Use of FEM in the Design of an HTS Insert Coil for a High Field NMR Magnet

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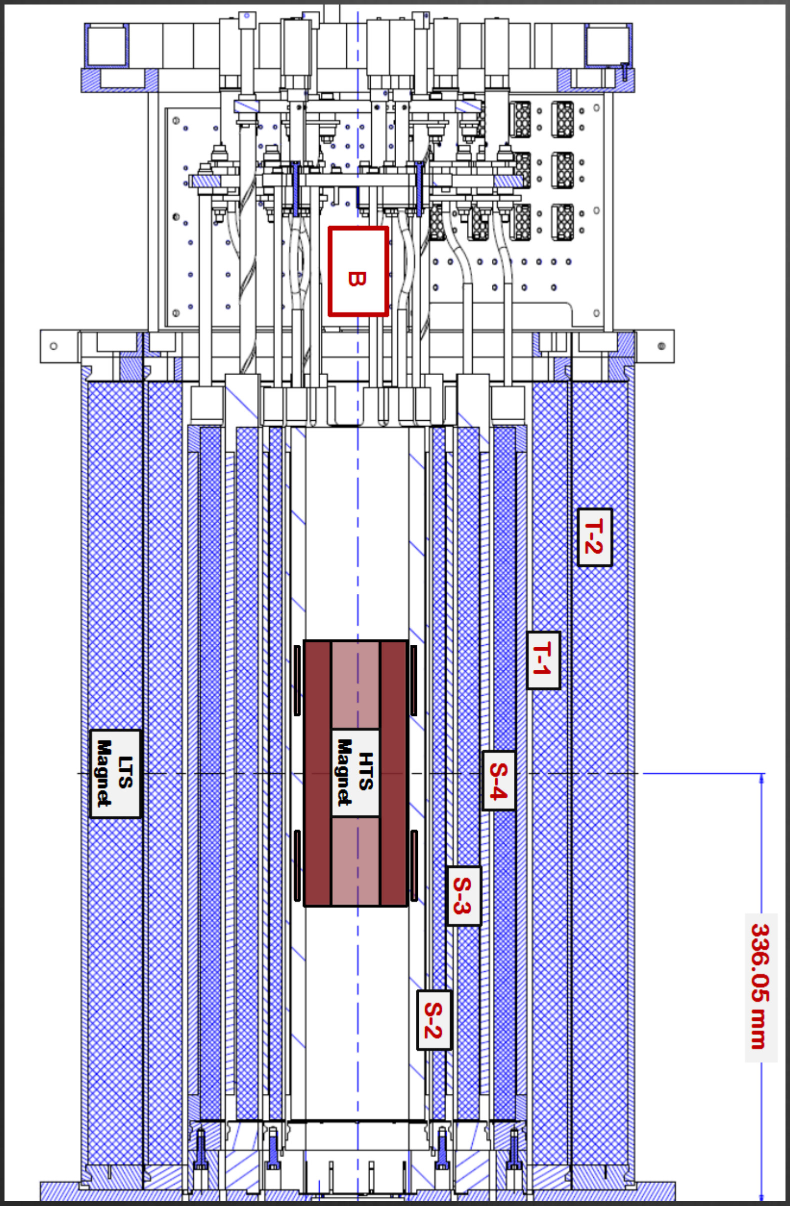
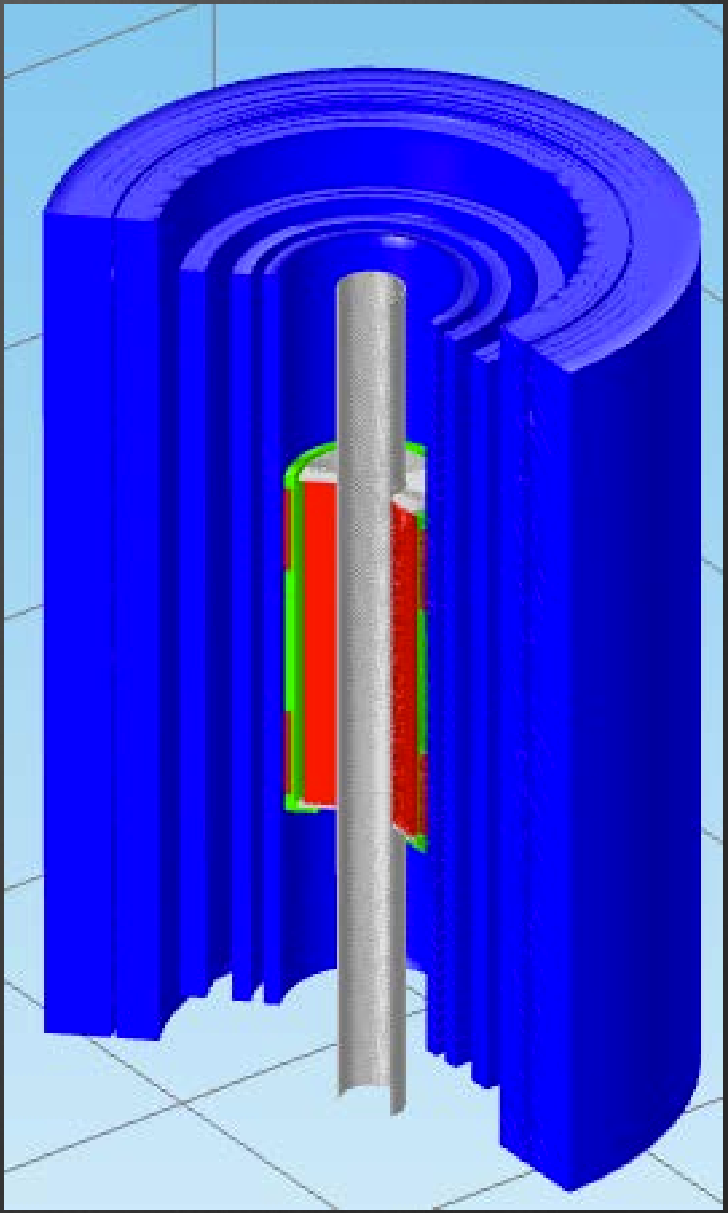
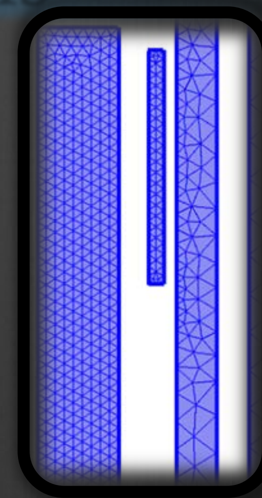
COMSOL CONFERENCE 2014 BOSTON

Platypus: An HTS NMR Magnet System





‘As Designed’ Magnetic Field Analysis



2D-axisymmetric geometry

- Low Temperature Superconductor (LTS)
  NbTi and Nb_3Sn
- High Temperature Superconductor (HTS)
  Bi2212 round wire

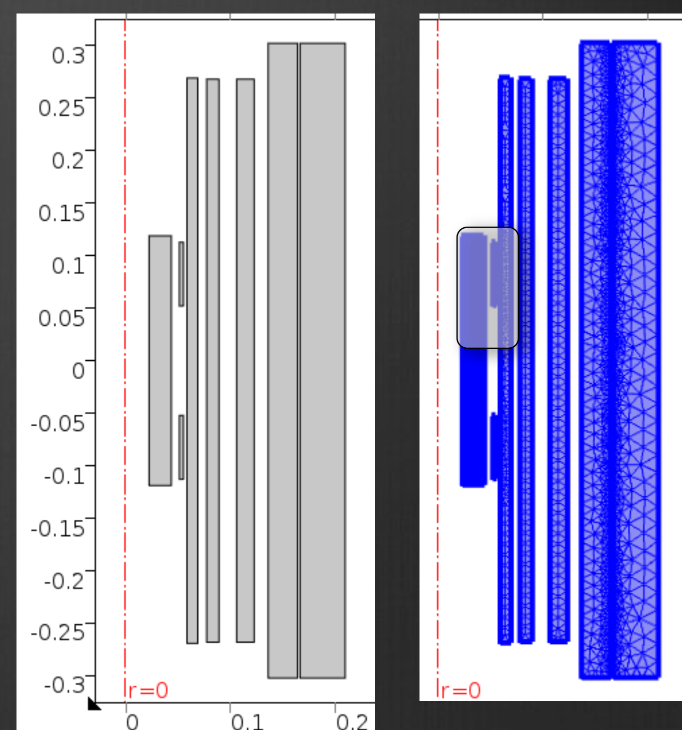
Magnetic Fields (mf) interface:

- General PDEs

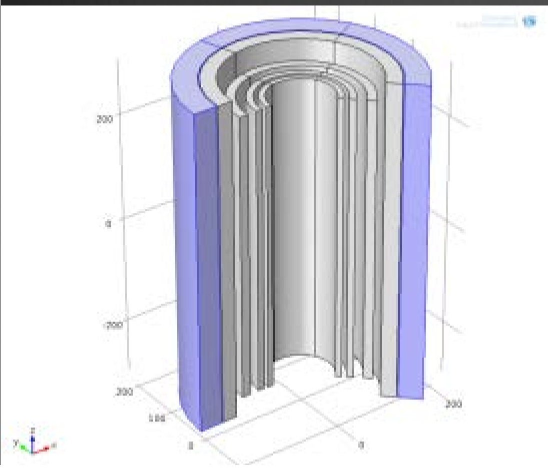
$$\nabla \times \mathbf{H} = \mathbf{Je}$$

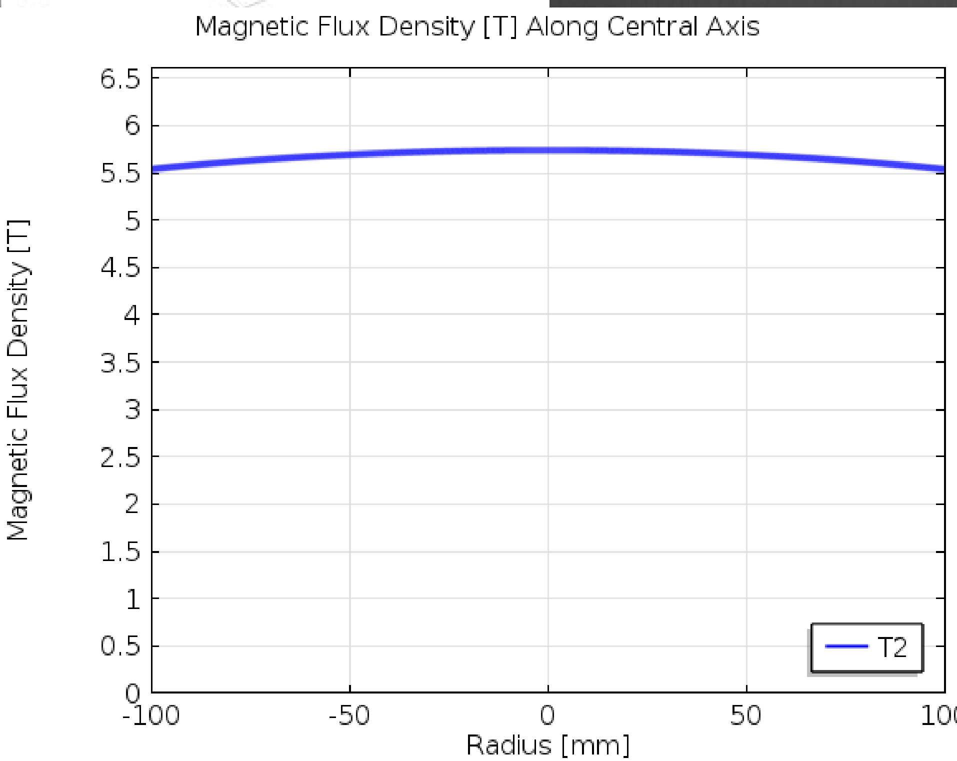
$$\mathbf{B} = \nabla \times \mathbf{A}$$

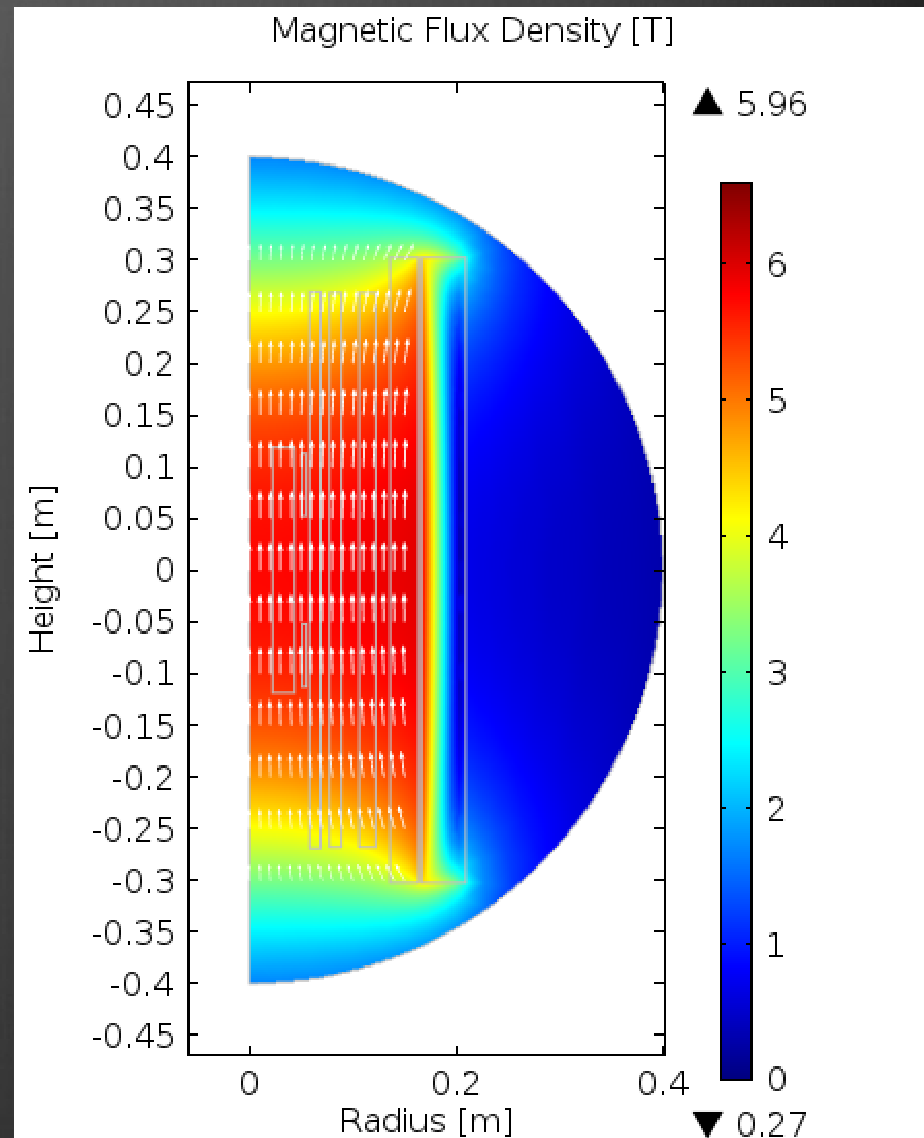
- Current (*I*) to coils
  LTS 137 A
  HTS 400 A
  Center: n =179, m =18
  Compensation: n = 46, m = 3
  with J_w defined as $I \cdot m \cdot n / area$
- Far field evaluated with perfect conductor



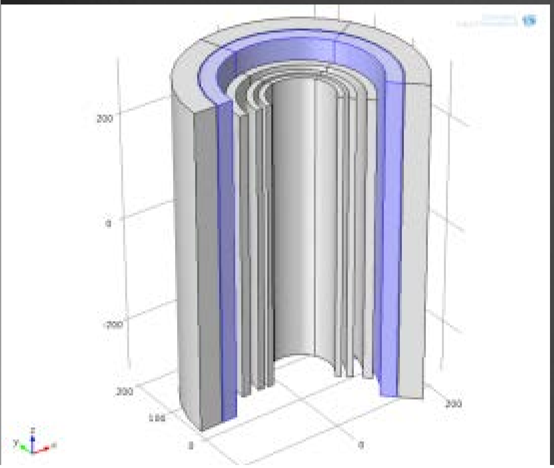
‘As Designed’ Magnetic Field Maps (LTS)

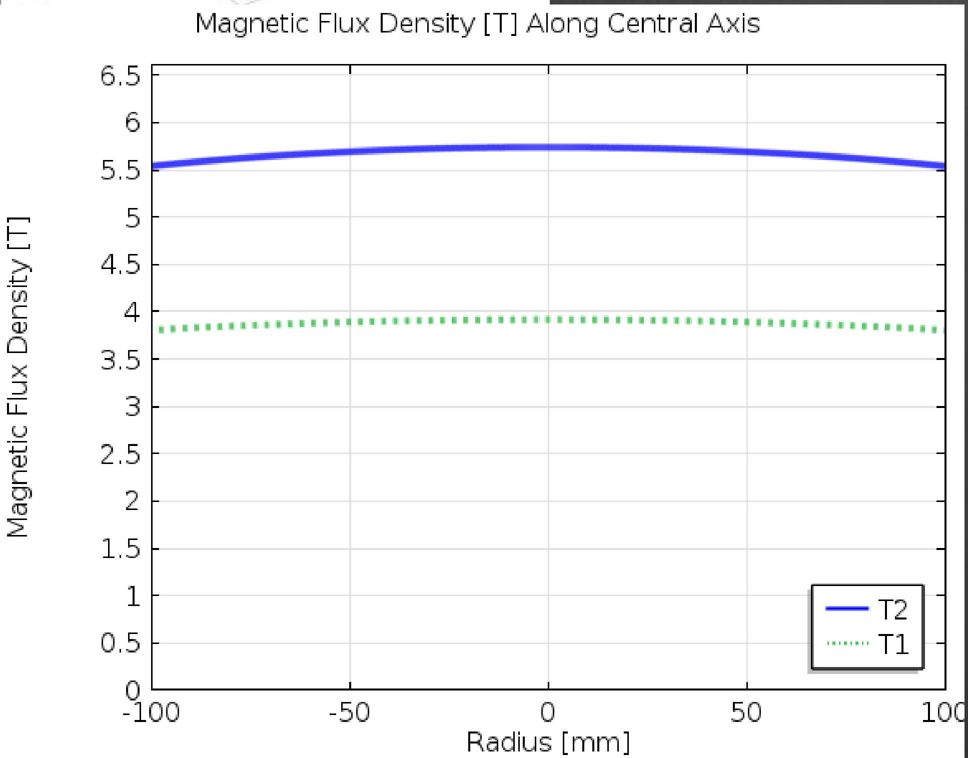


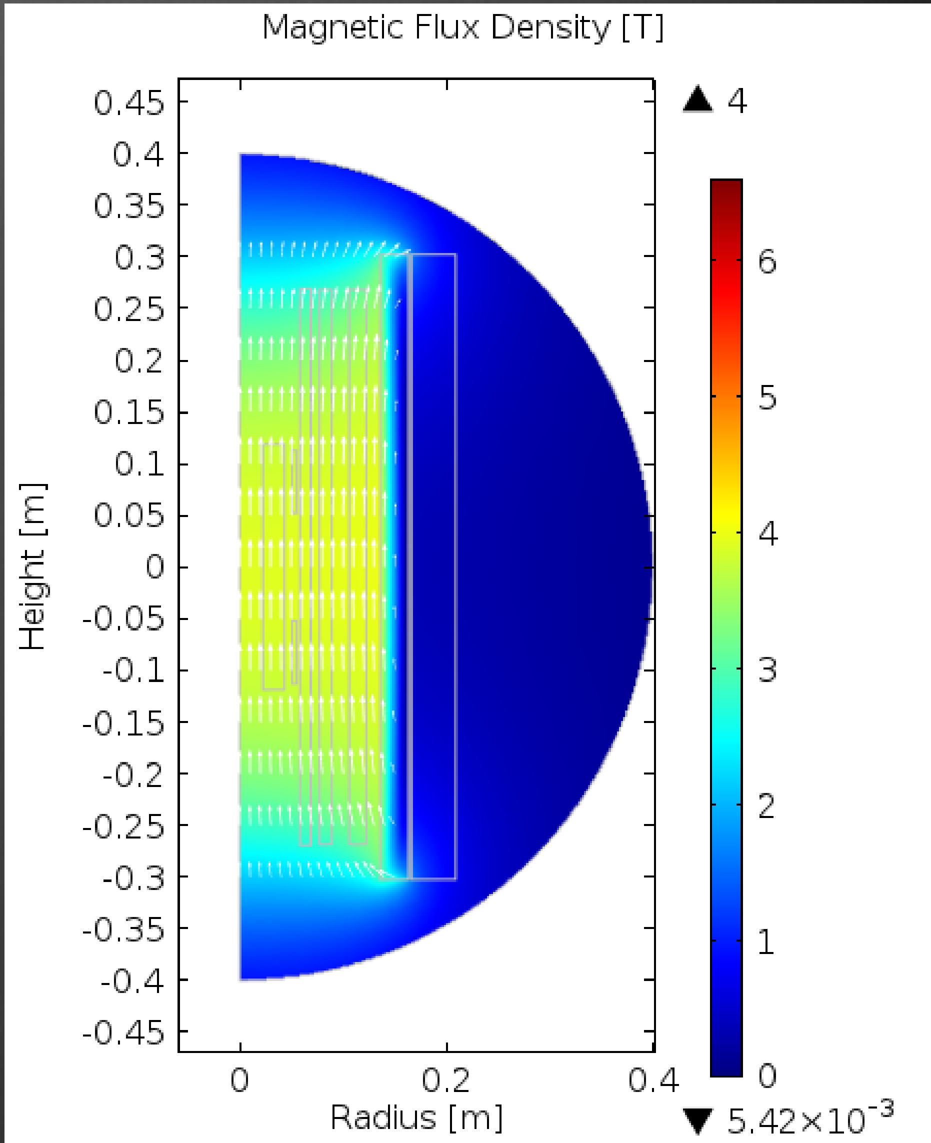




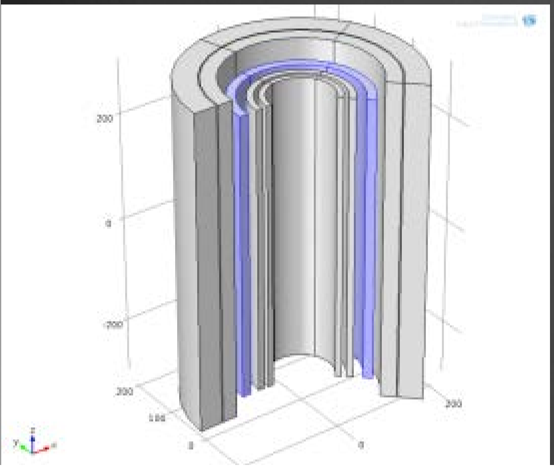
'As Designed' Magnetic Field Maps (LTS)

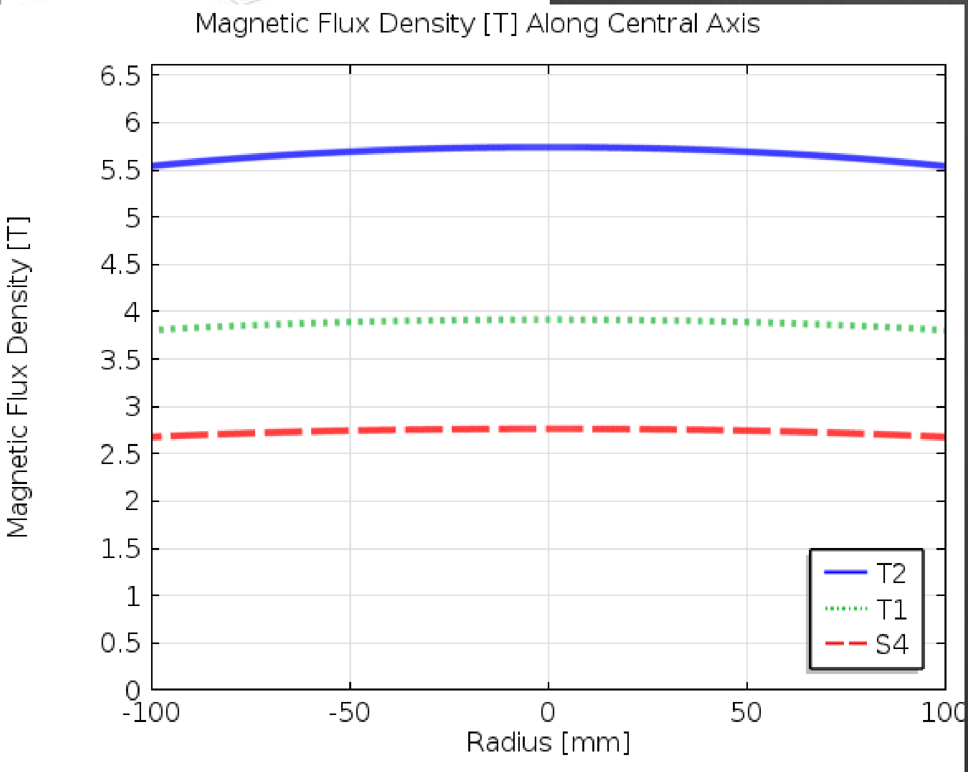


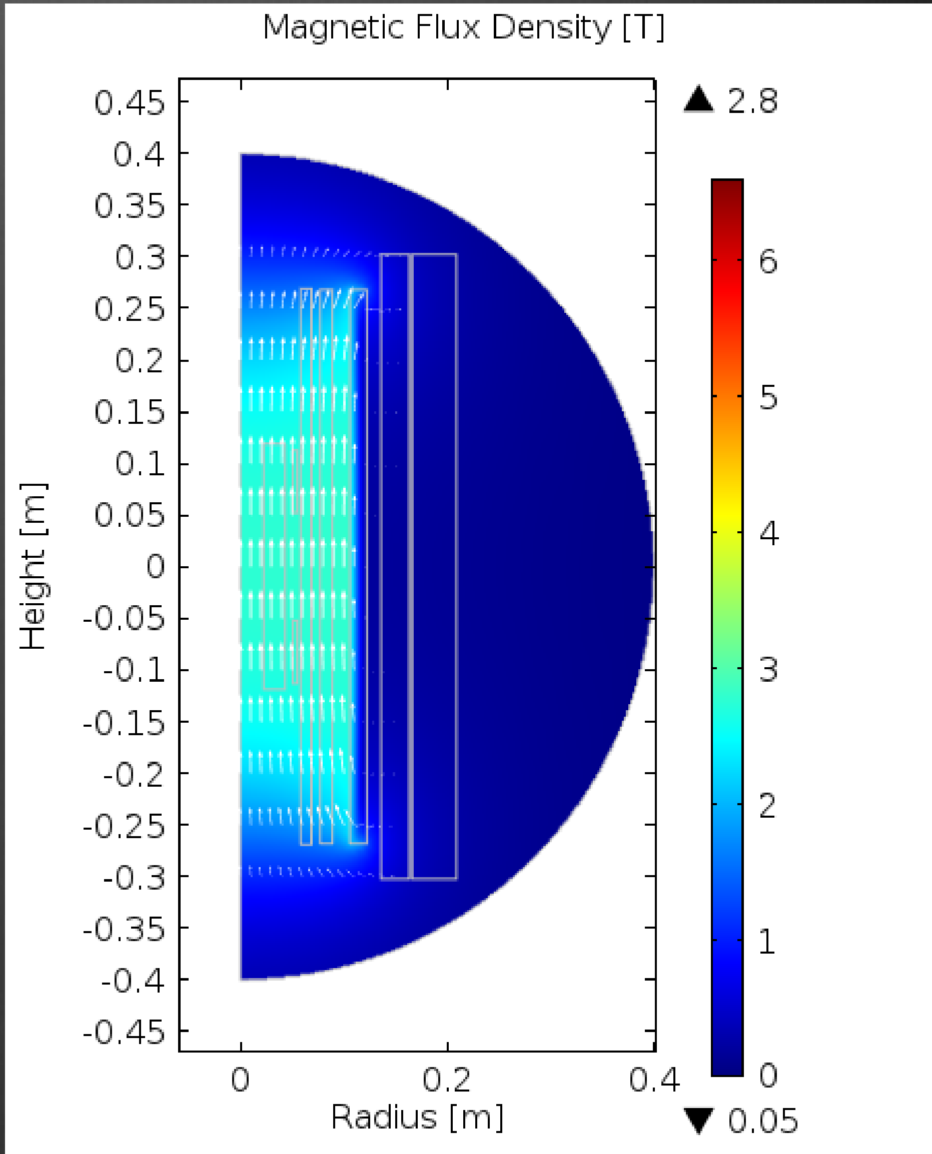




‘As Designed’ Magnetic Field Maps (LTS)







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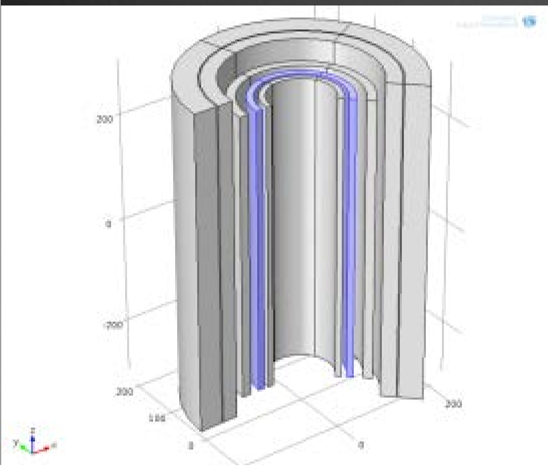

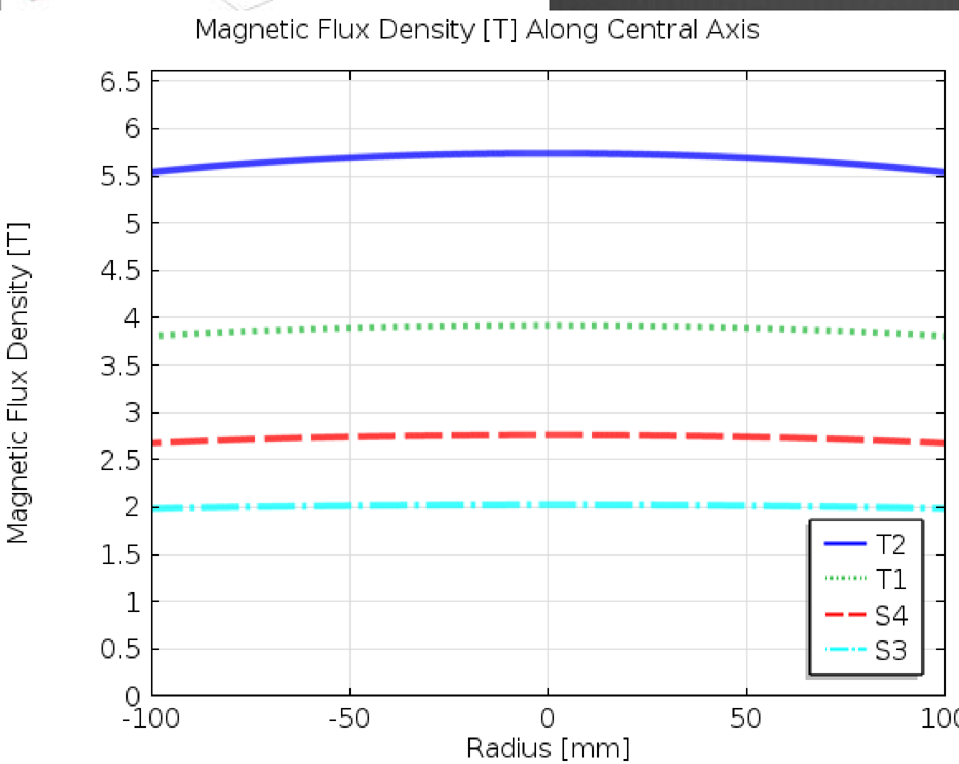

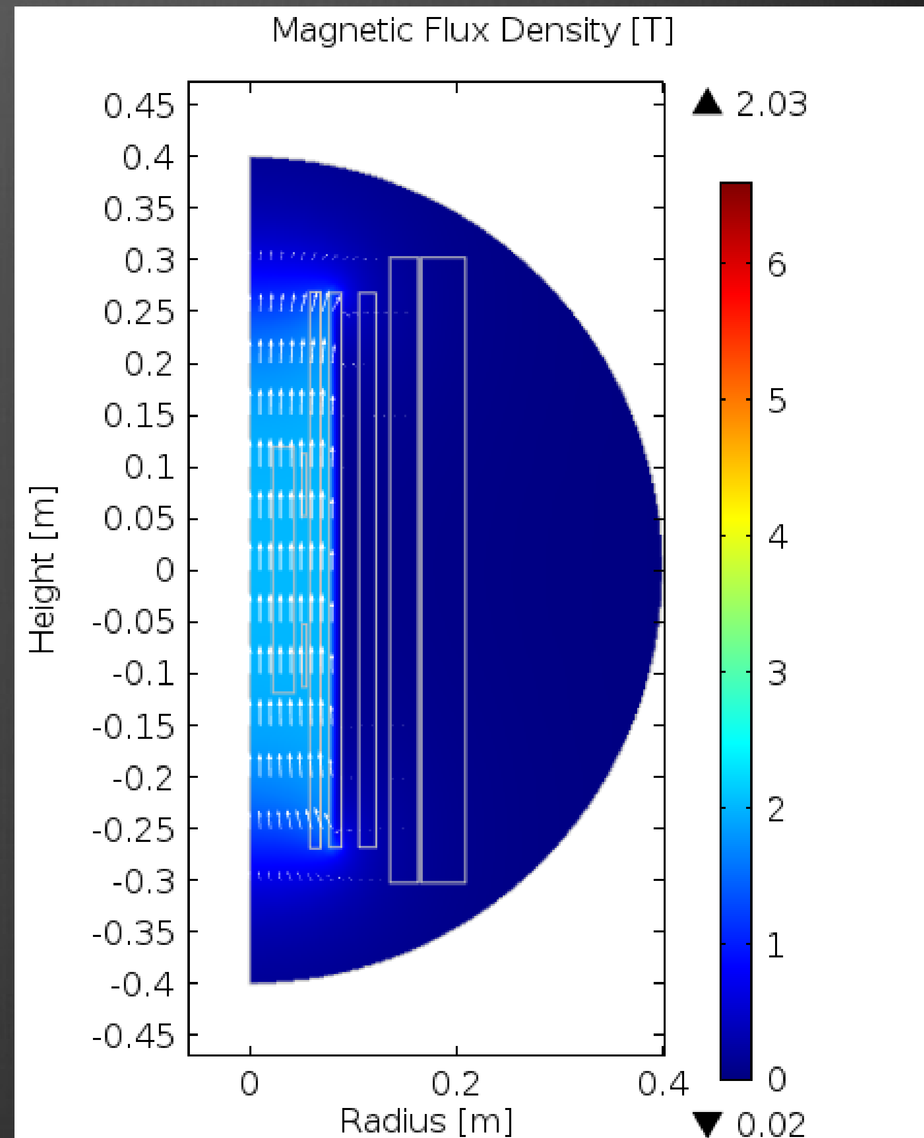

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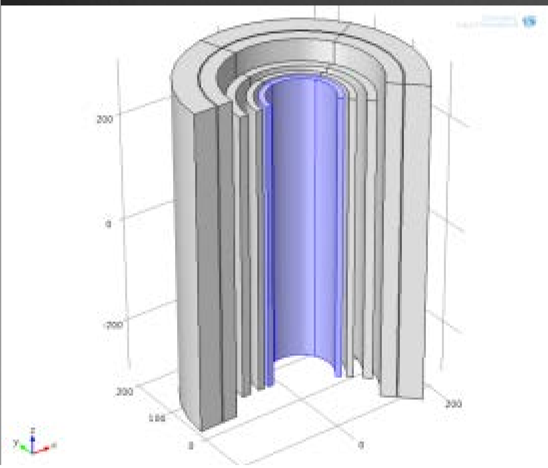
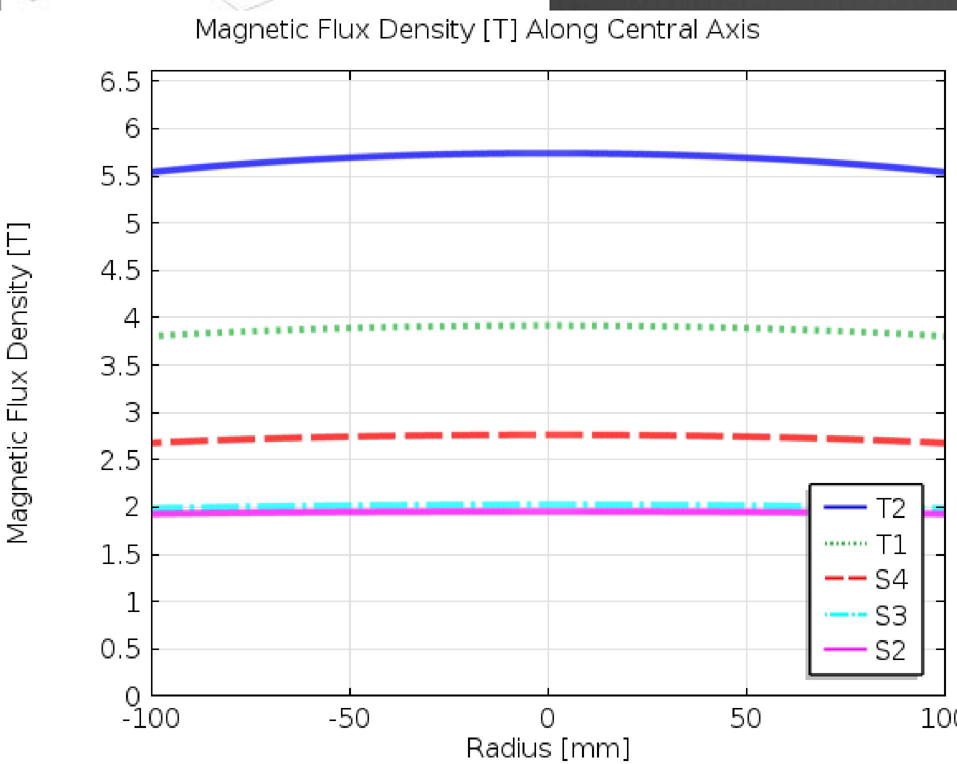
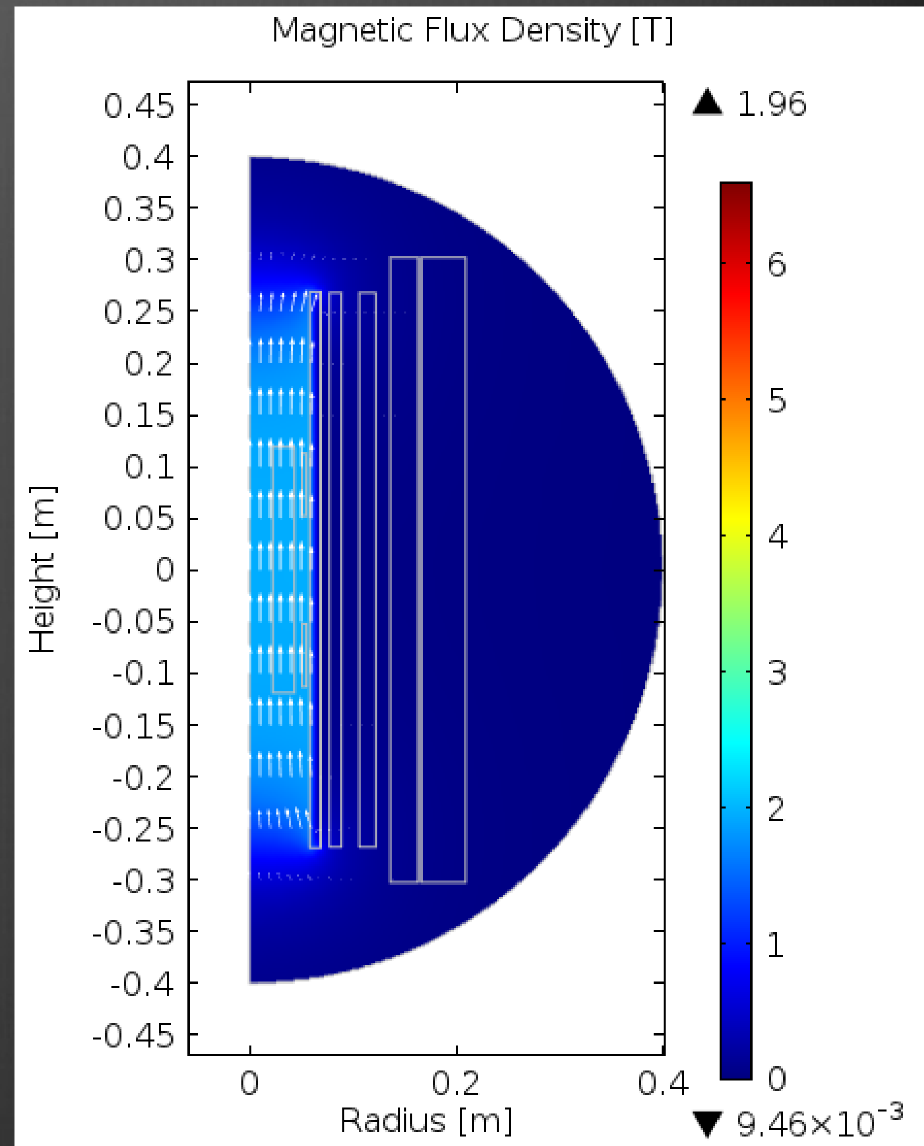
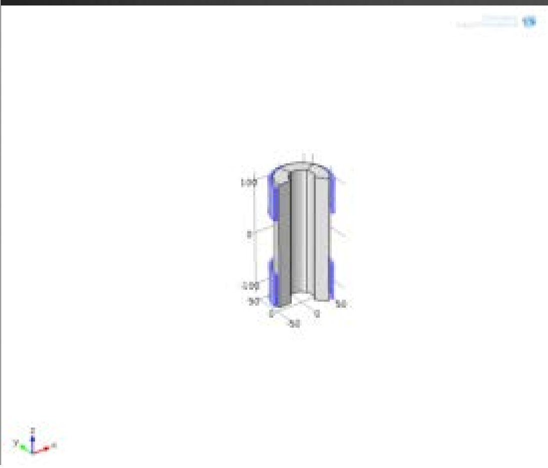
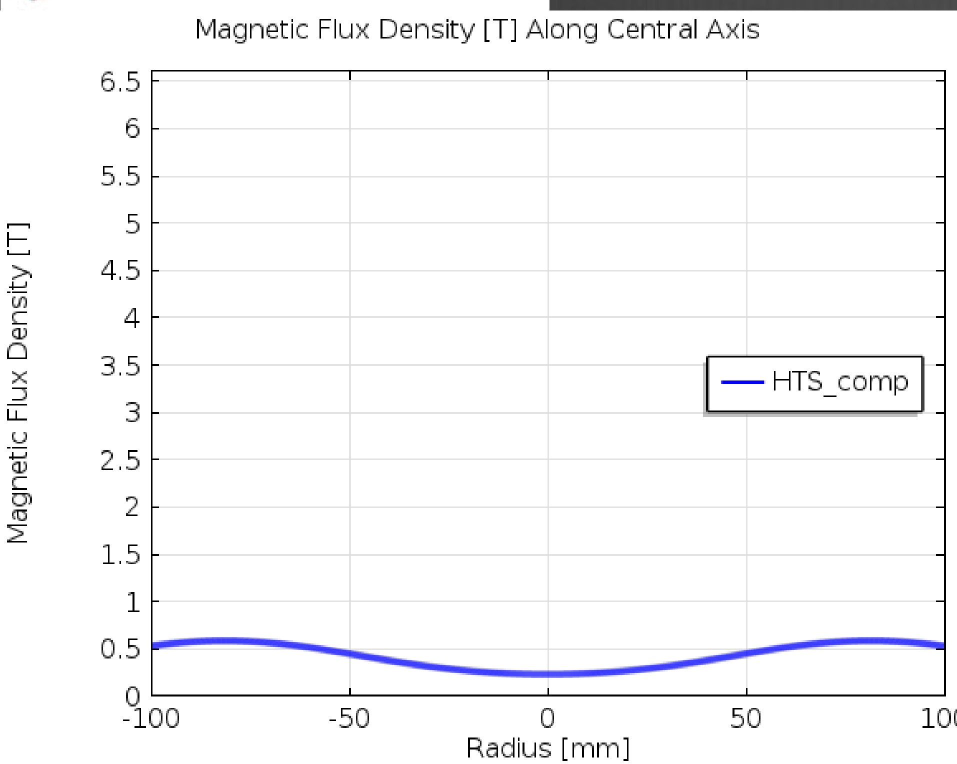


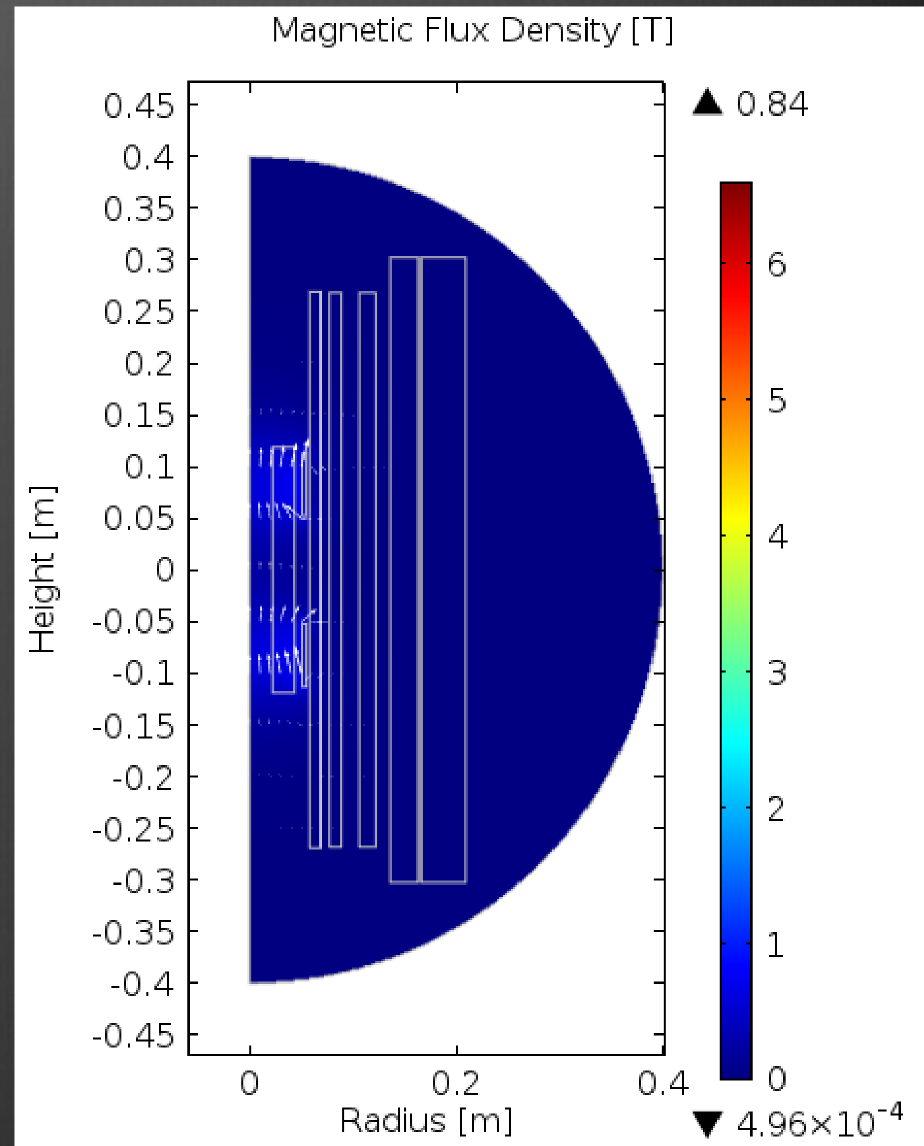




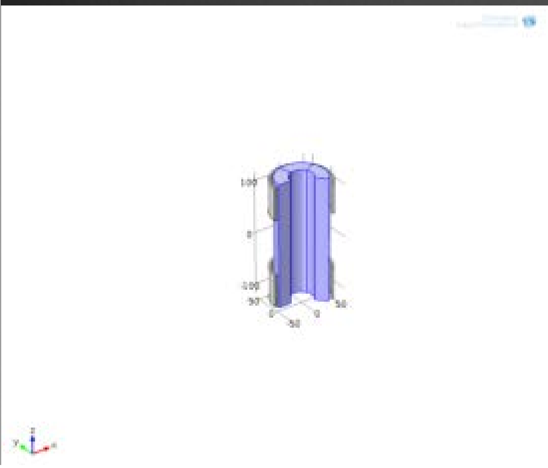
‘As Designed’ Magnetic Field Maps (HTS)

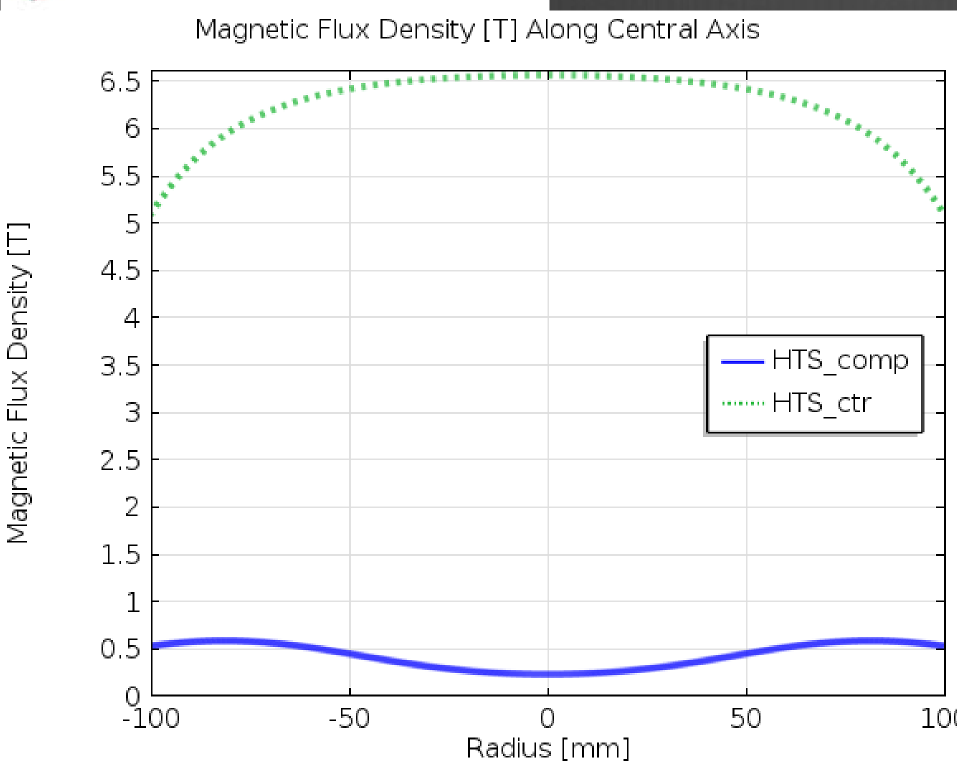


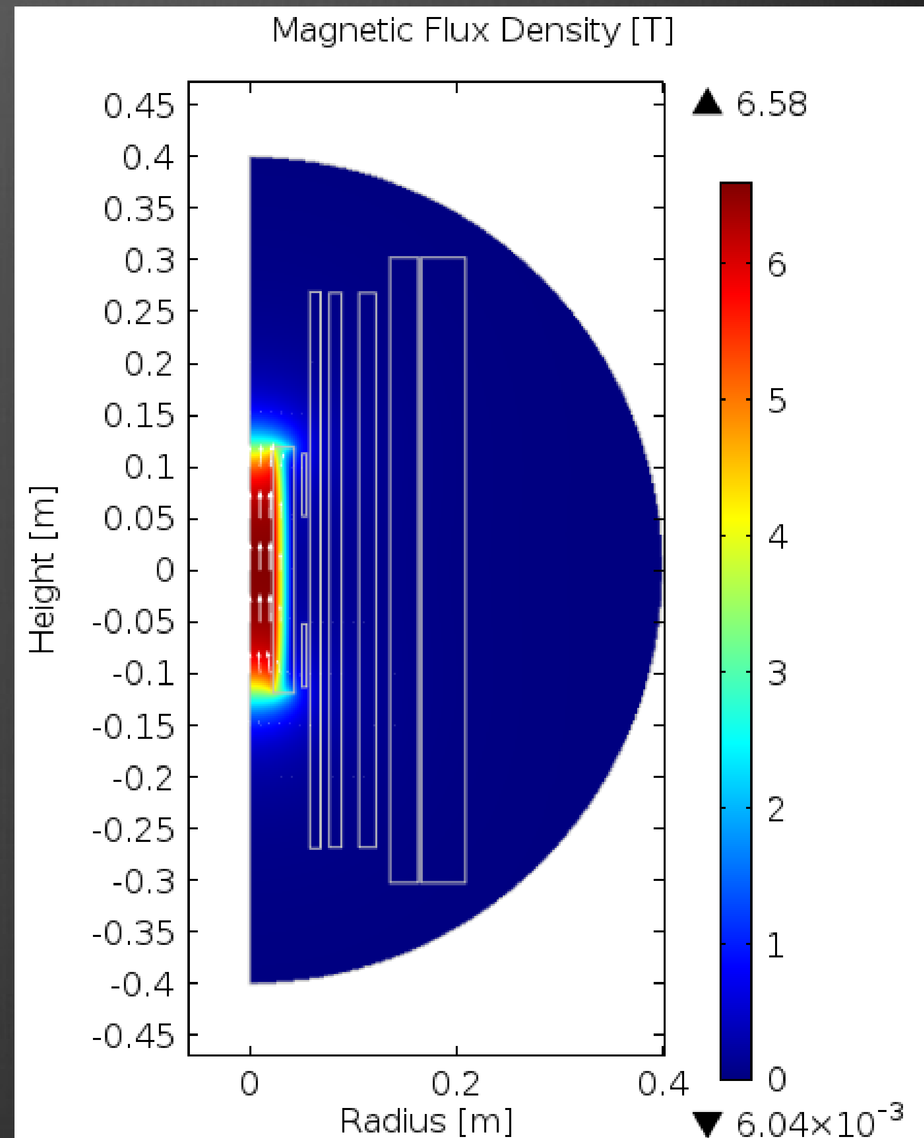




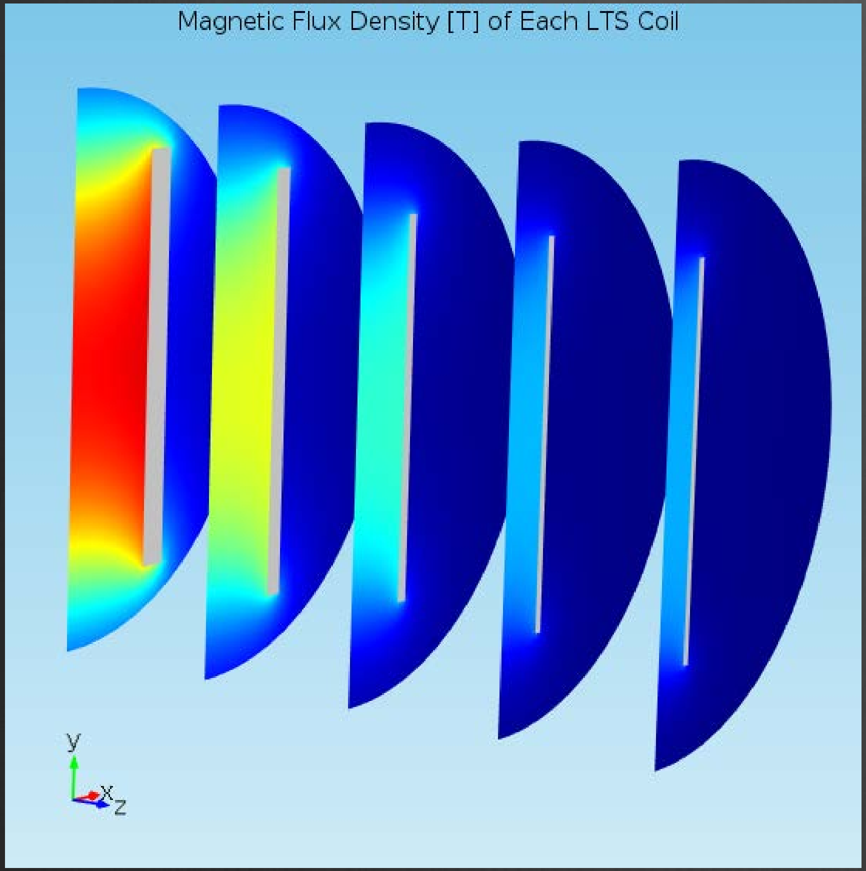
‘As Designed’ Magnetic Field Maps (HTS)

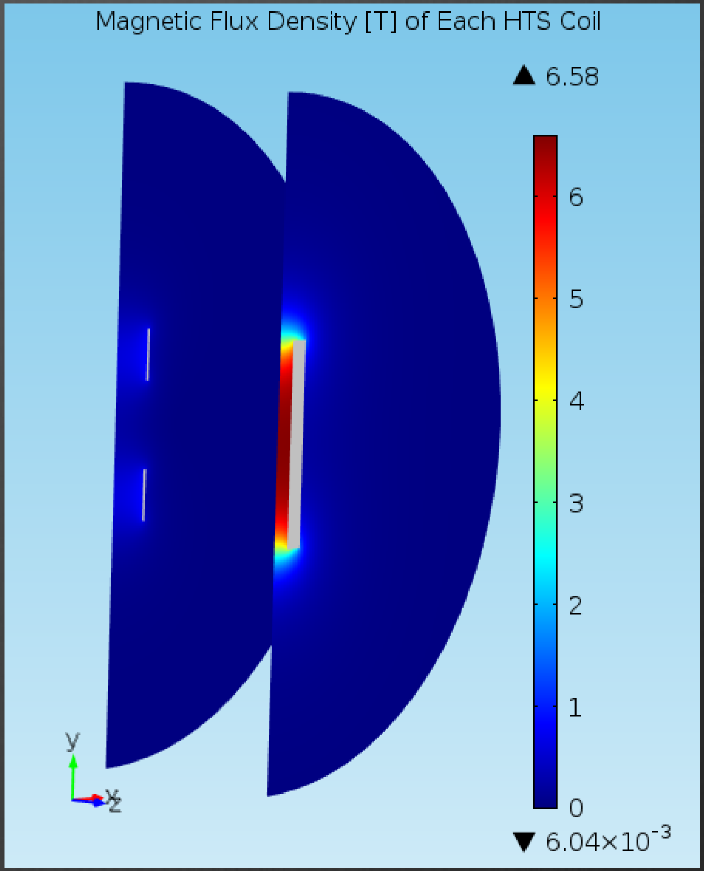




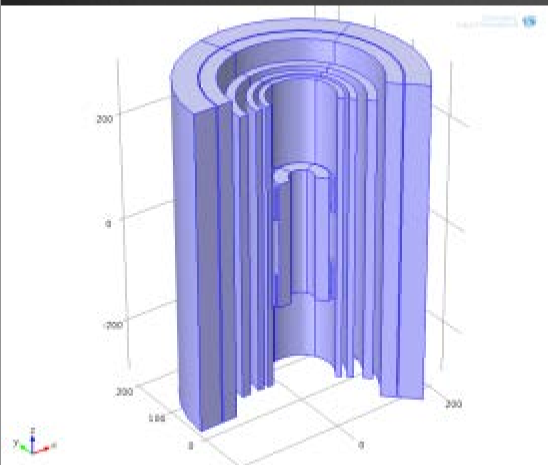


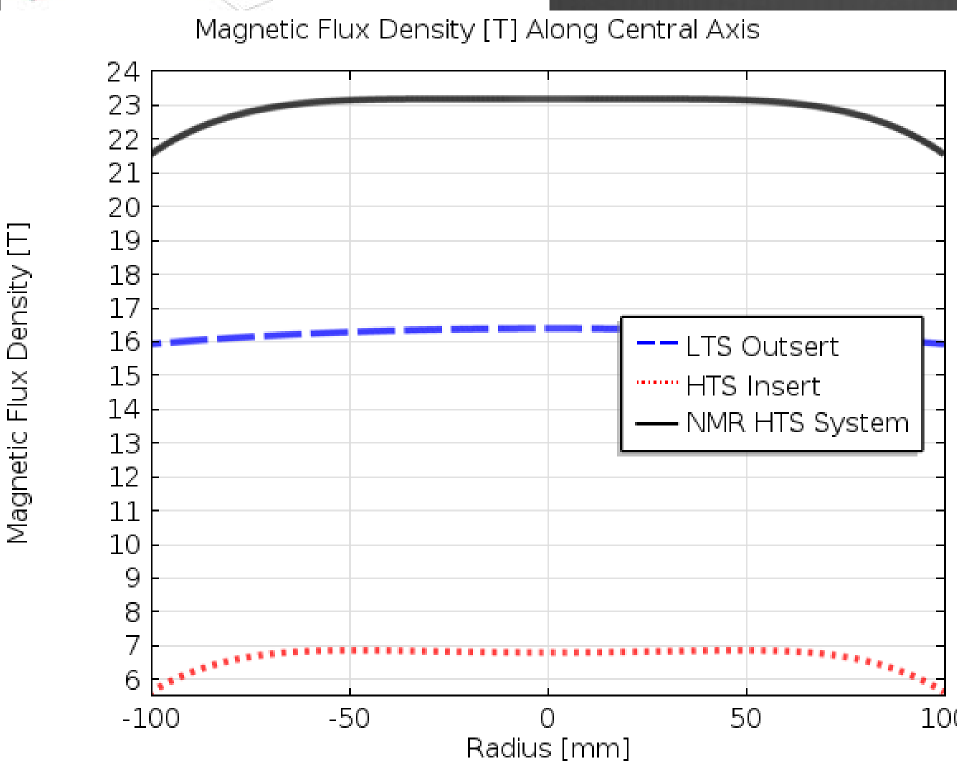
'As Designed' Magnetic Field Maps (all)

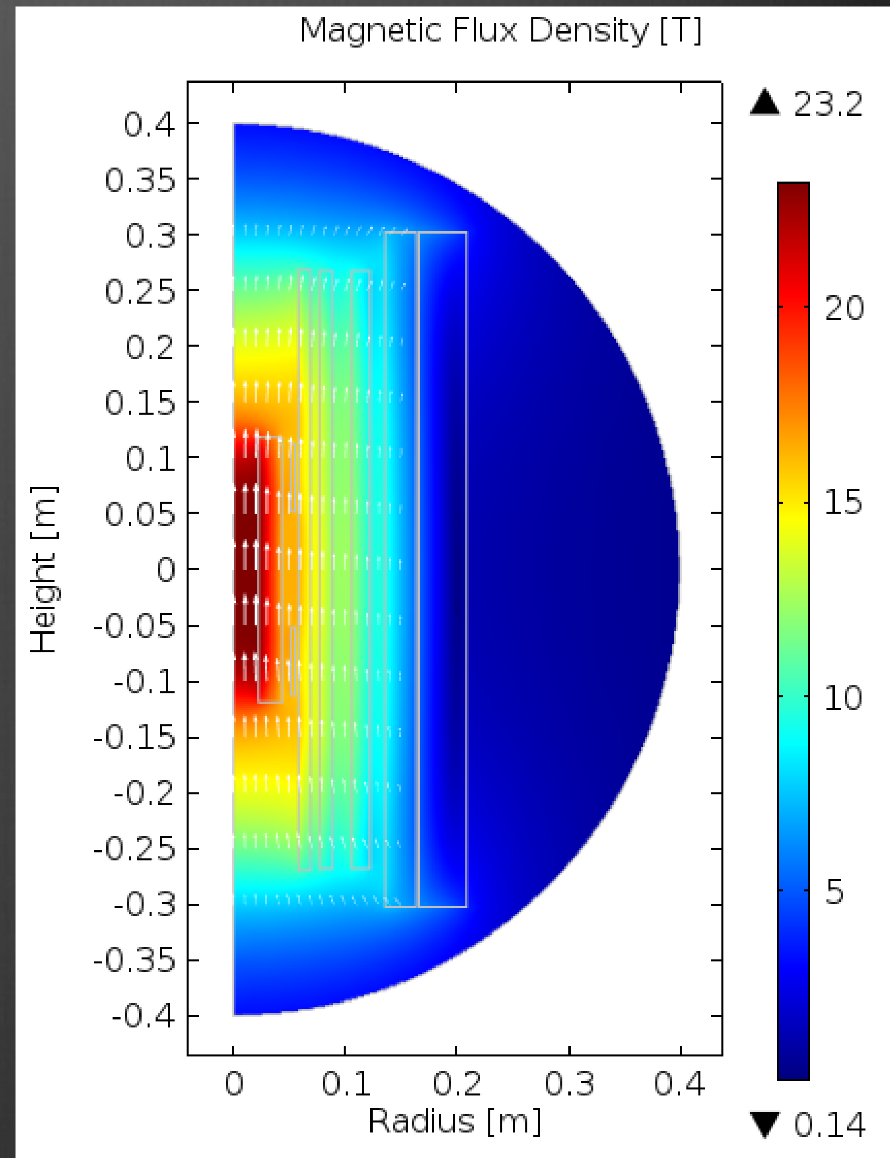




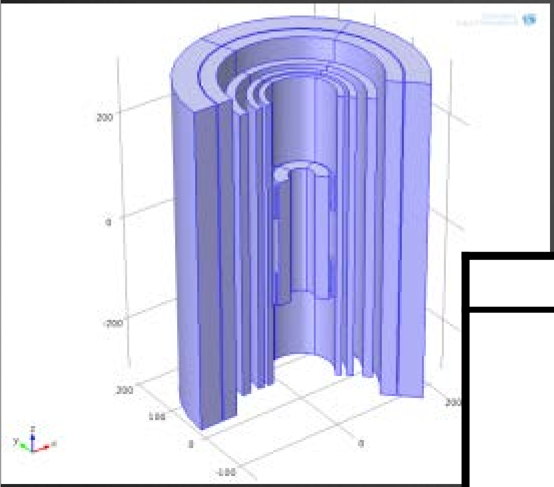
'As Designed' Total Magnetic Field Map







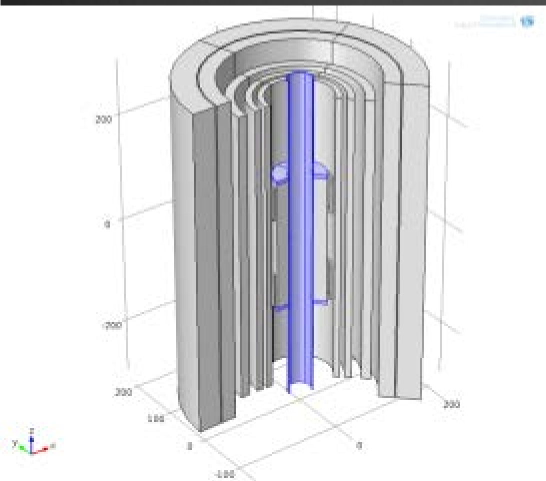
High Homogeneity Requirement

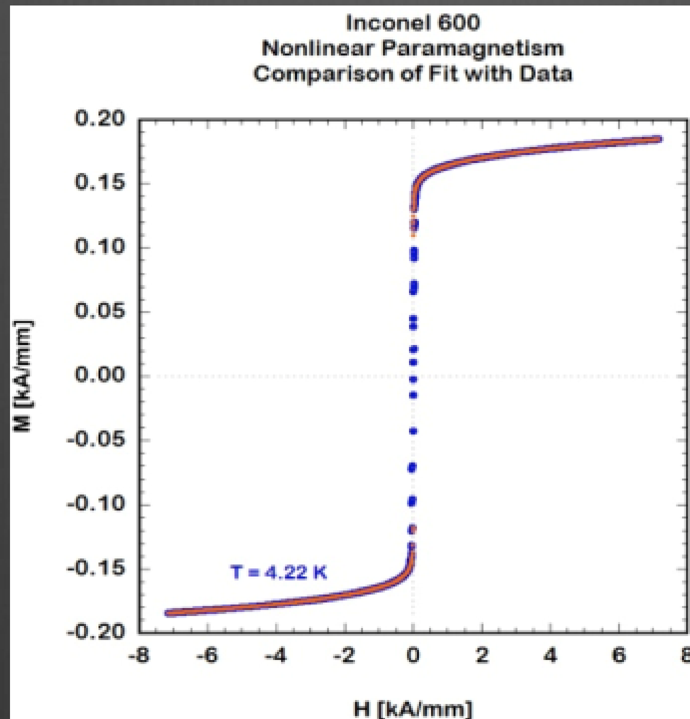


B(0,0) [T]	B(0,5mm) [T]	*h* [ppm]
1.954739	1.954688	
2.027699	2.027614	
2.766974	2.766788	
3.923075	3.922821	
5.748768	5.748296	
16.421254	16.420207	63.7877
6.577521	6.576254	
0.226399	0.228721	
6.803920	6.804975	-155.1064
23.225174	23.225182	-0.3383

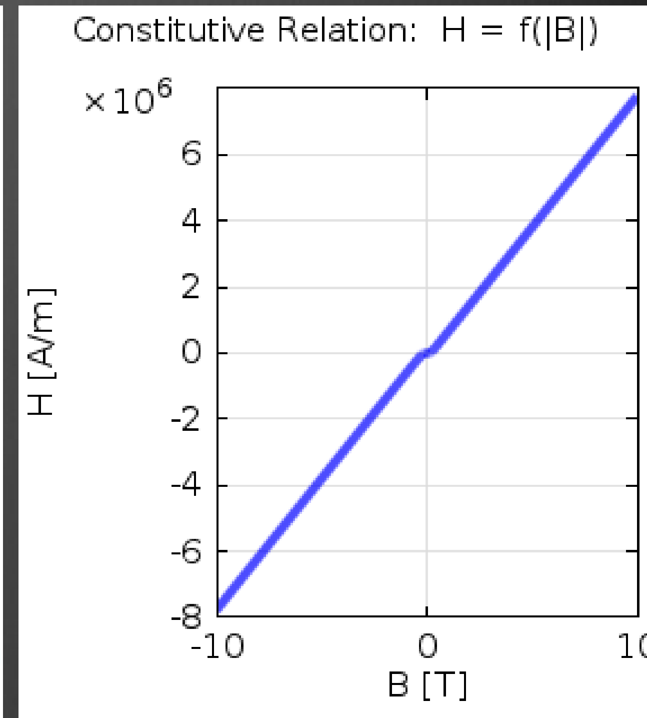
$$h\ [\text{ppm}] = \frac{B_z(0,0) - B_z(0,5)}{B_z(0,0)} \cdot 1e6$$

Concern of Mandrel Magnetization



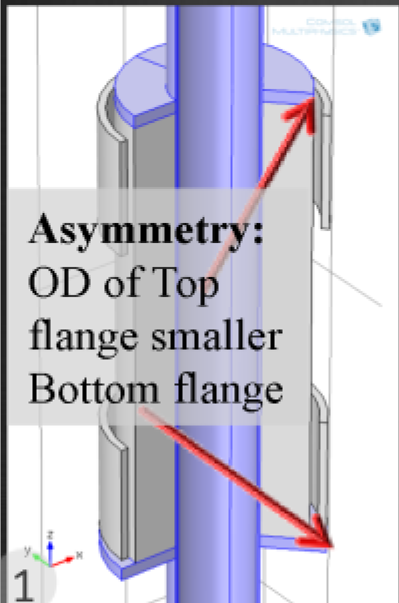


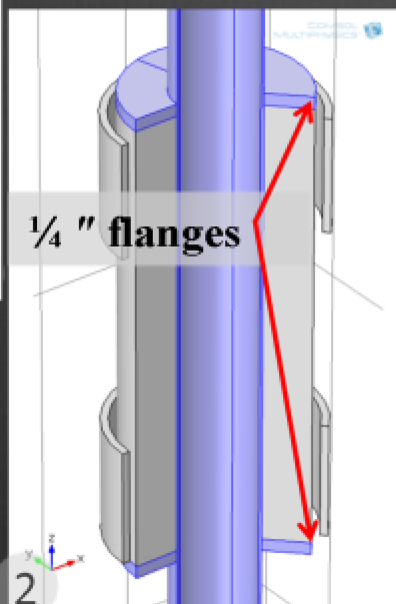
Magnetization (*M*) vs field strength (*H*) data collected by Jun Lu and fits provided by David Hilton.

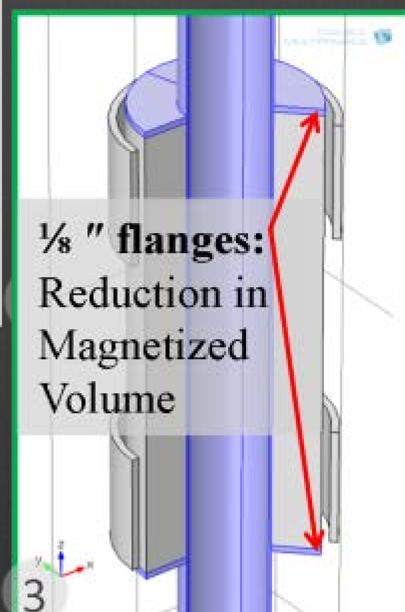


$$\mathbf{H} \equiv \left(1/\mu_0 \cdot \mathbf{B} - \mathbf{M}\right)$$

Mandrel Magnetization



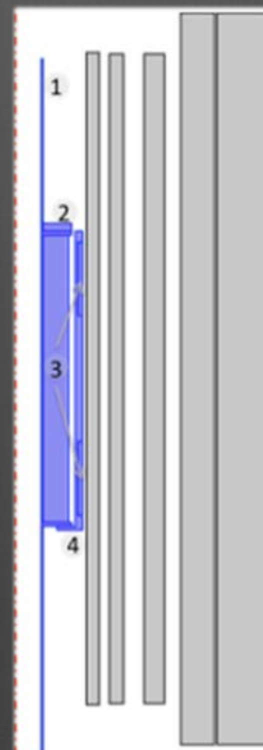


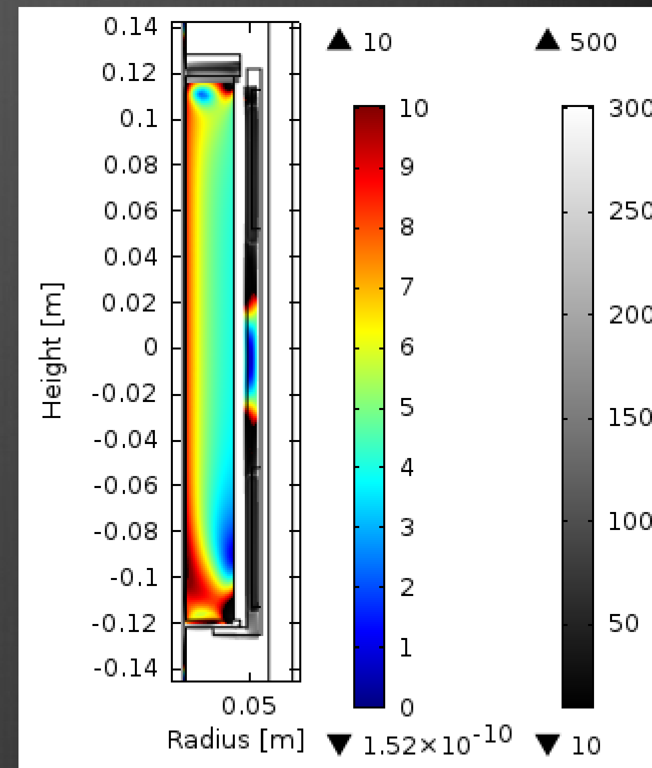


Concern of Thermal Contraction

2D-axisymmetric

- Active domains highlighted
- Material List:
  1. Inconel 600
  2. Alumina
  3. Stycast 1266
  4. G-10





Map of von Mises Stress [MPa]

Thermal Stress (tc) interface:

- General PDEs

$$-\nabla\cdot\sigma = \mathbf{F}_V$$

$$\rho C_p \mathbf{u}\cdot\nabla T = \nabla\cdot(k\nabla T) + Q$$

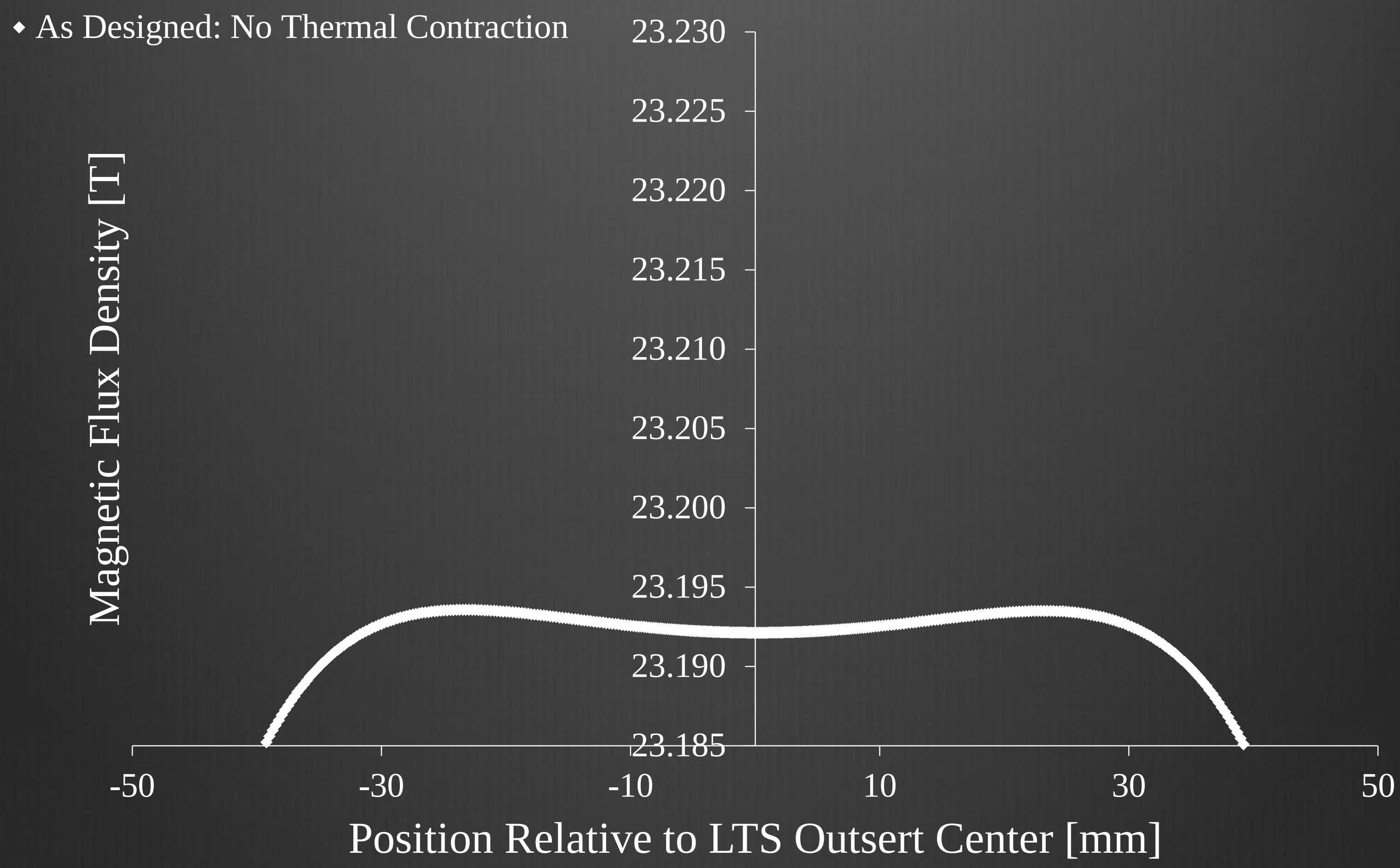
- Initial temperature *T = 300 K*
- Final temperature *T = 4.2 K* (everywhere)
- Fixed constraint at bottom of bore tube

$$\mathbf{u} = 0$$

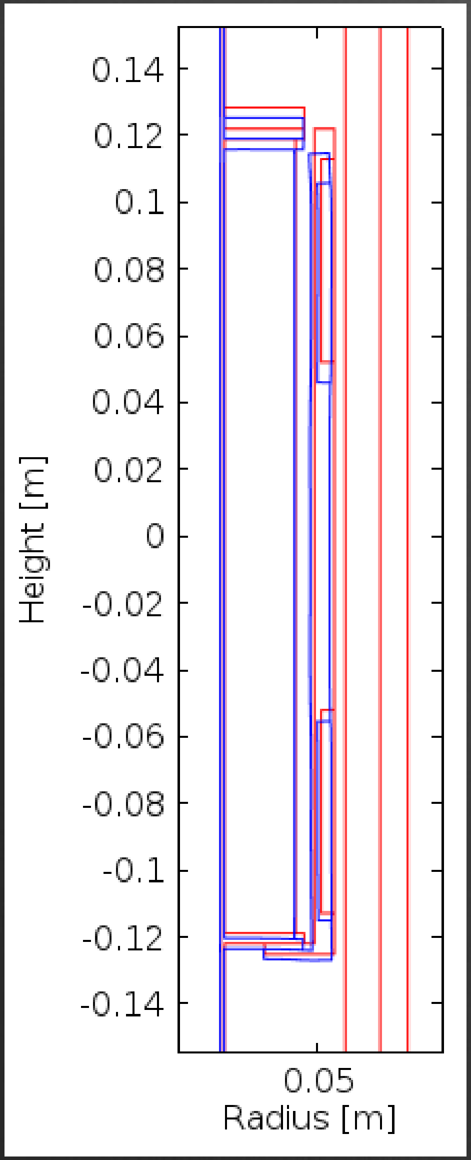
Moving Mesh (ale) interface:

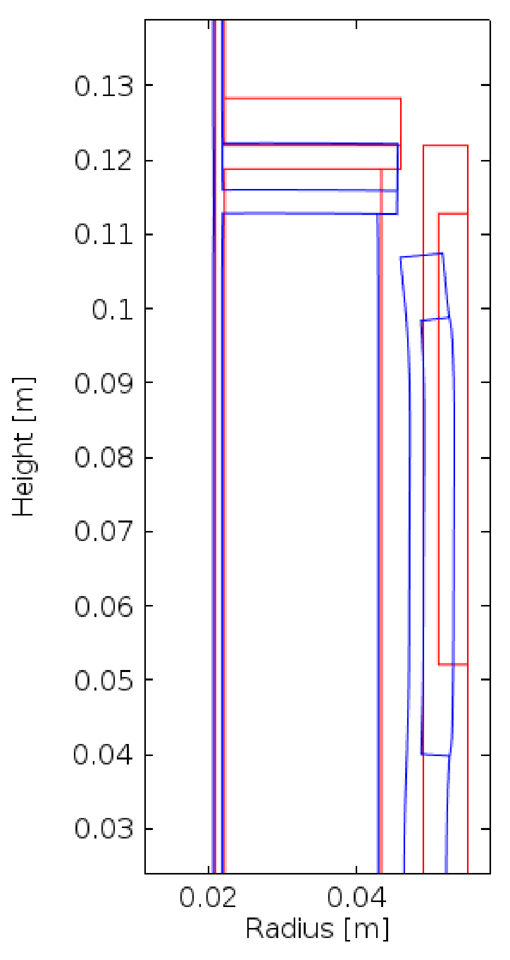
To keep track of all geometric deformations.

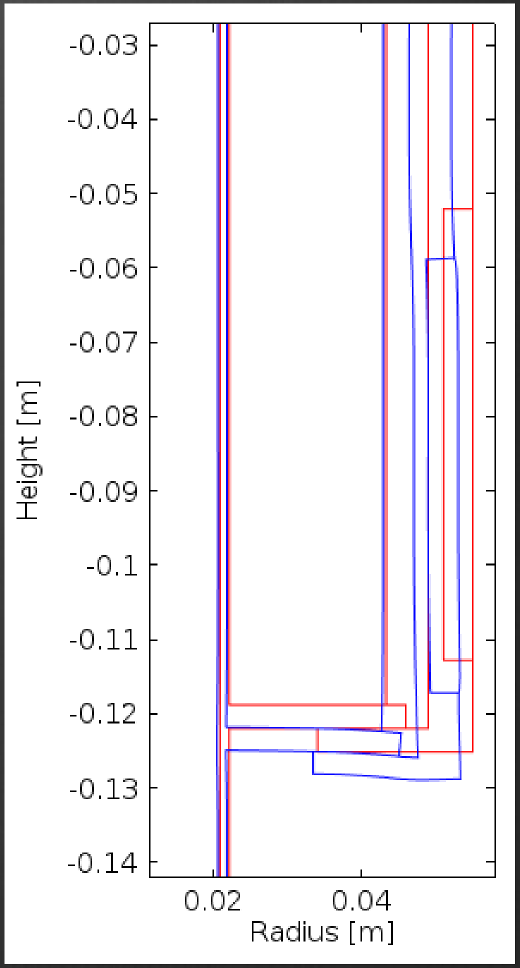
‘As Designed’ Total Field



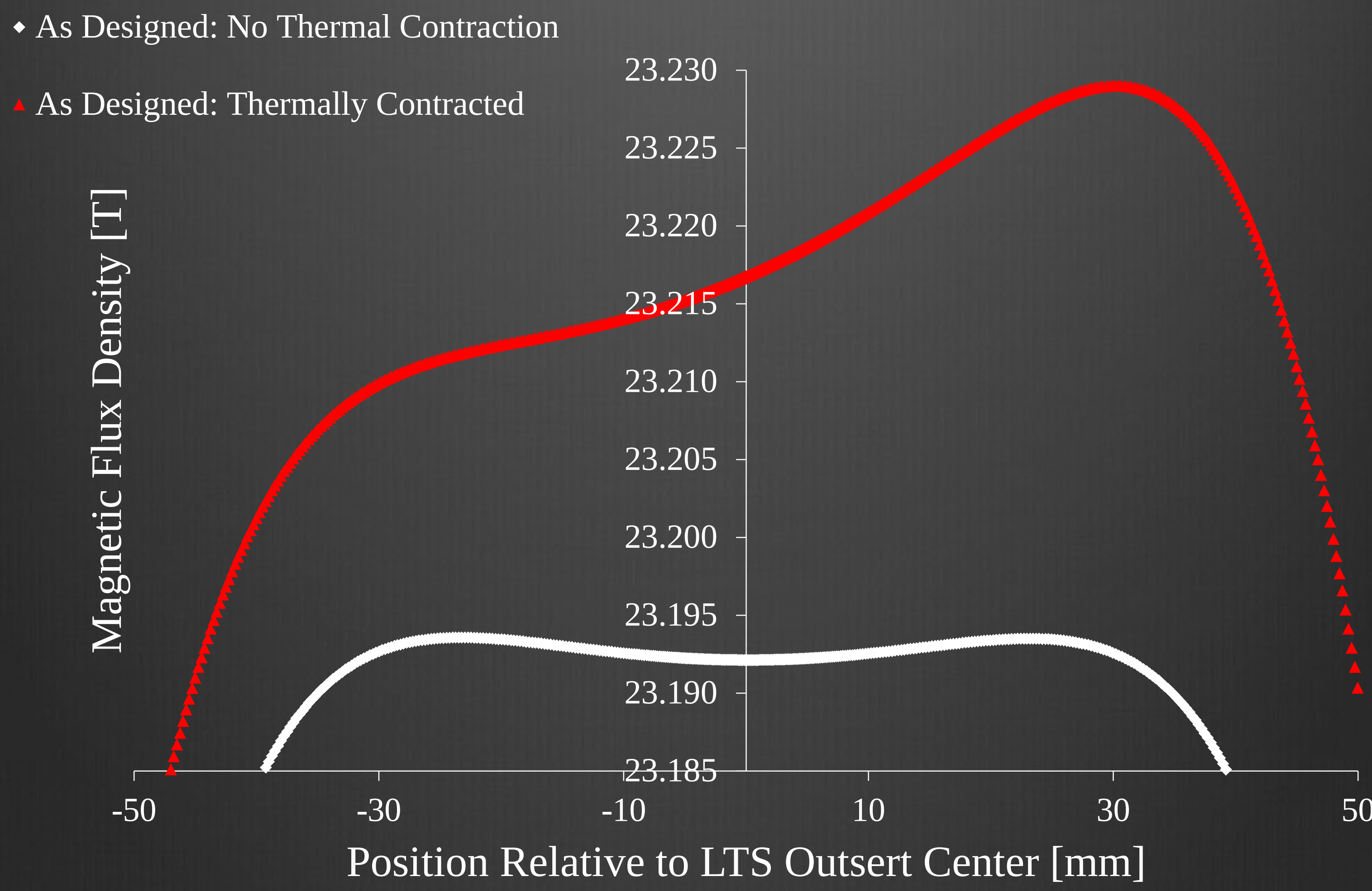
Thermal Contraction Compensation



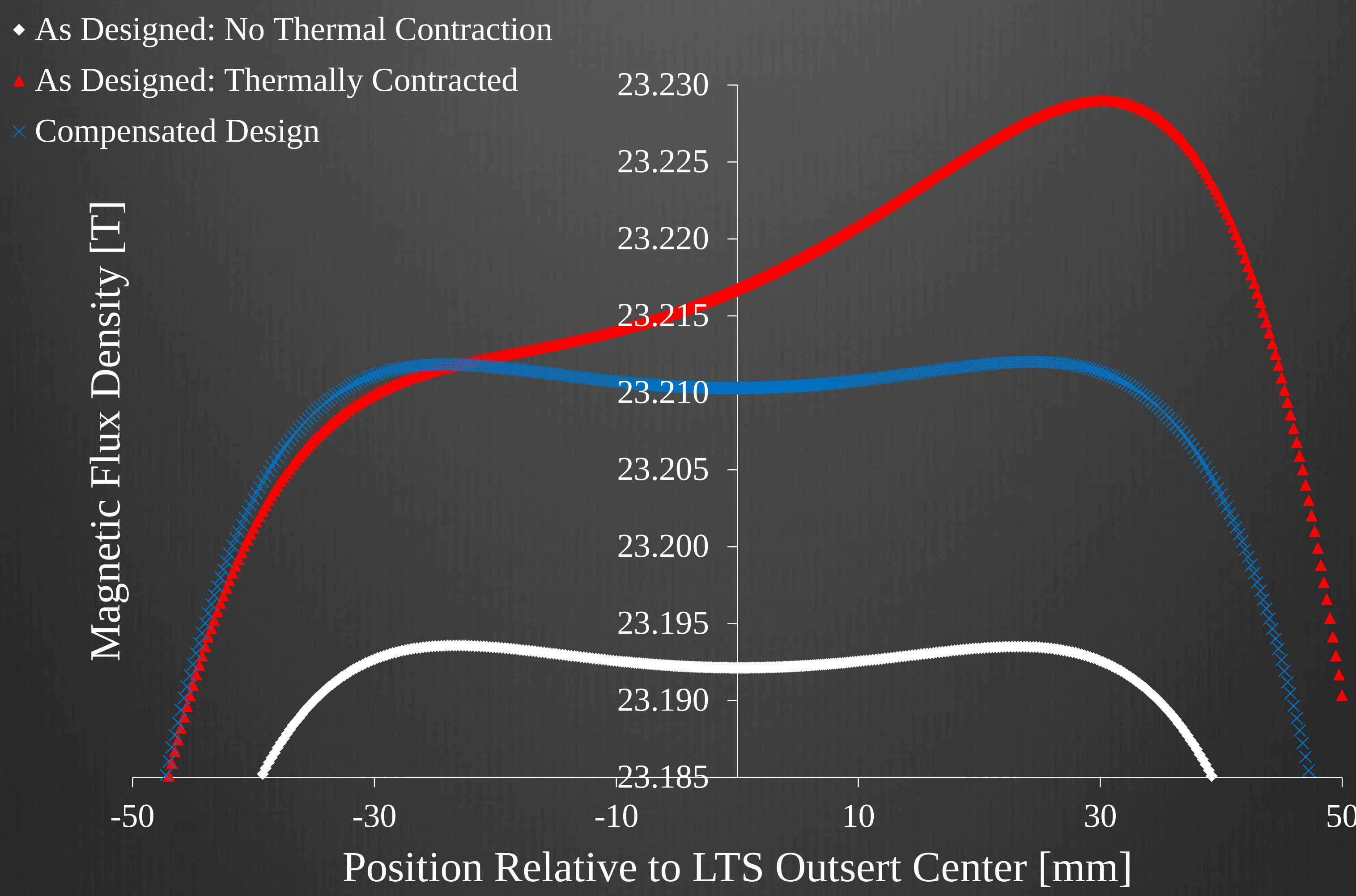




Field of Thermally Contracted 'As Designed'



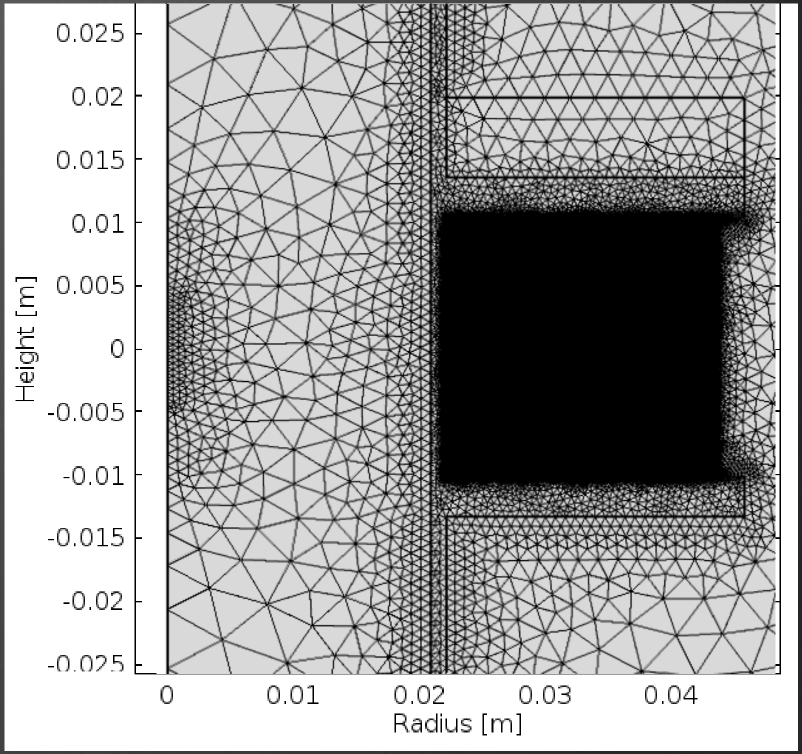
Compensated Thermal Contraction



Stress Analysis of Platypup (Stress Test Coil)

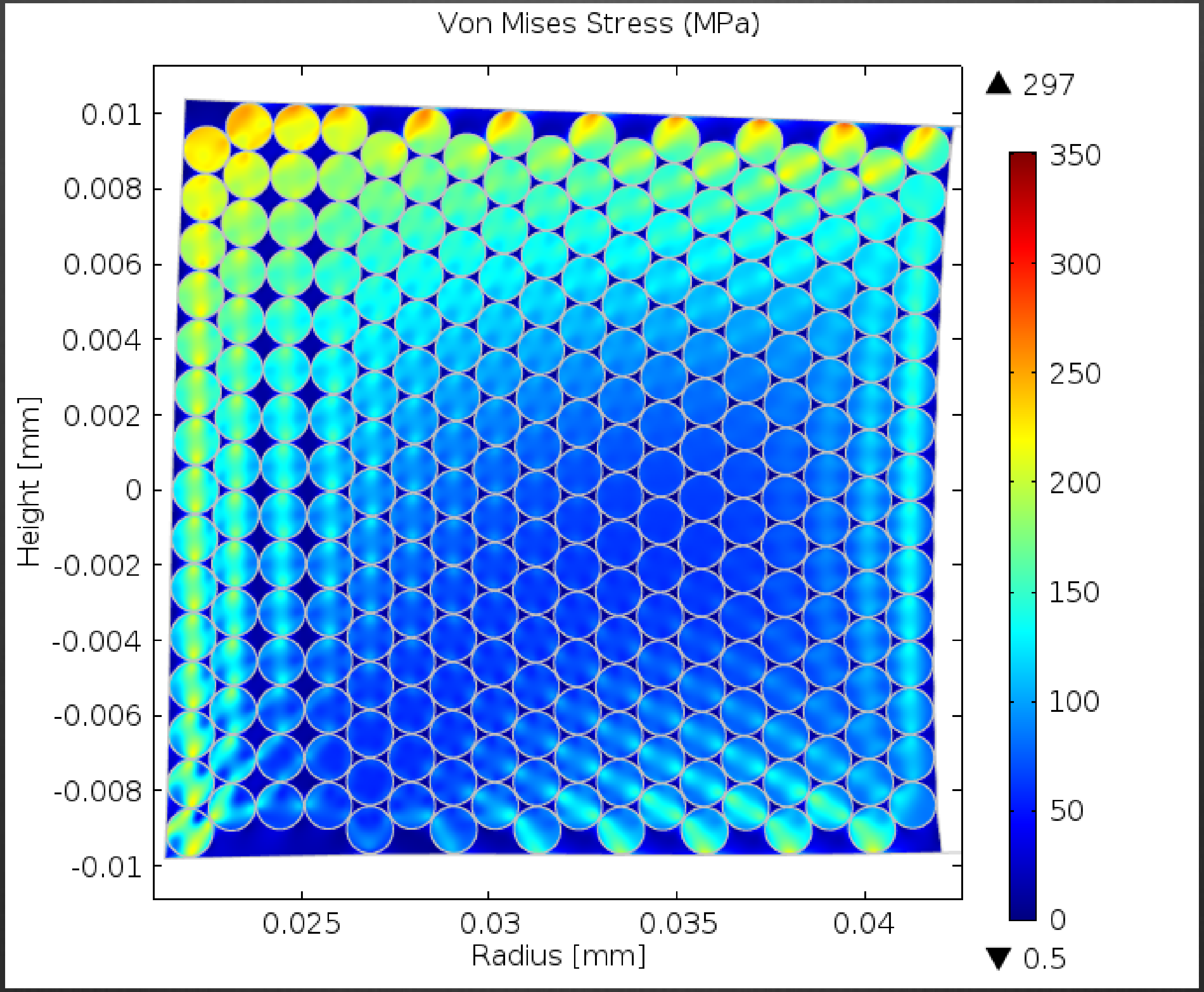
2D-axisymmetric

- Stress coil
  - 1.3 mm round wire
  - ~10% of Platypus height
- Material List:
  1. Inconel 600
  2. Alumina
  3. Silver
  4. Stycast 1266
- Assume good epoxy impregnation

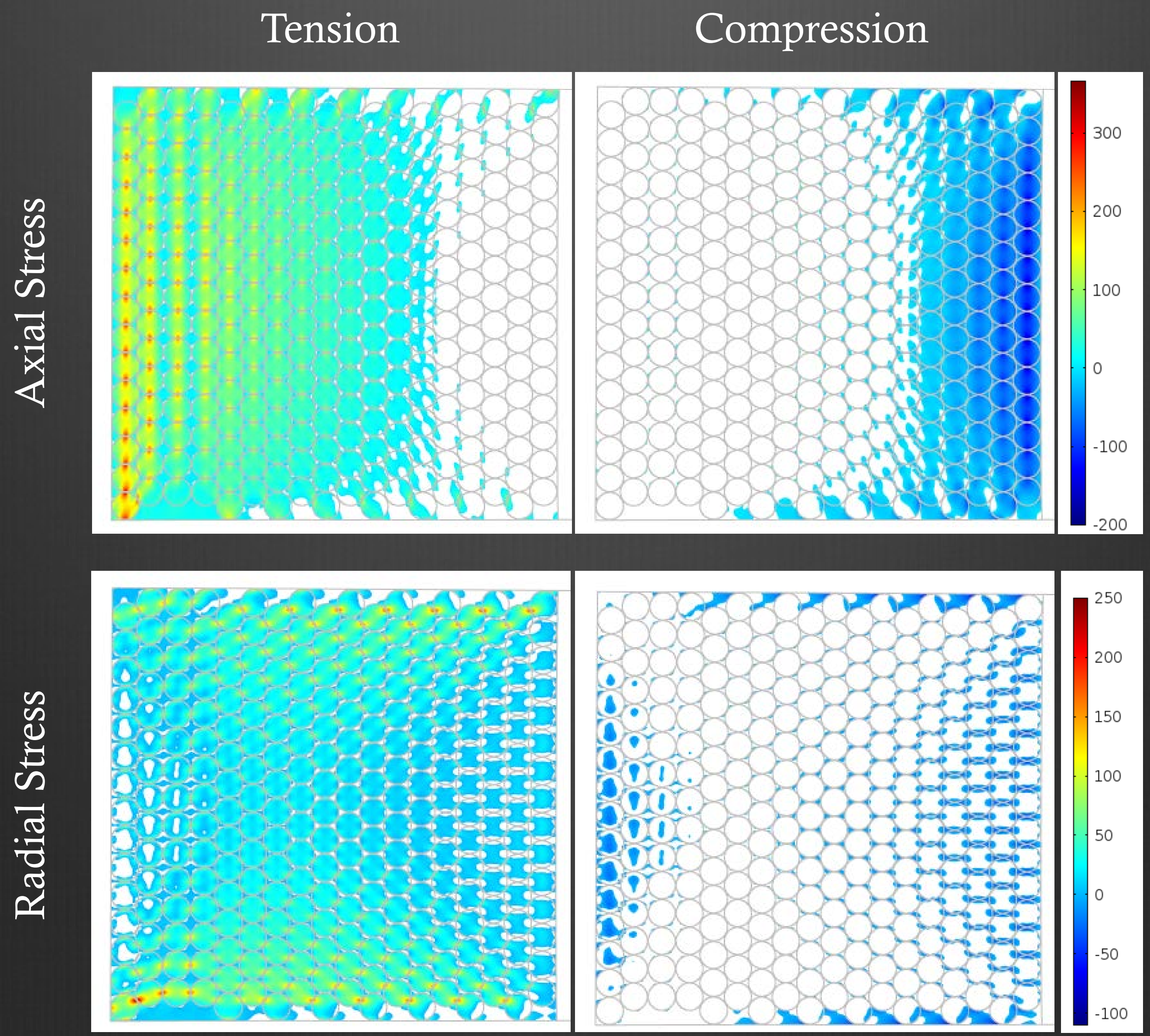


- Three step process:
  - First run thermal contraction to determine pre compression
  - Then run magnetic field analysis using J_e of each wire
  - Finally, run structural mechanics with Lorentz body force on wires

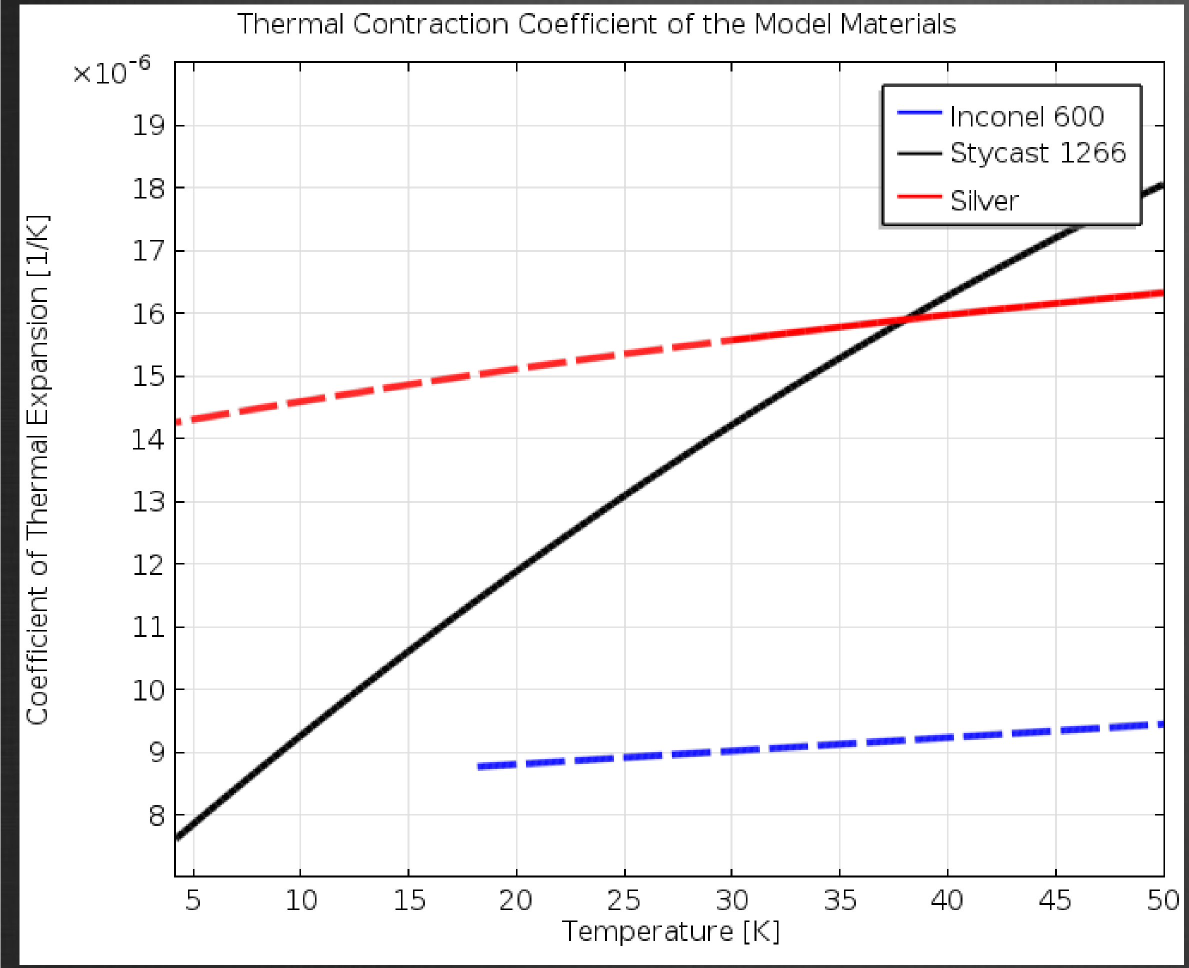
Exaggerated Thermal Stress Map



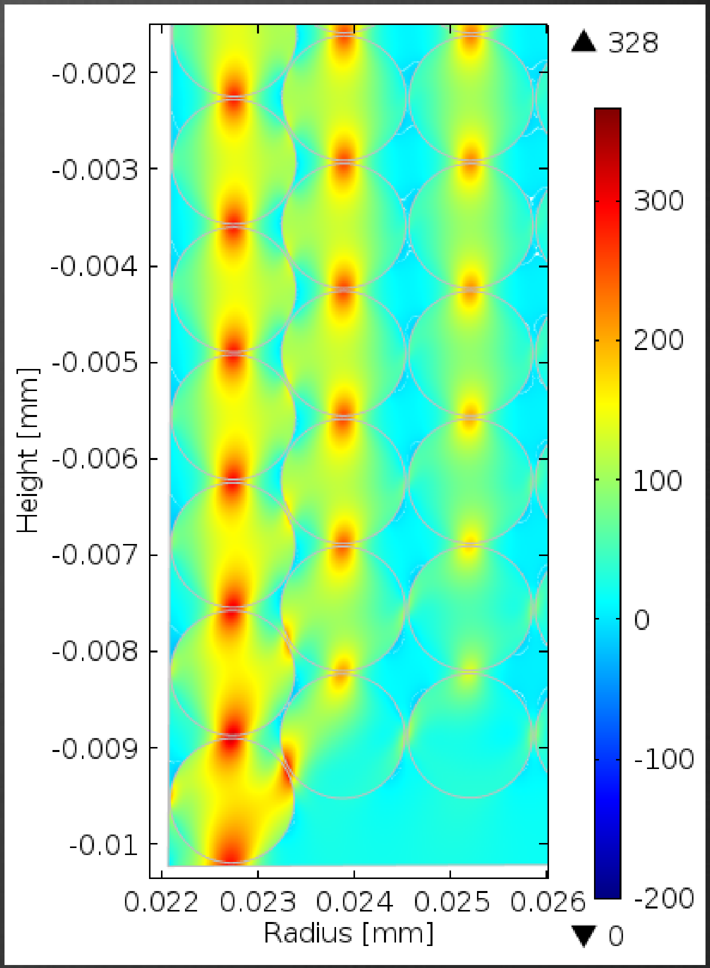
Thermal Stress Analysis Deconstructed



Coefficients of Thermal Contraction (*alpha*)



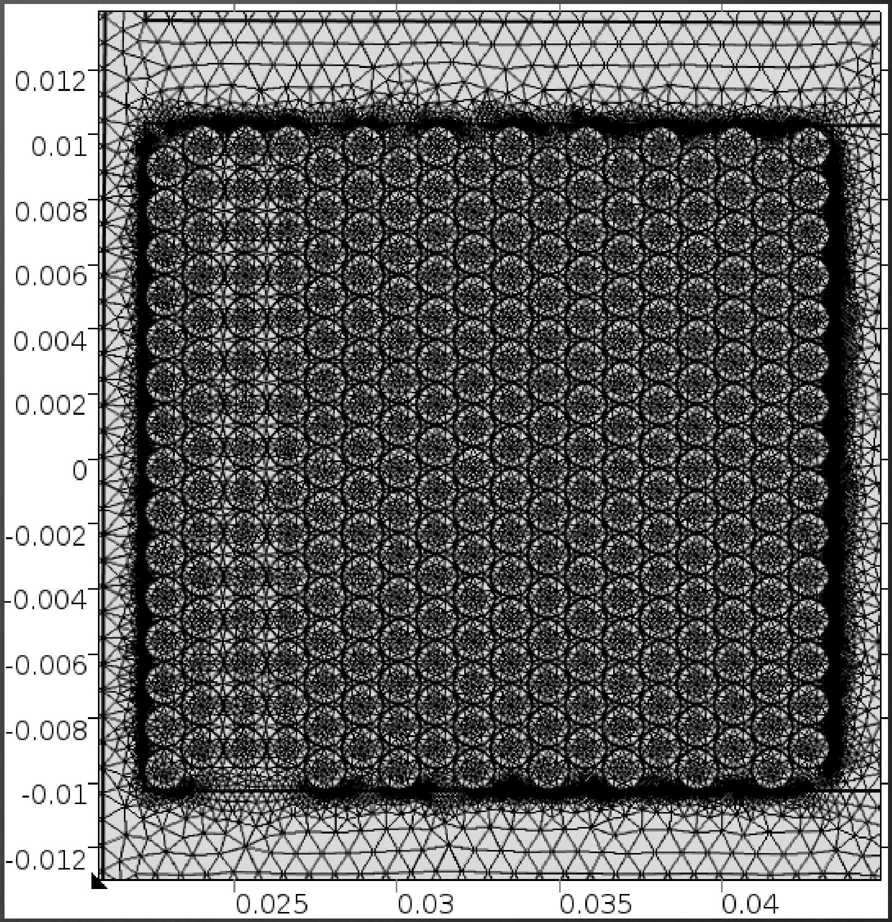
Axial Tension



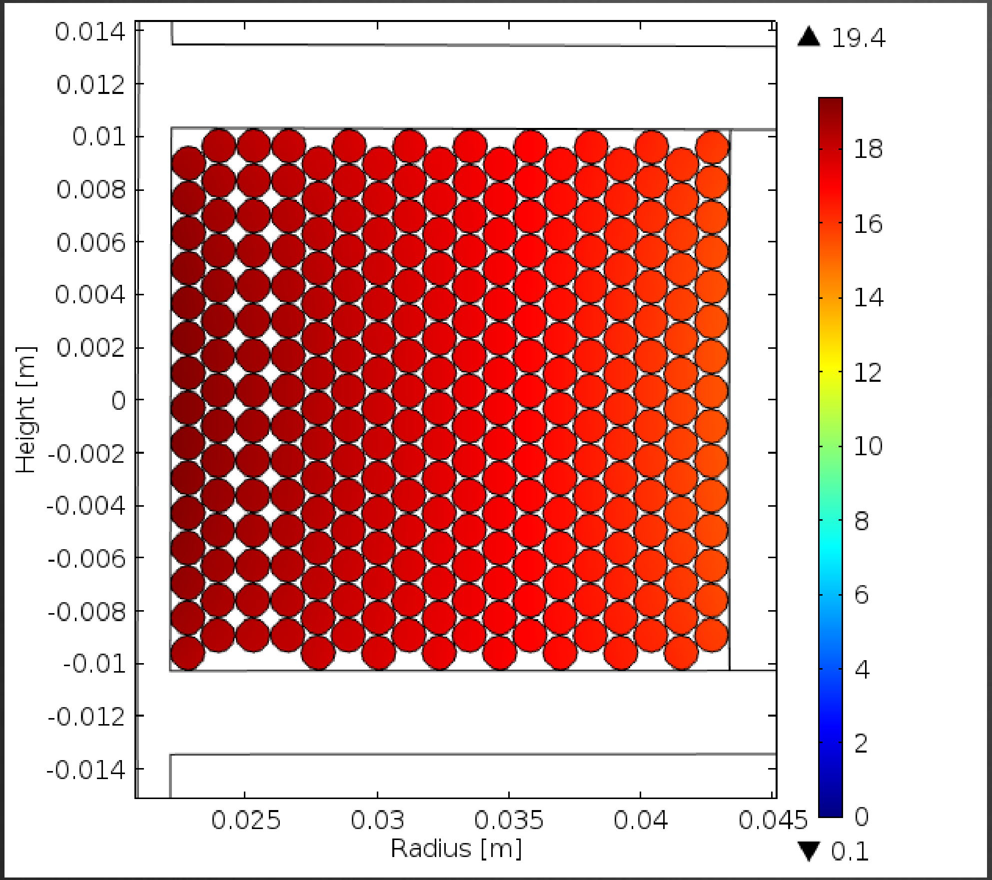
Step 2: Apply Current to Deformed Geometry

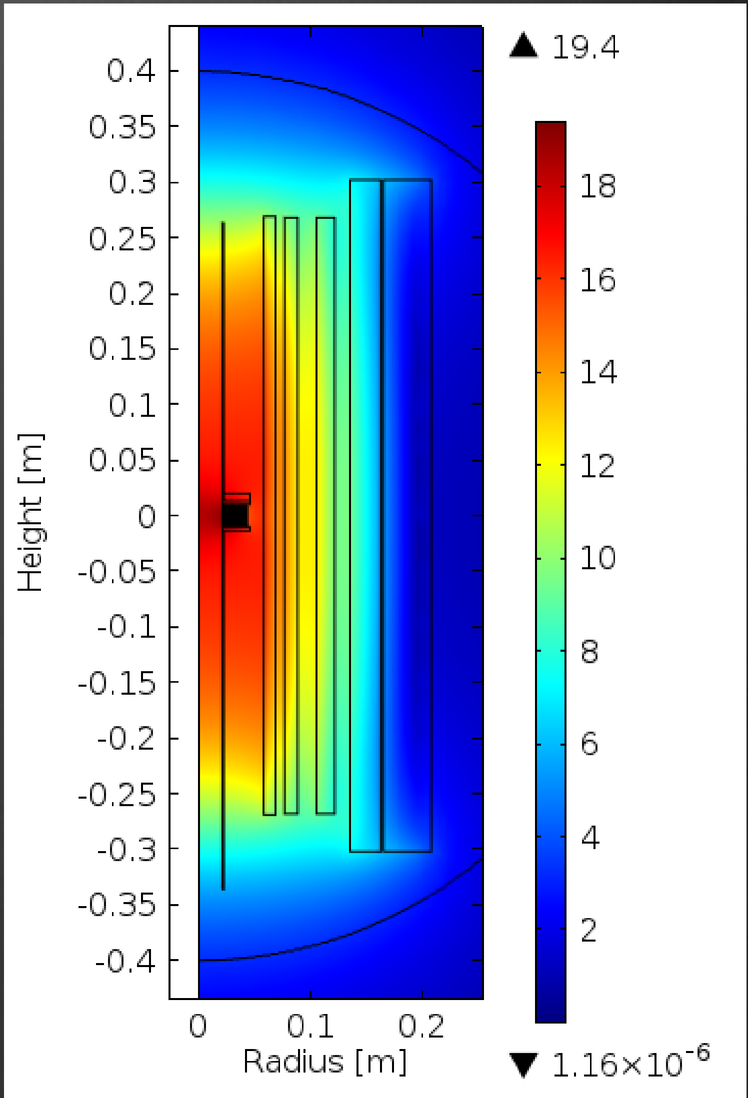
Magnetic Fields (mf) interface:

- Current (*I*) to coils 400 A
  Coil: n =15, m =18
  with J_e defined as *I/area*
- Far field evaluated with perfect conductor
- Platypup modeled as an insert in the LTS magnet the finished coil will be put into



Magnetic Field Calculation





Lorentz Body Force = **J** × **B**

Step 3: Structural Analysis

Solid Mechanics (solid) interface:

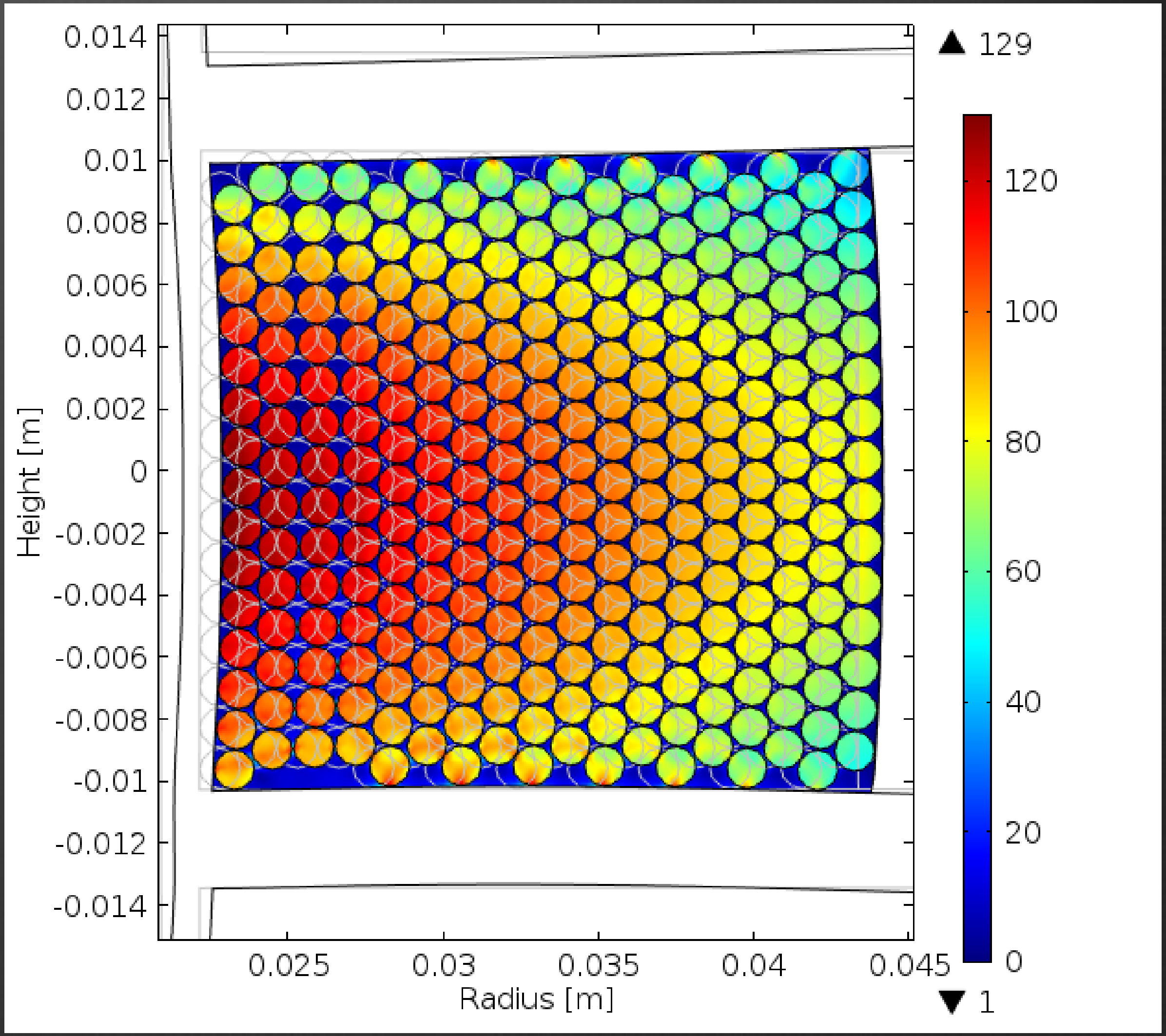
- General PDE

$$-\nabla\cdot\sigma = \mathbf{F}_V$$

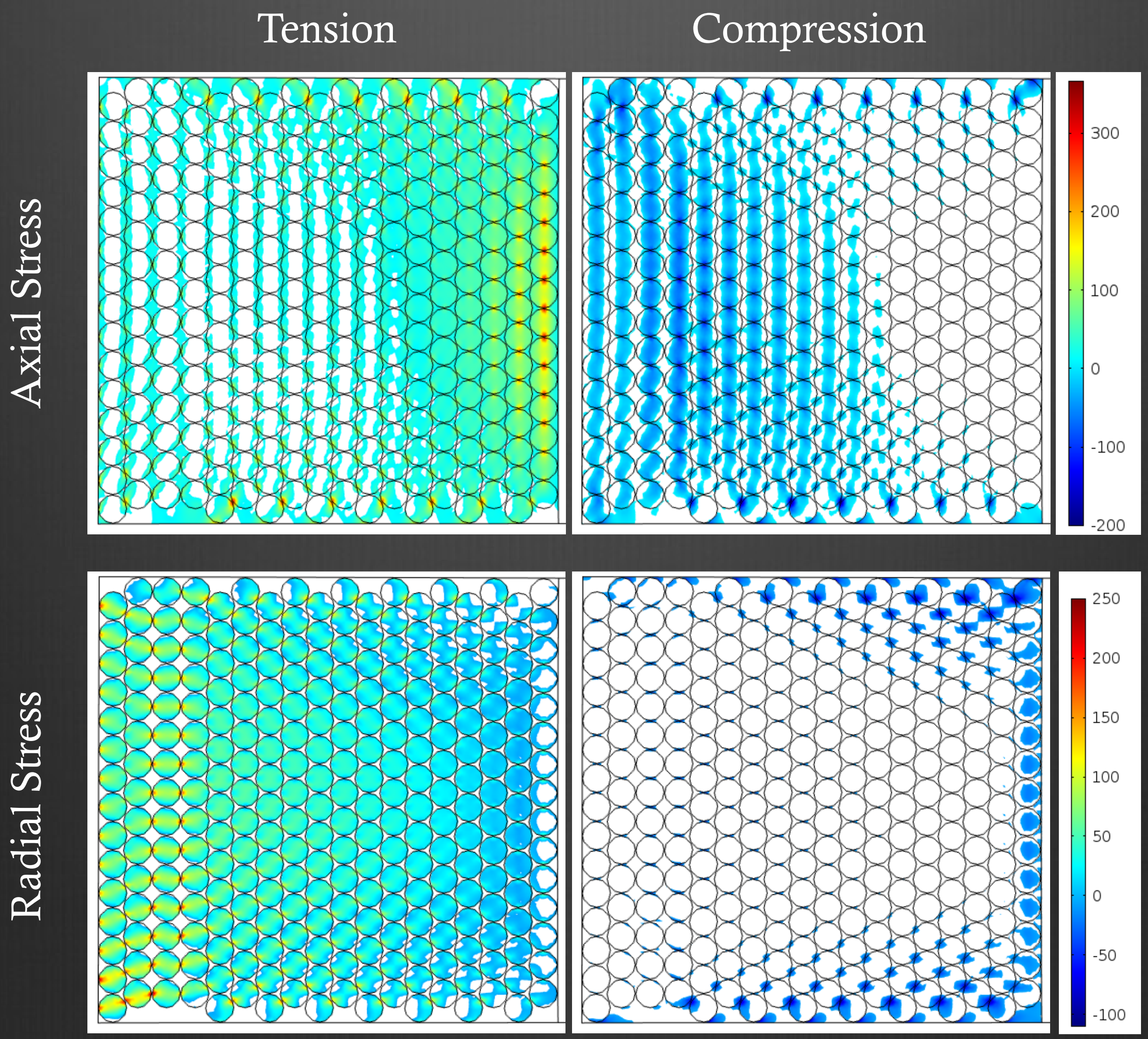
- Body force defined from magnetic field analysis:

$$\mathbf{F}_V = \mathbf{J} \times \mathbf{B}$$

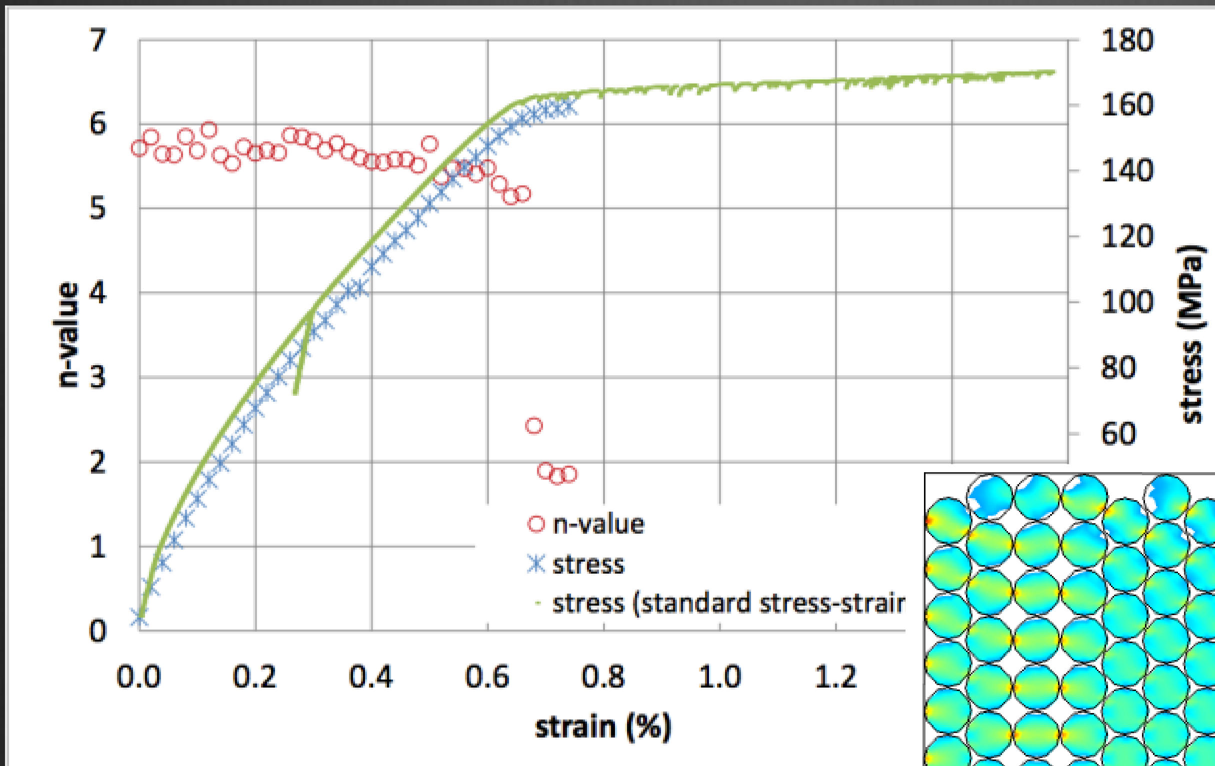
- Fixed Constraint at bottom of bore tube.

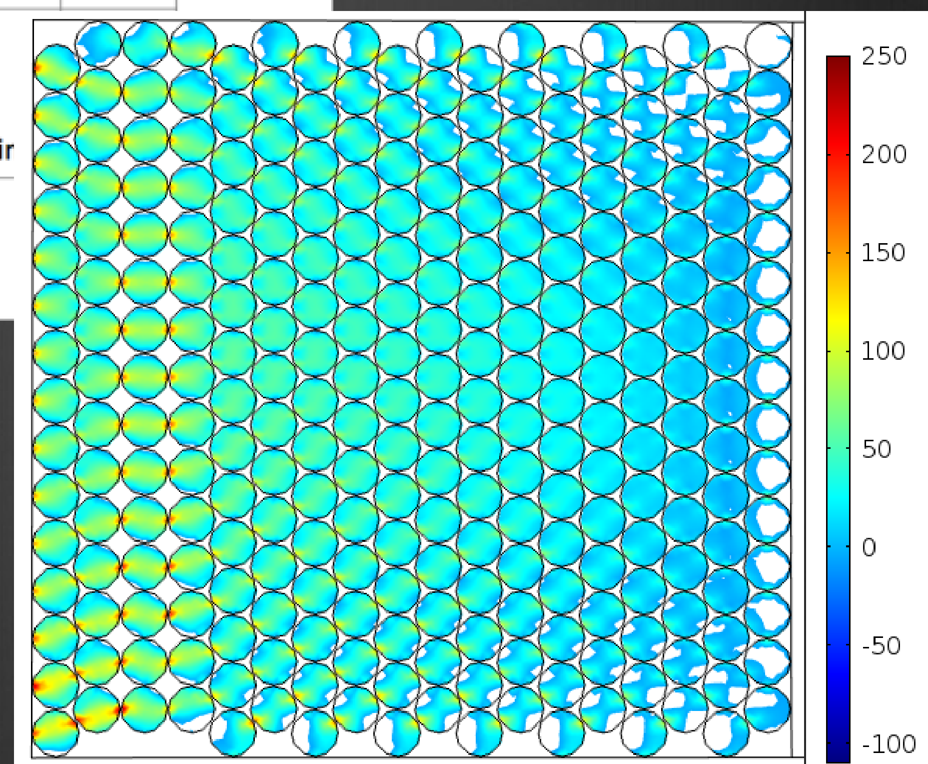


Final Stress Analysis Deconstructed



Radial Tension ~ Wire Tension





Summary

COMSOL Multiphysics has been extensively used to model the HTS NMR Magnet System

- Preliminary magnetic field analyses agree well with analytical field calculations done prior to the onset of numerical modeling.

- Volumetric magnetization shown to have an appreciable effect on the homogeneity of the produced field.

- Thermal contraction of the Platypus design needs to be fully understood to achieve the ~1 ppm field homogeneity target.

- A three step approach:
  thermal stress → *magnetic field analysis* → *structural mechanics*
  provides insight to the true stress experienced by each winding in the winding pack.