HTS MODELLING 2016

5th International Workshop on Numerical Modelling of High Temperature Superconductors

NC STATE UNIVERSITY

Multiphysics Model for Large Non-Insulated REBCO Multi-Coil Magnets with Stability-Enhanced Mechanisms

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SCHWARTZ GROUP

Department of Materials Science and Engineering

Outline

- Motivation
- Model description
- Self-protection mechanisms in NI coils
- Stability enhancement mechanisms
  - Reducing risk of quenching during charging/discharging
  - Preserving magnetic field during quench recovery
- Conclusions

Motivation

- Some advantages of NI coils:
  - Highly thermally and electrically stable: due to low turn-turn electrical and heat resistances, current and heat not only flow along conductors but also across conductors
  - High coil constant
  - Self-protection may be a possibility
    - No need to dump all current→ faster recovery to original state
    - Transient conditions must be acceptable for ~1 second or more
- Some disadvantages of Ni coils:
  - Uncontrolled current flow (which leads to higher stability)
    - Slow charging and discharging time
    - Local current concentration
  - Self-protected coils have limited control over
    - Maximum peak temperature during transients
    - Magnetic field profile and magnitude during transients

Goals & General Approach

- Goals
  - Study the underlying mechanisms that enable self-protection in NI coils
  - Enhance operational stability by controlling current and heat flows by manipulating turn-turn electrical and thermal resistances
  - Enable mission-critical applications such as aviation motors/generators
- General Approach
  - To study quench and charging/discharging behaviors in NI coils, ***entire*** coil must be modeled
    - Mutual inductance from all turns of all coils
    - Current flow involves entire length of a cluster of neighboring turns during current sharing occurs
    - Thermal propagation remains local
    - Electrical behavior must be modeled with spirally-wound turns, not co-centric turns
- Difficult to model all turns in 2D or 3D via FEM
- Most viable modeling approach couples equivalent circuit network with 2D or 3D thermal and magnetic field models

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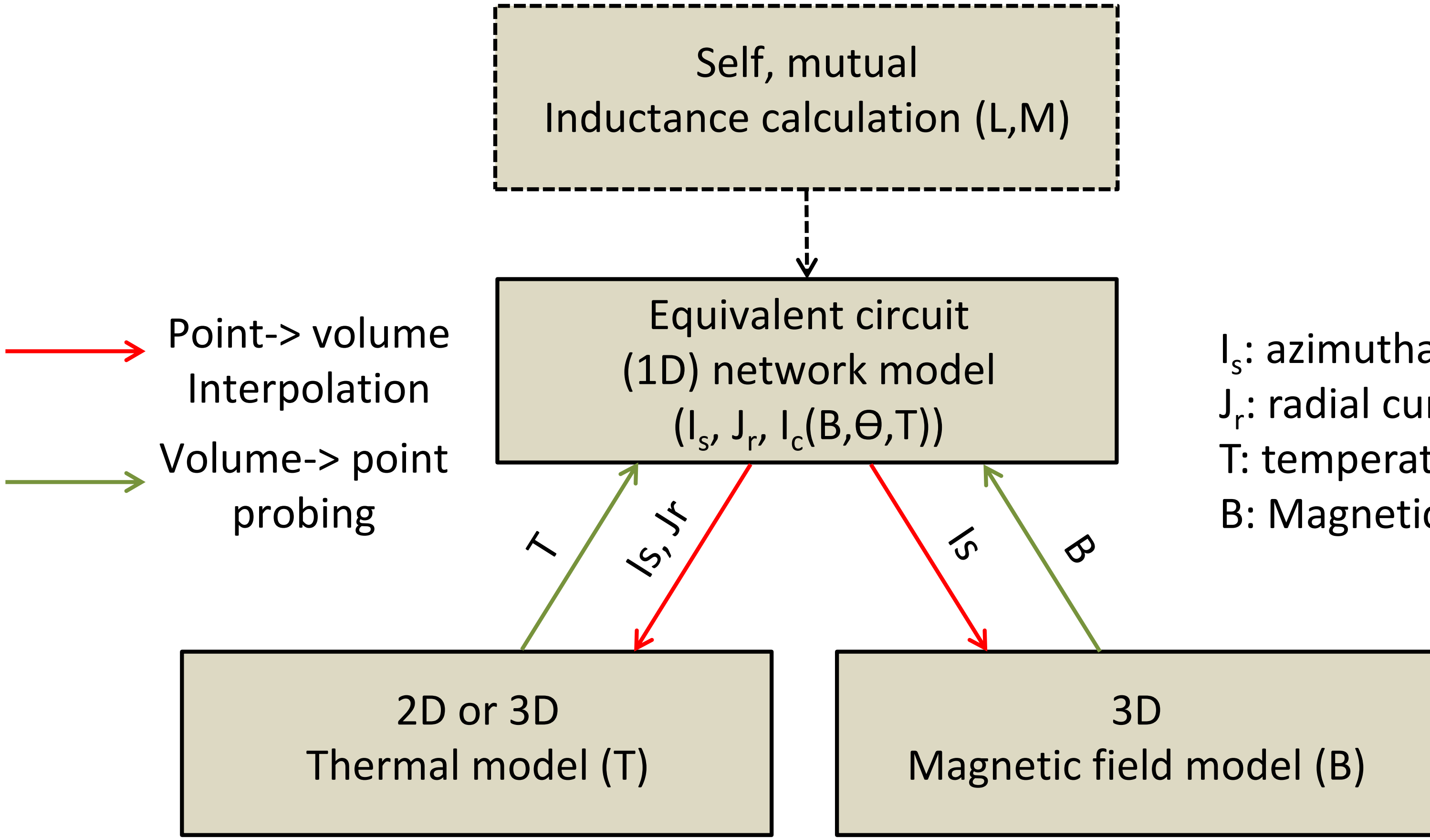
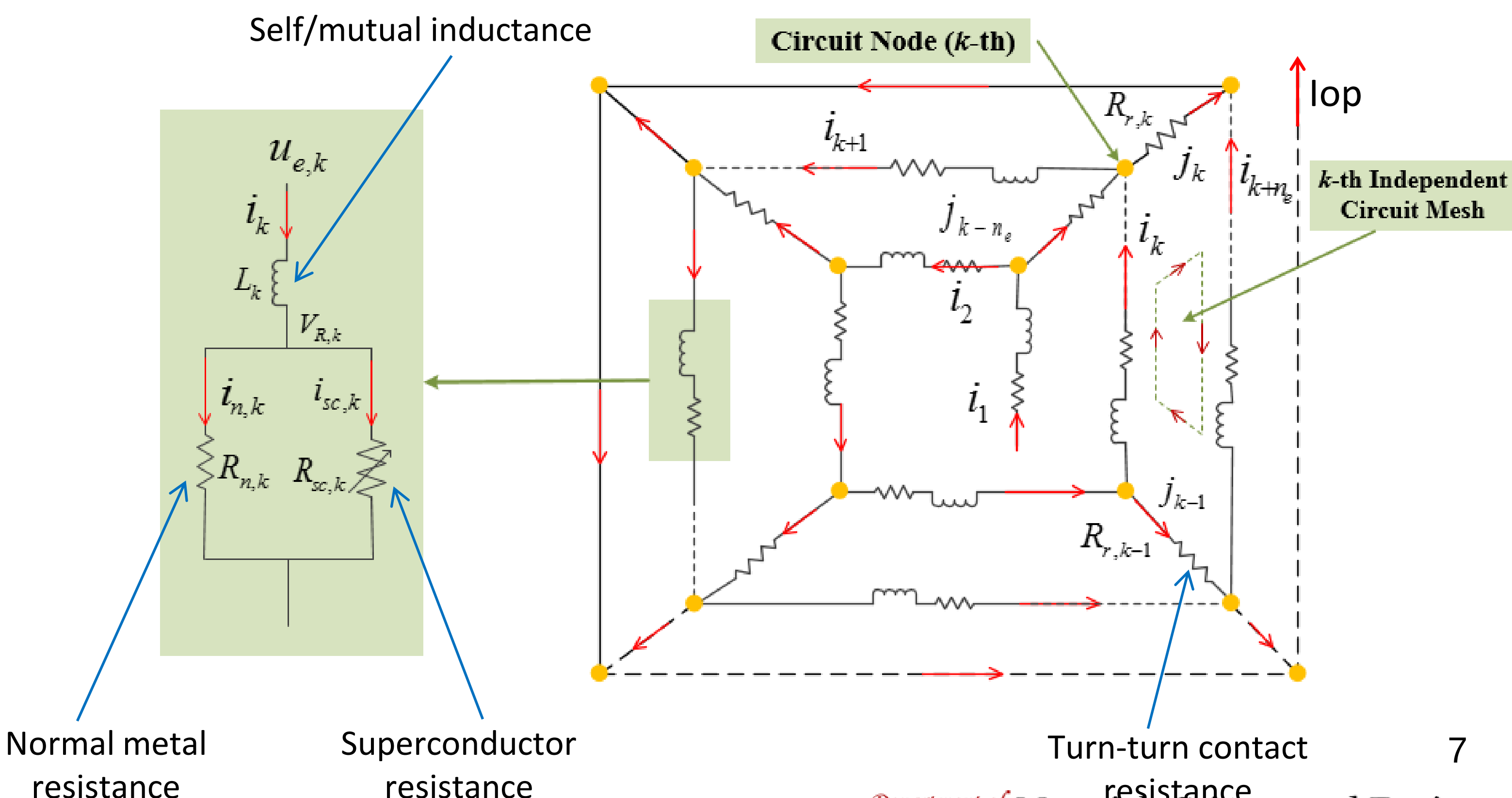
Coupled multiphysics full-scale NI multi-coil model



I_s: azimuthal current
J_r: radial current density
T: temperature
B: Magnetic field

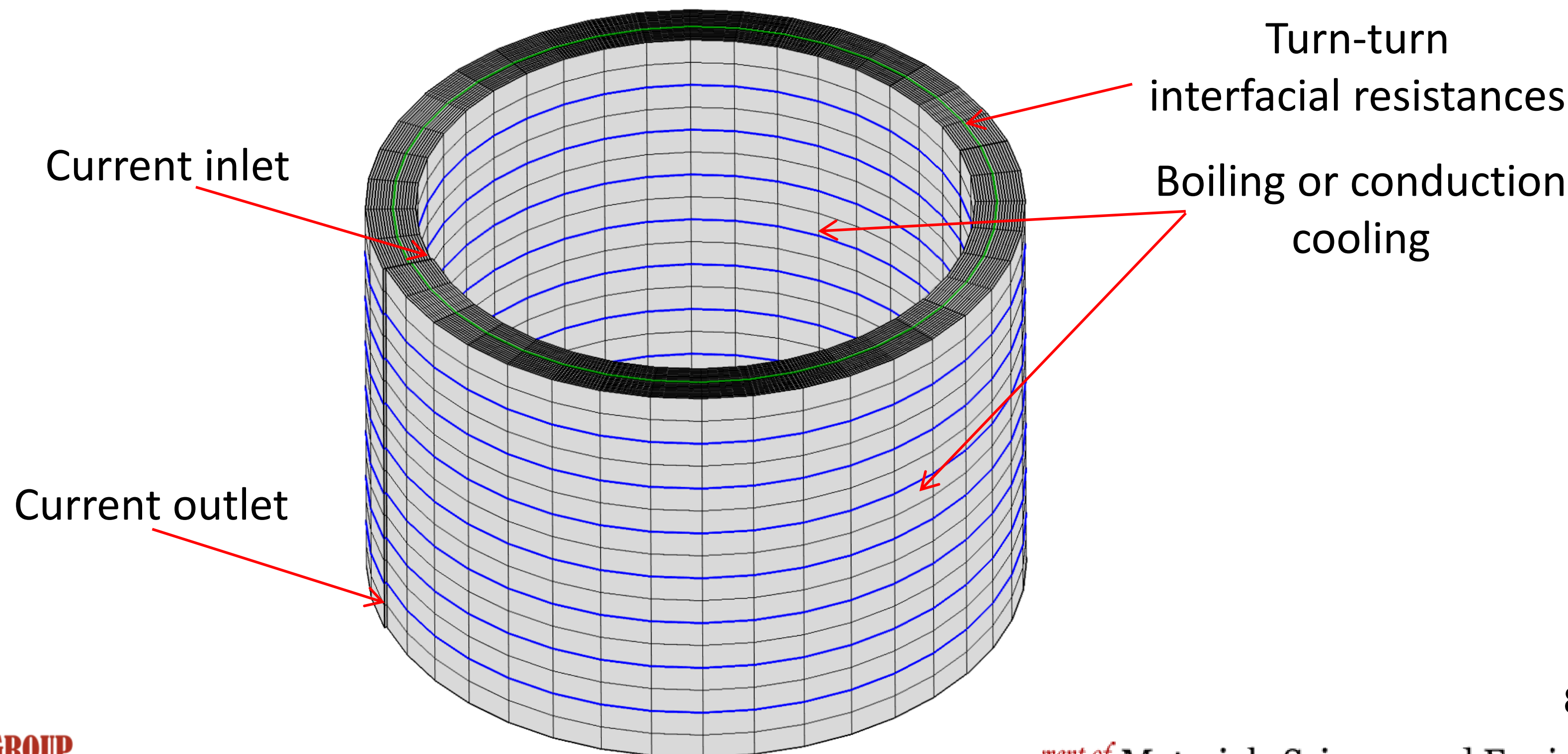
Quench-enabled equivalent circuit network model

- Any number of turns and coils, in any dimensions
- Capable of modeling quench w/temperature-dependence and power law for superconductor current
- Most computationally intense part of model
  - Use adaptive # of nodes-per-turn to reduce ODE system size
  - Denser nodes-per-turn in highly dynamic volumes, e.g., where quench happens

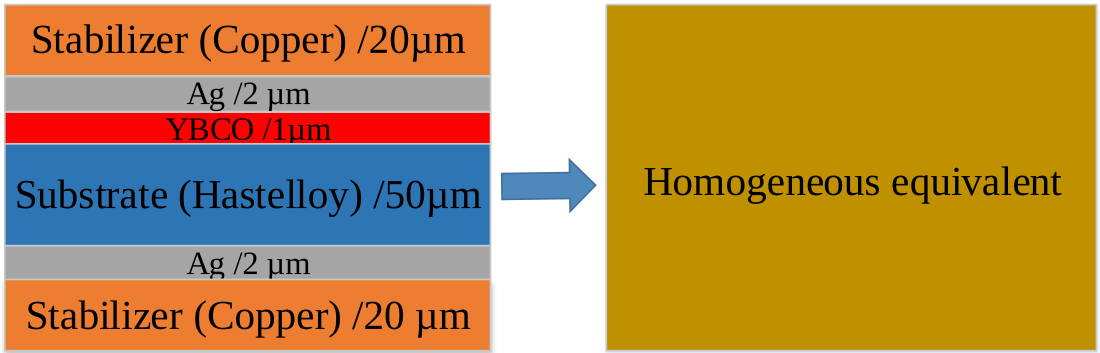


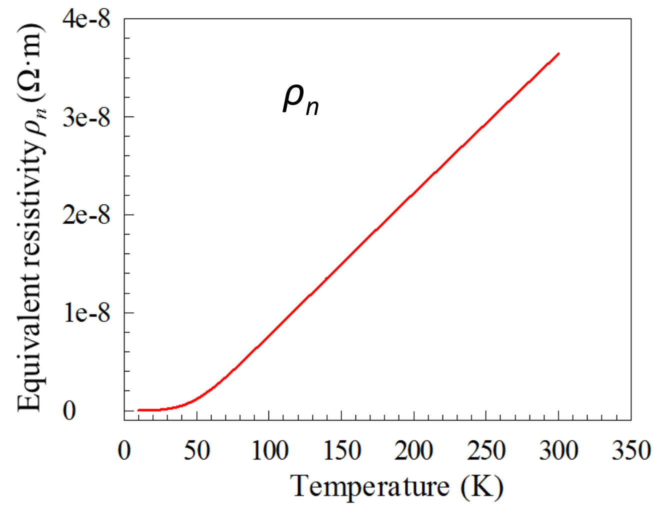
3D multi-coil thermal and magnetic field models

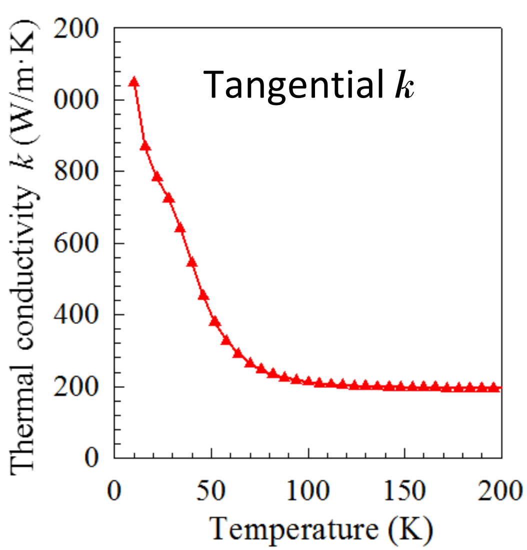
- Thermal + magnetic field models
  - Same configuration as network model– any numbers of turns and coils
  - Also spirally wound
- Add arbitrary turn-to-turn thermal and electrical contact/interfacial resistances to manipulate thermal & electrical behaviors
- Use point-to-3D interpolations and 3D-to-point probes to couple network and 3D models

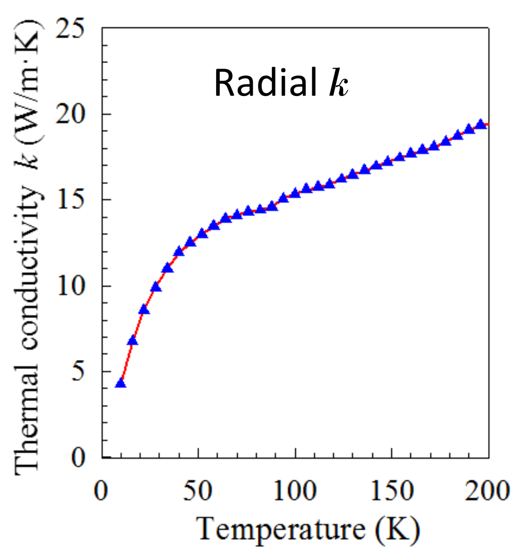


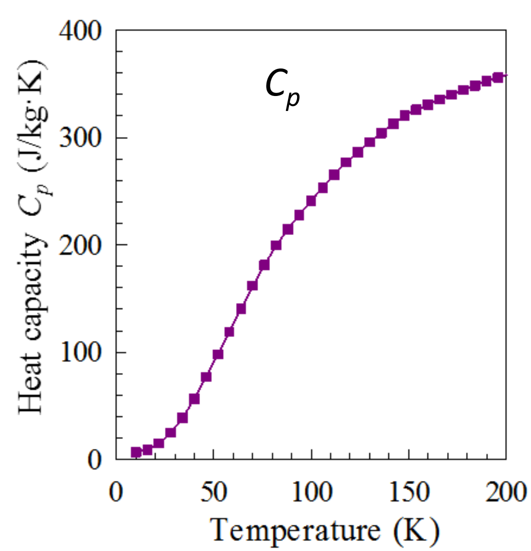
Temperature-dependent homogenized conductors











Model building via COMSOL GUI

Matlab codes
Convert ODEs, etc into COMSOL scripts

$$i_k - i_{k+1} + j_{k-n_e} - j_k = 0$$

$$u_k - u_{k+n_e} - j_{k-1}R_{r,k-1} + j_k R_{r,k} = 0$$

$$u_k = L_k \frac{di_k}{dt} + \sum M_{k,l} \frac{di_l}{dt} + V_{R,k}(i_k, I_{c,k}, T_k)$$

$$E_0 l_k \left(\frac{i_{sc,k}}{I_{c,k}}\right)^n - (i_k - i_{sc,k})R_{n,k} = 0,$$

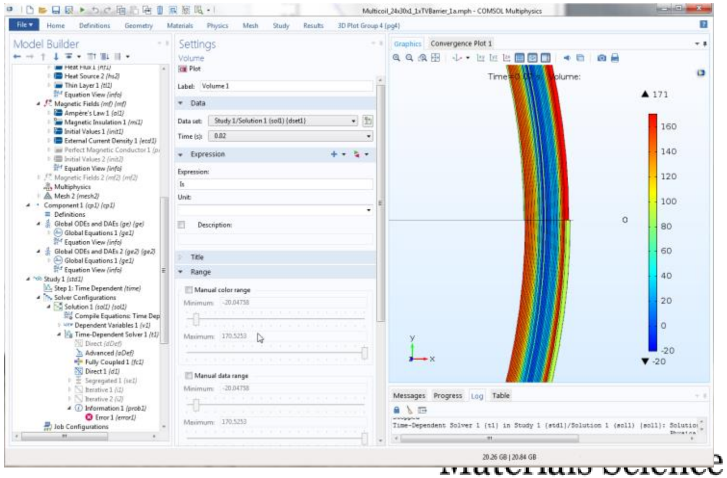
Power law

$$V_{R,k} = E_0 l_k \left(\frac{i_{sc,k}}{I_{c,k}}\right)^n$$

COMSOL scripts
Combined with COMSOL .mph file

```
⋮
odename=['ge',num2str(i)];
model.physics.create(odename, 'GlobalEquations');
model.physics(odename).identifier(odename);
model.physics(odename).feature('ge1').set('name', SSv);
model.physics(odename).feature('ge1').set('equation', SSe);
model.physics(odename).feature('ge1').set('initialValueU', Su0);
model.physics(odename).feature('ge1').set('initialValueUt', Sut0);
model.physics(odename).feature('ge1').set('description', Sde);
⋮
```

COMSOL Model
runs as single .mph file



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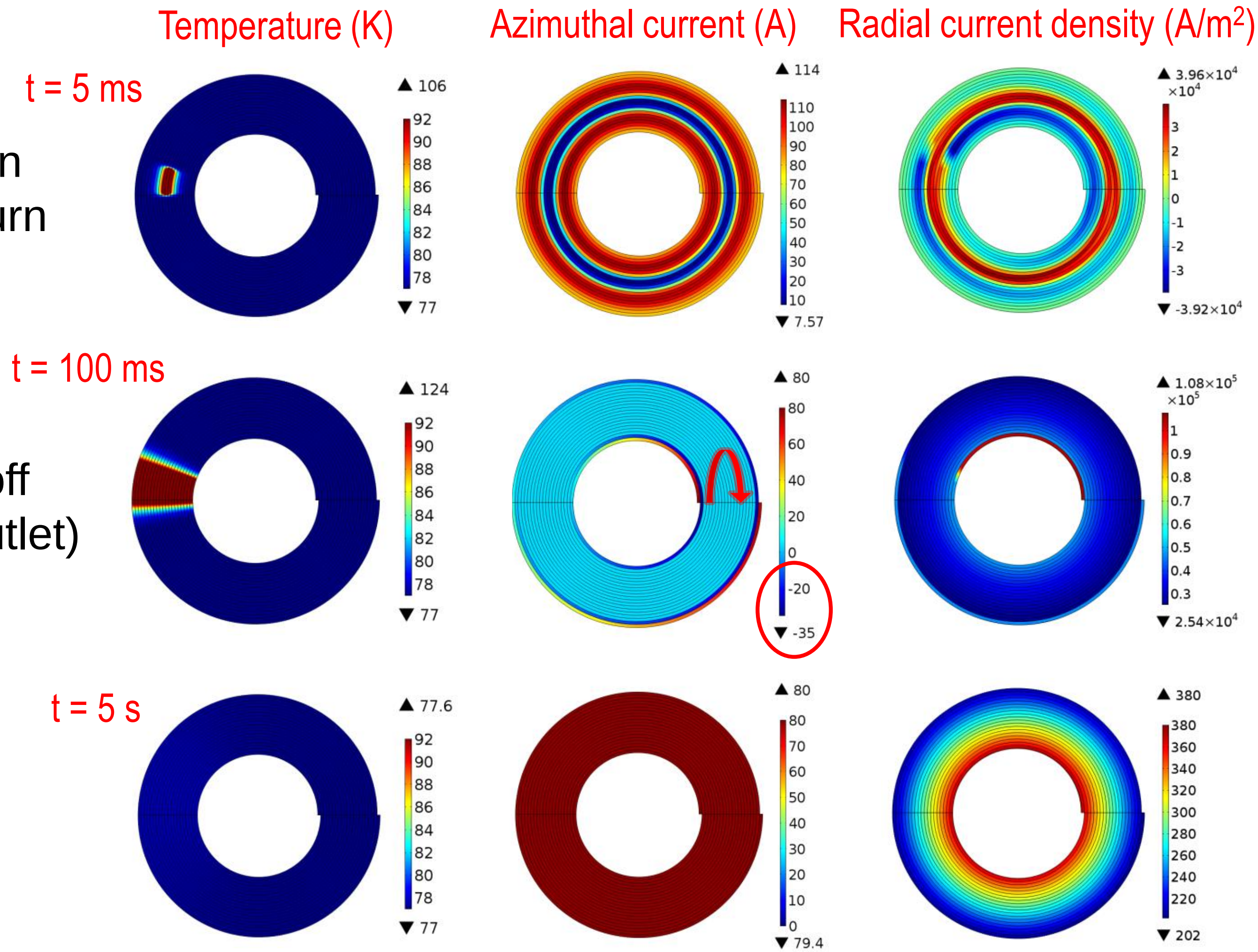
Self-protection mechanism

Current redistribution occurs along entire turn

Complete thermal cutoff (current reverses to outlet)

Complete recovery



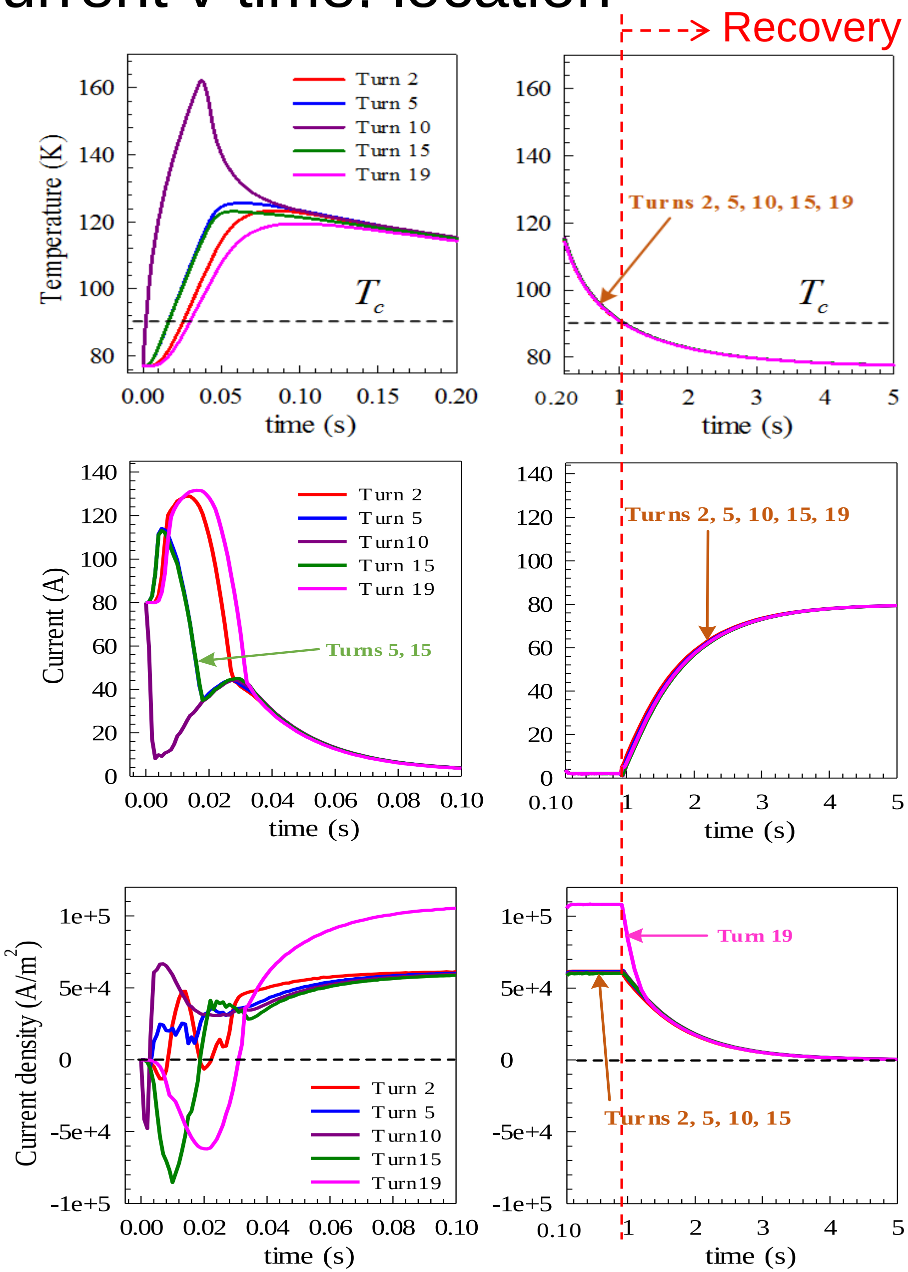
Y. Wang, W.K. Chan and J. Schwartz, Supercond. Sci. Technol. 29 (2016) 045007

Temperature & current v time. location

Temperature
- Heat pulse ends at t~0.04 sec

Azimuthal current
- Neighboring turns accommodate current from hot-spot until becoming normal
- Current transients continue until ~1 sec

Radial current density



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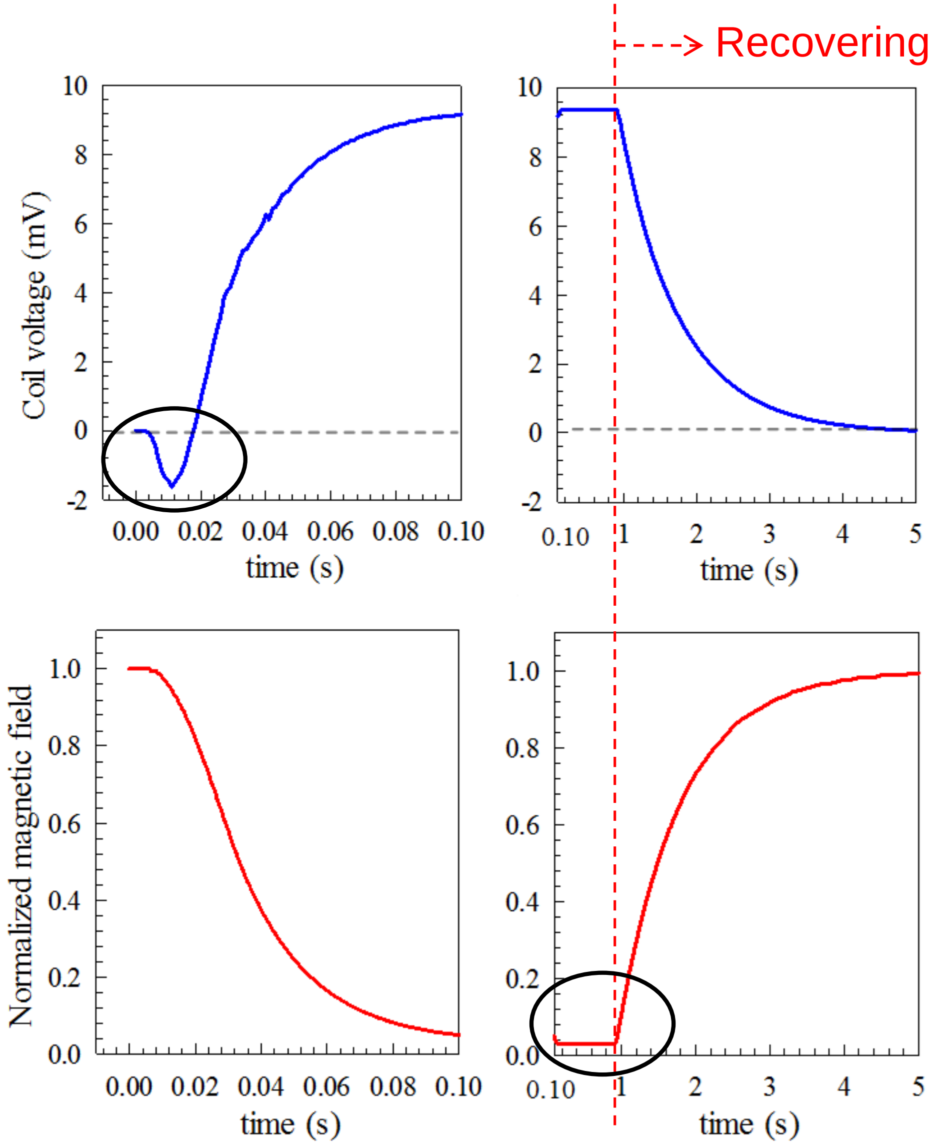
Voltage and magnetic field versus time

- Potential quench detection signal

- Central axis magnetic field drops to ~ zero
- Significant problem for some applications?



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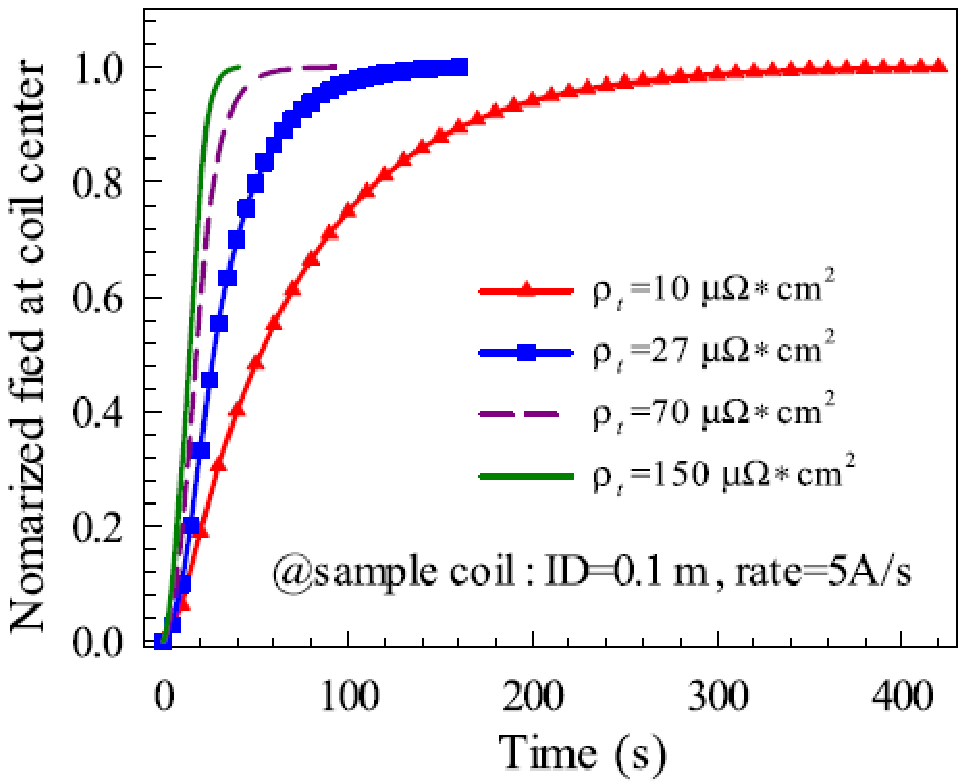
What is the role of the turn-to-turn contact resistance on time-to-steady-state?



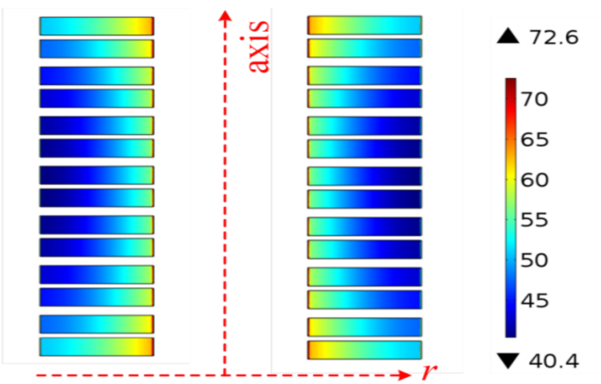
Y. Wang and H. Song, Supercond. Sci. Technol. 29 (2016) 075006

Current distributions during charging/discharging

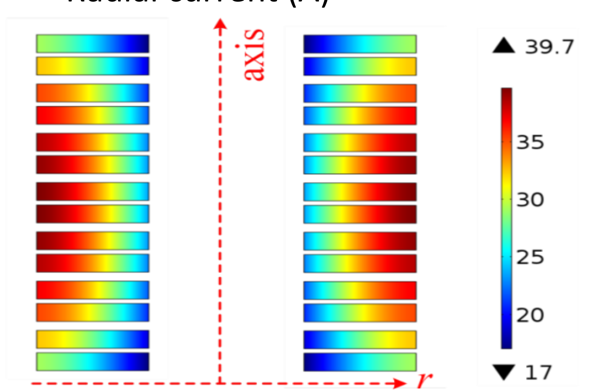
- Very non-uniform current distributions in conventional NI

Charging

Azimuthal current (A)

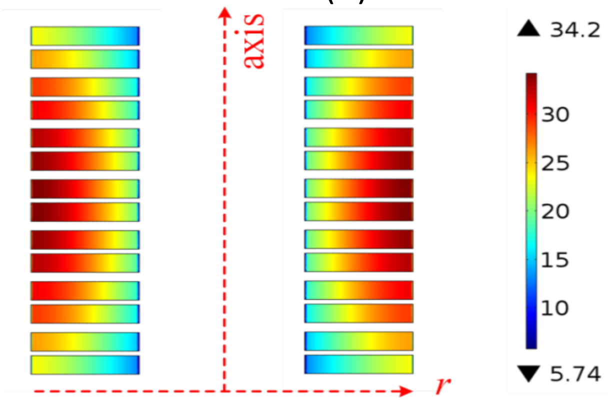


Radial current (A)

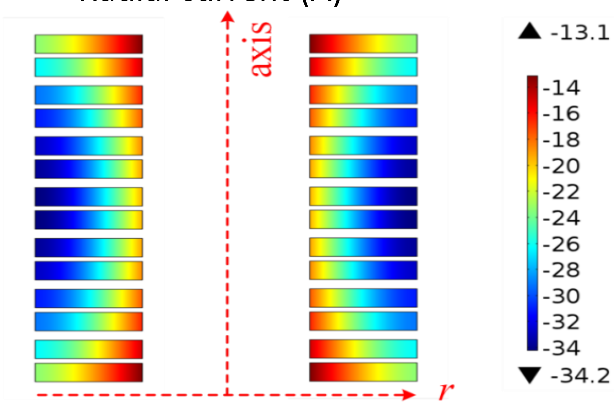


Fast discharge

Azimuthal current (A)



Radial current (A)



A new concept: Graded-Resistance NI Magnet

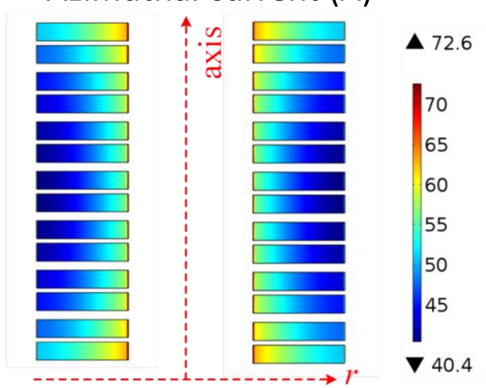
- There are NI and partially-insulated coils with different constant turn-turn resistances
- Here we proposed *grading* the turn-turn resistances in a designed manner to control current and heat flows. There are two variants of this concept:
- **Intra-coil grading**
  - The turn-to-turn resistances are graded with respect to all the turns within the same coil. The turn-to-turn resistance between two adjacent turns can vary from those of other turns within the same coil.
- **Inter-coil grading**
  - The turn-to-turn resistances are graded with respect to all the coils within the same magnet. Every coil within the magnet has a fixed turn-to-turn resistance, but the resistances may be different from those of other coils within the magnet.

Engineering the transient current distributions via graded resistances

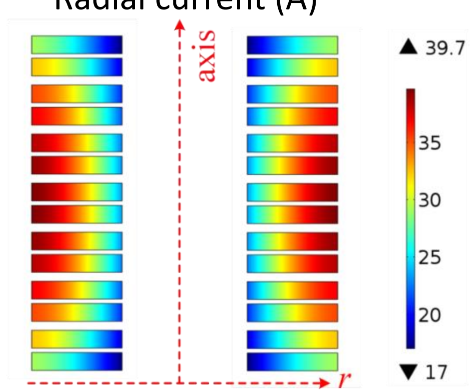
- Currents more evenly distributed radially and axially by intra + inter-coil grading

Charging in a conventional NI magnet

Azimuthal current (A)

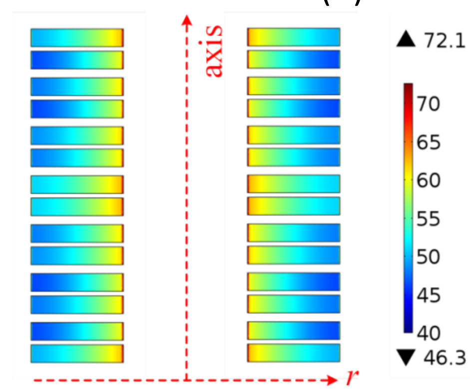


Radial current (A)

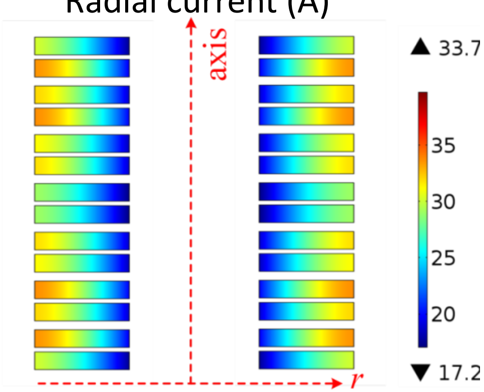


Charging in a inter-coil graded magnet

Azimuthal current (A)

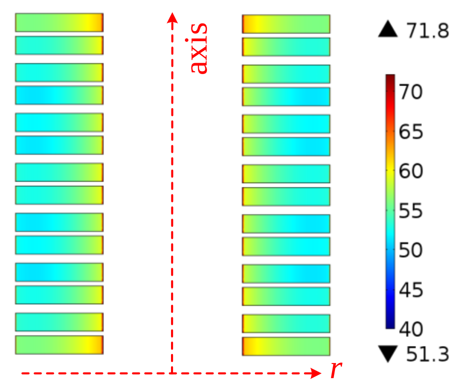


Radial current (A)

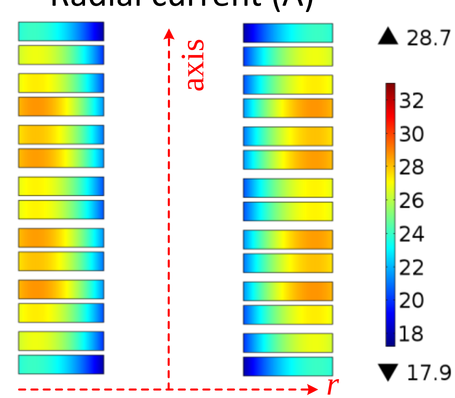


Charging in a intra- & inter-coil graded magnet

Azimuthal current (A)

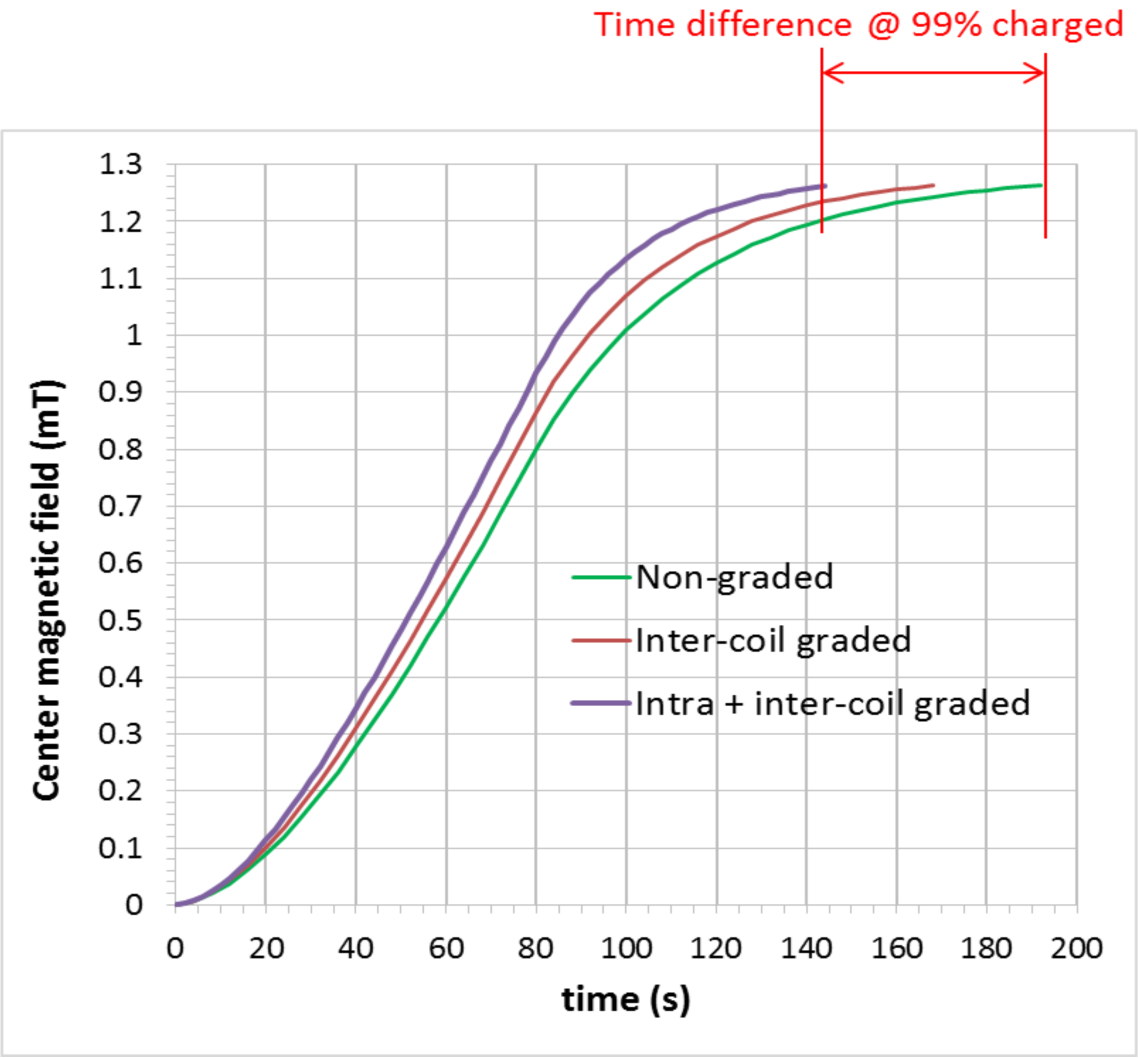


Radial current (A)



Radial current (A)

Effect of grading on charging/discharging times



Charging and discharging times are reduced by 25%

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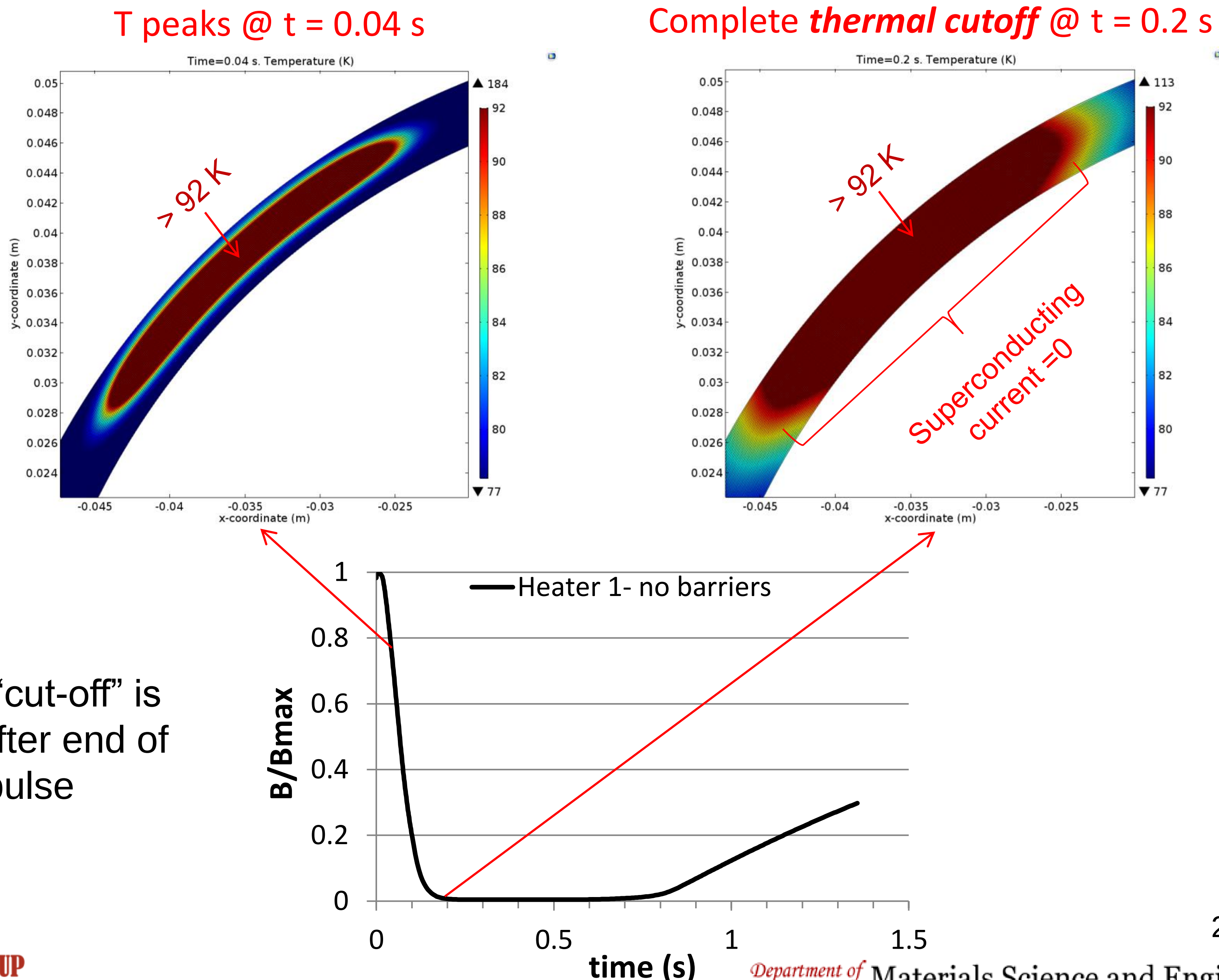
Thermal cut-off versus magnetic field drop in a conventional NI coil

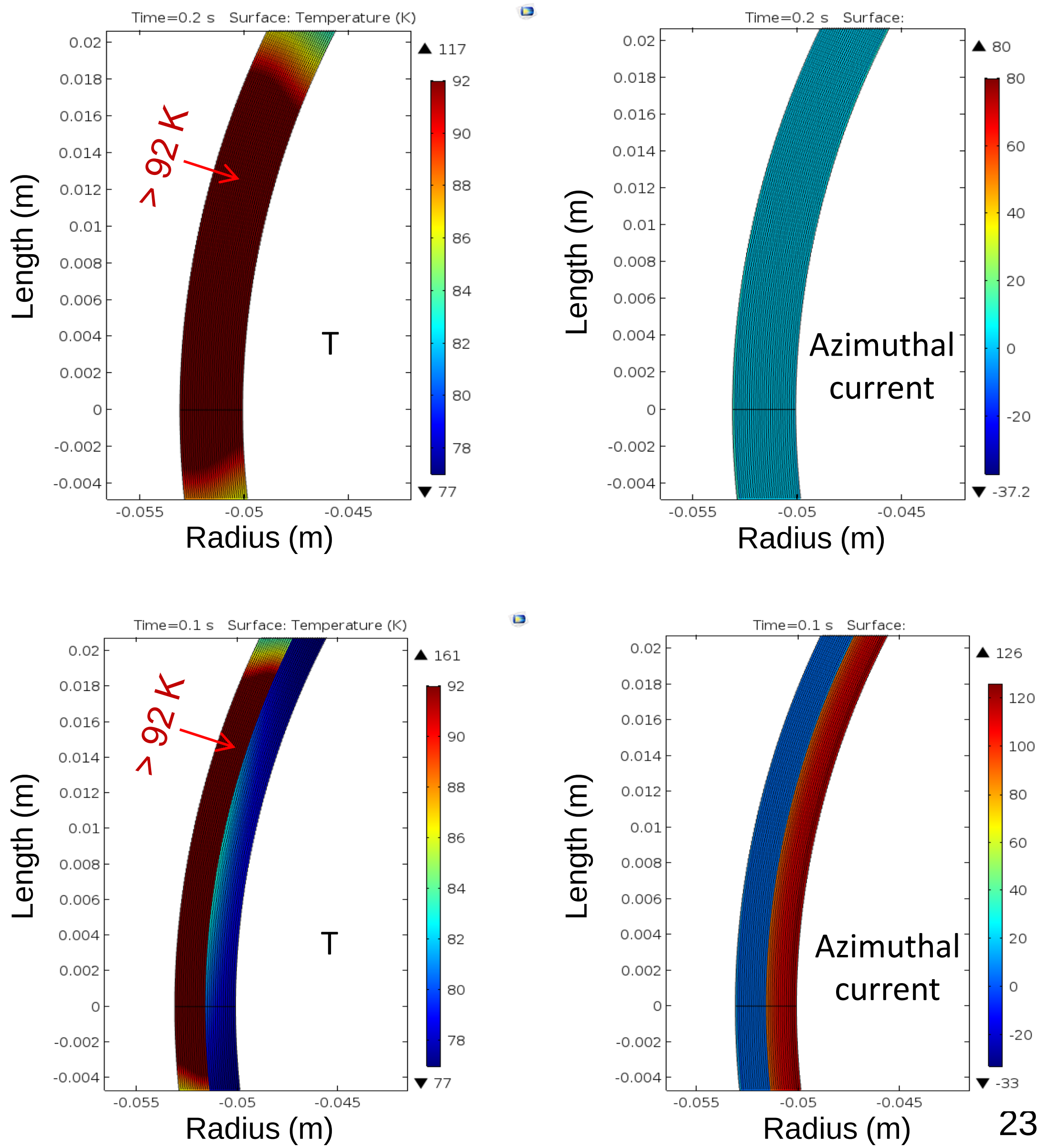


Field "cut-off" is well after end of heat pulse

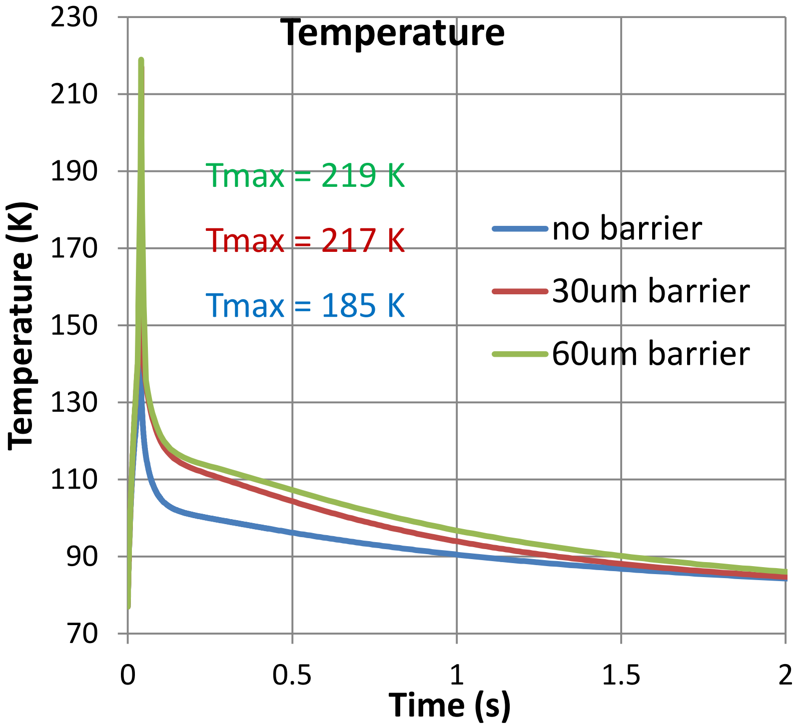
Single barrier solution to avoid thermal cut-off

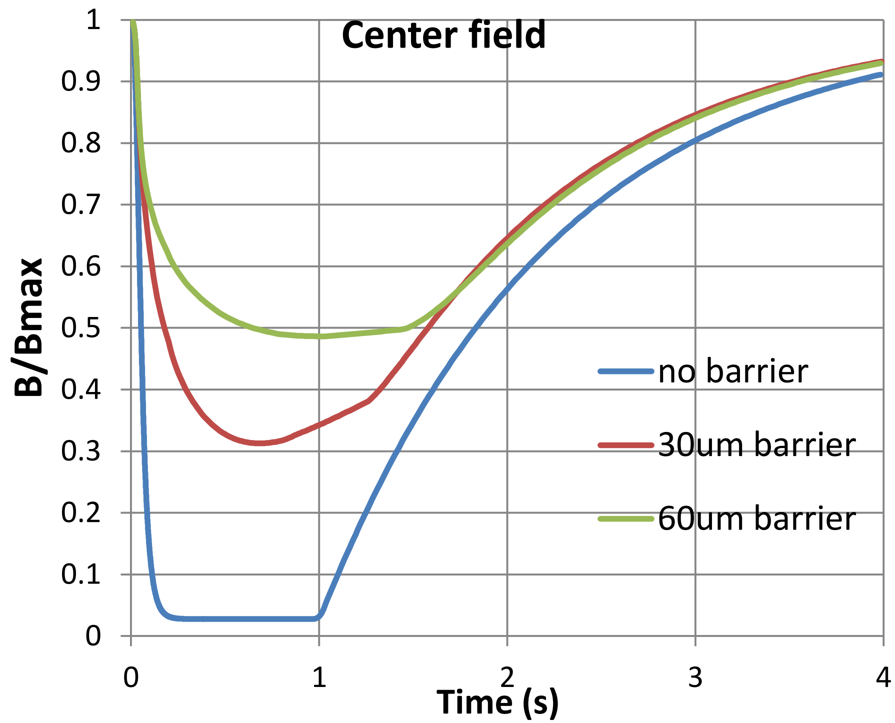
No barrier @ complete thermal cutoff

With Kapton barrier at center
Total I does not → 0



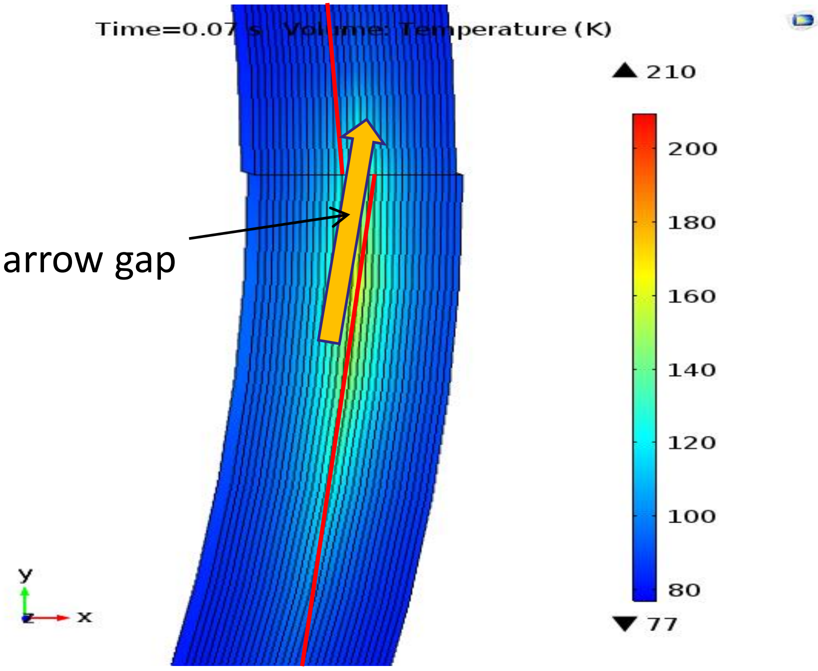
Temperature and central magnetic field profiles





Problem with single-barrier solution

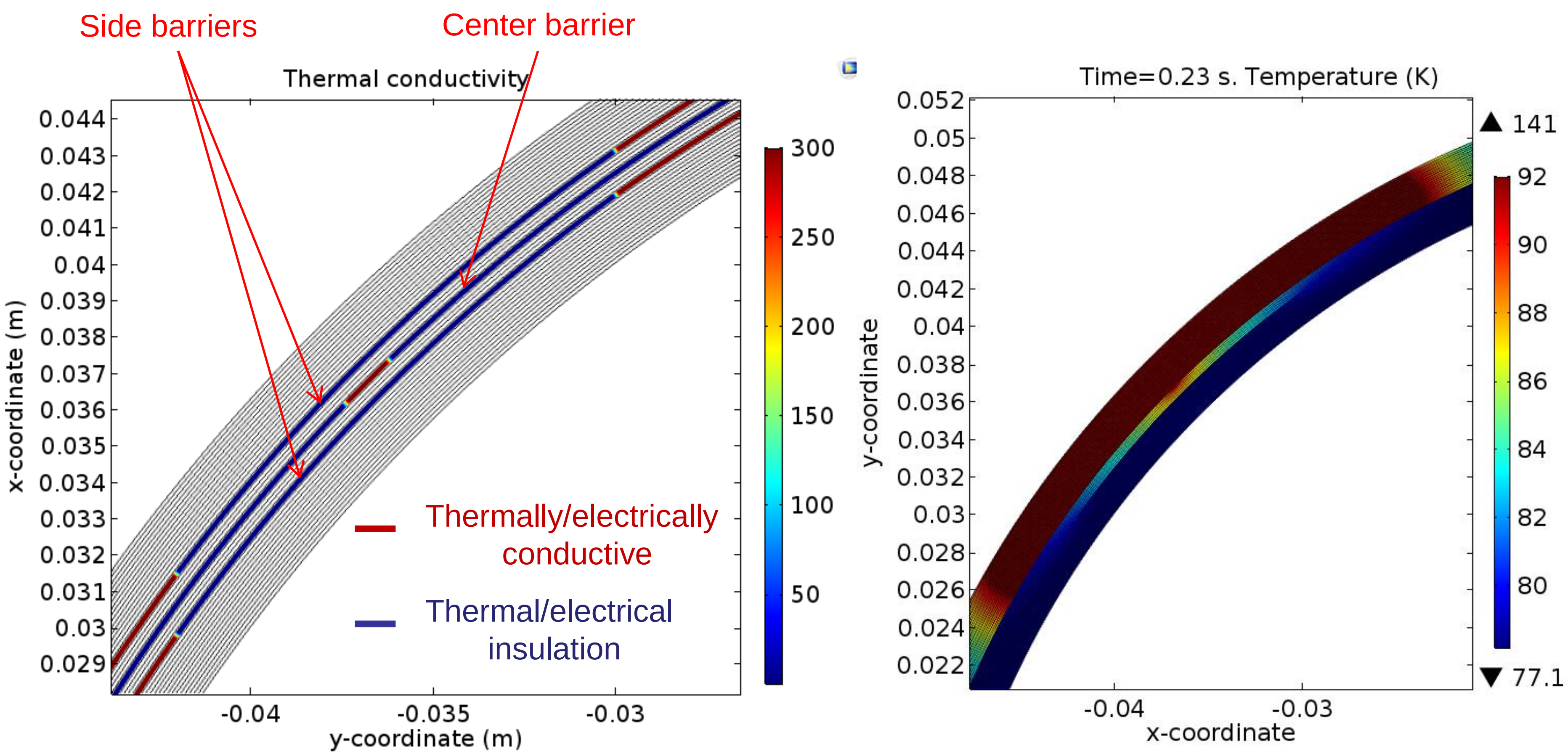
- With single Kapton barrier => good B-field preservation but hot spot created between the start-end gap of the barrier
  - Caused by current squeezing through the narrow passage between the start-end gap



Hot spot near current leads

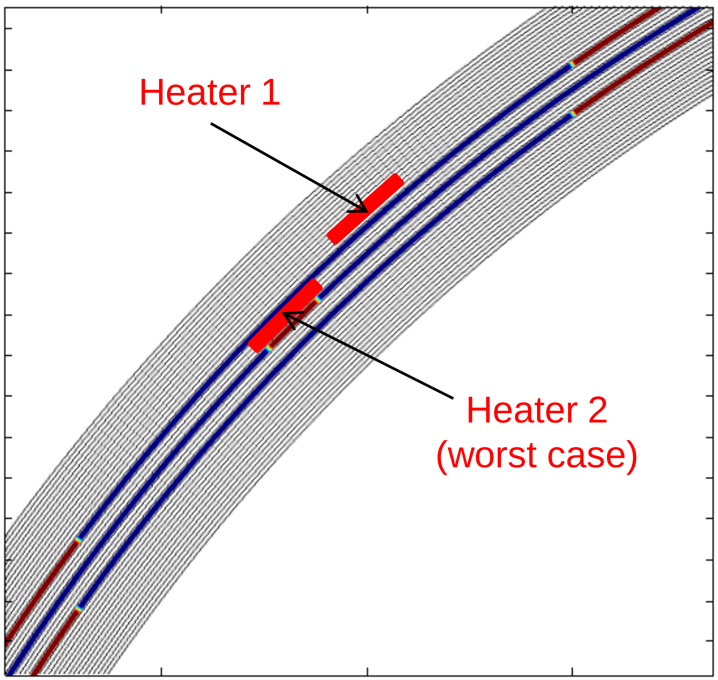
Multi-barrier, modified partially-insulated coil

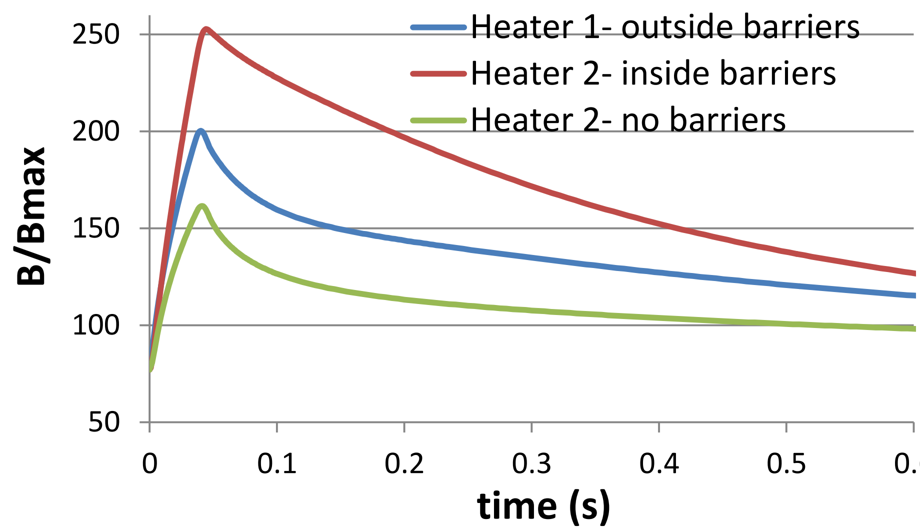
- Add narrow conductive "holes" to center barrier at equal distance to let current flow from one side to the other
- Add short "side barriers" to contain heat flow from conductive holes
- A special case of intra-coil grading

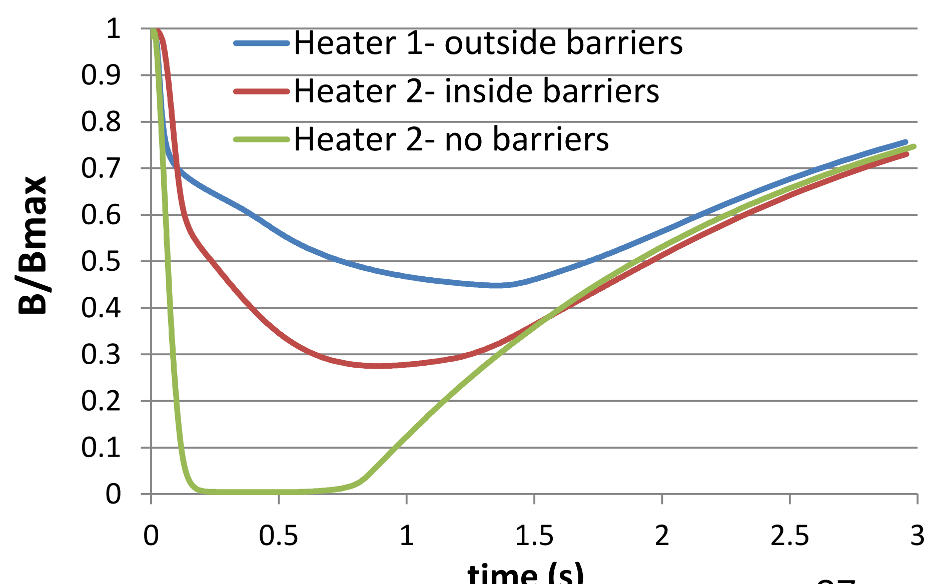


Improved magnetic field stability

- Worst case happens for heater located inside barriers
- Still recovers even with very high peak temperatures

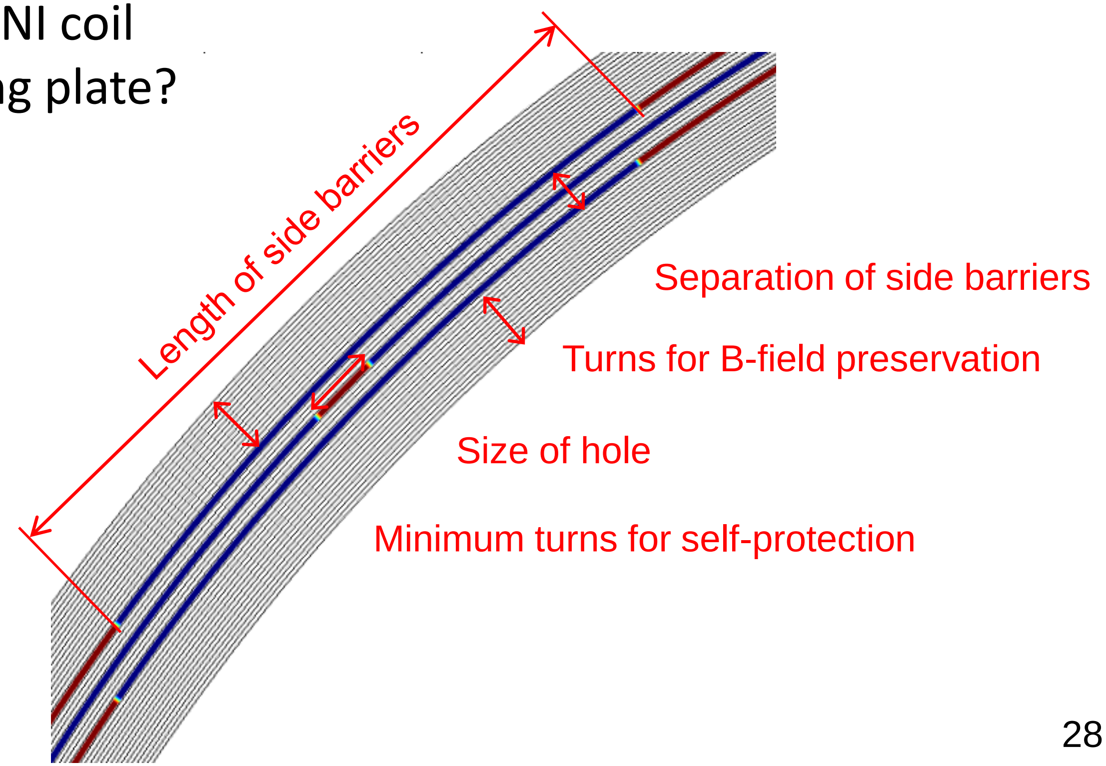






Engineering the current and heat flow via barriers

- Criteria:
  - Minimum turns to maintain self-protection capability
  - Size of conductive holes
  - Length, thickness and separation of side barriers
    - → peak temperature, time to recover
- The more turns, the better and easier to reduce peak T and maintain B-field
  - Allow wider separation of side barriers → lesser increase in peak T, as compared to original NI coil
- Extended barrier as cooling plate?
- Effects on grading?



Conclusions

- Goals
  - Study underlying self-protection mechanisms in NI multi-coil magnets
  - Study and manipulate effects of turn-turn resistances
  - Enable critical-mission applications
- Results
  - Current sharing occurs along the entire turns when a section of the turn turns normal
  - Graded resistances redistribute current evenly, thus reducing the risk of quenching
  - Graded resistance barriers prevent complete thermal cutoff, thus preserving magnetic field
- More generally – using resistance as a spatially-varying design variable allows creative approaches to magnet design that can be driven by the applications