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Exploring the limits of passive quench protection in high-stored-energy non-insulated superconducting magnets

2025 International Conference on Magnet Technology (MT29)

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025.
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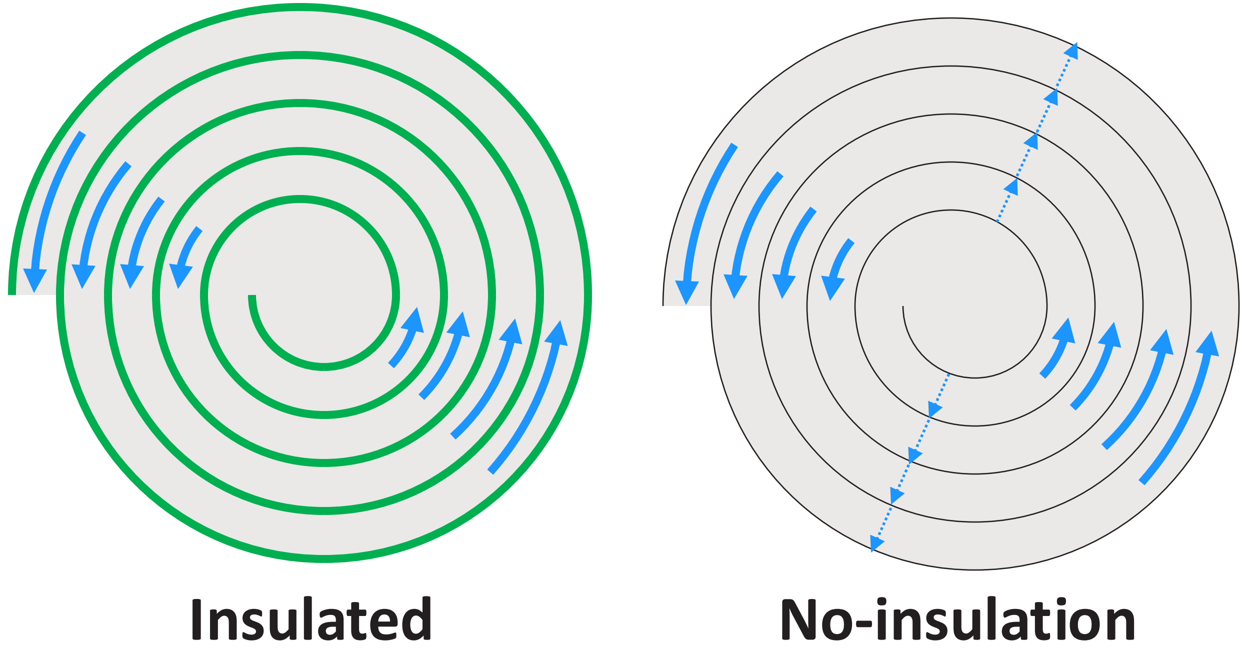
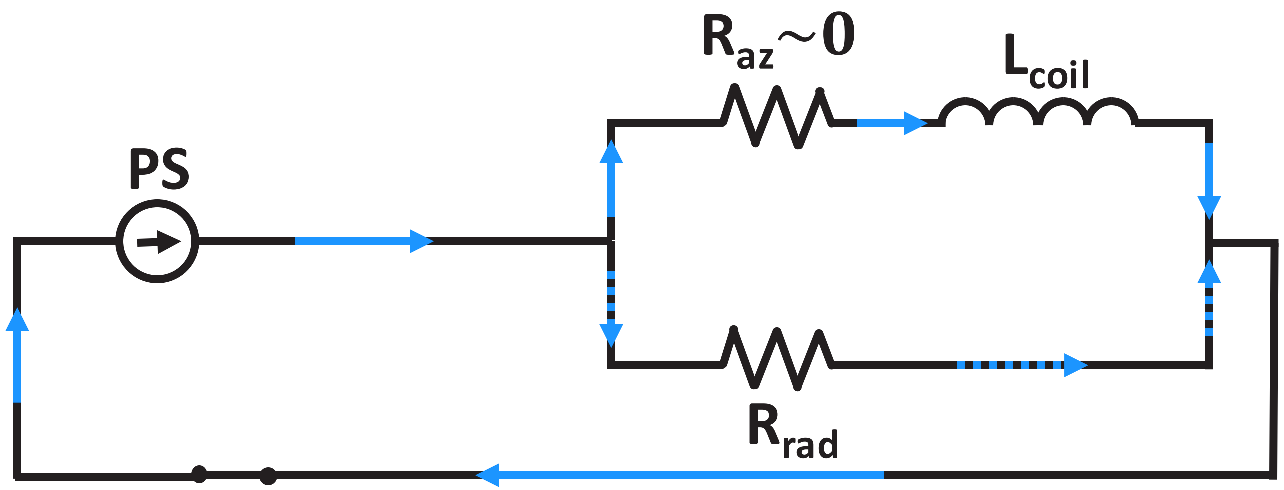
What are no-insulation coils?

- **No-insulation (NI)** coils: lack turn-to-turn insulation
  - **Metal-insulated (MI)/partially-insulated (PI)** coils: metal "insulation" between turns
- Will be using NI as catch-all term for these types of magnets
- Benefits of NI coils
  - Increased current density
  - Lower peak operating voltage
  - Simplified manufacturing
  - **Potential for passive protection against quench damage**
- This talk focuses on thermal quench damage mechanisms





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Gaps exist in understanding of NI passive quench safety

[S. Hahn et al, 2010]

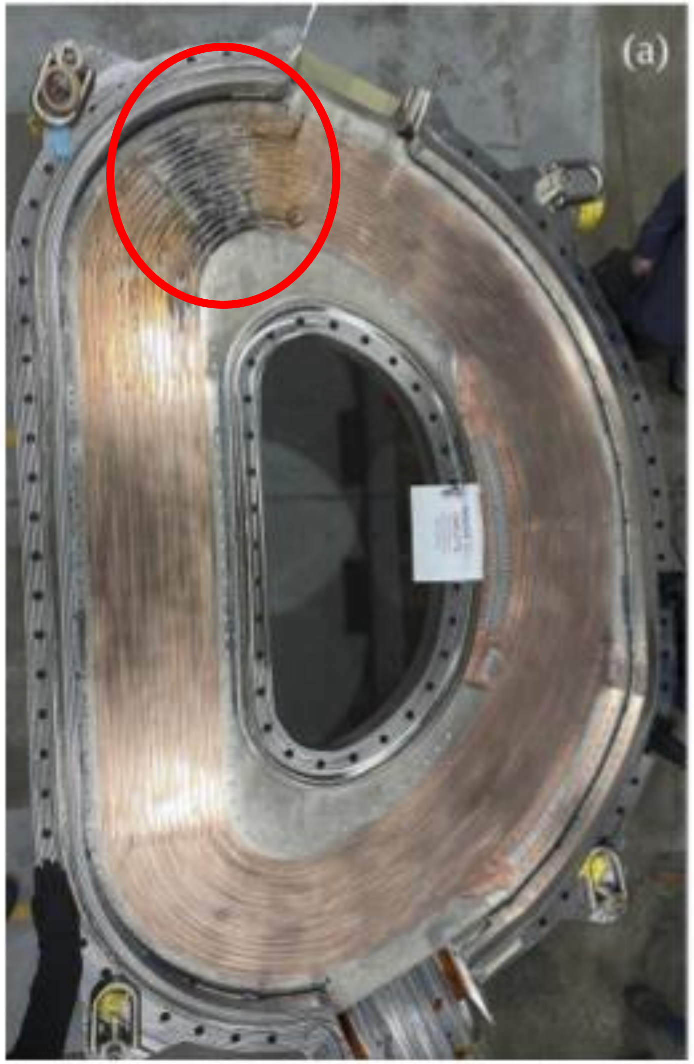
- Tape-wound coil, 2010
- Low I_{op} (100s A) & J_e
- Highly symmetric I_c
- **Passively protected**

[G. Ertl, 2021]

- SPARC TFMC, 2021
- Wound from stacks of many tapes
- High I_{op} (30kA+) & J_e
- 67MJ stored energy (quench)
- Non-symmetric I_c throughout coil
- **Not passively protected**

A closer look at TFMC quench

- TFMC was intentionally open-circuit quenched at 31.5kA
- Lower I_c, T_{cs} in the corners due to high field
  - Current surpassed I_c locally → began spreading into Cu cap
  - Local hotspot formed
- Race between hotspot feedback loop and global energy dump
- Hotspot won: burn occurred before energy was dumped



[Z. Hartwig et al, 2024]

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How do we ensure NI coils are passively quench-safe?

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[S. Hahn et al, 2010]

- Tape-wound coil, 2010
- Low I_{op} (100s A) & J_e
- Highly symmetric I_c
- **Passively protected**

Need to understand design and operating conditions that enable passive quench protection in NI coils

Large-scale magnet experiments are resource-intensive

Need fast & accurate quench models

[G. Ertl, 2021]

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- High I_{op} (30kA+) & J_e
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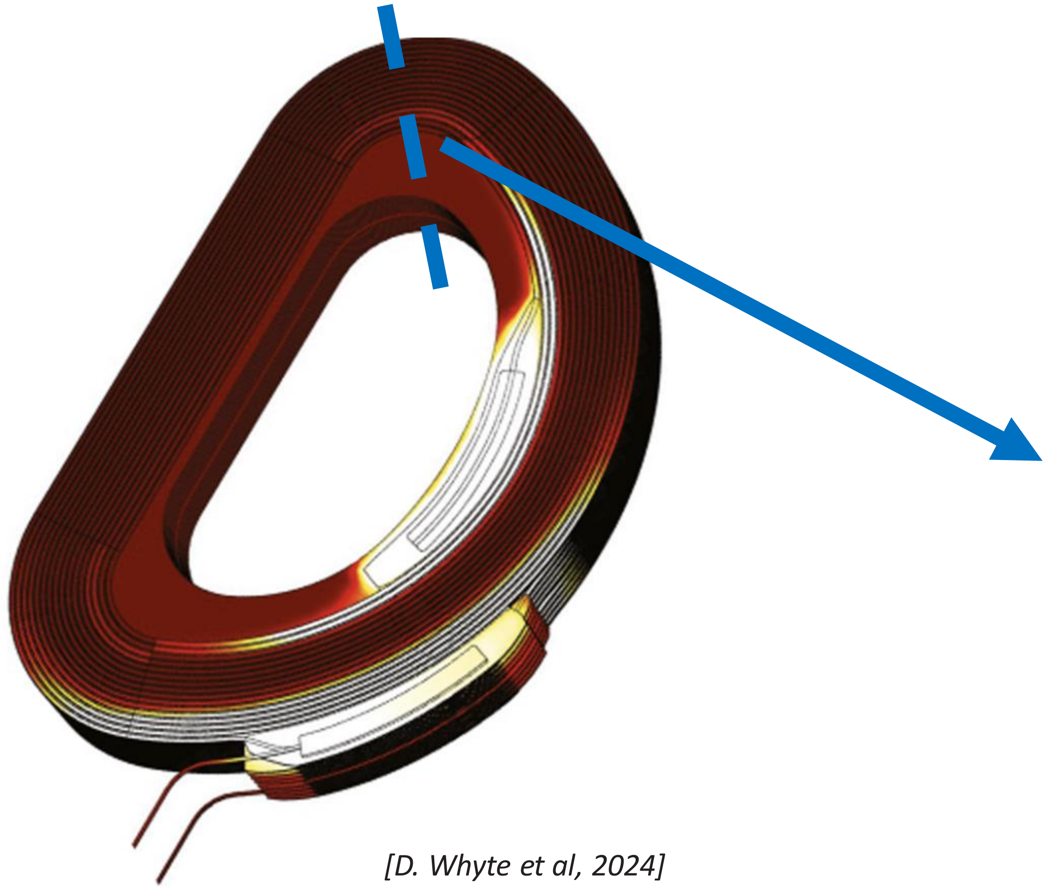
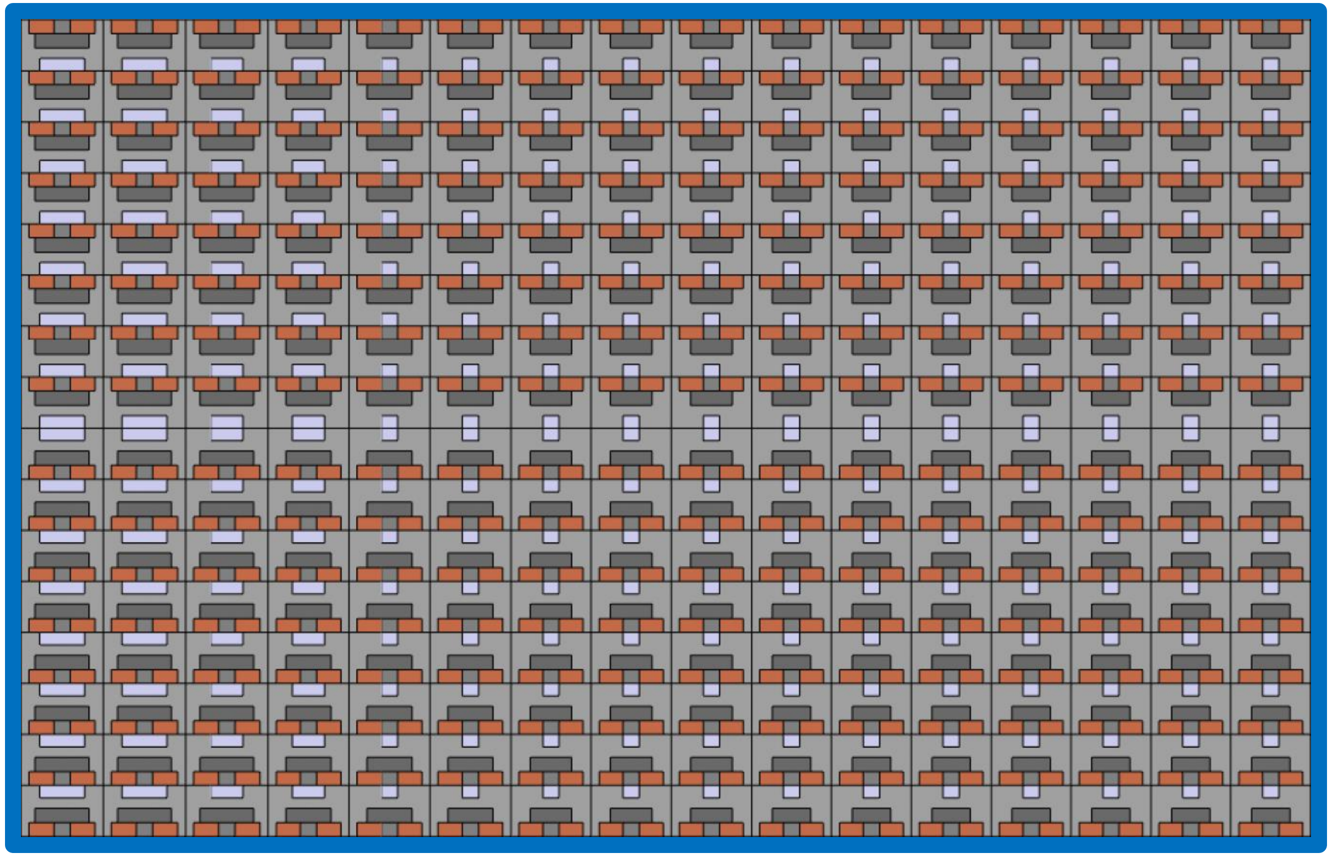
Modeling in 3D vs 2D

3D Spiral Model

2D Axisymmetric Model



[D. Whyte et al, 2024]



O(10M) Degrees of Freedom (DoF) →

Very high-fidelity, too slow for parameter space exploration

O(100K) DoF →

Well-suited for rapid iteration & exploration

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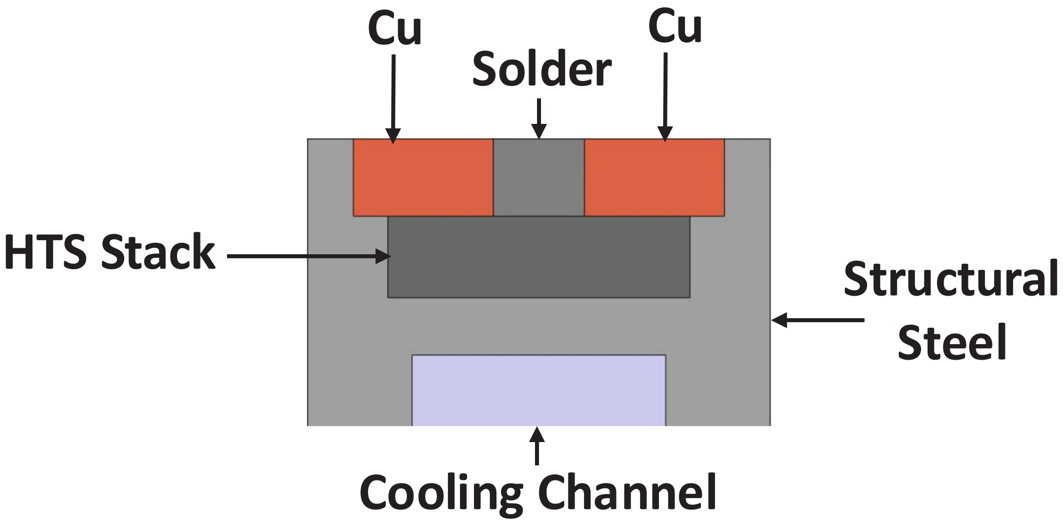
Model utilizes HTS tape homogenization

- Maintained individual unit cell materials, but homogenized tapes
  - E-J power law for REBCO, n = 20
  - Parallel, resistive current paths included



$$C_p^{tape} = f_{Cu} C_p^{Cu}(T) + f_{Ha} C_p^{Ha}(T)$$

$$k_{tape} = f_{Cu} k_{Cu}(T) + f_{Ha} k_{Ha}(T)$$

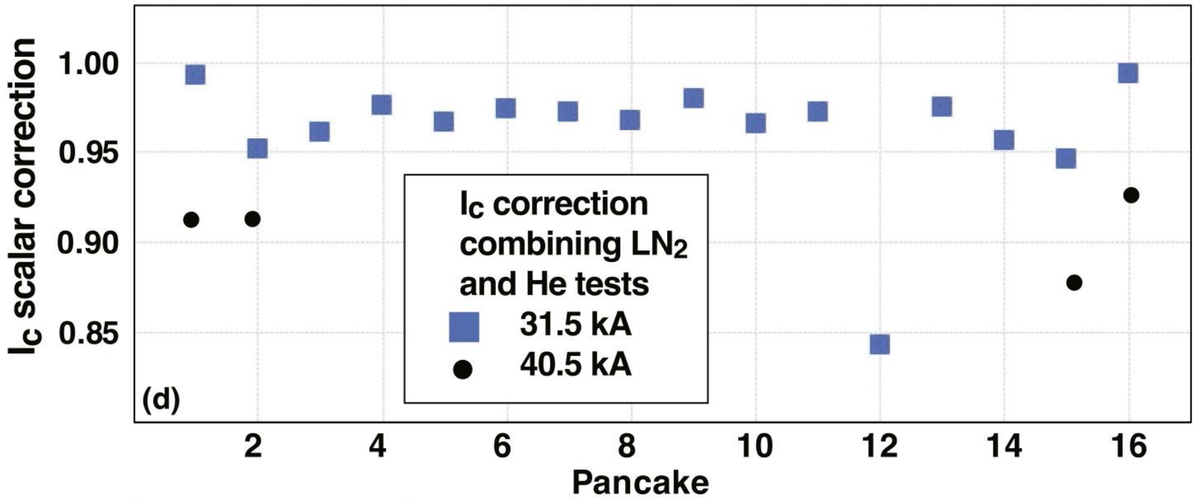
$$\rho_{tape} = \left(\frac{1}{\underset{\uparrow}{\rho_{sc}}} + \frac{f_{Cu}}{\rho_{Cu}} + \frac{f_{Ha}}{\rho_{Ha}} \right)^{-1}$$

$$\rho_{sc} = \left(\frac{E_c}{J_e} \right) \left(\frac{J}{J_e} \right)^{n-1}$$

D. Korsun et al, IEEE Trans. Appl. Supercond., vol. 35, no. 5, August 2025

Model utilizes HTS tape homogenization

- Maintained individual unit cell materials, but homogenized tapes
  - E-J power law for REBCO, n = 20
  - Parallel, resistive current paths included
- $J_e(B,T,\Theta)$ from empirical tape data
  - Not exact match for data used in TFMC
  - Includes measured pancake-by-pancake I_c correction factors



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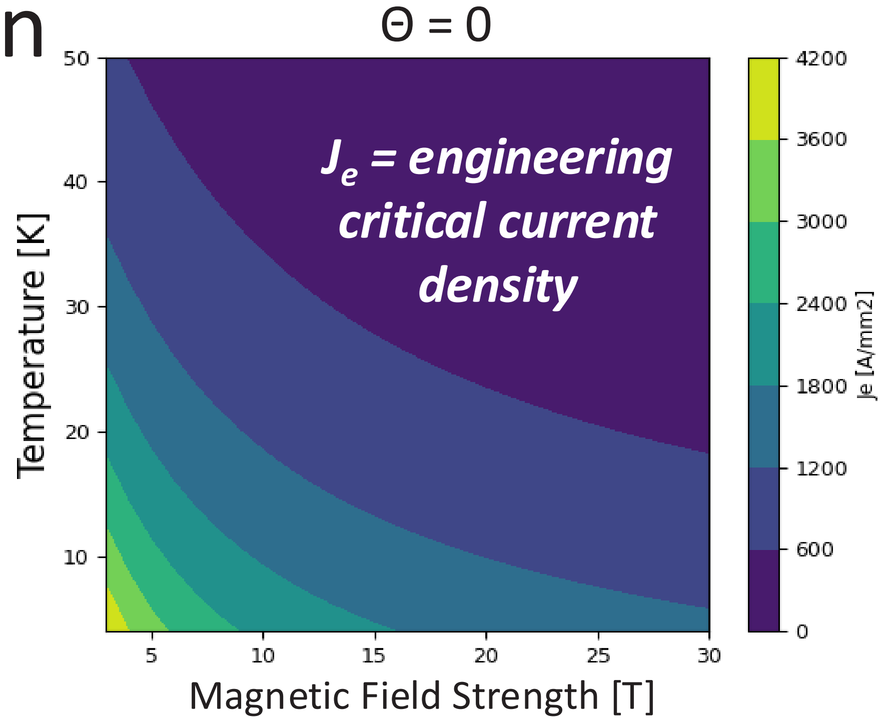
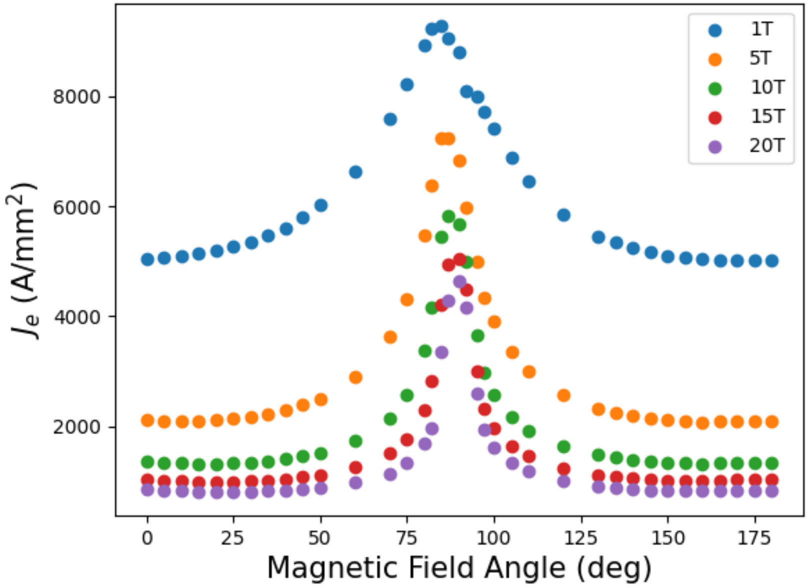


J_e = engineering critical current density



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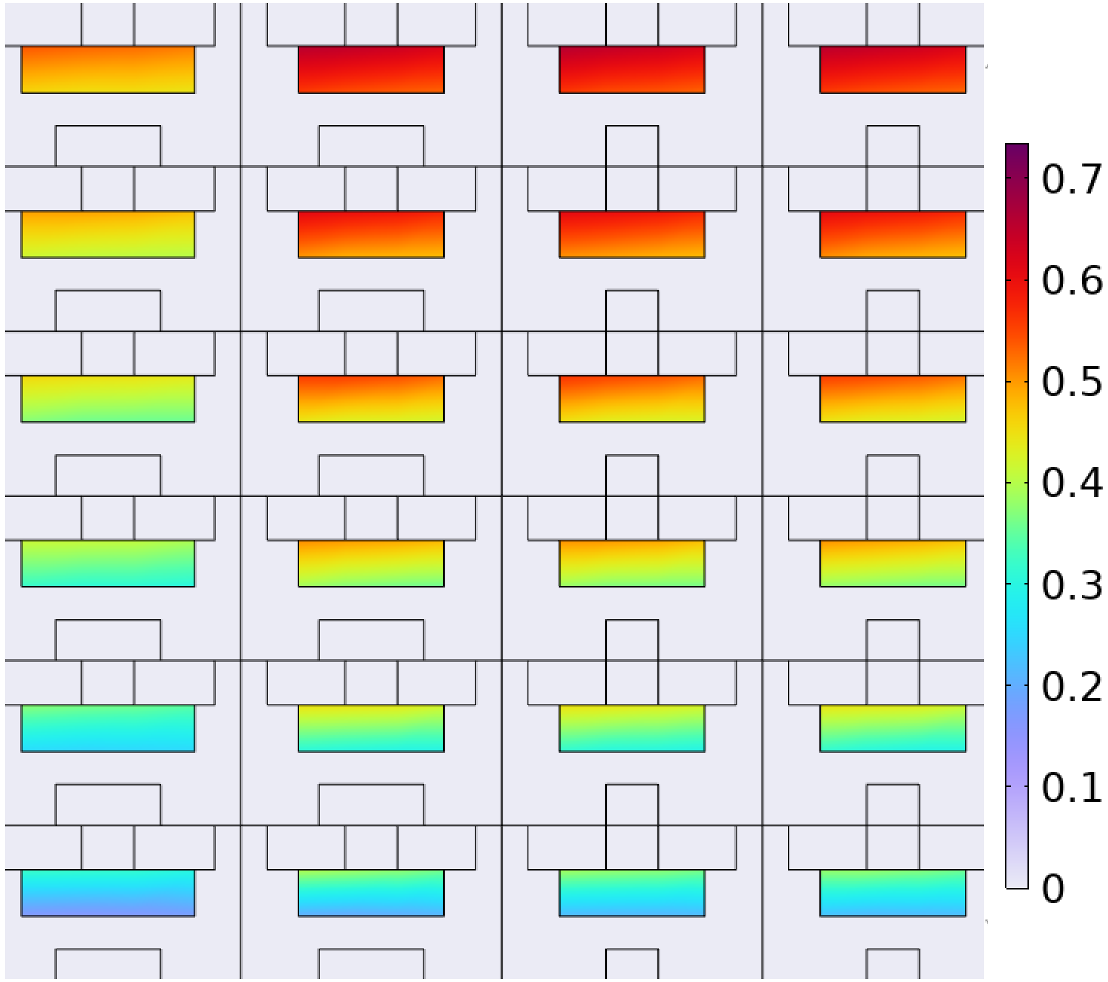
  - E-J power law for REBCO, n = 20
  - Parallel, resistive current paths included
- $J_e(B,T,\Theta)$ from empirical tape data
  - Not exact match for data used in TFMC
  - Includes measured pancake-by-pancake I_c correction factors
- T- and B-dependent properties for other materials
- **All properties calculated pointwise**

Local J/J_c



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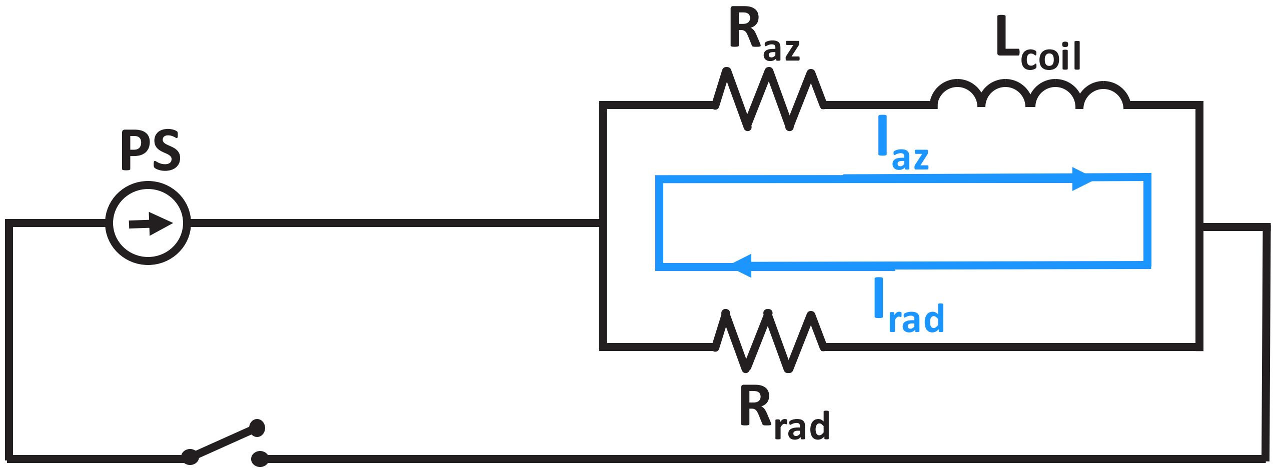
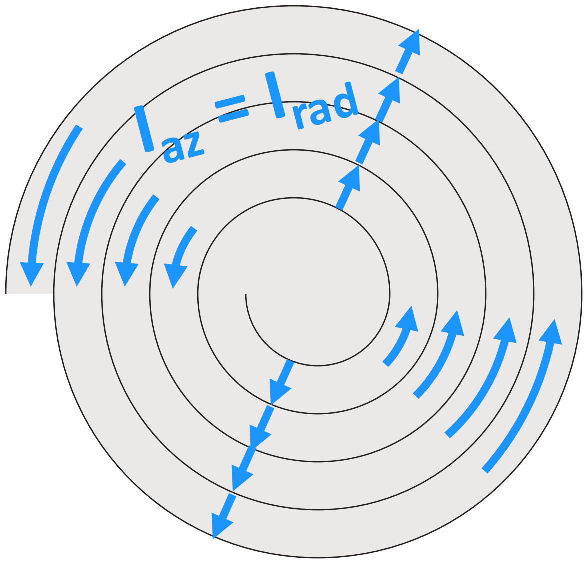
Radial current flow initiates quench

- Open-circuit quench forces entire stored energy to dump into coil
- Radial current flow arises to close loop: $I_{az} = I_{rad}$
  - Eventually causes avalanche quench
  - Does not naturally occur in 2D





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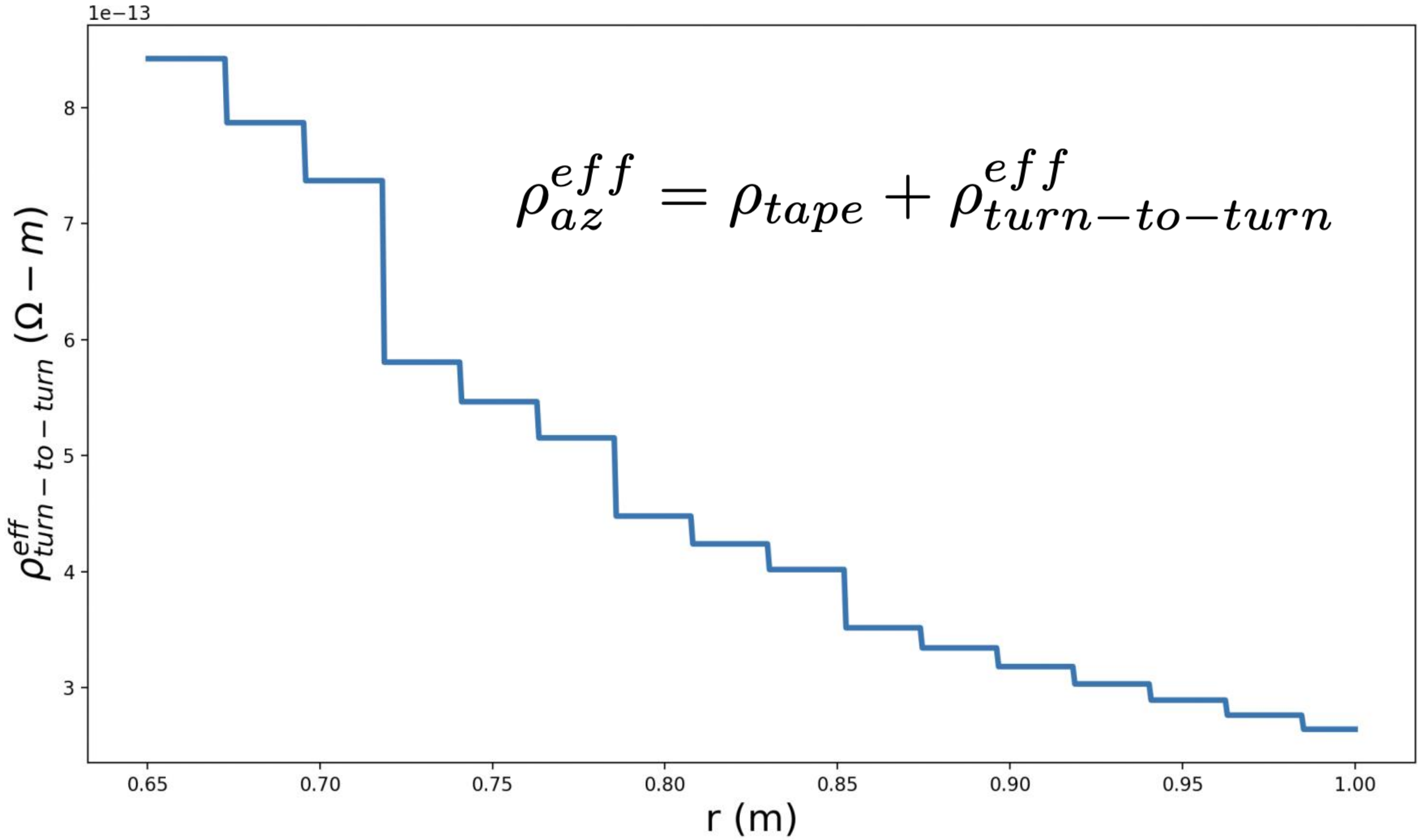
- Radial current flow arises to close loop: $I_{az} = I_{rad}$
  - Eventually causes avalanche quench
  - Does not naturally occur in 2D
- Solution: effective turn-to-turn resistivity added in series to azimuthal path
  - Resolved turn-by-turn

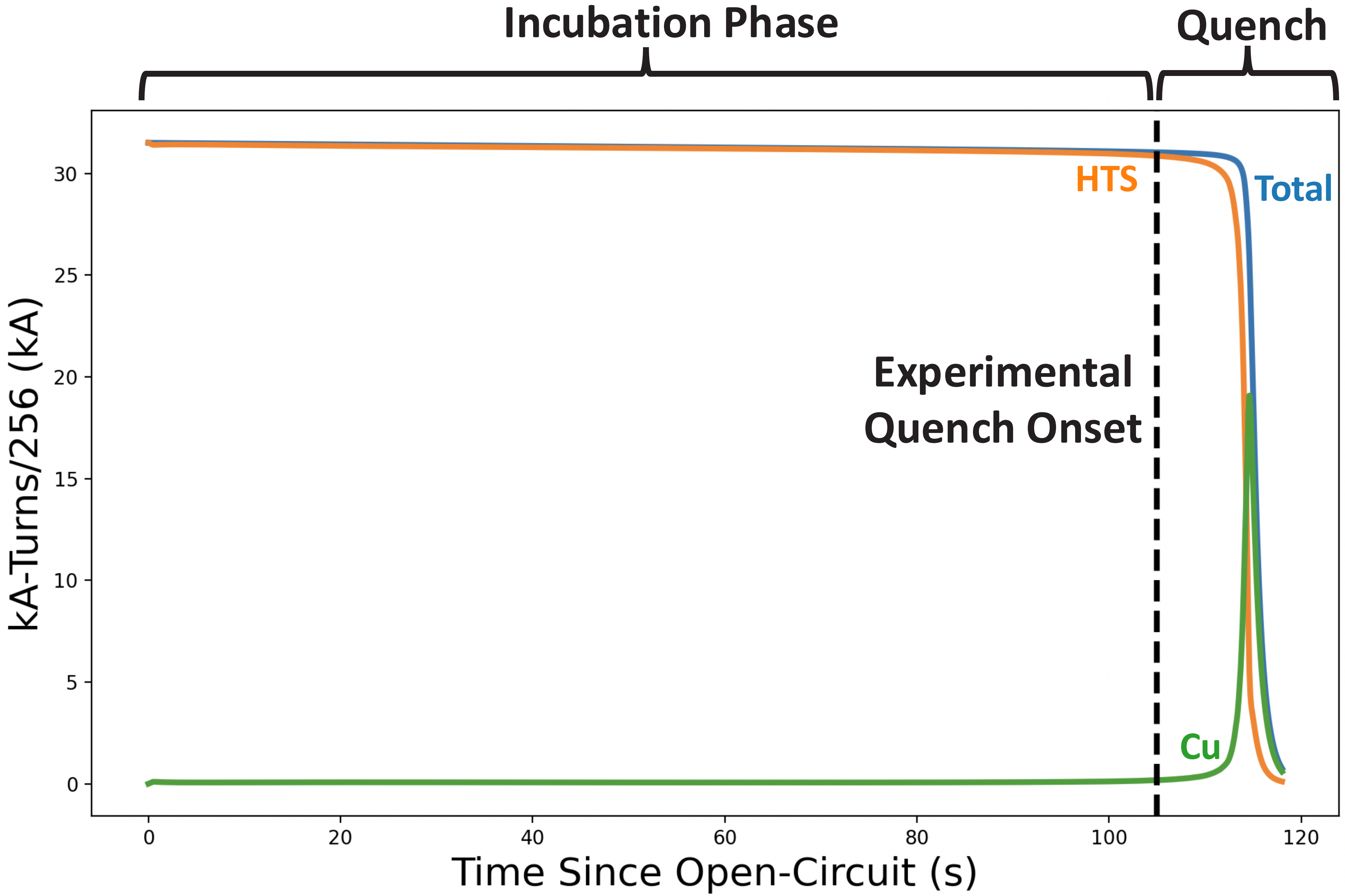


$$\rho^{eff}_{az} = \rho_{tape} + \rho^{eff}_{turn-to-turn}$$

$$\boldsymbol{\rho_{stack}} = \begin{bmatrix} \rho_{tape} & 0 & 0 \\ 0 & \rho^{eff}_{az} & 0 \\ 0 & 0 & \rho_{tape} \end{bmatrix}$$

D. Korsun et al, IEEE Trans. Appl. Supercond., vol. 35, no. 5, August 2025

2D model replicates timing of quench onset



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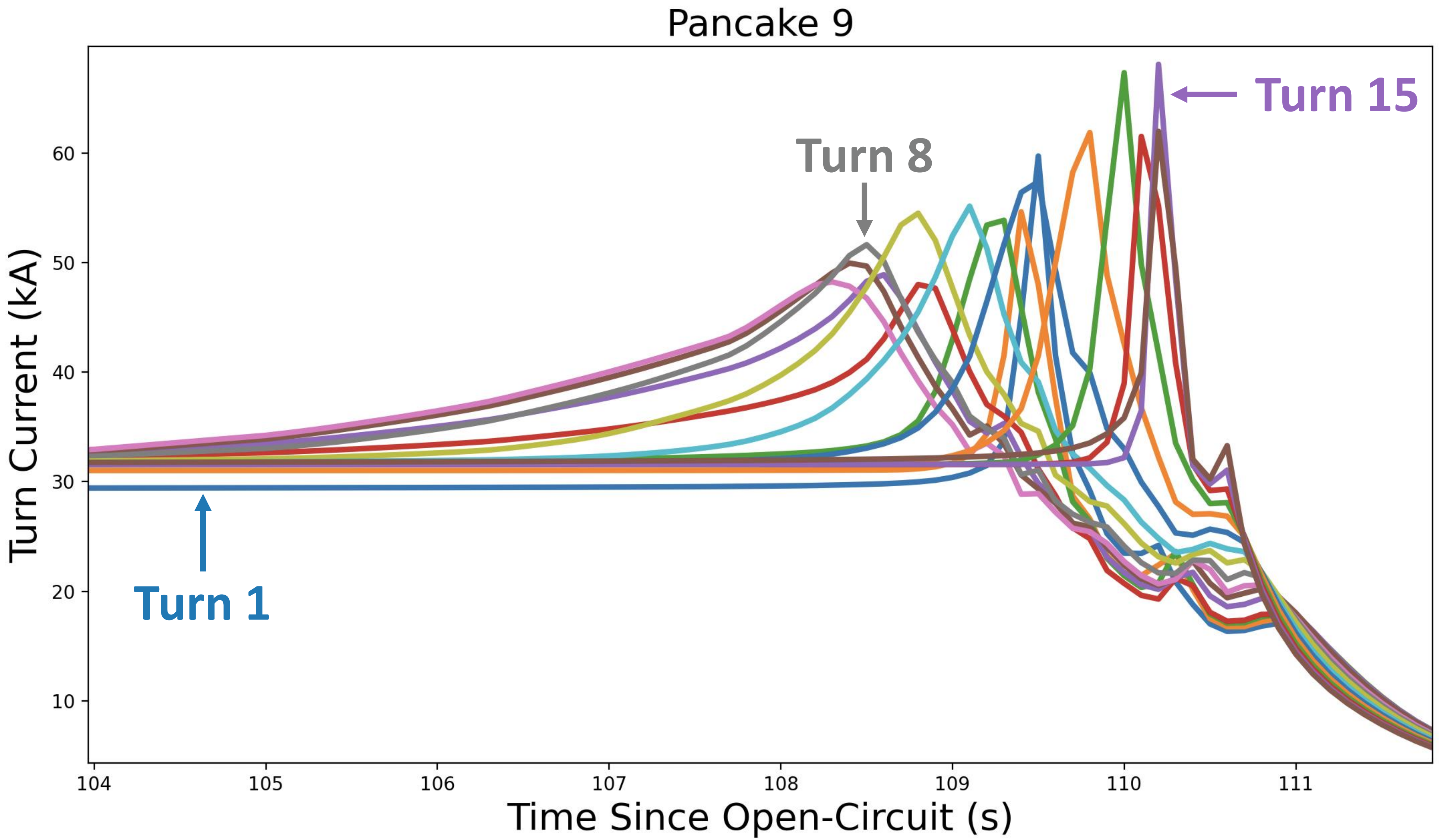
2D model reproduces characteristic avalanche quench



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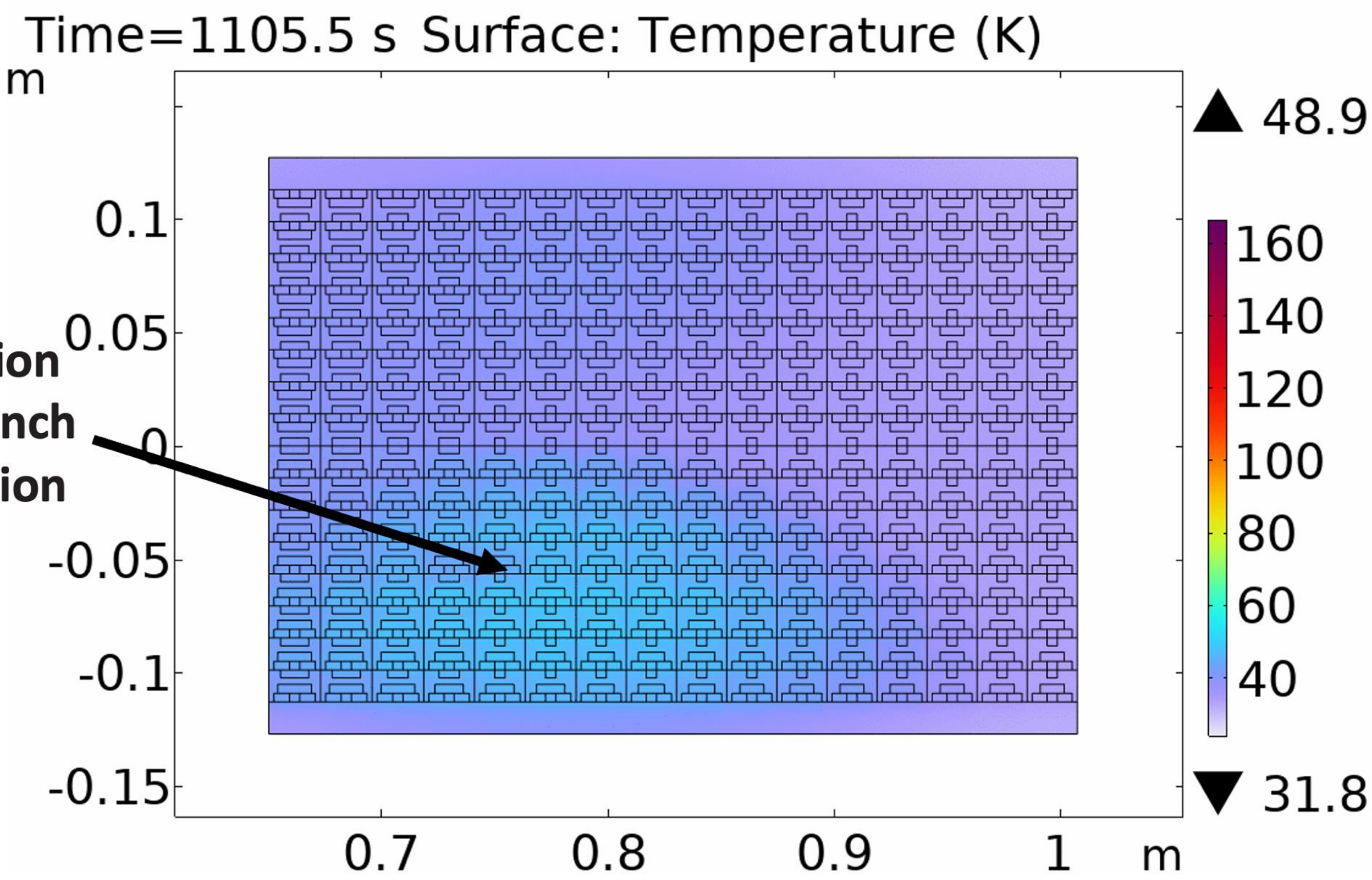
Starting location of quench front matches experiment



Location of quench initiation

- Full quench runs in ~12hrs on 8 cores
- Significantly **underpredicts** TFMC peak temperature (>1000K)

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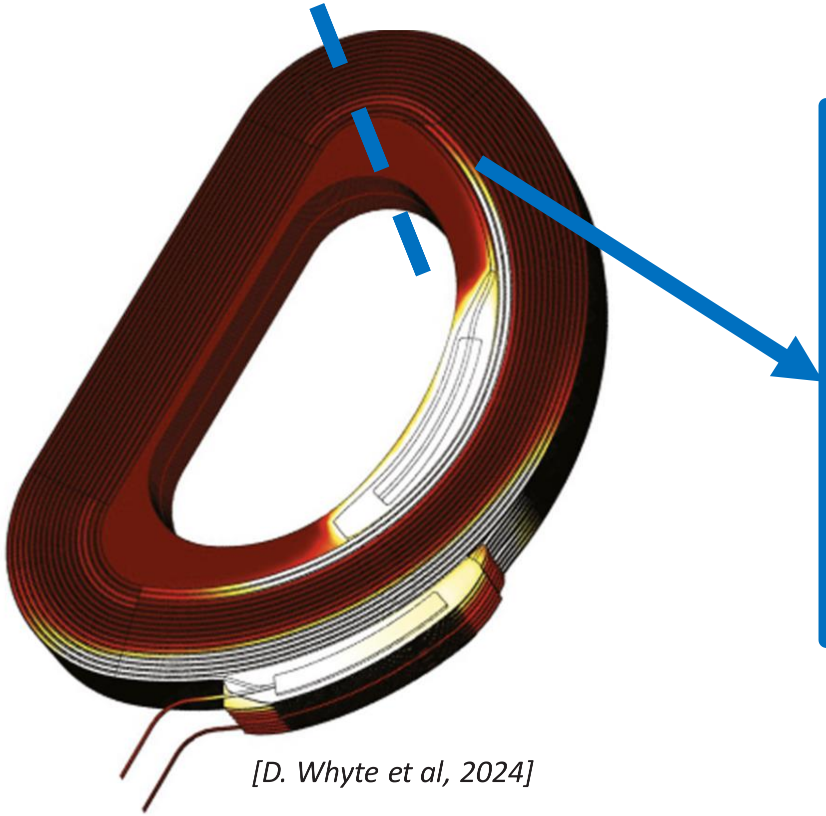
What does this tell us?

- TFMC would likely have survived quench if energy had been deposited (roughly) azimuthally uniformly
- Stored energy and stored energy density matter on a global scale
  - Need enough thermal mass to absorb stored energy
- But having enough mass to take stored energy isn’t enough in non-axisymmetric coils – necessary, but not sufficient
  - In this case: need coil to dump globally faster than local hotspot can burn
- **2D models not suitable for mapping thermal passively-safe quench space of non-axisymmetric coils**
  - **Need azimuthal resolution to allow for hotspot formation**

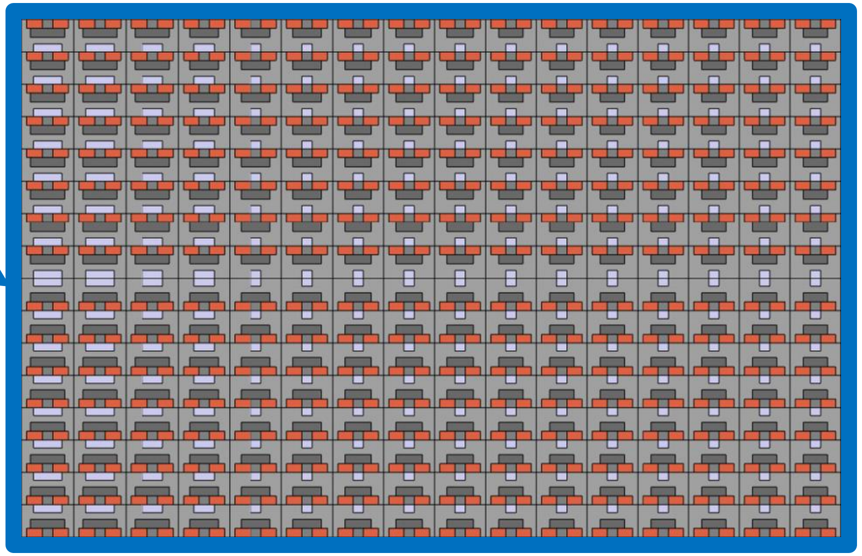
Neither 3D nor 2D models suited for rapid iteration

3D Spiral Model:
O(10M) DoF per TF coil



[D. Whyte et al, 2024]

2D Axisymmetric Model:
O(100K) DoF per TF coil



High-fidelity, but too slow

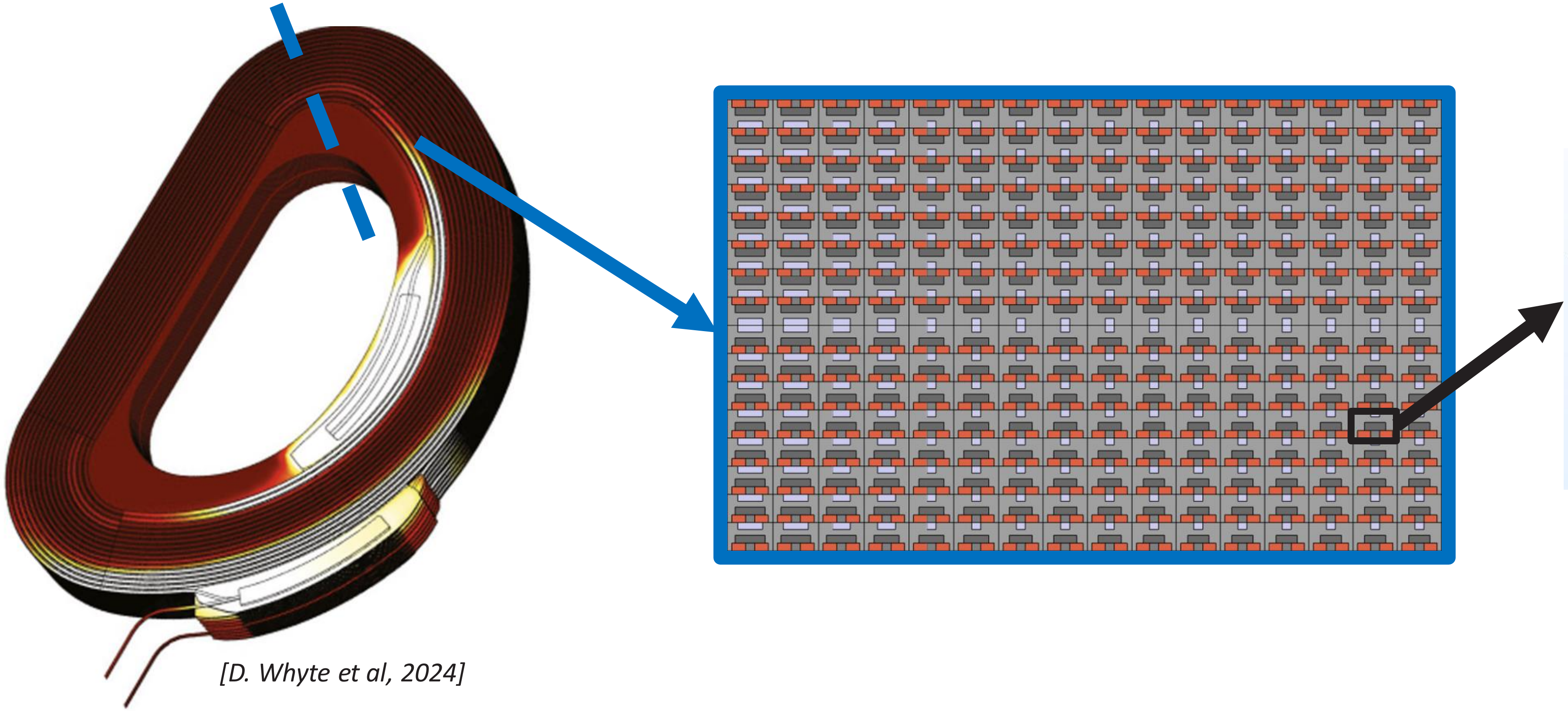
Very fast, but lacks azimuthal resolution

What if you modeled individual turns?

3D Spiral Model:
O(10M) DoF per TF coil

2D Axisymmetric Model:
O(100K) DoF per TF coil

3D Turn Model:
O(10K) DoF per turn


[D. Whyte et al, 2024]

High-fidelity, but too slow

Very fast, but lacks azimuthal resolution

Accounts for hotspot formation, but missing global physics

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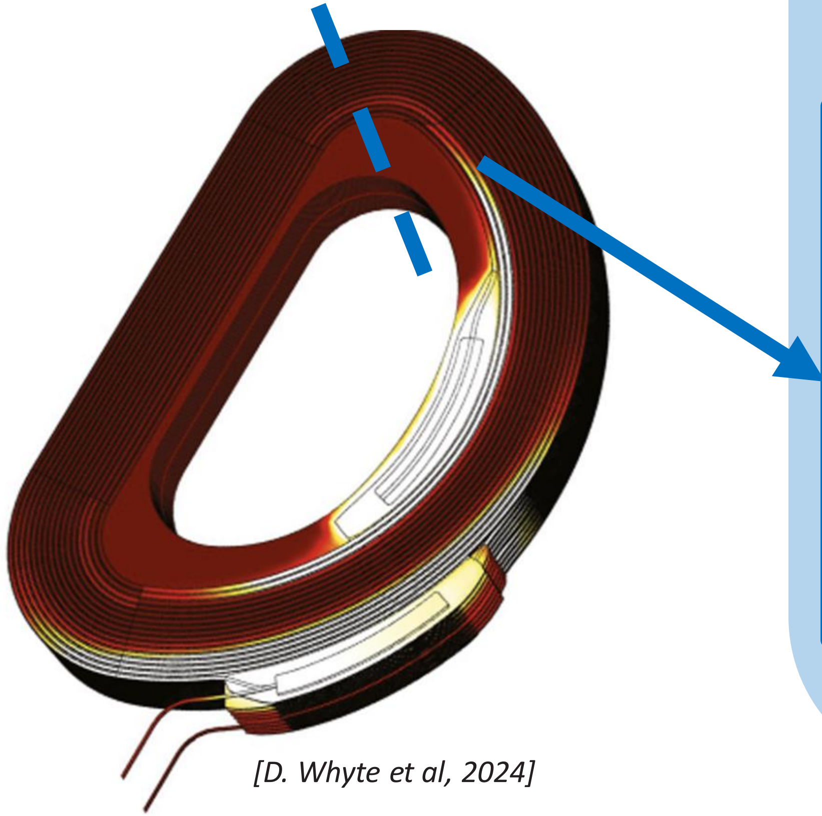
What if you modeled individual turns?

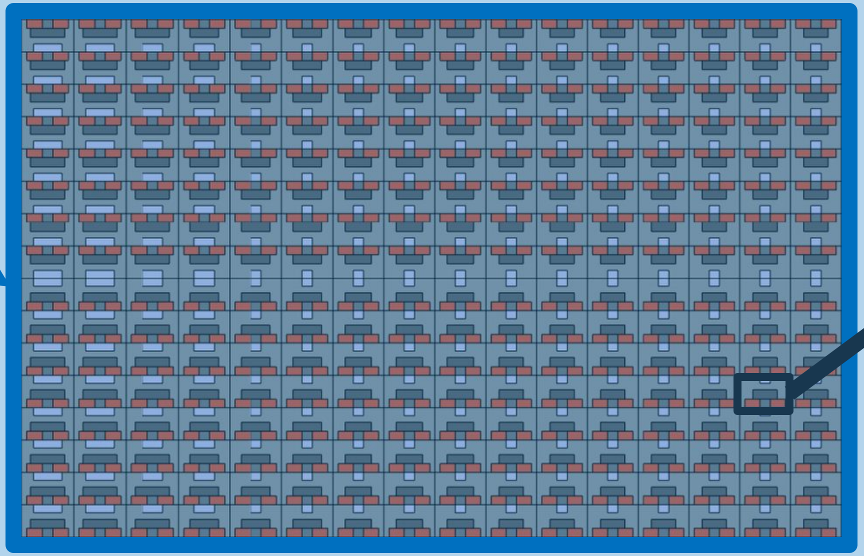
3D Spiral Model:
O(10M) DoF per TF coil



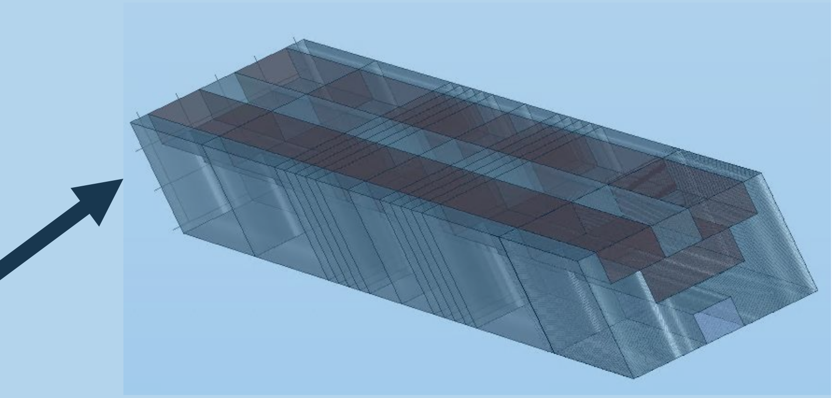
[D. Whyte et al, 2024]

High-fidelity, but too slow

2D Axisymmetric Model:
O(100K) DoF per TF coil



3D Turn Model:
O(10K) DoF per turn



2.5D non-axisymmetric quench model:

fast, accurate global physics, allows hotspot formation

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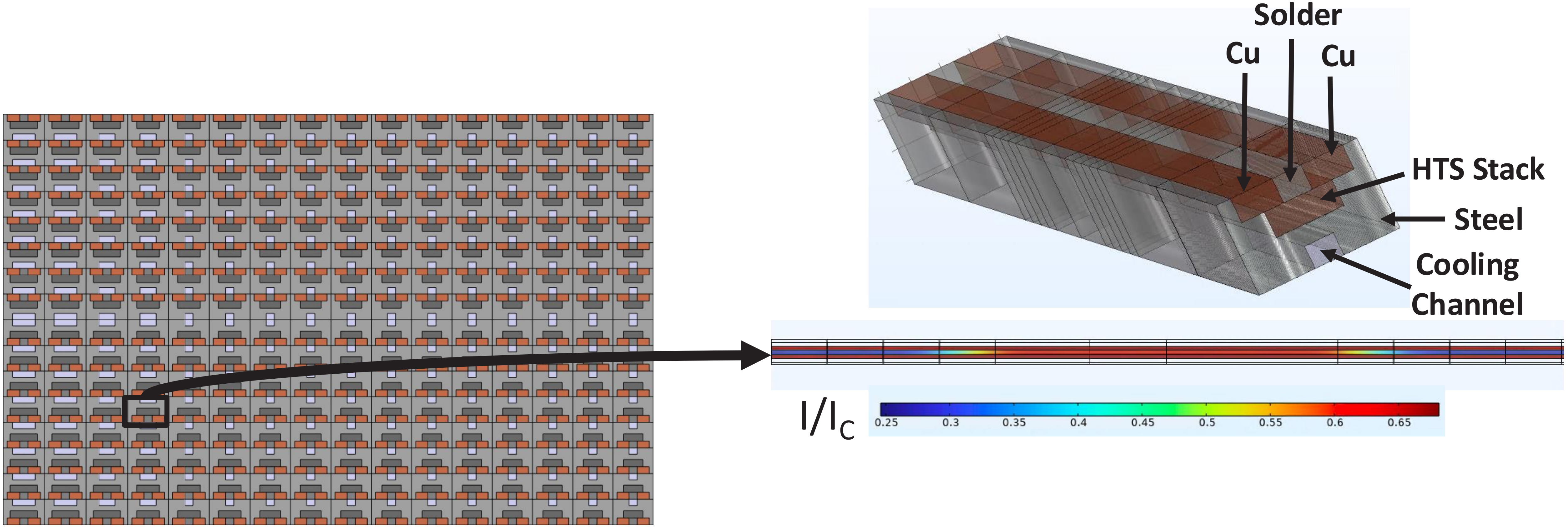
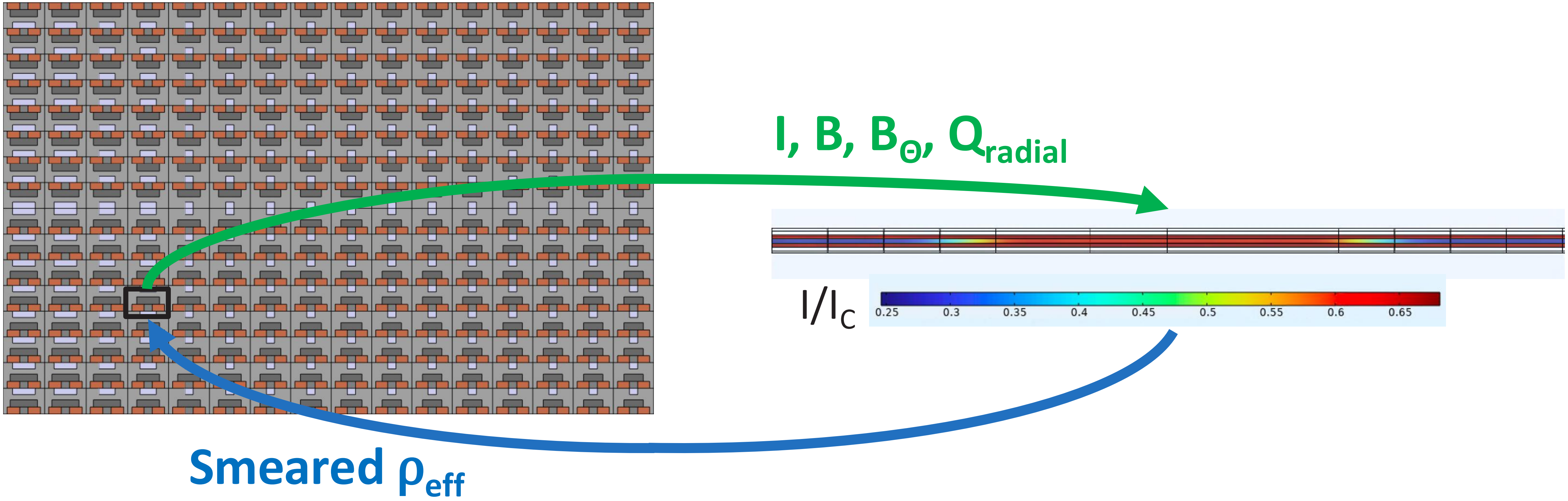
Model a single turn in 3D geometry



2D and 3D components solved together during quench

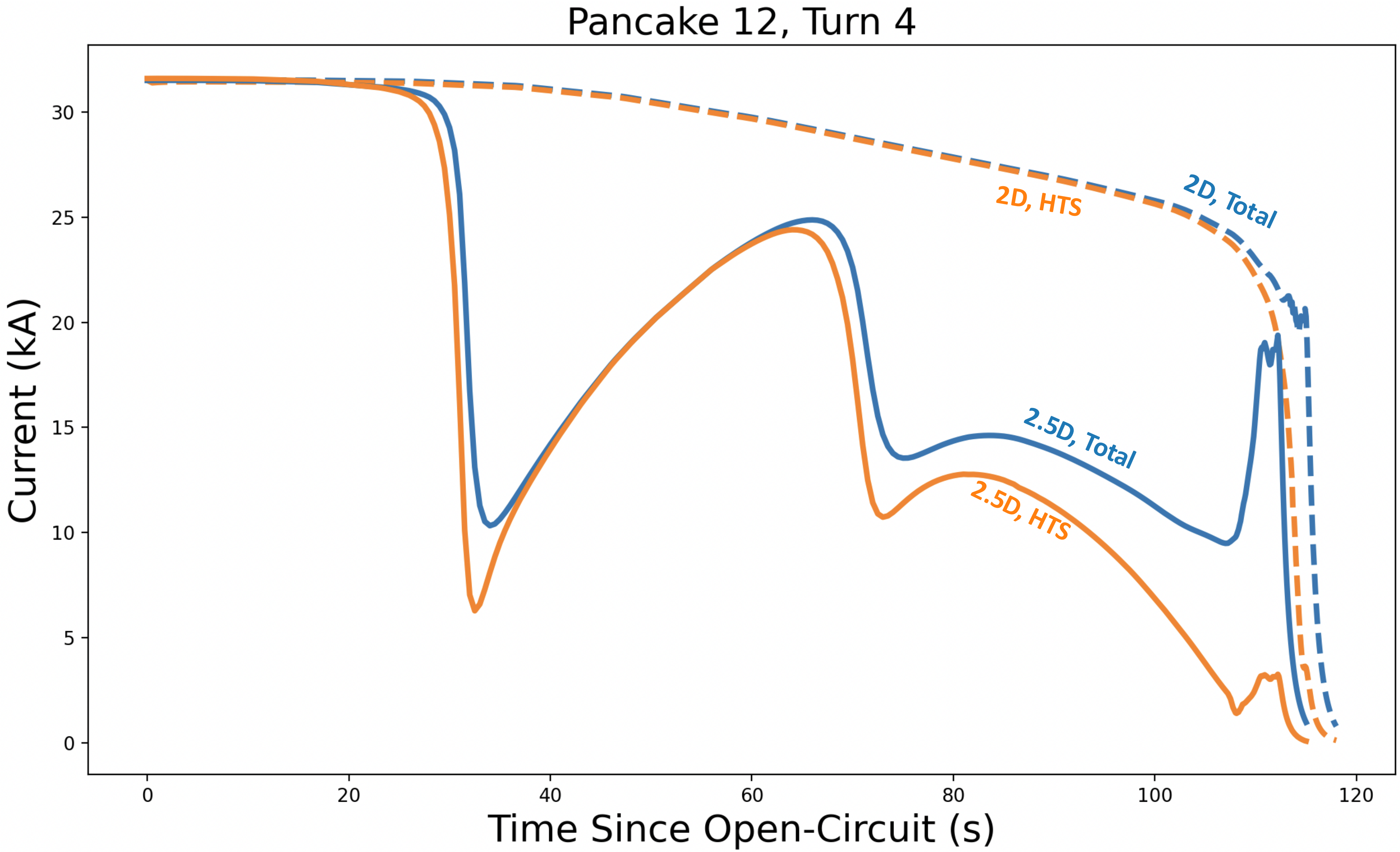
- Global quench evolves in 2D axisymmetric model
- Computed ρ_{eff} allows 2D model to “see” hotspot for self-consistent quench evolution



I, B, B_{Θ}, Q_{radial}

Smeared ρ_{eff}

Quench impacted by hotspot formation, as expected



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Adjacent turns pick up current to conserve flux

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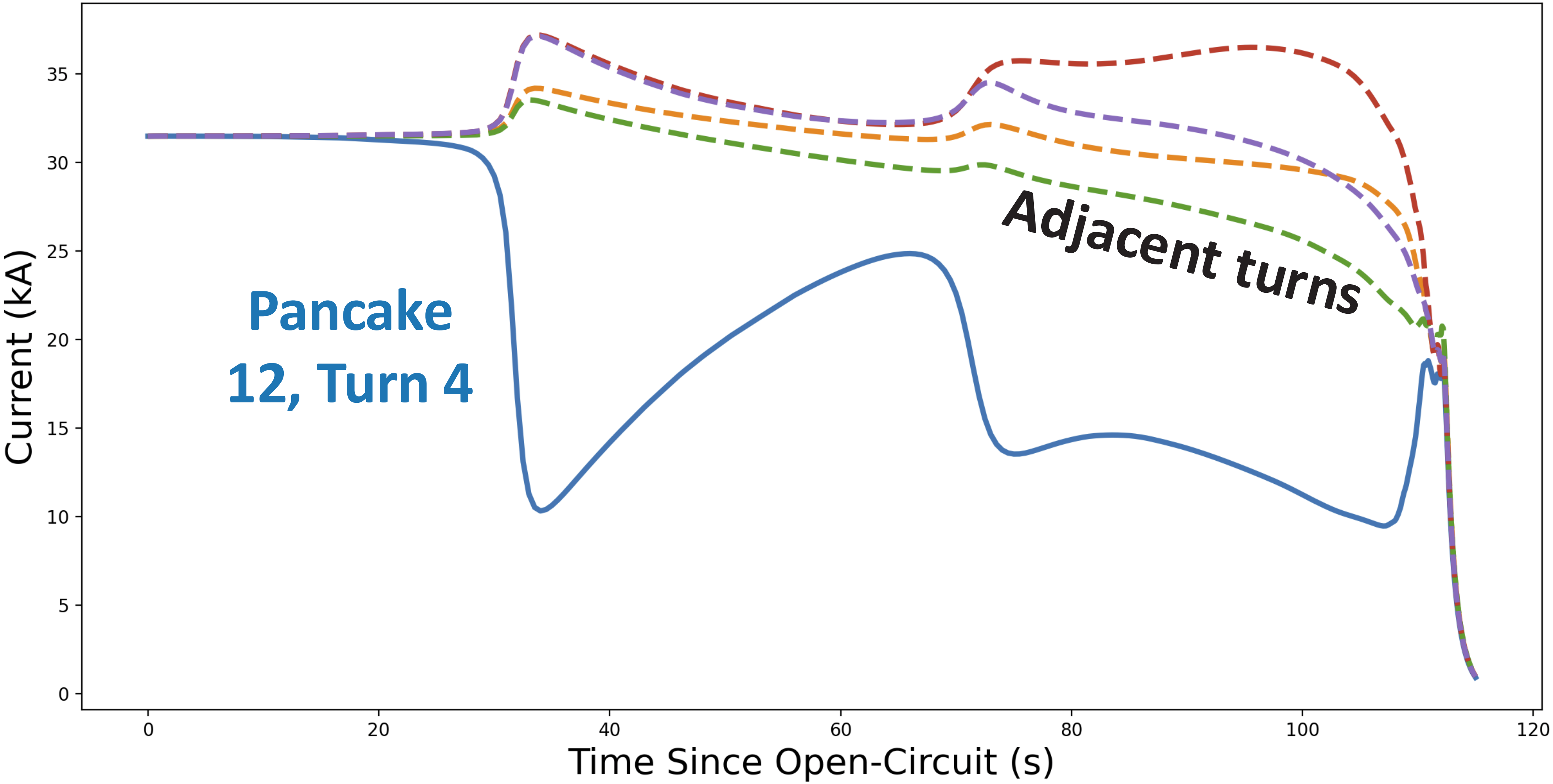

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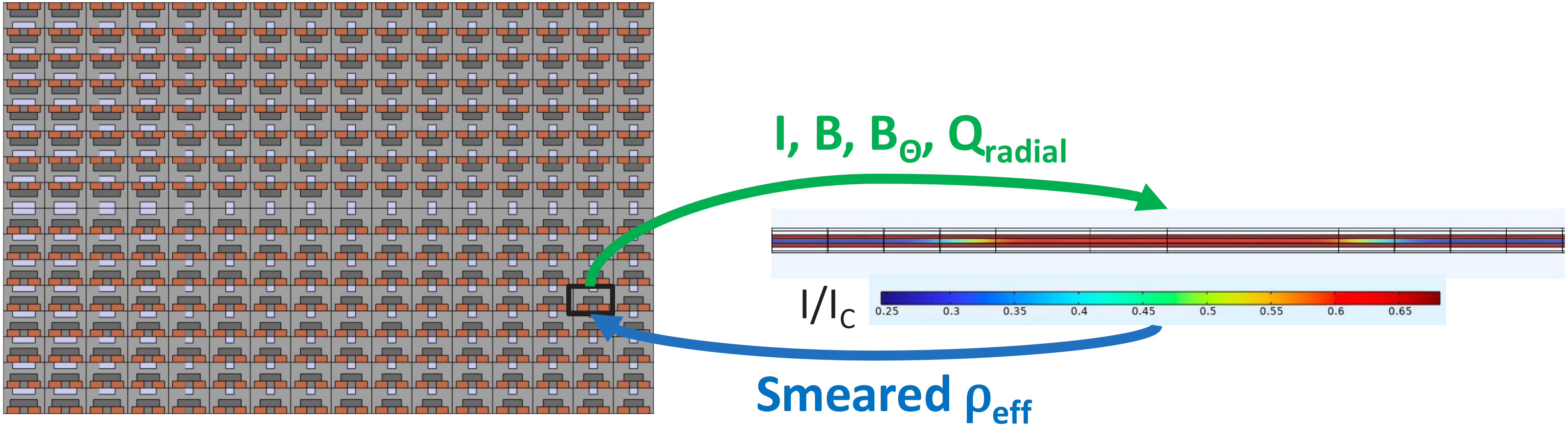
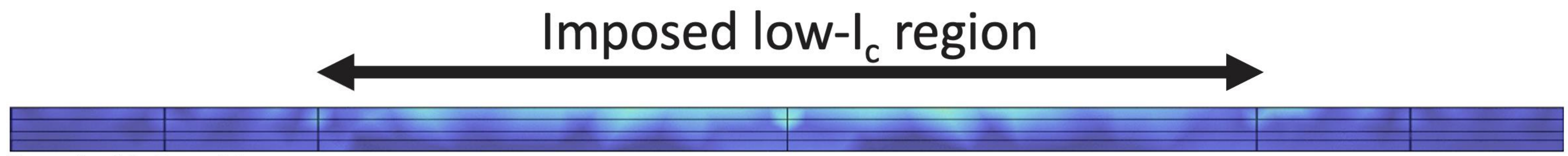
Can we obtain a TFMC-like burn?

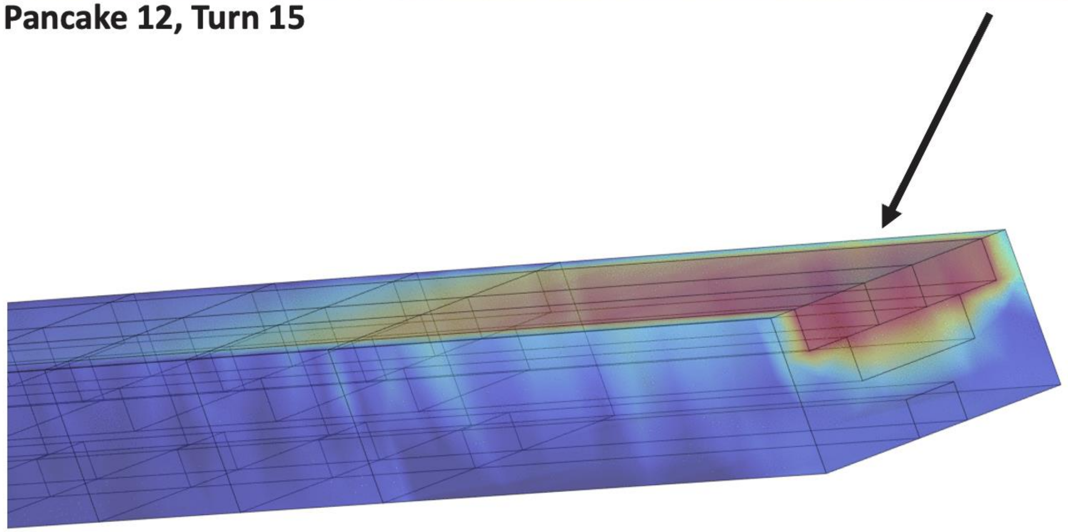


$I, B, B_\Theta, Q_{radial}$

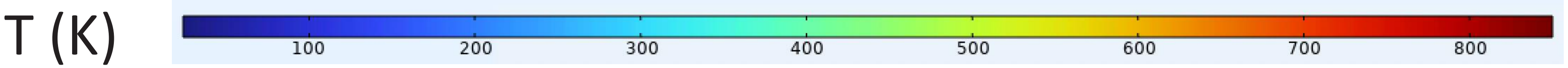
Smeared ρ_{eff}

2.5D model more closely reproduces TFMC burn





- Model runs in <48hrs on 8 cores
- To melt solder, took <25% of turn's stored energy (<0.1% of total stored energy)



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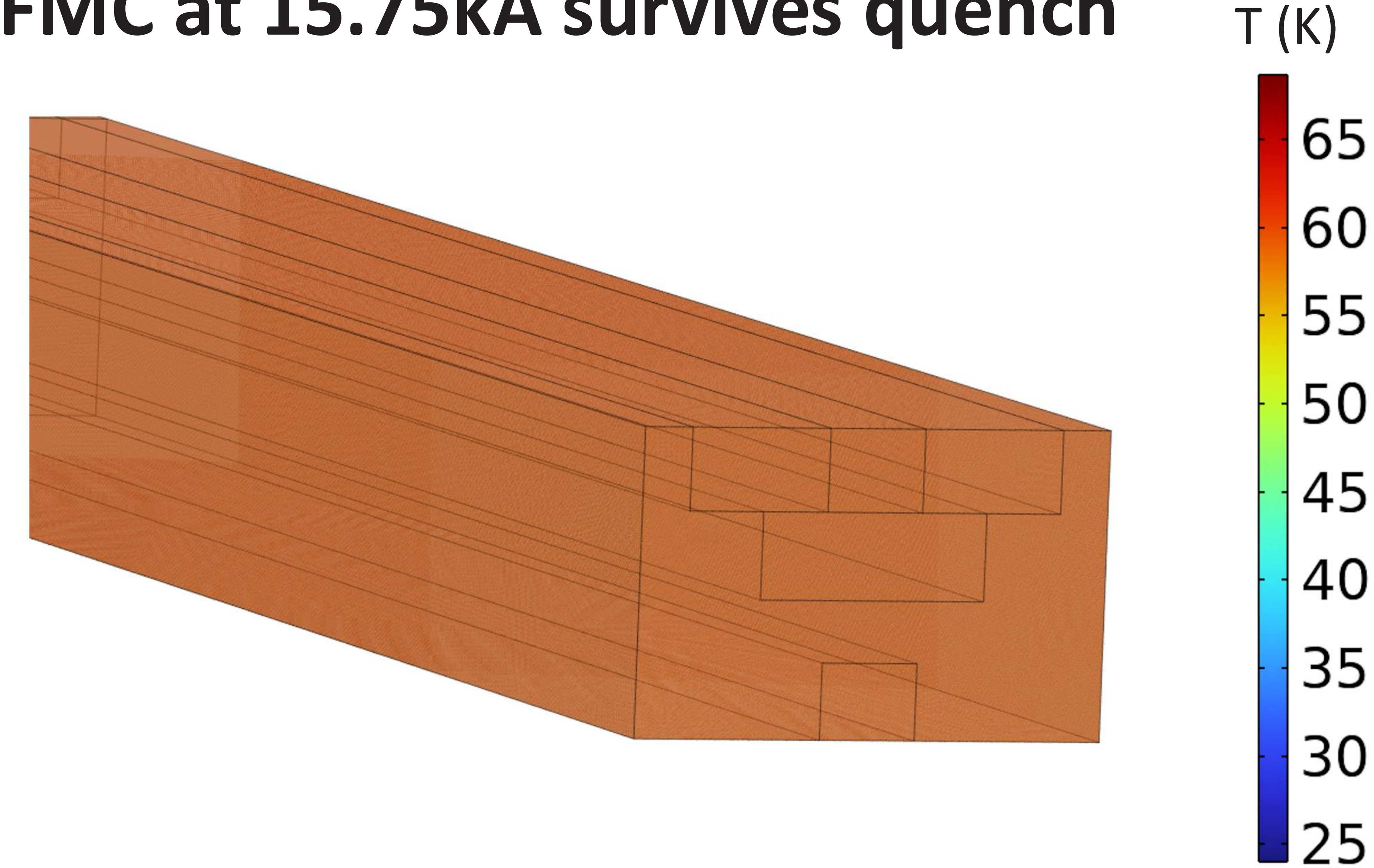
Operating conditions also influence coil survivability

- **TFMC at 15.75kA survives quench**



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Summary

- NI coils with large stored energies can survive quench – if energy is deposited (mostly) uniformly
  - But if not (non-axisymmetric): stored energy is only one part of the picture
  - Local hotspot formation is another potential failure mode
- As a result: non-axisymmetric NI coils can’t be assumed to be passively safe from thermal quench damage
- Need to understand design and operating conditions that enable passive protection against thermal quench damage in NI coils
  - Explore using computationally-efficient, simplified non-axisymmetric quench models, such as 2.5D model

Contact

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