User Defined ANSYS Elements for 2D & 3D Multiphysics Modeling of Superconducting Magnets

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ABSTRACT

Computational modeling of superconducting magnets allows for predicting and understanding magnet behavior. The commercial software ANSYS is a widely used finite element software for mechanical, thermal, and electromagnetic modeling of superconducting magnets. ANSYS also allows its user to create custom elements by programming the elements' properties and finite element matrices. These user elements can capture additional material properties and physics that current ANSYS elements do not. Once compiled, they are then compatible with all other aspects of the software, including geometry generation, meshing, solving, and post-processing. Additionally, these elements can be coupled and used with the multiphysics solver. We have developed two element types: one which uniformly models a superconducting strand and used for modeling entire magnets, the other which uses the A-V formulation to model bulk superconductor. Here we present simulation results using both elements: modeling a Nb_3Sn Undulator from Argonne National Lab and reproducing the magnetization curve for a superconducting filament in a changing background field.

Overview of Custom Elements

Keep all features of standard ANSYS ...
- Modeler, mesher, post-processor
- Transient electromagnetic and thermal solvers
- Multi-physics solver
- External circuit coupling

Create new elements by
- Writing code to generate FEM matrices, element properties
- Compiling custom version of ANSYS

... and add what is missing with user elements
- Interfilament coupling currents using equivalent magnetization [1]
- Current sharing + quench loss
- Coupling to thermal model with T, B, dependent material properties

Element Uses and Completed Studies

Uniform Stranded Elements
- Dipole magnets (dump resistor and CLIQ)
  - Verified with COMSOL and STEAM developed at CERN
- Quenchback in Nb_3Sn Undulators
- Quench propagation studies

A-V Conductor Elements
- Verification of single filament magnetization
- Reproduced HTS modeling website benchmark for bulk disc magnetization

References

[1] M. Wilson, *Superconducting Magnets*. Oxford University Press, 1983.

[2] T. Ogasawara, Y. Takahashi, K. Kanbara, Y. Kubota, K. Yasohama, and K. Yasukochi, "Transient field losses in multifilamentary composite conductors carrying dc transport currents," *Cryogenics*, vol. 20, no. 4, pp. 216-22, 1980.

Acknowledgements

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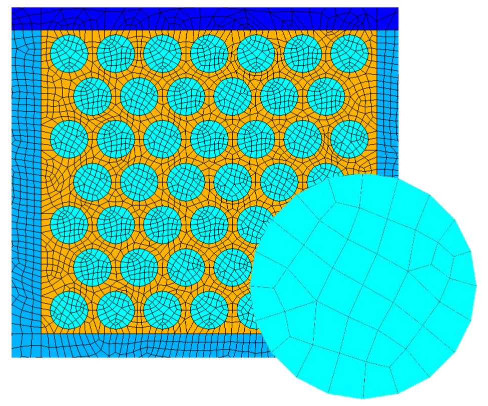
Uniform Strand Elements

Custom elements for large scale modeling
- Uniform modeling of superconducting strand
- Current density uniform through strand
- Couple custom thermal and magnetic
- Useful for modeling entire magnets



Thermal Element
- DOF: temp
- Material properties with temp, RRR, B, quench state

Given *B* and *I*
- Quench state, current sharing
- Heating from quench

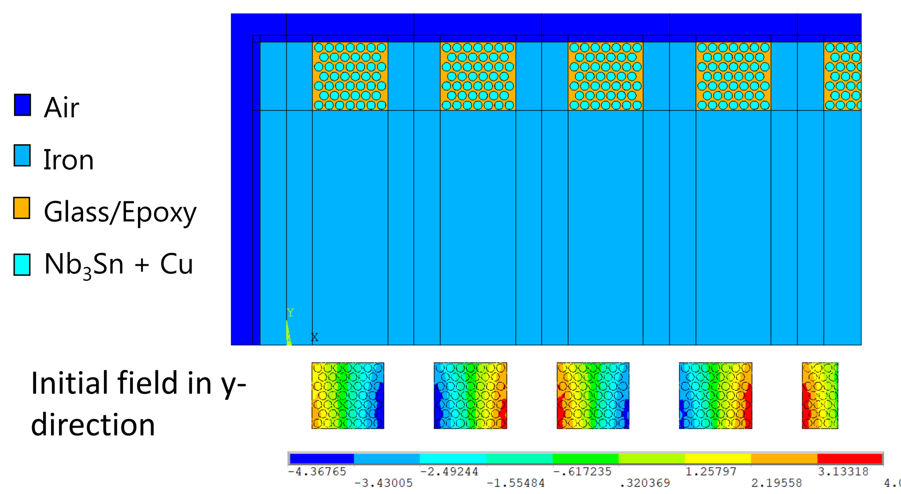
temp →

← Joule heating, B, quench state

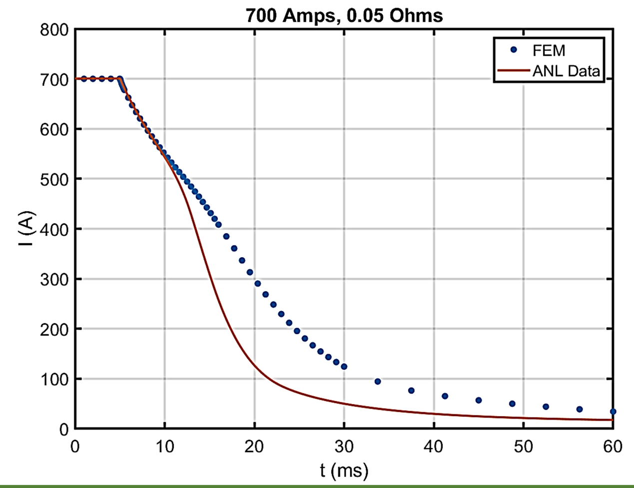
Magnetic Element
- DOF: A_z, I, emf
- Circuit coupling or applied current density
- Material properties with temp, RRR, B, quench state
- IFCC via equivalent magnetization [1]
- Quench state, current sharing
- Loss from quench, IFCC, hysteresis

Modeling of Nb_3Sn ANL Undulator with 2D & 3D Custom Elements

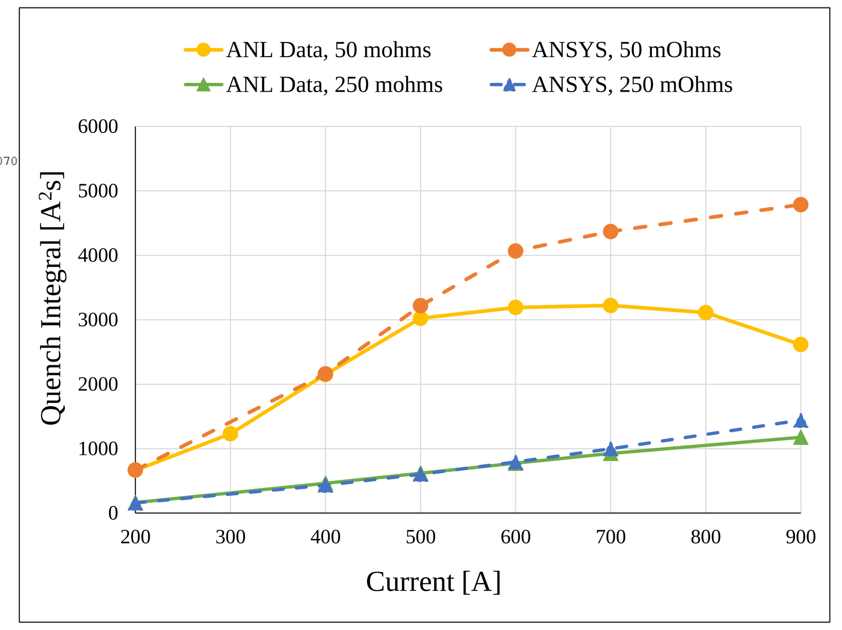
ANL Short Undulator Model



Original Model
The initial element model did not match data from ANL at currents above 500 A

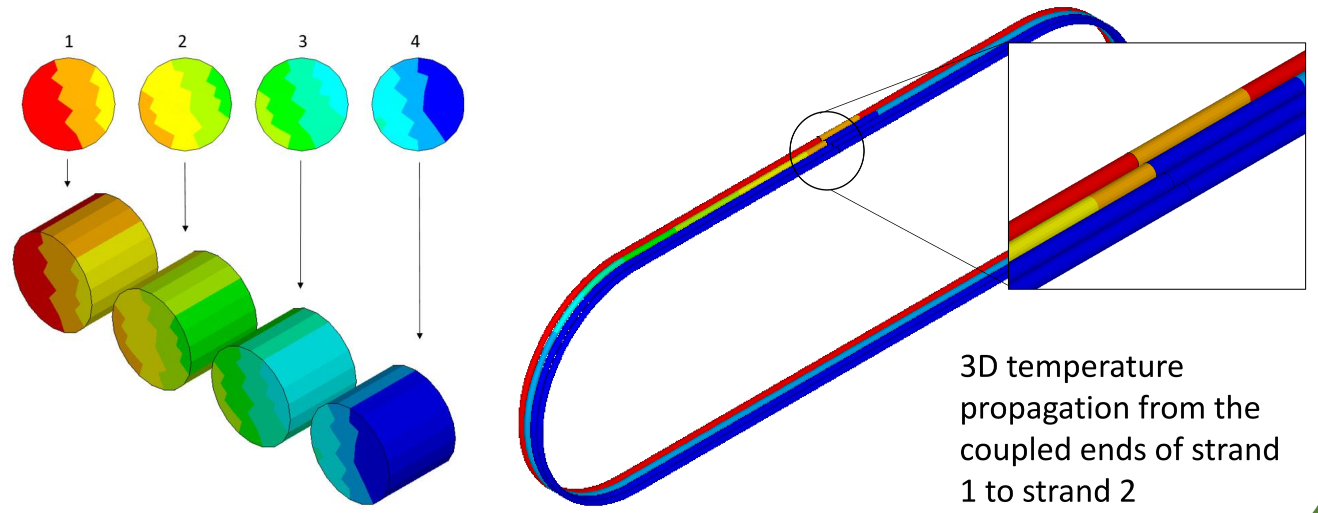


Aim
Predict current decay for undulators at ANL to improve design of quench protection system and ensure a low hot spot temperature



Sensitivity Tests
- Mesh size
- Time stepping
- Cu resistivity fits
- Increased end field
- Eddy currents
- Quench propagation
- IFCC time constant
- Hysteresis losses
- Reduce epoxy thermal cond.

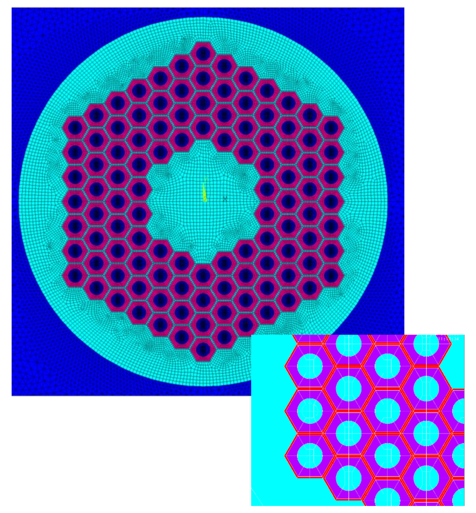
Quench Propagation Tests
The magnetic loads from the 2D simulation were applied to a 3D thermal model. Little change in the current decay was seen.



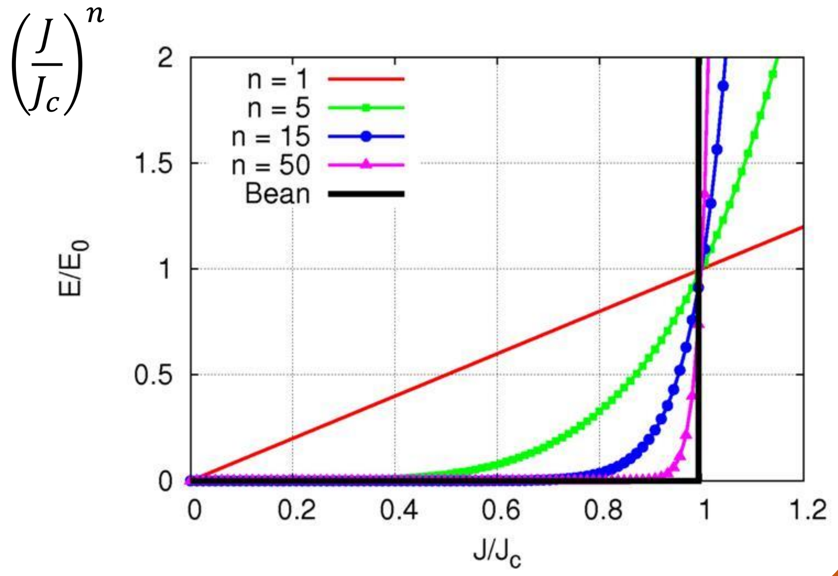
3D temperature propagation from the coupled ends of strand 1 to strand 2

A-V Filament Elements

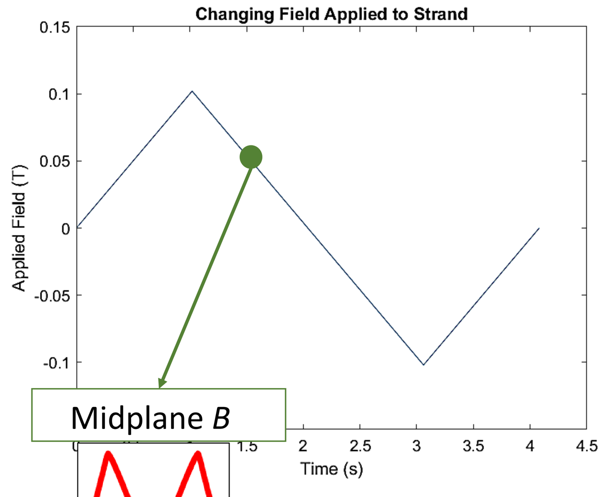
Custom element for bulk SC
- Conductive paths defined in geometry/mesh
- Uses A-V formulation to model bulk superconductor
- Uses E-J power-law formulation
  - As $n \to \infty$, the model approaches critical state behavior



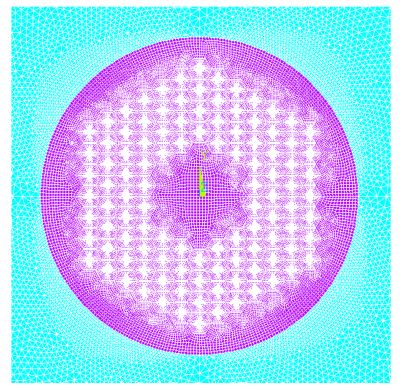
$$E = E_0 * \left(\frac{J}{J_c}\right)^n$$

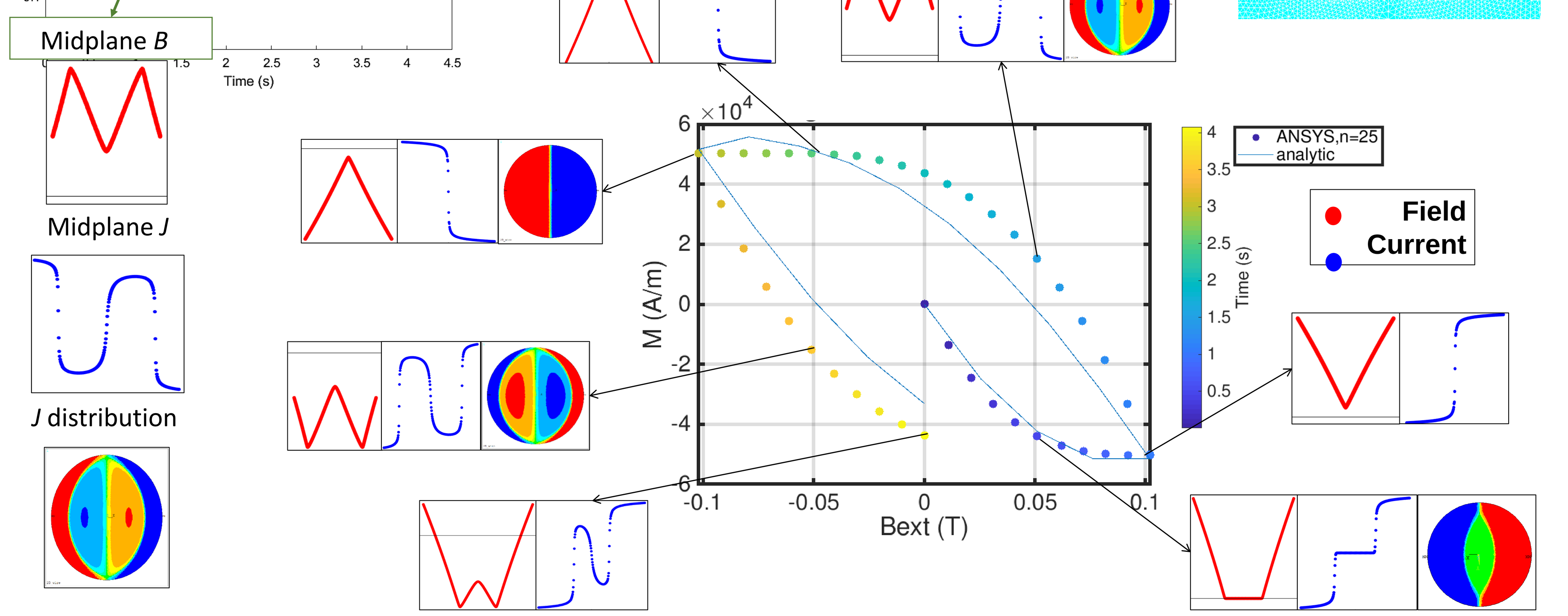


Single SC Filament Magnetization in Changing Background Field



- Fixed Jc = 3x10[8] with n=25
- Ramp up to full penetration field and back down
- Shielding current classic elliptical shape
- Smallest error where *J* changes sign only once





Final Results: transport current + no current sharing

- The addition of transport current loss [2], had the most effect on the result.

$$Q_{new} = (1 + i^2)Q_{tot}$$
$$i = \frac{I}{I_c}$$

- By removing current sharing from the model, forcing a faster quench, the model shows the best results.
- New model can better predict hot spot temperature for the ANL undulator.