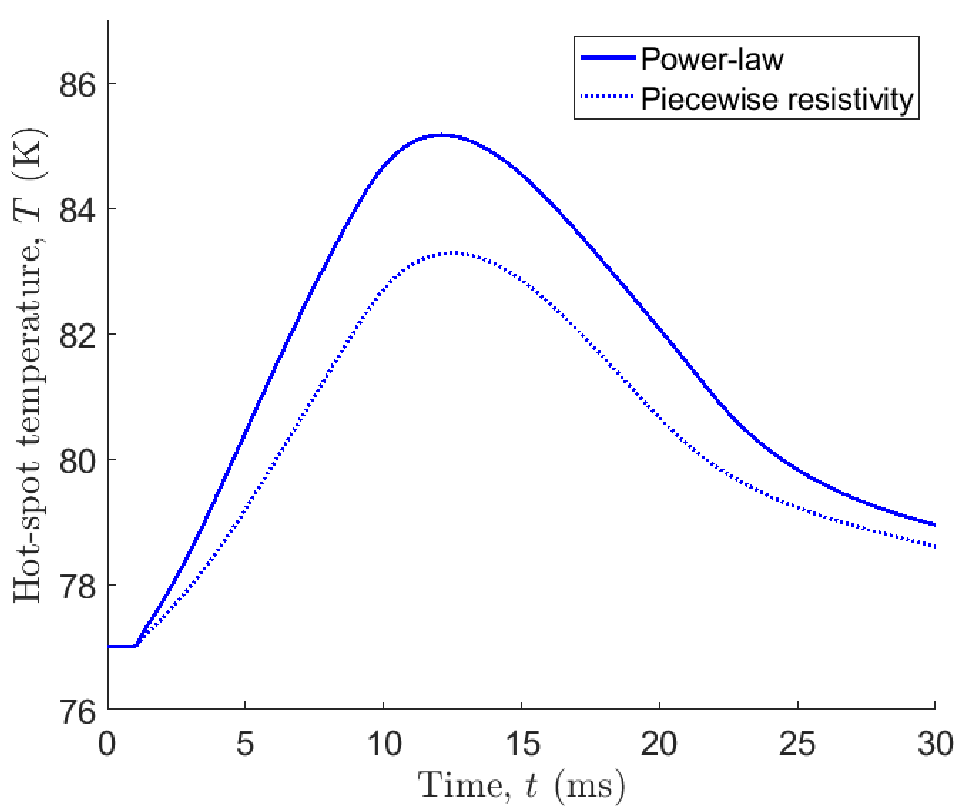


The model used has very little to no effect on the simulation for commercial tape!

Commercial tape:

Power-law vs. piecewise resistivity (magneto-thermal)



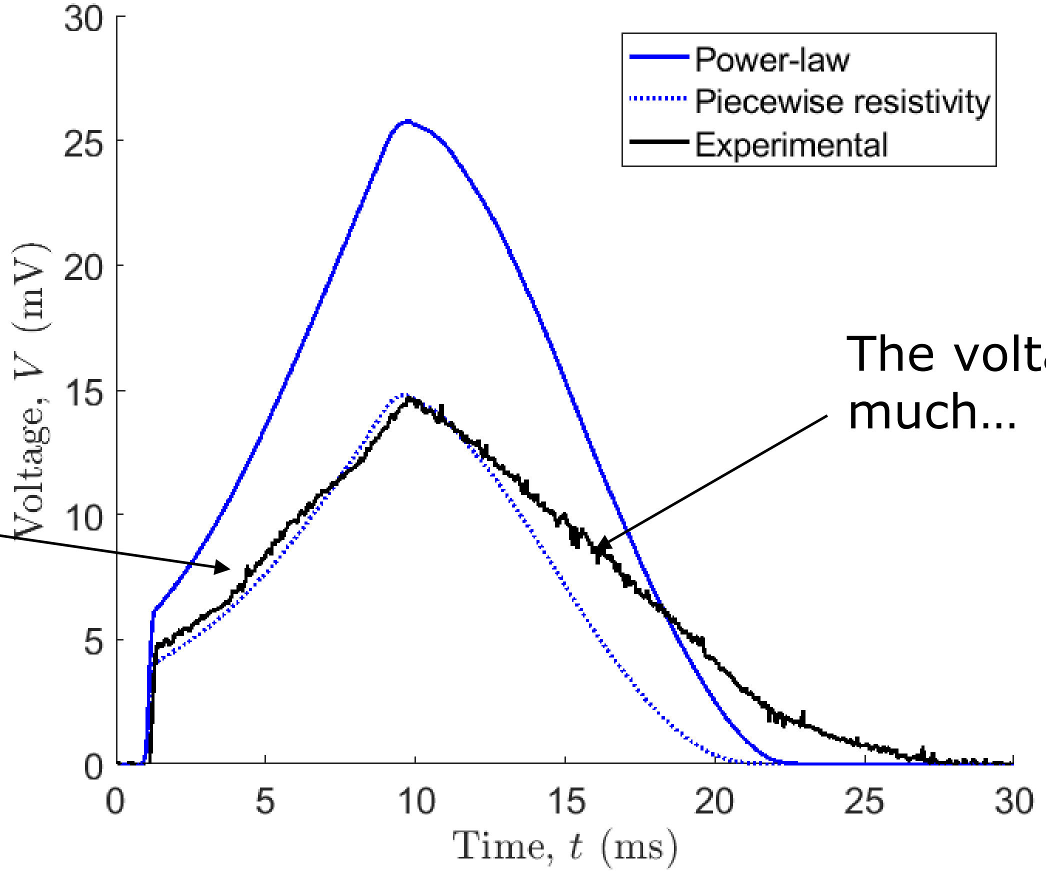


RESULTS

Commercial tape:

Comparing with experimental data

The voltage rise much better represented with the piecewise resistivity



The voltage drop, not as much…

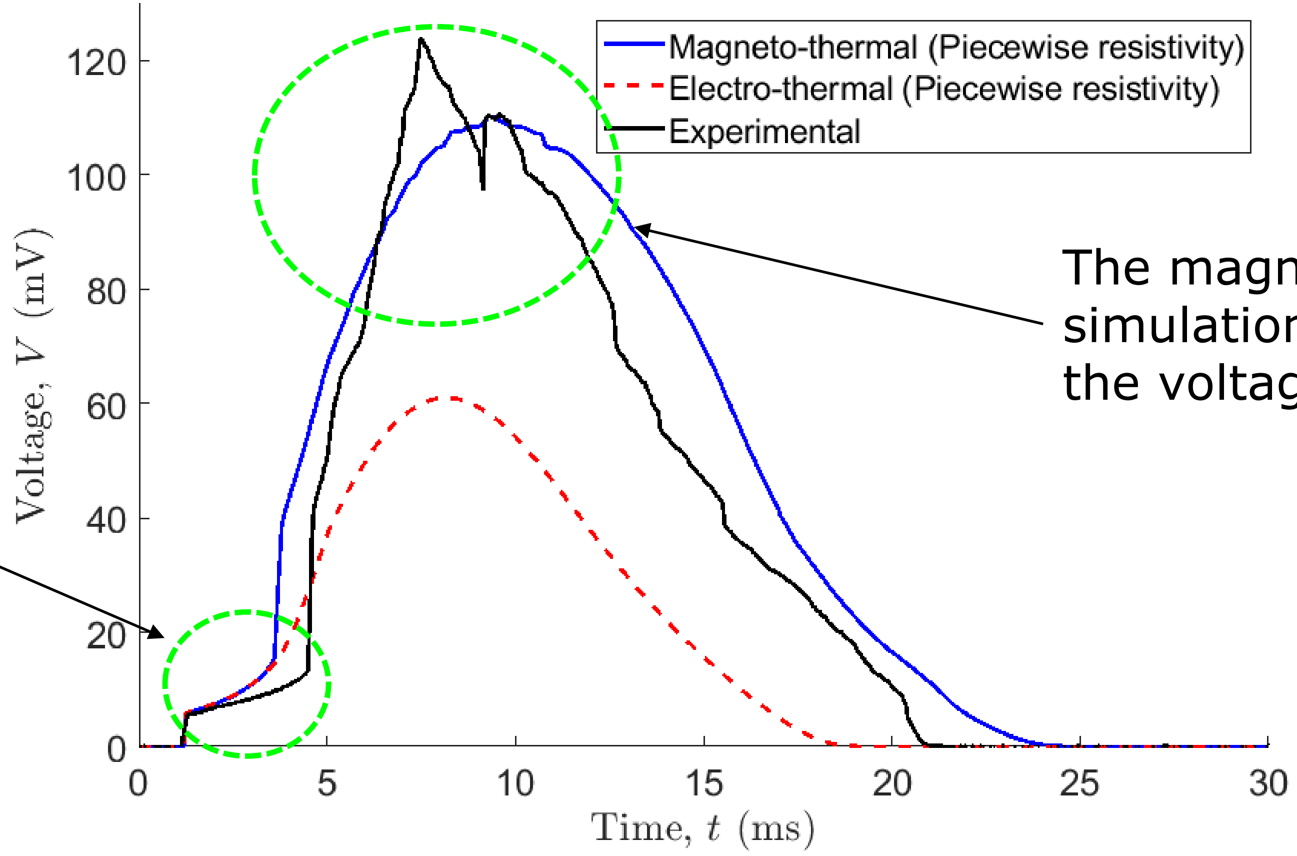
Remarks for the commercial tape

- Electro-thermal simulations are probably good enough for commercial tapes (when magnetodynamic effects are negligible)
- During the quench propagation, both models also give similar results
- Flux flow regime is important to consider in resistivity model

CFD tape:

Let's compare the electro-thermal and magneto-thermal model (piecewise resistivity)

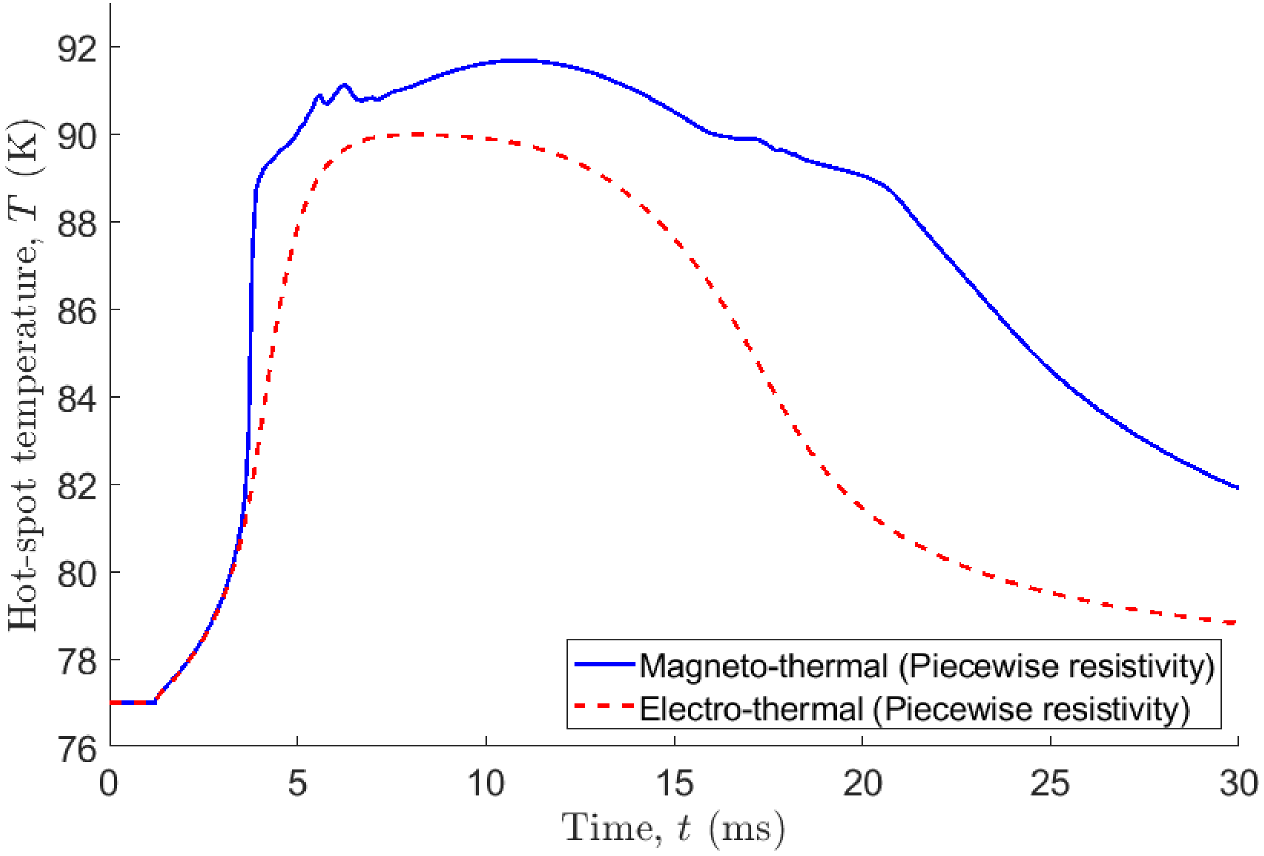
Initially, both models give very similar results



The magneto-thermal simulation better represents the voltage rise and peak

CFD tape:

And what about the temperature?



Remarks for the CFD tape

- Power-law not shown for CFD tapes, but still overshoots the voltage as expected
- The idea of CFD architecture is to count on current transfer **on the sides** of the tapes ➔ magnetodynamic effects are not negligible
- CFD simulations are prone to a lot of convergence issues!

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SUMMARY AND OUTLOOK

- Multiple simulation approaches were tested on a relatively simple 3-D benchmark

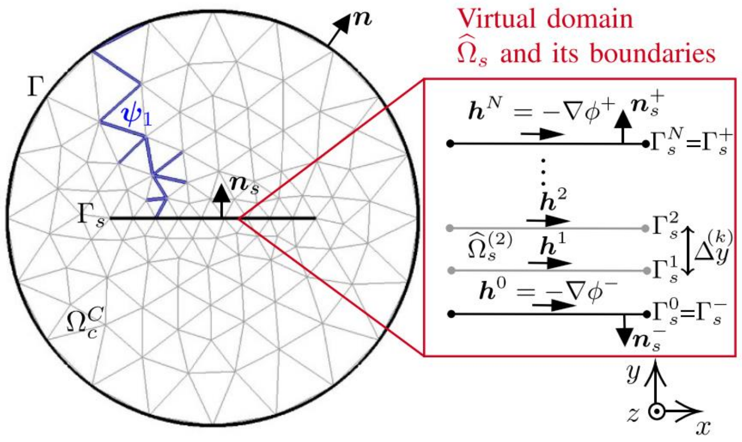
- **For commercial tapes:** V (numerically efficient) and $\mathbf{H} - \phi$ (physically accurate) formulations give almost identical results

- **For more complex tape architectures (CFD):** Electro-thermal (V) simulations are often not sufficient

- **Moreover:** We always need to be careful on the resistivity model we are using, the voltage rise in the pre-quench regime is extremely sensitive!

Next steps

- Calibrate the piecewise resistivity with measurements (this summer)
- Compute the minimum quench energy with $\mathbf{H} - \phi$
- Implement the benchmark in BELFEM



B. De Sousa Alves et al., SuST 35 (2), 024001 (2021)

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