User Defined ANSYS Elements for Multi-Physics Modeling of Superconducting Magnets

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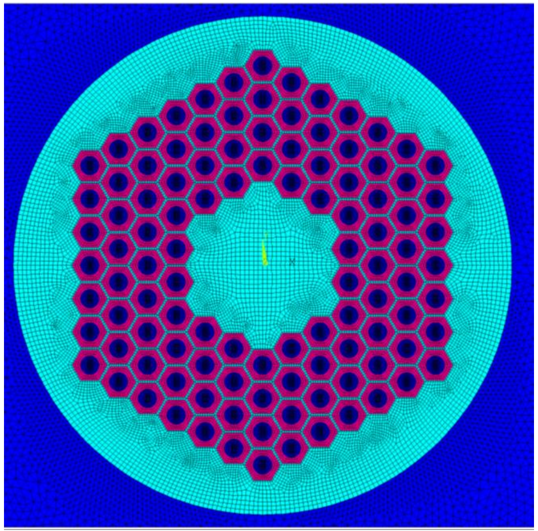
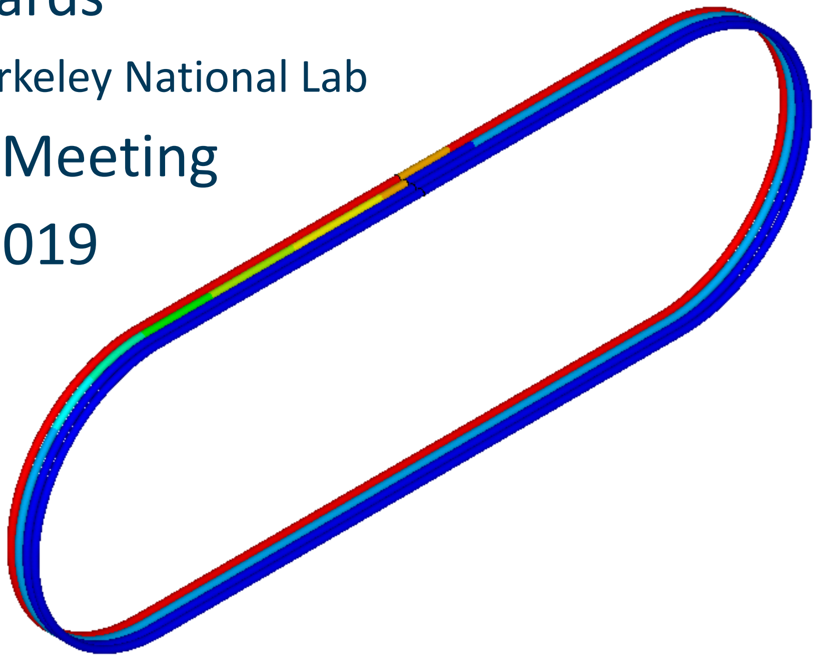


MDP General Meeting

Aug 28, 2019



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U.S. MAGNET DEVELOPMENT PROGRAM

BCMT BERKELEY CENTER FOR MAGNET TECHNOLOGY

Can Extend ANSYS Element to Include Superconducting Specific Behavior

Keep all features of standard ANSYS…

- modeler, mesher, post-processor
- transient electromagnetic and thermal solvers
- eddy currents in structure
- external circuit coupling
- yoke saturation

New 2D elements created by

- writing code which generates FEM matrices
- compiling a custom version of ANSYS

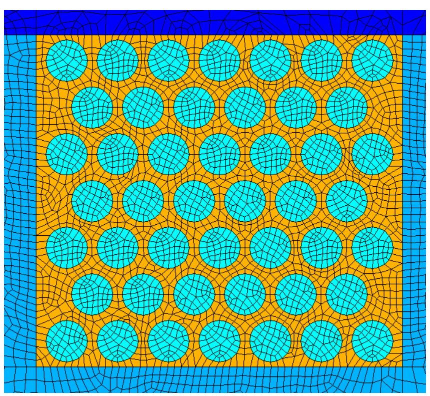
... and add what is missing with user elements

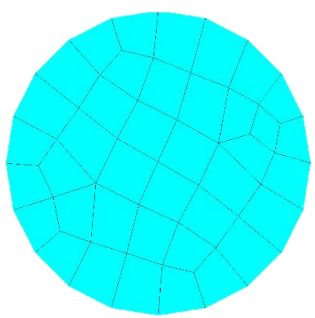
- equivalent magnetization for interfilament coupling currents
- current sharing + quench loss
- coupling to thermal model with full (T,B) mat. prop.

Two Main Custom Elements Developed

A_z-curr-emf

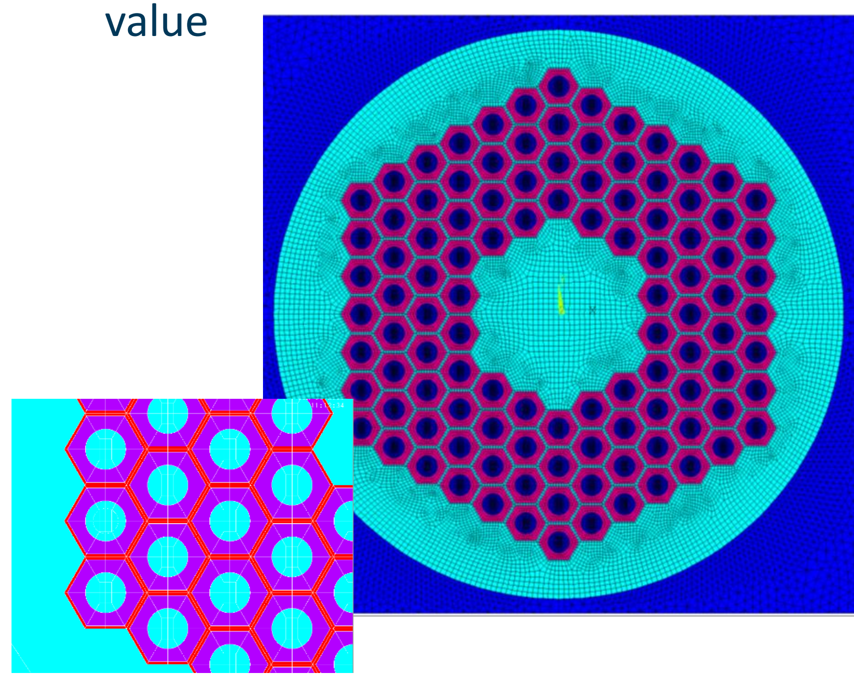
- Uniform modeling of superconducting strand
- Current density uniform through strand
- Involves the coupling of custom thermal and magnetic elements
- Useful for modeling entire magnets





A-V formulation with E-J power law

- Conductive paths defined in geometry/mesh
- Current density as an elemental value



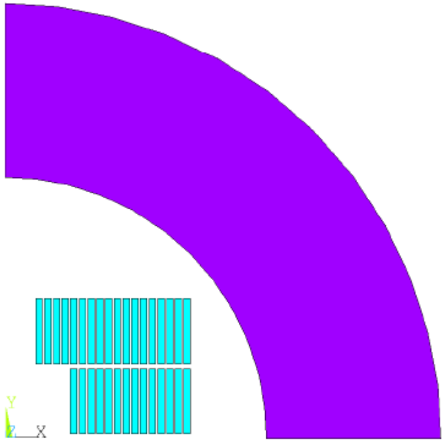
Element Uses

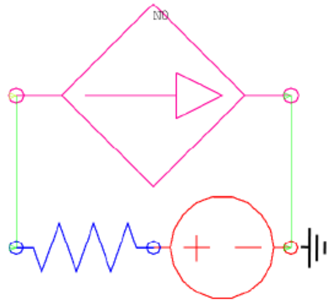
Stranded Uniform Elements

- Previous work by Lucas:
  - Dipole (dump resistor and CLIQ)
  - Verified with COMSOL and STEAM developed at CERN
- Quenchback in Nb_3Sn Undulators
- Quench propagation studies

A-V Conductor Elements

- Magnetization studies





The two conductor layers and iron yoke of the Nb3Sn dipole ANSYS model are shown with the dump resistor circuit

* L. Brouwer, D. Arbelaez, B. Auchmann, L. Bortot, and E. Stubberud, "User Defined Elements in ANSYS for 2D Multiphysics Modeling of Superconducting Magnets," 2019

Uniform Custom Thermal Elements

Default Thermal

- 1D: linear, 2 node
- 2D: quadratic, 8 node
- 3D: linear, 8node

- DOF: Temp
- Material properties with temp.

→

Custom Thermal

- Default +
- Material properties with RRR, B, and quench state
  - NIST, CUDI, MATPRO
- Quench state, current sharing (given B, I)
- Heating from quench
- Voltage drop, resistance

- Allows modeling of quench propagation and thermal properties with changes in field and transport current
- Previous quench propagation studies have been performed in ANSYS but used a fixed field*

*S. Caspi, L. Chiesa, P. Ferracin, S. A. Gourlay, R. Hafalia, R. Hinkins, A. F. Lietzke, and S. Prestemon, "Calculating Quench Propagation with ANSYS," IEEE Transactions on Applied Superconductivity, Vol 12, No 2, June 2003

Uniform Custom Magnetic Elements

Default Magnetic

- 2D: quadratic, 8 node
- DOF: A_z , i, emf
- Material properties with temp.
- Circuit coupling or applied current density

Custom Magnetic

- Default +
- Material properties with RRR, B, and quench state
  - NIST, CUDI, MATPRO
- IFCC (equivalent magnetization)
- Quench state, current sharing
- Hysteresis loss
- Heating from quench and IFCC

Allows modeling of quenchback from IFCC (for use with CLIQ)

Material and Other Options

Options that can be adjusted using the element key options and real constants

Materials

Superconductor

- NbTi, Nb_3Sn

Stabilizer

- Cu

Non-Conductor Material

- G10 (isotropic)

Additional Options

Can be used for sensitivity testing

- Jc fit function parameters
- Force superconducting or quench
- Turn off current sharing
- Turn off IFCC
- Fix time constant
- Scaling factor for current sharing and τ

Required Inputs

Key options and real constants that are required for the simulation

Both Elements

- S_c : cross section of strand (1D, 2D)
- f_{cond} : fraction of conductor in coil
- f_{sc} : fraction of superconductor
- RRR

Thermal

- B : field for material prop.
- J : current density (if not coupled)

Magnetic

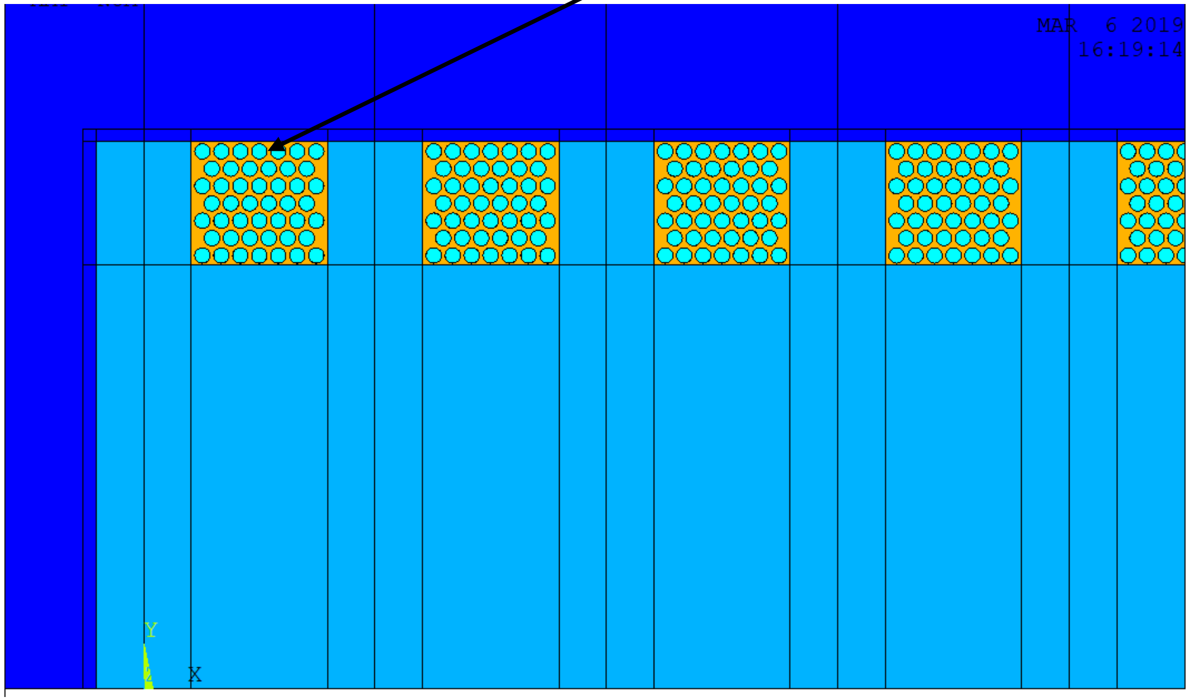
- Current direction (+z, -z)
- N_c : number of turns in coil
- L_c: effective length for coil resistance
- L_i : effective length for coil inductance
- L_p : filament twist pitch
- ρ_{eff}/f_{eff} : IFCC scaling parameter for stabilizer resistivity

Undulator Magnet Study with ANL

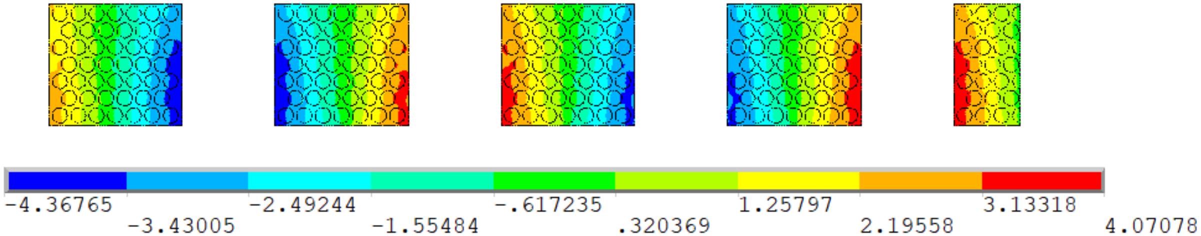
ANL Short Undulator Model

- Air
- Iron
- Glass/Epoxy
- Nb_3Sn + Cu

Custom Thermal + Magnetic



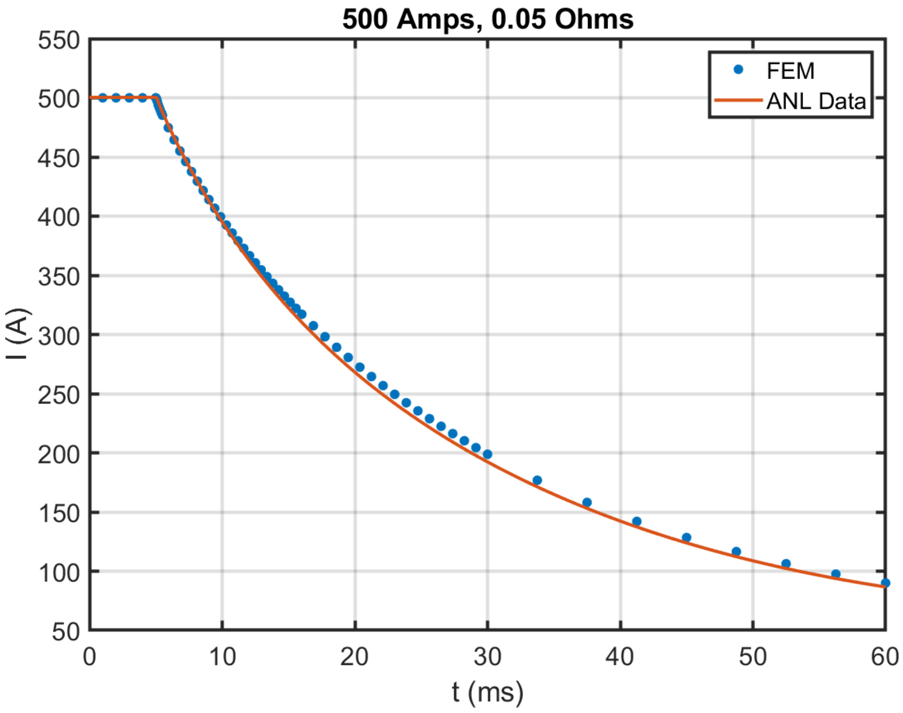
Initial y-dir flux

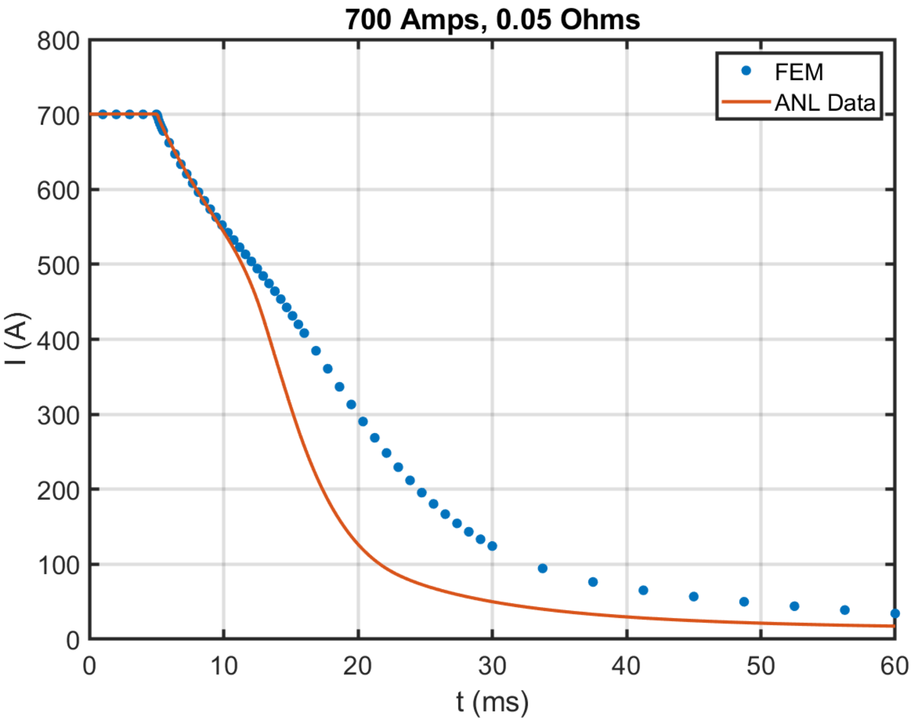


Undulator Magnet Initial Results: 50 mΩ

Initial results compared to data from Argonne

- Error increases with current

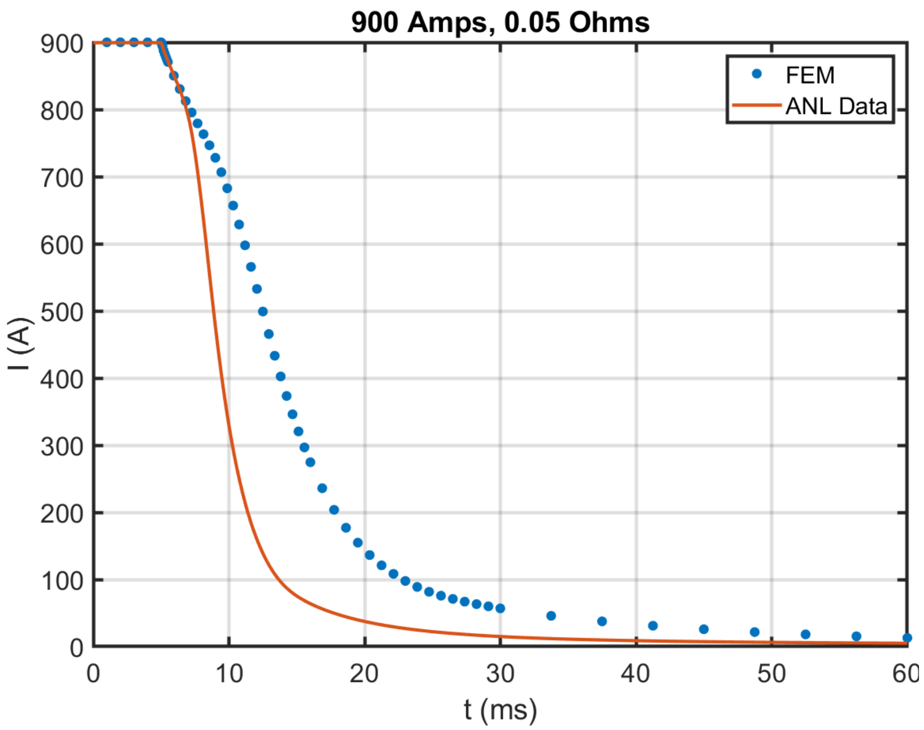


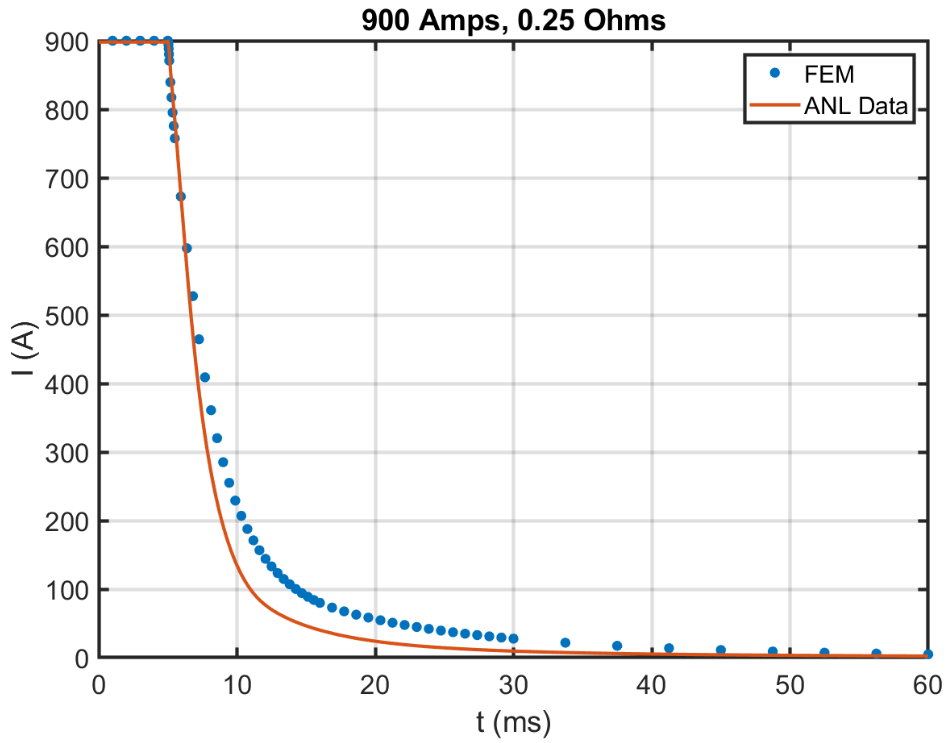


Undulator Magnet Initial Results: 900 A

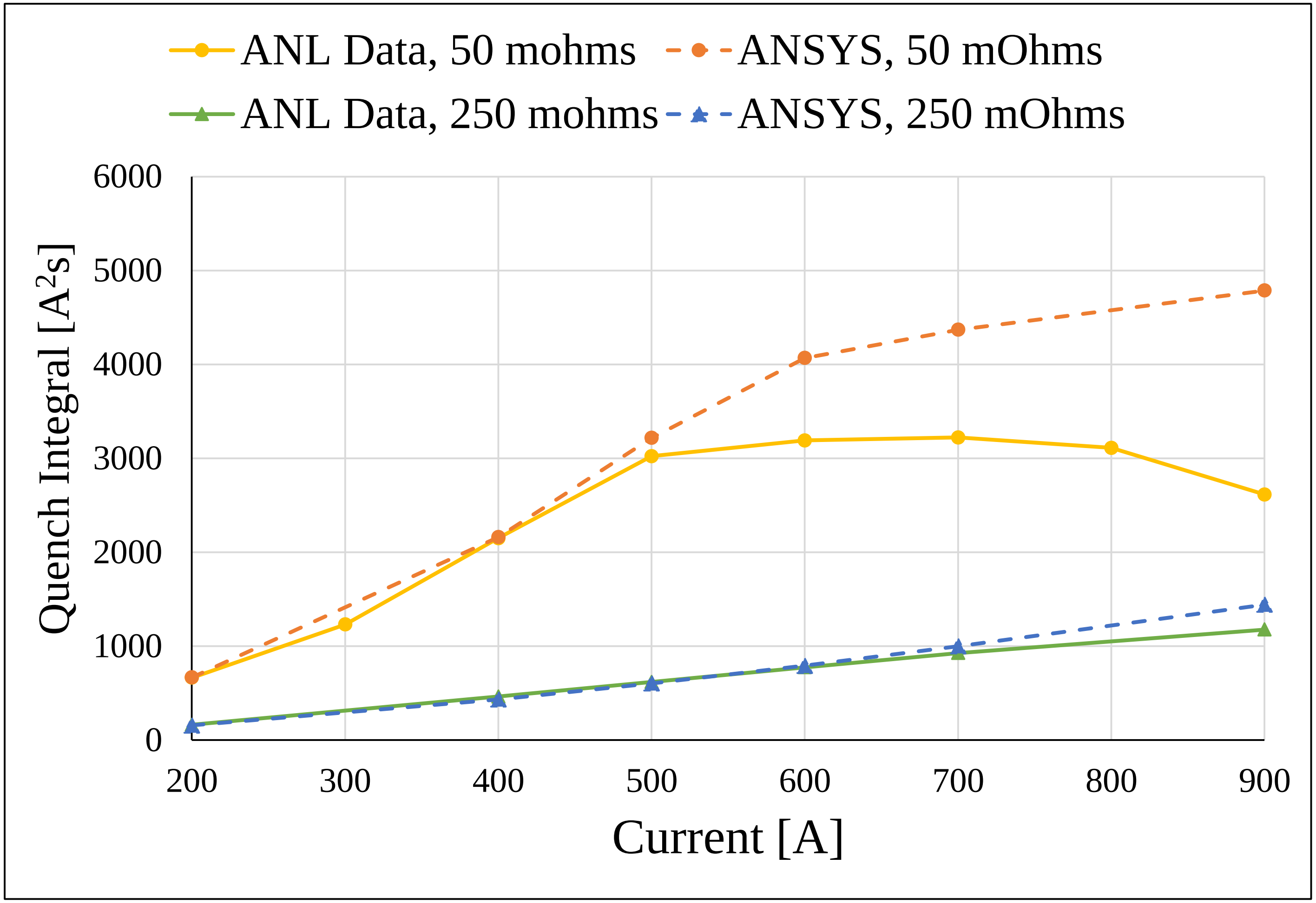
Initial results compared to data from Argonne

- Error increases with decreasing dump resistor



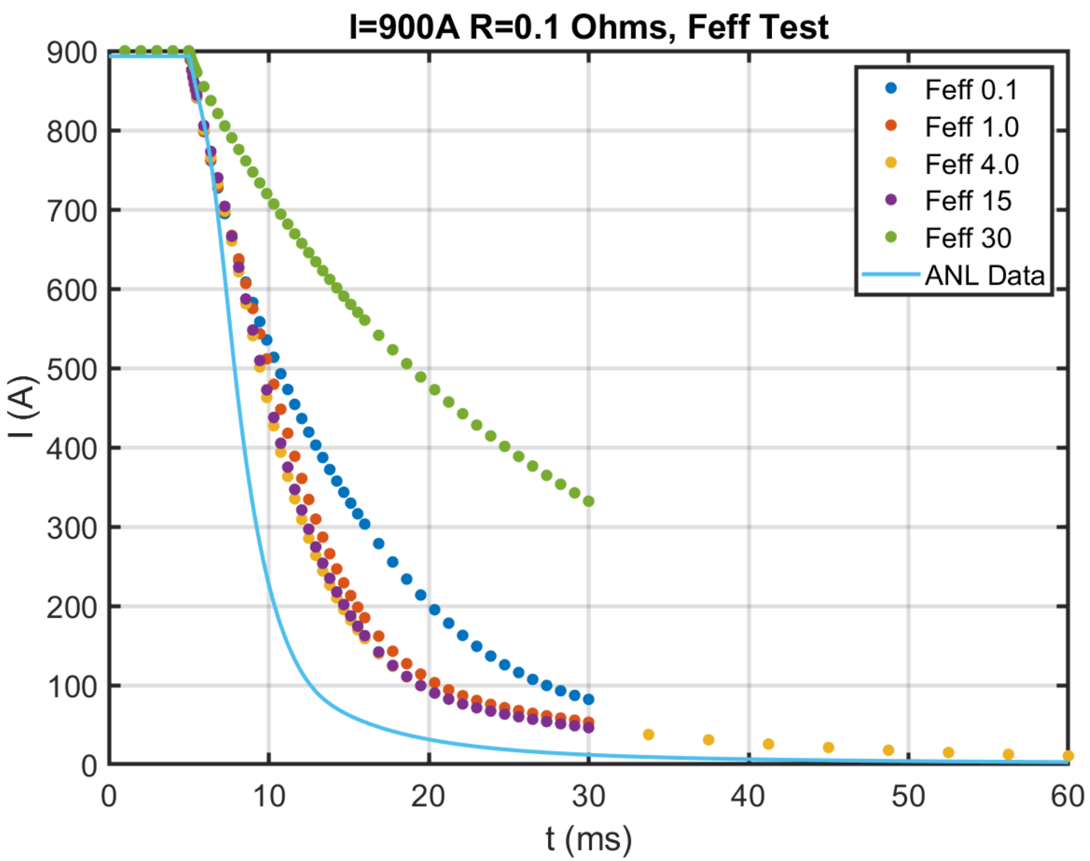


Undulator Magnet Results: Quench Integral



Undulators: Sensitivity Tests

Effect of changing the time constant scaling factor, f_{eff}



- Extremely non-linear response

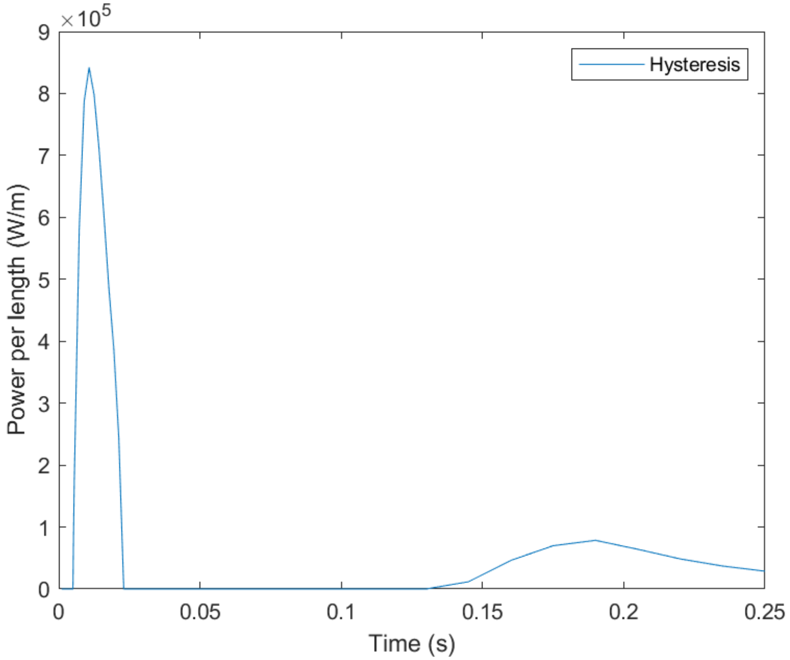
$$\tau = \frac{\mu_0}{2\boldsymbol{\rho_{eff}}}\left(\frac{L}{2\pi}\right)^2$$

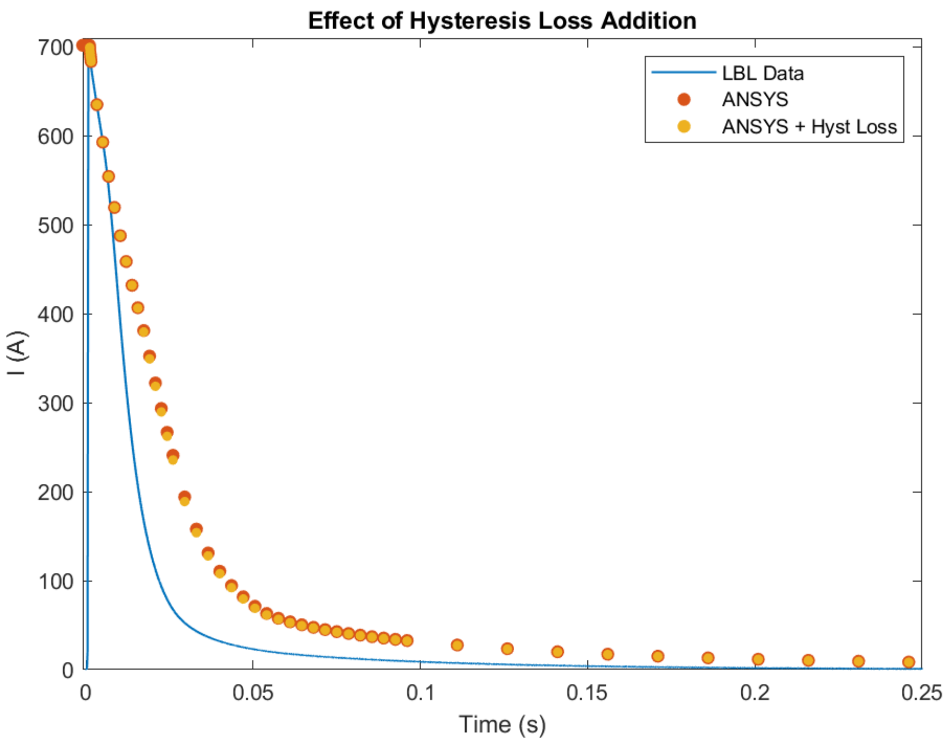
Undulators: Sensitivity Tests

Effect of adding Hysteresis losses

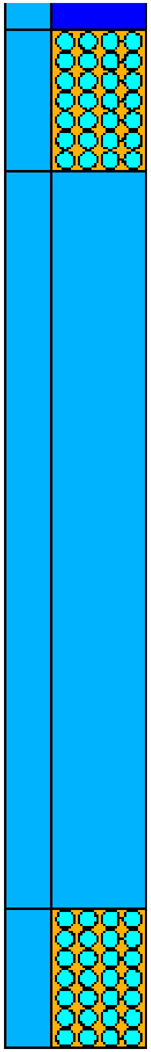
$$Q_{mag} = \frac{2}{3\pi} J_c(B,T) d_{eff} \dot{B}_t$$

d_{eff} = effective filament diameter



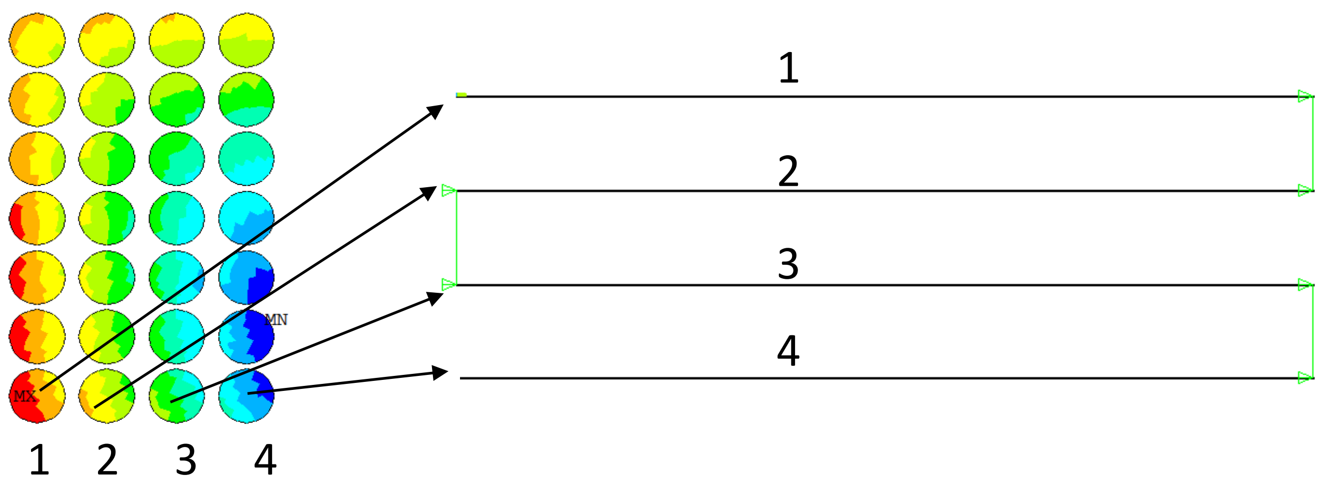


1D Quench Propagation Model



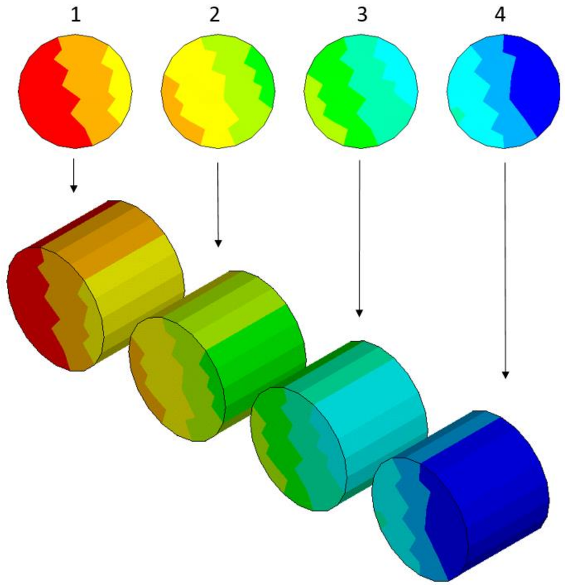
Undulator Magnet

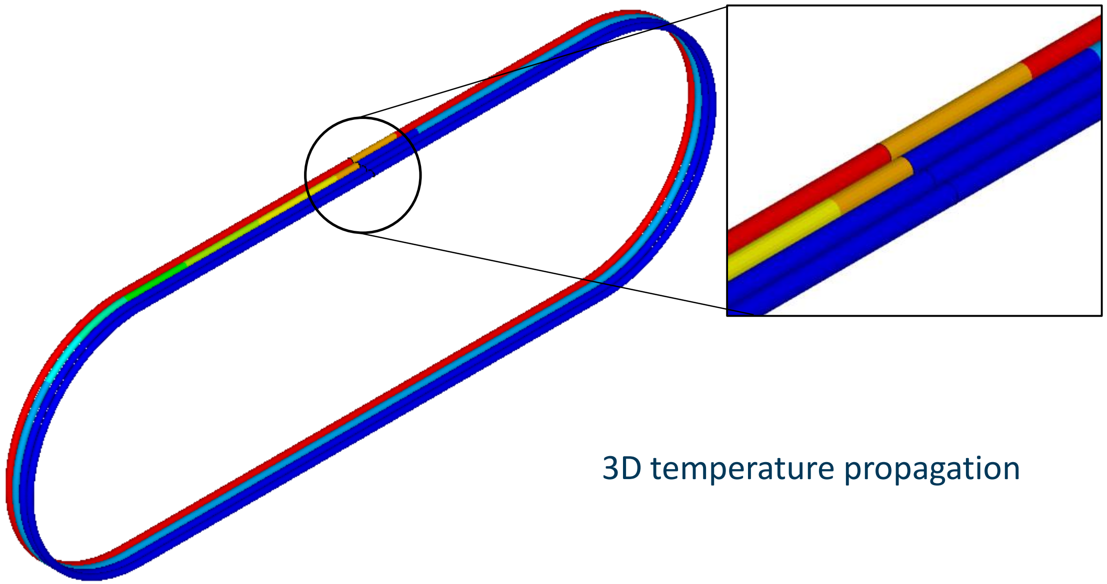
- 2D model assumes immediate quench propagation in z-direction but does not account for propagation from one strand to another
- Apply average current, field, and IFCC losses over time from 2D adiabatic case to 1D
- Calculate temperature, current sharing, quench, and resistive losses
- Couple ends of model to propagate quench



3D Quench Propagation Model

- 3D model meshed exactly as the 2D model
- 2D elemental values were applied to corresponding 3D elements
- Strands were modeled symmetrically and coupled at ends for easier geometry modeling

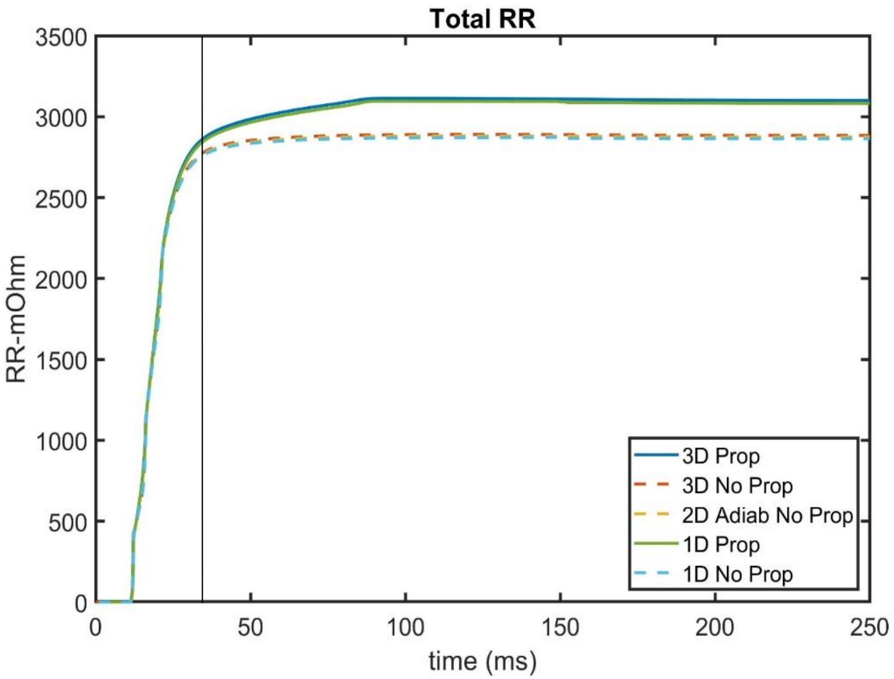


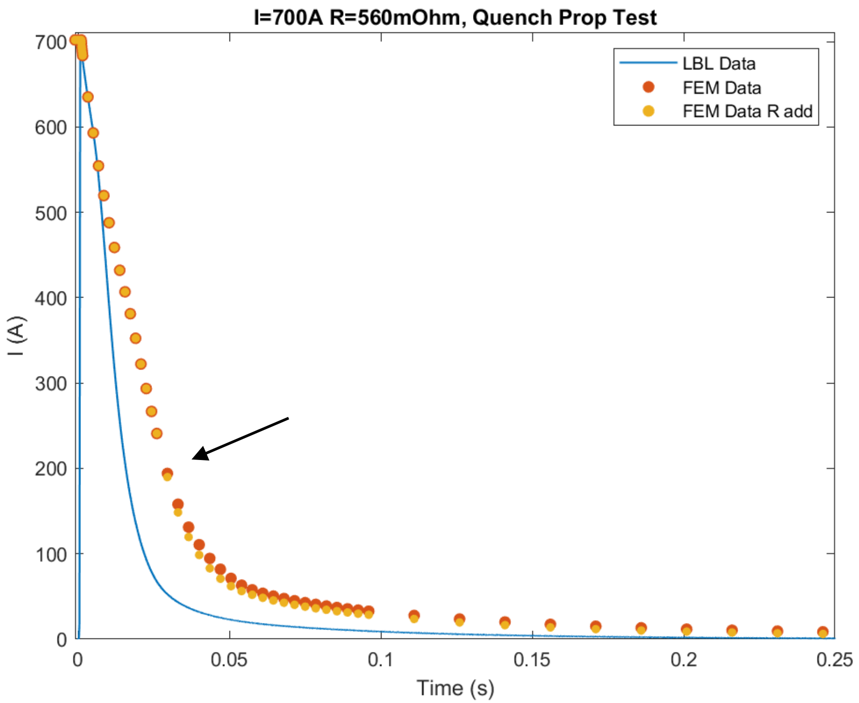


3D temperature propagation

Resistance increase from propagation added to original model

- To check the model the ends were initially left unconnected (‘No Prop’)
- Total magnet resistance measured
- Difference in resistance (240 mΩ added to 2D dump resistor around 30 ms (black line and arrow)





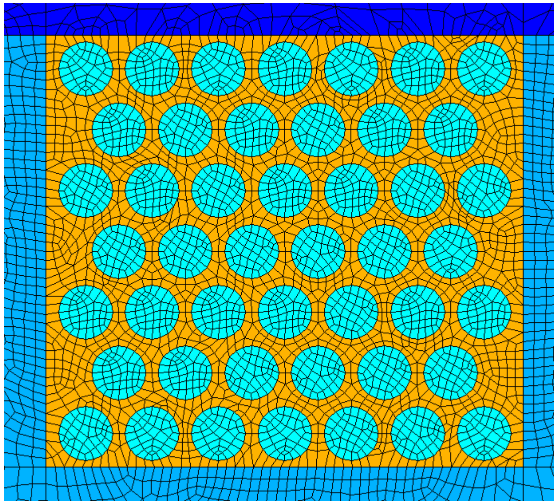
Uniform Custom Element Summary

Summary

- Thermal elements: 1D, 2D, 3D
- Magnetic elements: 2D
- Thermal elements great for quench propagation models
- Thermal + Magnetic element coupling great for accelerator magnet modeling

Future Work

- Look at possible strain effects in undulator
- Explore more detailed IFCC formulation
- Add epoxy to quench propagation study

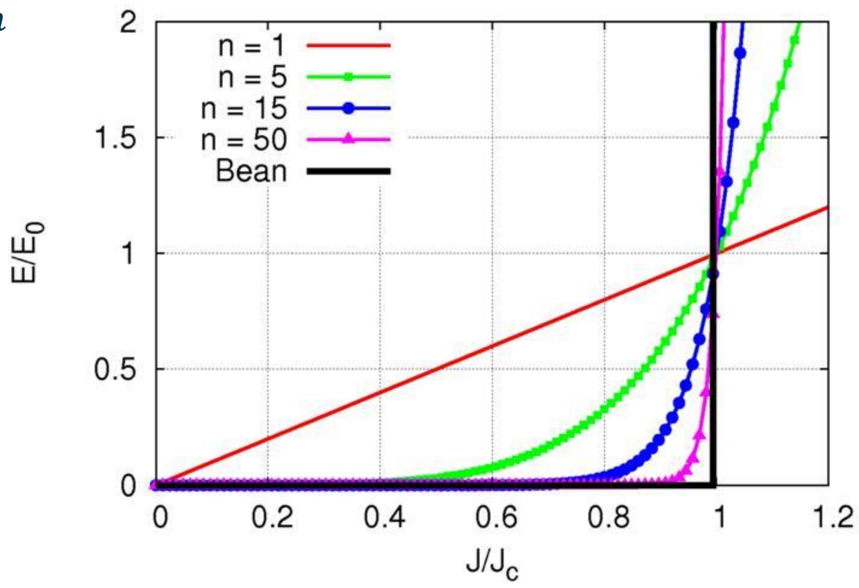


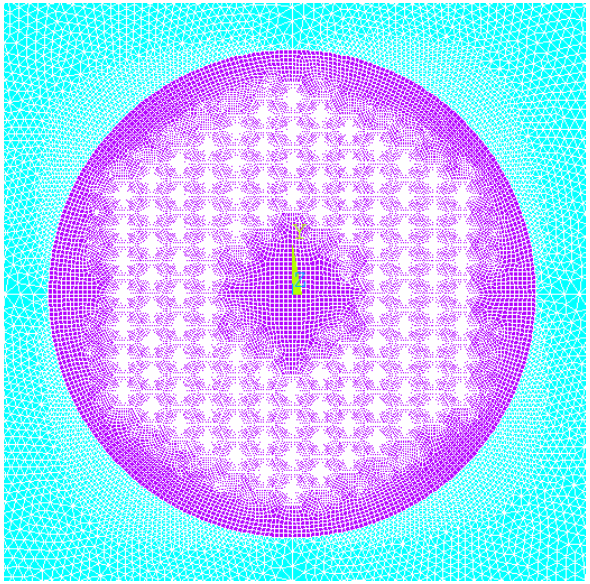
U.S. MAGNET DEVELOPMENT PROGRAM

Bulk Magnetization Elements

- Conductive paths defined in geometry/mesh
- Uses A-V formulation to model bulk superconductor
- Uses E-J power-law formulation
    - As $n \rightarrow \infty$, the model approaches critical state behavior

$$\boldsymbol{E} = \boldsymbol{E_0} * \left(\frac{J}{J_c}\right)^n$$

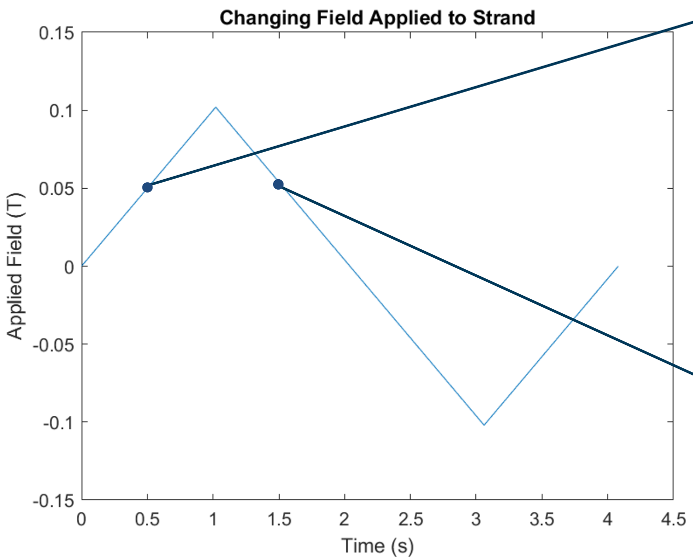


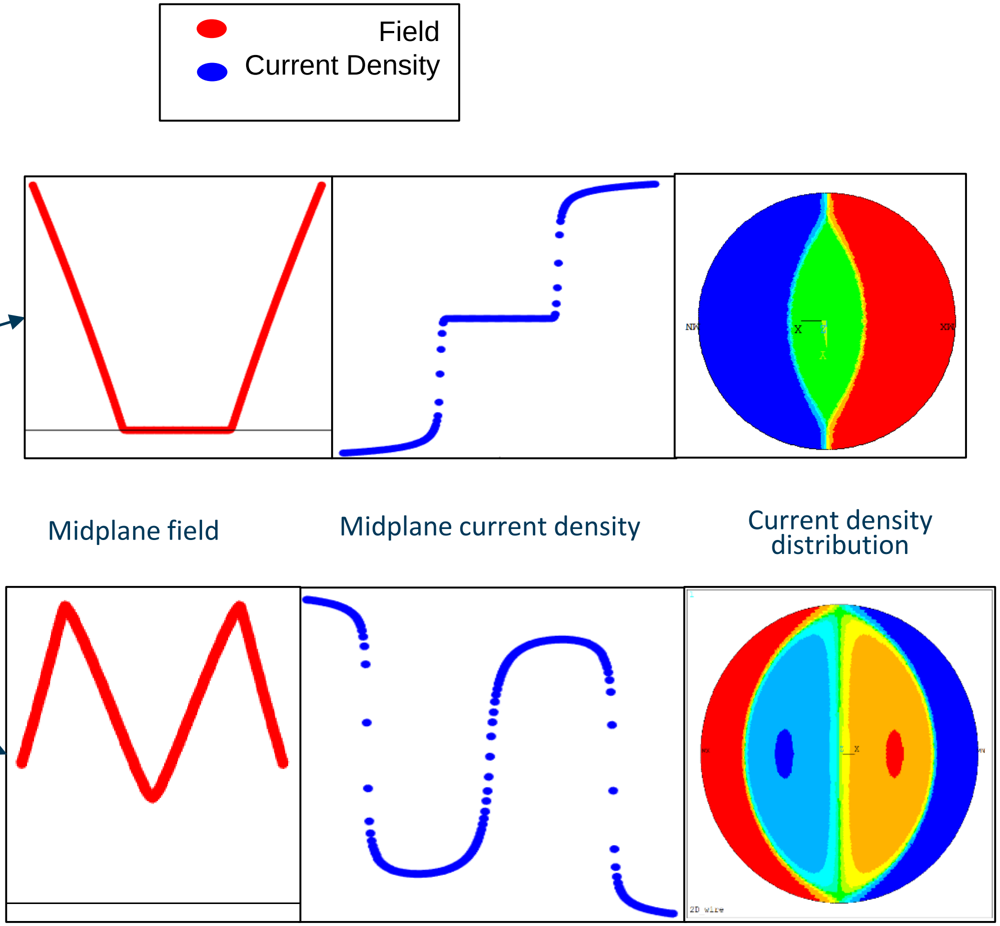


Single SC filament surrounded by air

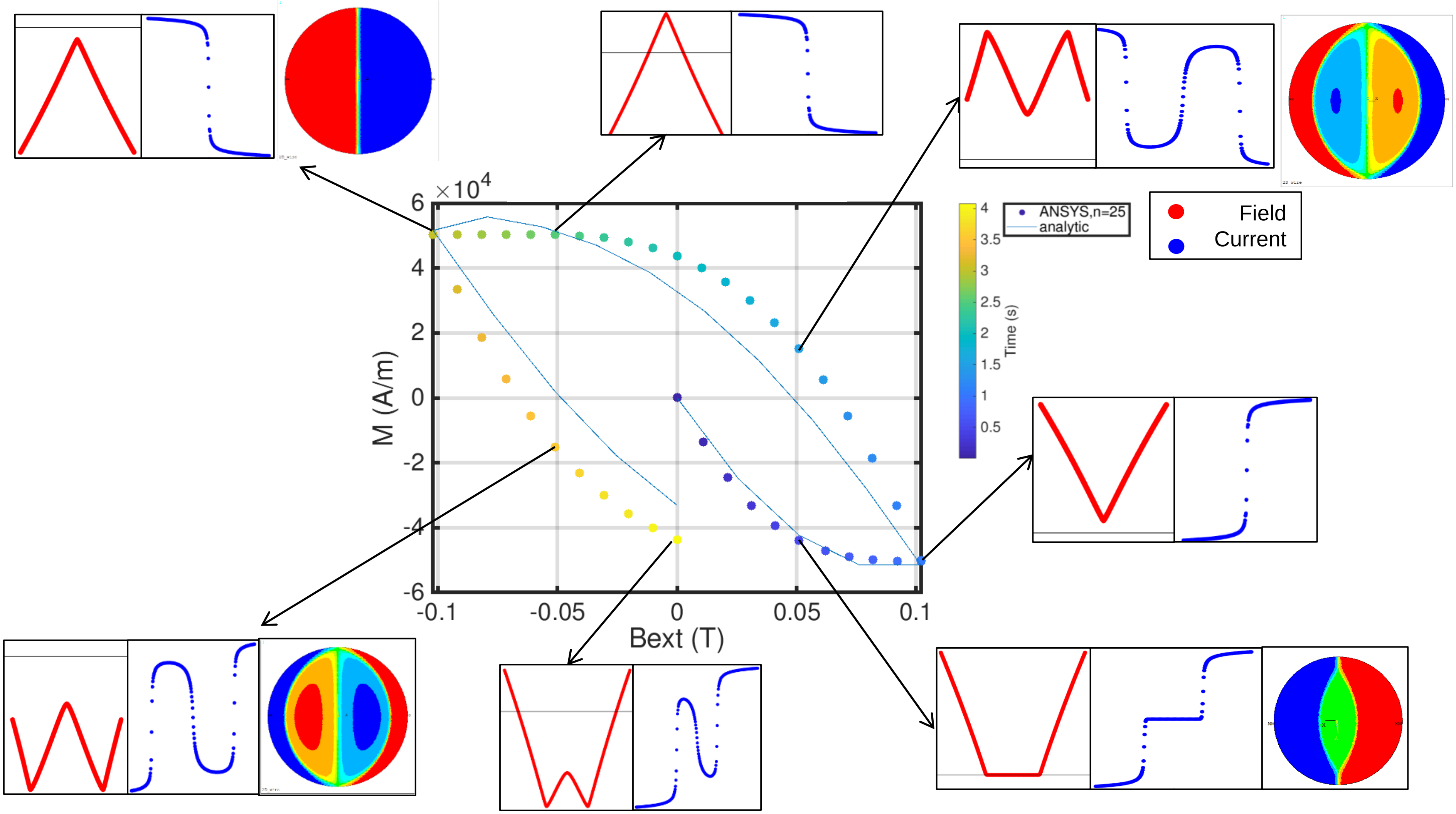
Superconducting Filament in Changing Field

- Fixed Jc = 3×10^8 with n=25
- Ramp up to full penetration field and back down to create Magnetization curve





Magnetization of Single SC Filament



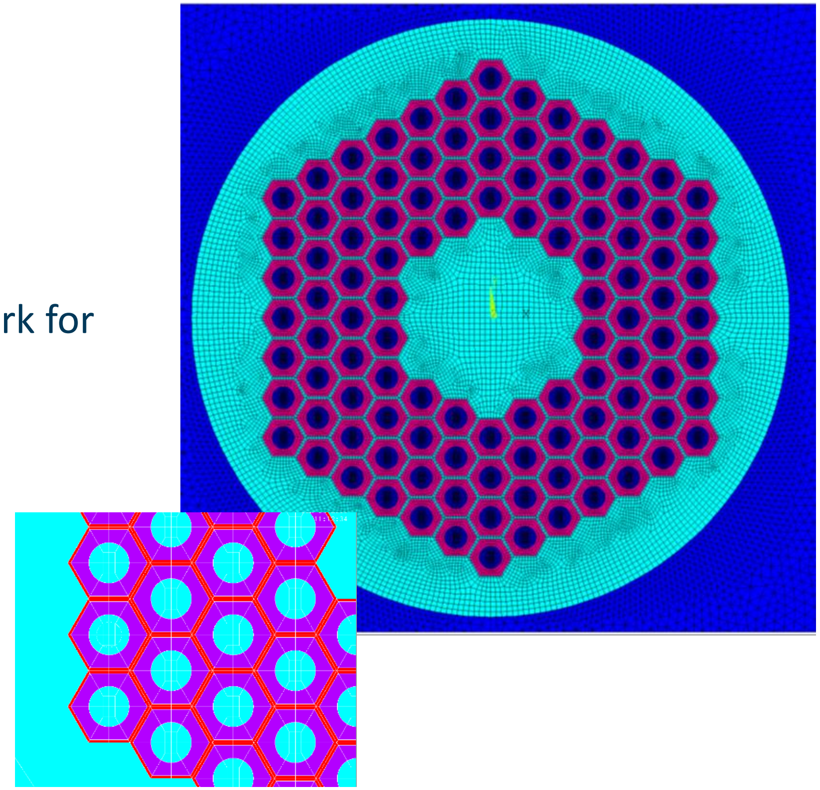
A-V Bulk Custom Element Summary

Completed

- Magnetic elements: 2D
- Magnetization studies
  - Verification of single filament
  - Reproduced HTS modeling website benchmark for bulk disc magnetization

Future Work

- Add Jc as a function of B
- Sub-strand modeling
- Dynamic modeling of HTS cables/tapes



IFCC Equations

Assumes uniform external vertical field

$$\tau = \frac{\mu_0}{2\rho_{eff}} \left(\frac{L}{2\pi}\right)^2$$

$$B_i = B_e - \tau \dot{B}_i$$

$$M_e = -\frac{2\tau}{\mu_0} \dot{B}_i$$

$$P_e = \overrightarrow{M_e} \cdot \overrightarrow{B_i}$$