Multiphysics FEA to Investigate Design Strain Constraints for Solenoids *Heading Towards* Aspected and Reinforced HTS

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Outline

•Motivation: HTS Towards High Field (30+ T) NMR Magnet Systems: *Platypus*
•$Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212), Processing, and Coil Properties

•COMSOL Multiphysics for modeling coils

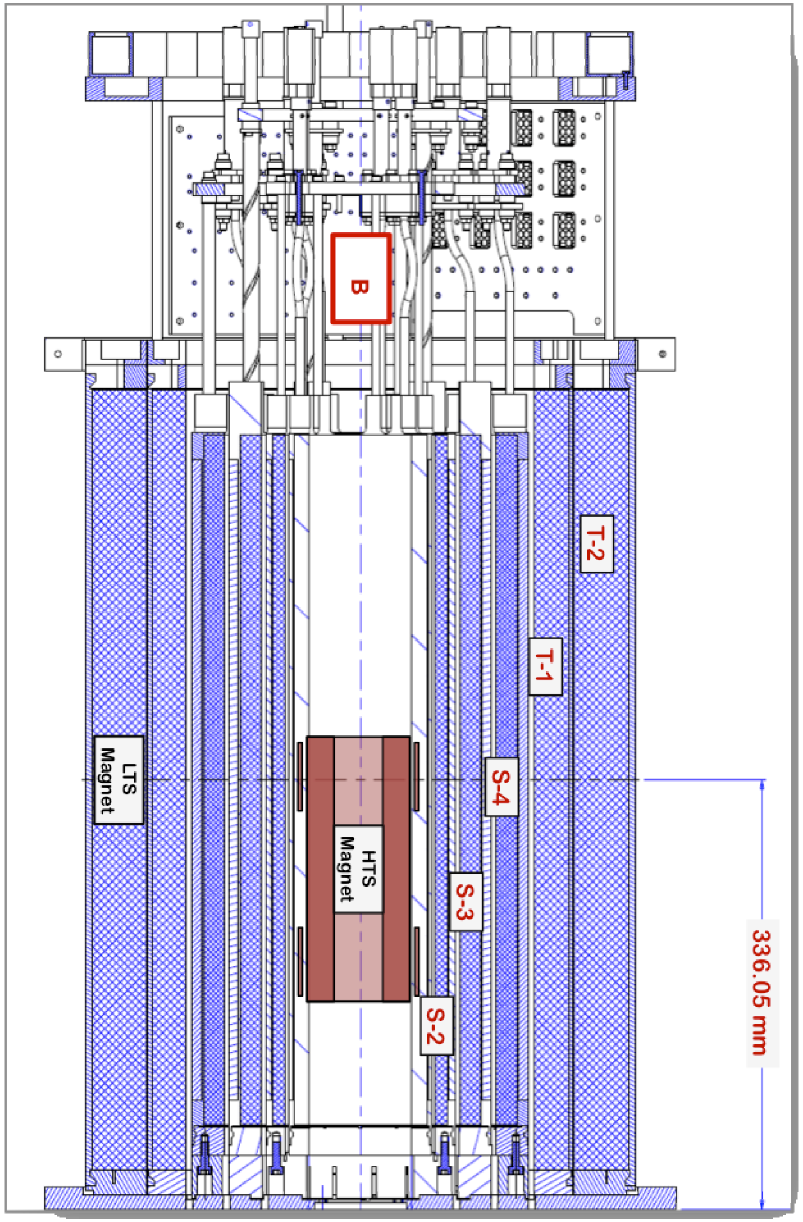
- Building of These Models
- Field Computations
- Structural Mechanics (fully coupled)
- Added Thermal Stresses

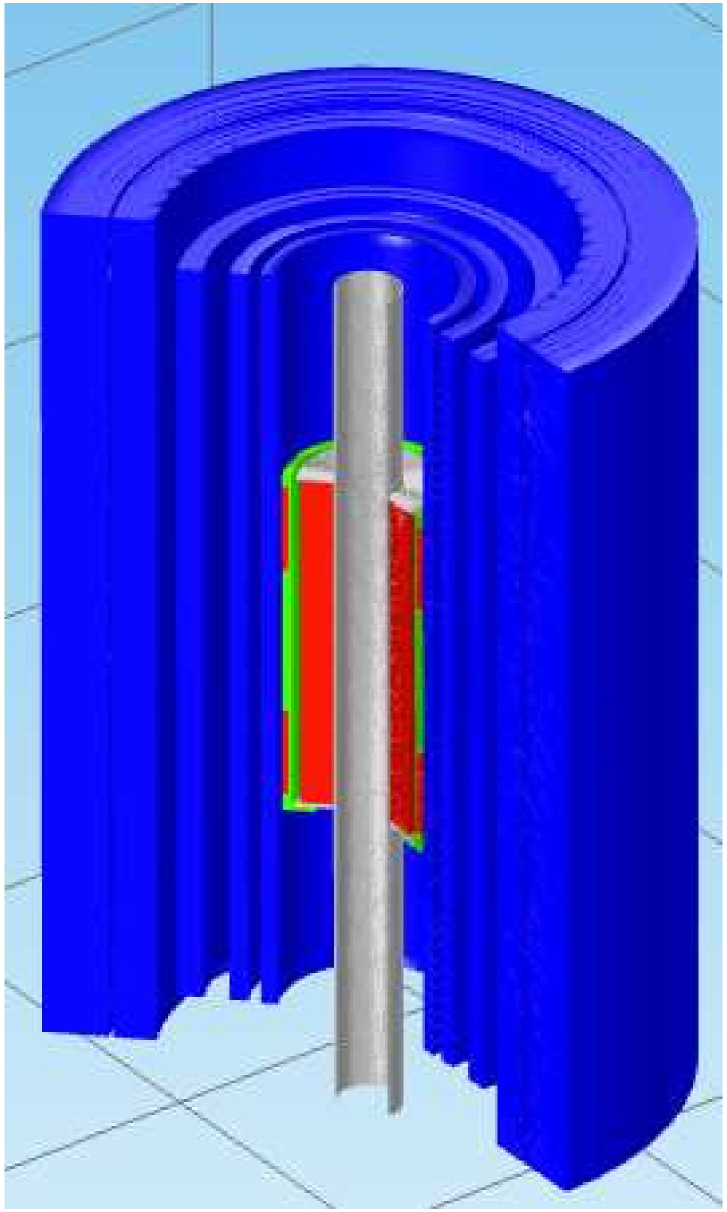
•Development of a Test Plan for experimental prototype coils

•Introduction of coil reinforcement methods

•Entering realm of React-and-Wind Conductors (Bi2223, ReBCCO), and otherwise laminated, aspected Bi2212

Platypus: An HTS NMR Magnet System

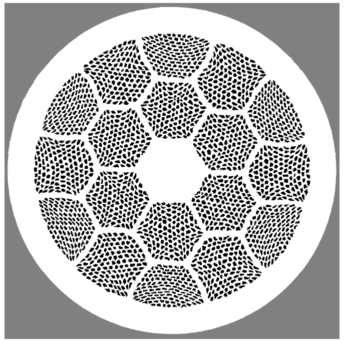




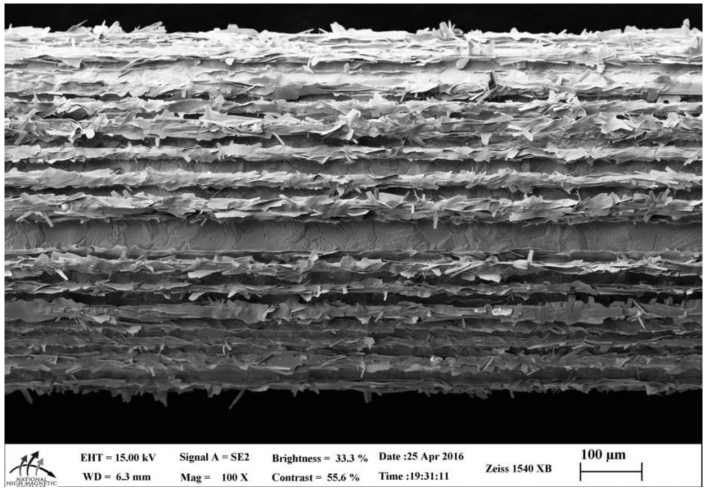
Processing Bi2212RW (OP HT)

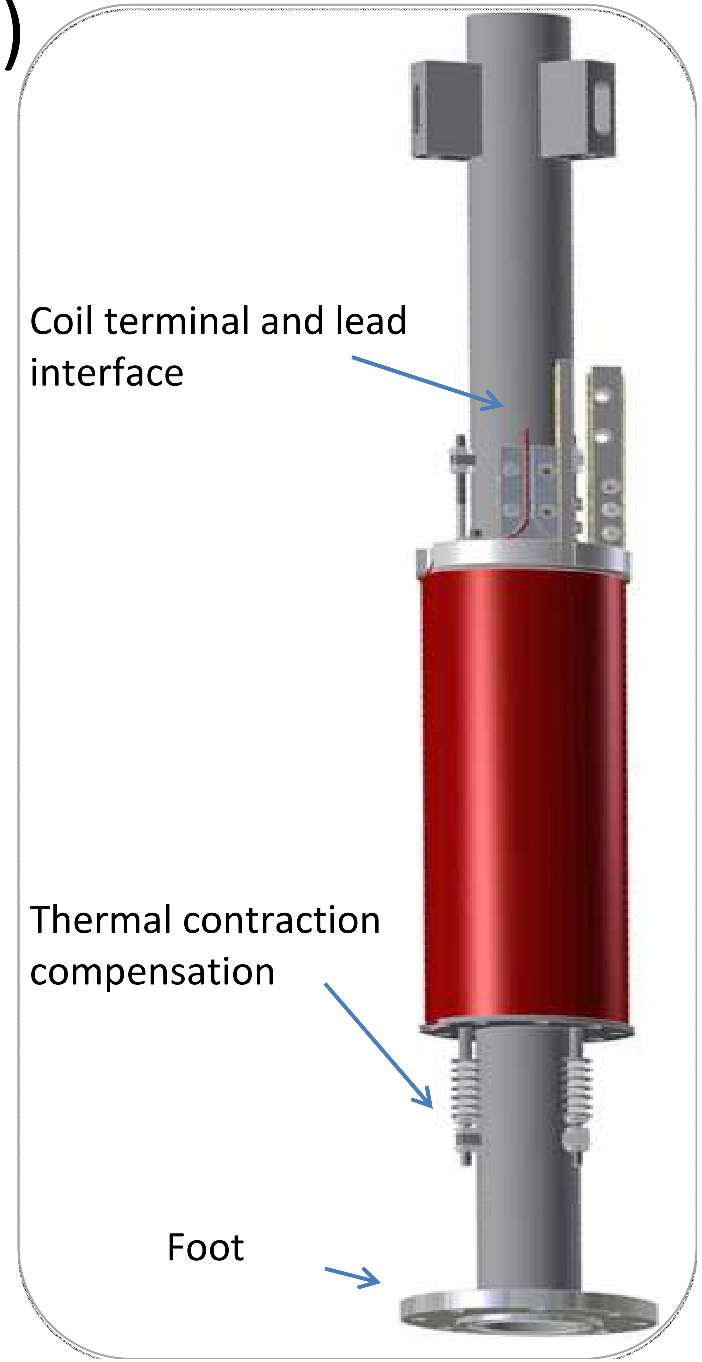
OP HT:
890 degC, 50 atm

Wire begins as powder in tube:

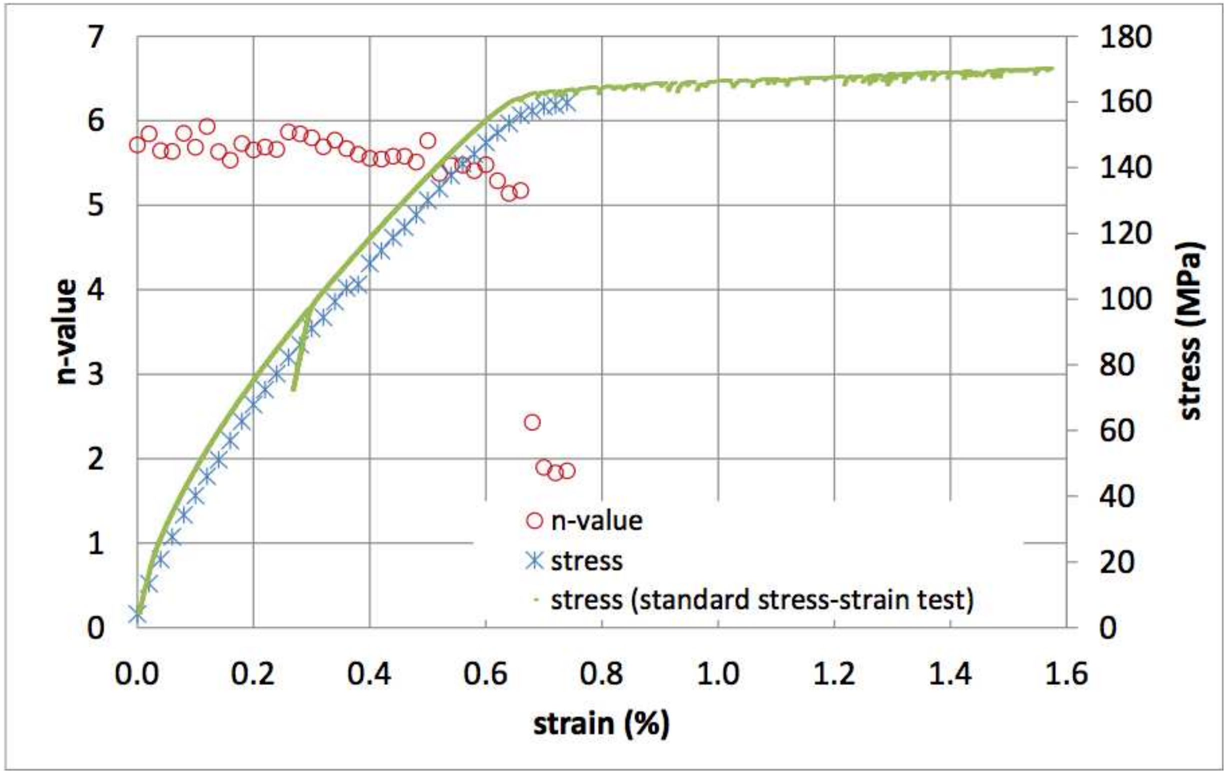


Final product is
superconducting ceramic strands:



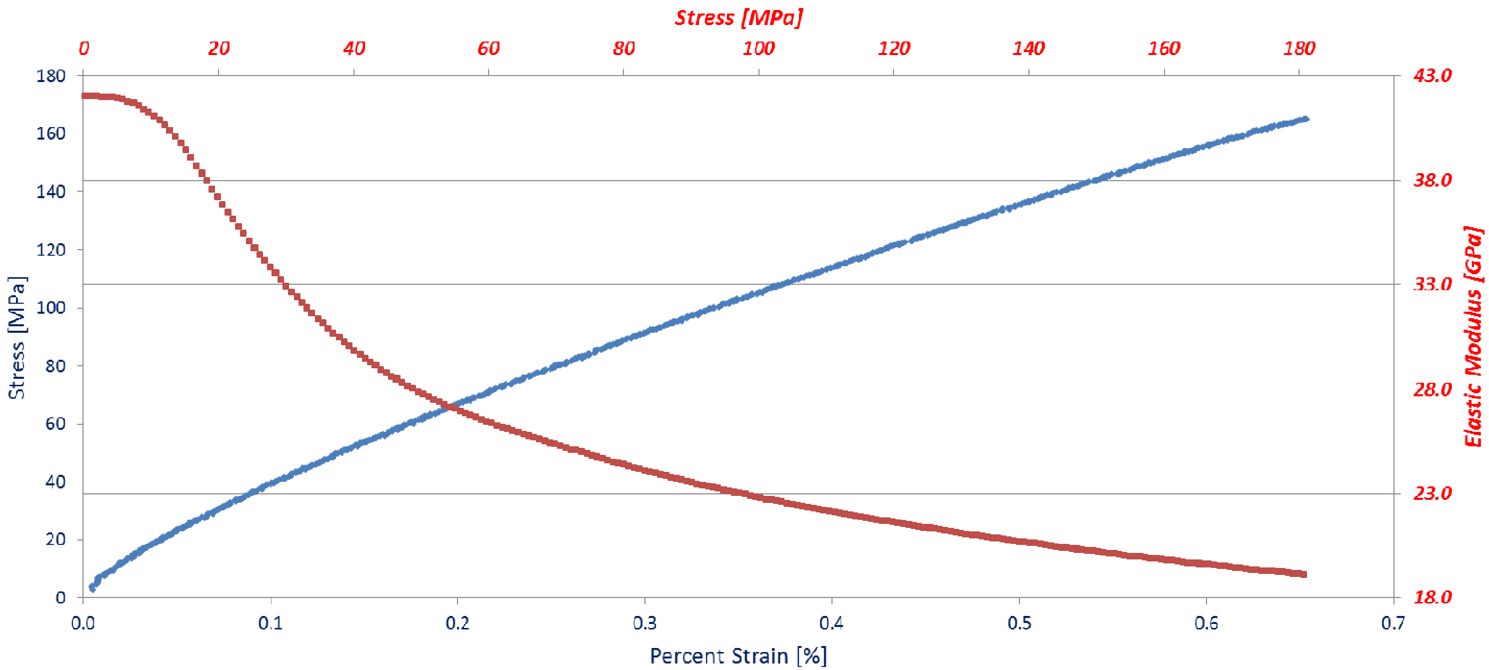


Bi2212 Critical Strain 'cliff'



AZIMUTHAL STRAIN (i.e. axial tension along wire) of 0.6% is known to break the ceramic filaments and degrade conductor critical current, plot from C.Scheurlein.

Bi2212 Experimental Stress-Strain Curve



Nonlinear Elasticity Modulus for Bi2212 Conductor

•Plotted on the primary axis is a typical stress-strain curve from D.McRae and B.Walsh

•Plotted on the secondary axis stress-dependent modulus for all stress calculations of the conductor – modulus taken as the tangential modulus and formulated as a function of stress

•Note the low modulus beyond 120 MPa

(i.e. easier to strain conductor at higher stress)

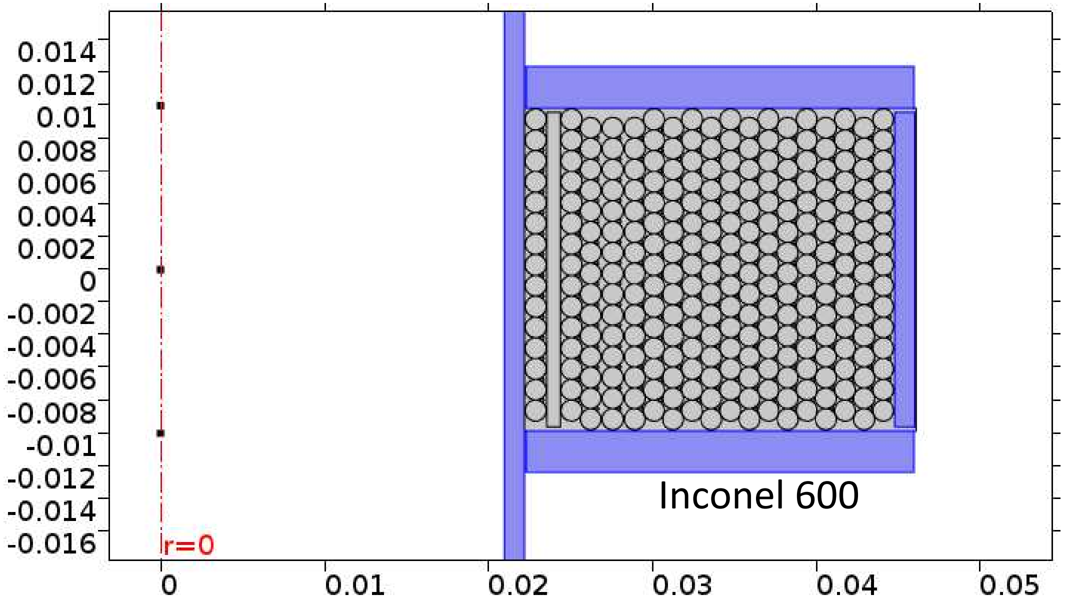
Building a Model: *Platypup* – the prototype coil

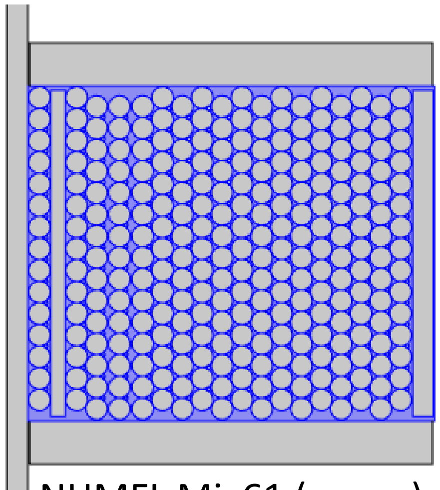
Model based on 2D-axisymmetric, Hex-Packed Winding – after OPHT (shown here is a particular cross section of *Platypup3* featuring an azimuthal slice with a crossover from Layer 3 to Layer 4)

Each domain attributed independent material properties (527 domains for model shown)

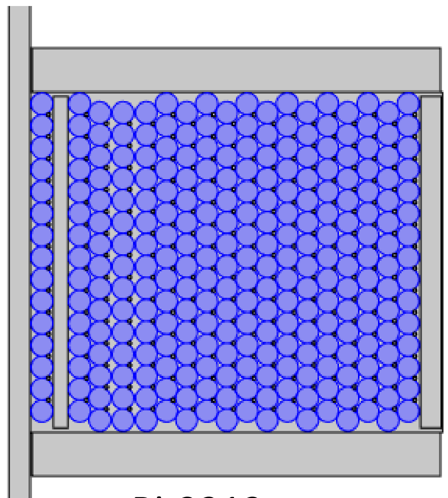
All properties at 4.2 K, and thermal contractions determined from integrated α's between 300 K and 4.2 K

*Magnetization of Inconel600 later utilized to study material effect on field homogeneity



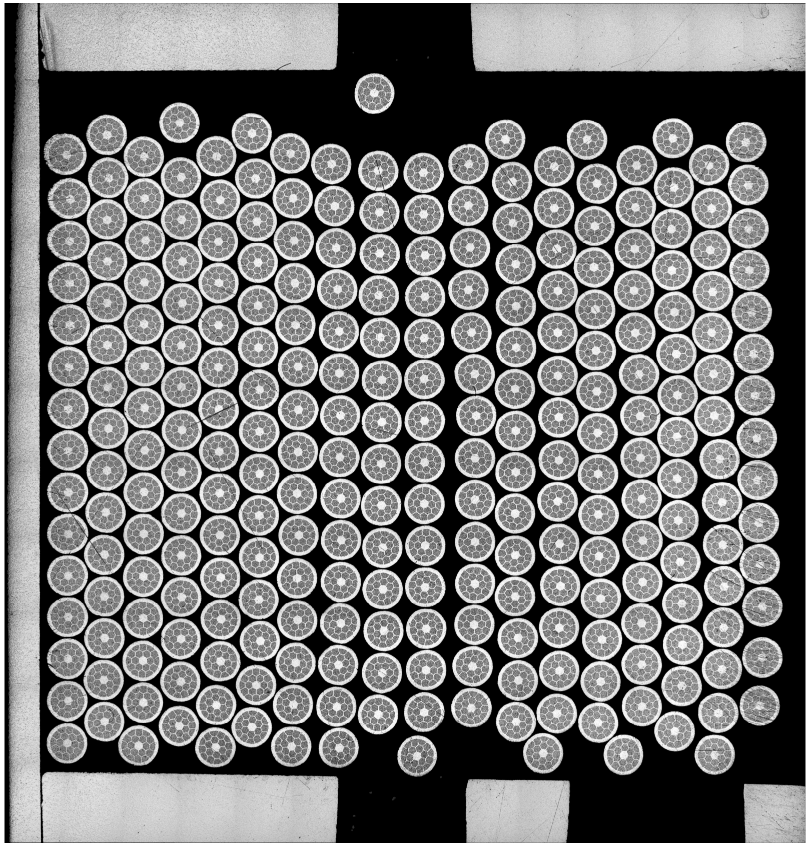


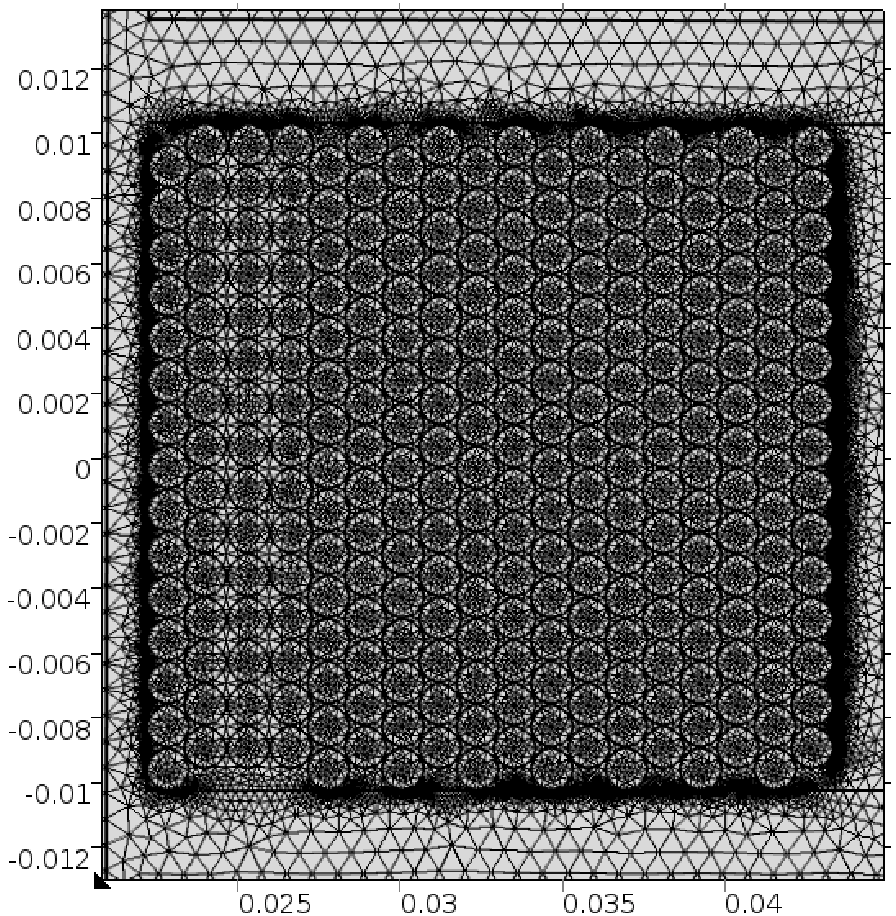
NHMFL Mix61 (epoxy)



Bi-2212

Comparison of Ideal vs Real:





PDE Assumptions

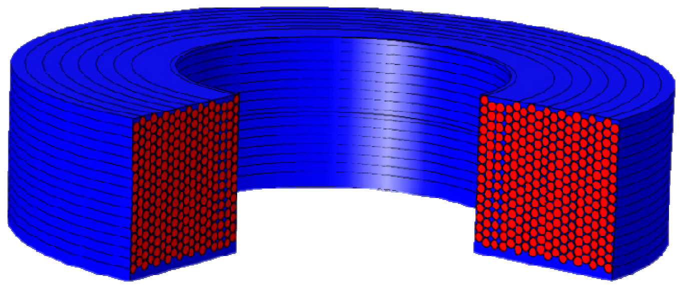
Magnetic Fields (mf):

- General PDEs

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

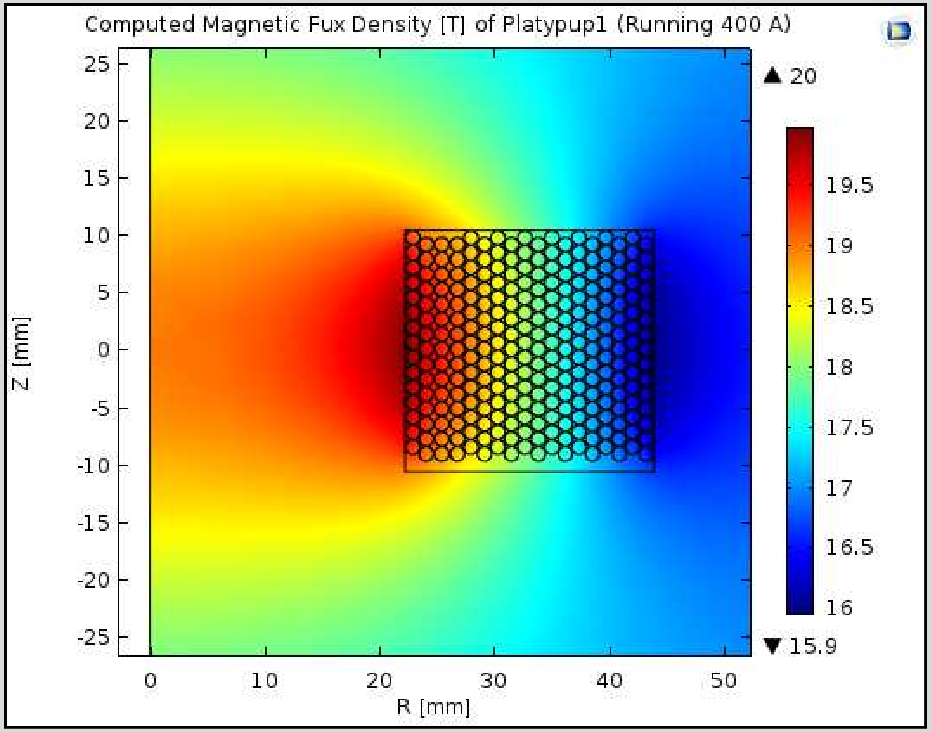
$$\mathbf{B} = \nabla \times \mathbf{A}$$

- J_e defined as *Current / Area_of_EachWire*
- Far field evaluated with perfect conductor

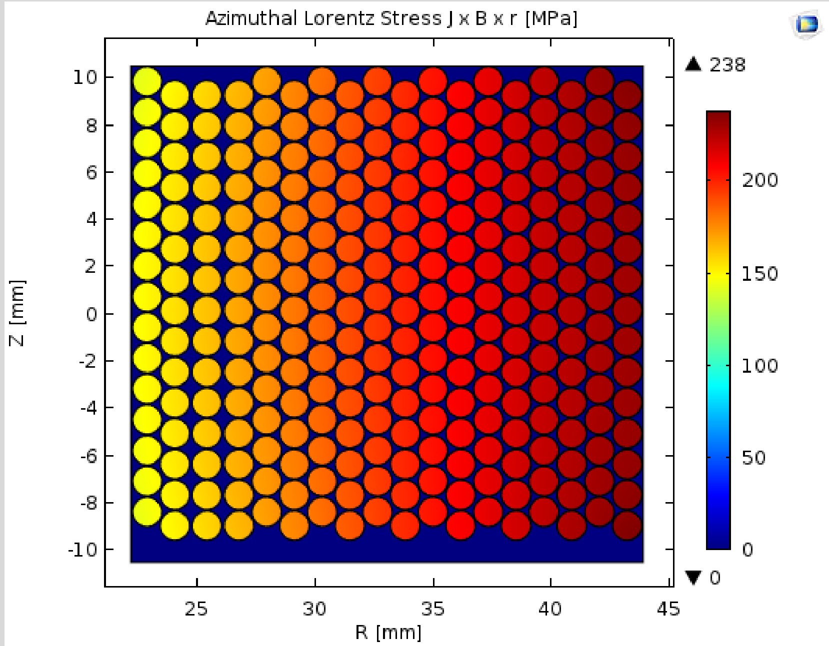


Platypup1

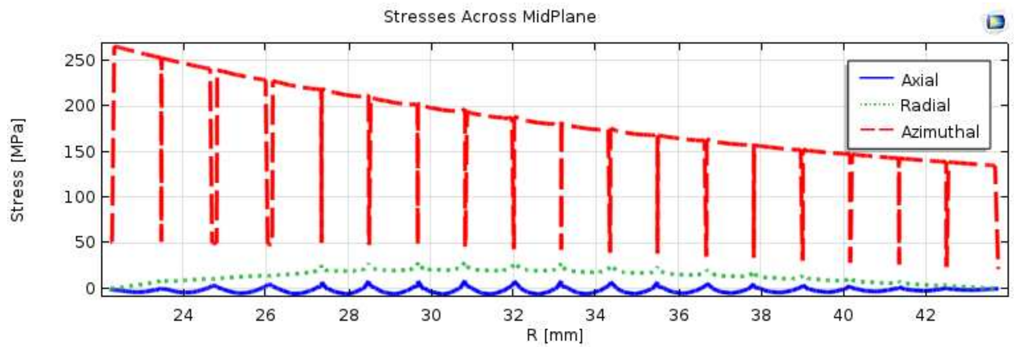
PARAMETER		DESCRIPTION
WireD	1.3[mm]	Bare Wire
WireIns	0.047[mm]	InHouse Total Insulation
CondD	WireD+WireIns	Insulated Conductor
WireDD	0.955*WireD	
WireInsD	0.6*WireIns	Densified Properties
CondDD	WireDD+WireInsD	
Curr	400[A]	Insert Current
a1_ctr	a2_bore	Inner Radius
a2_ctr	a1_ctr+(6+(m_ctr-3)*sqrt(3))*(CondD)/2	Outer Radius
b_ctr	(n_ctr+0.5)*(CondDD)/2	Half Height (densified)
m_ctr	18	Layers
n_ctr	15	Turns (windings per layer)
J_e	Curr/(pi/4*WireDD^2)	Transport Density per Wire
Bckgrnd	17[T]	Cell4 Background Field

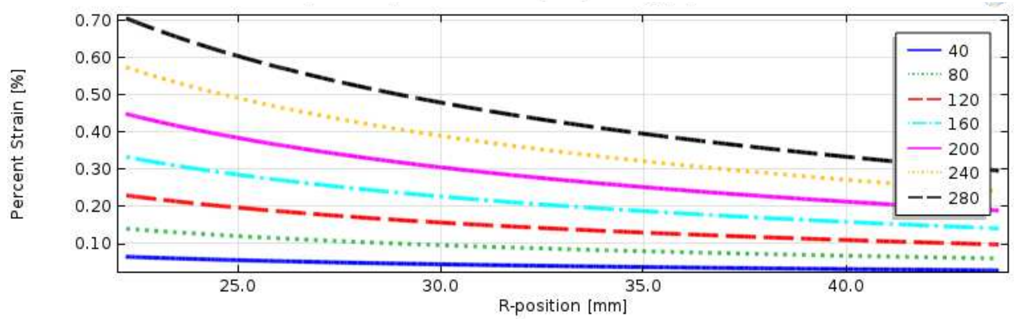


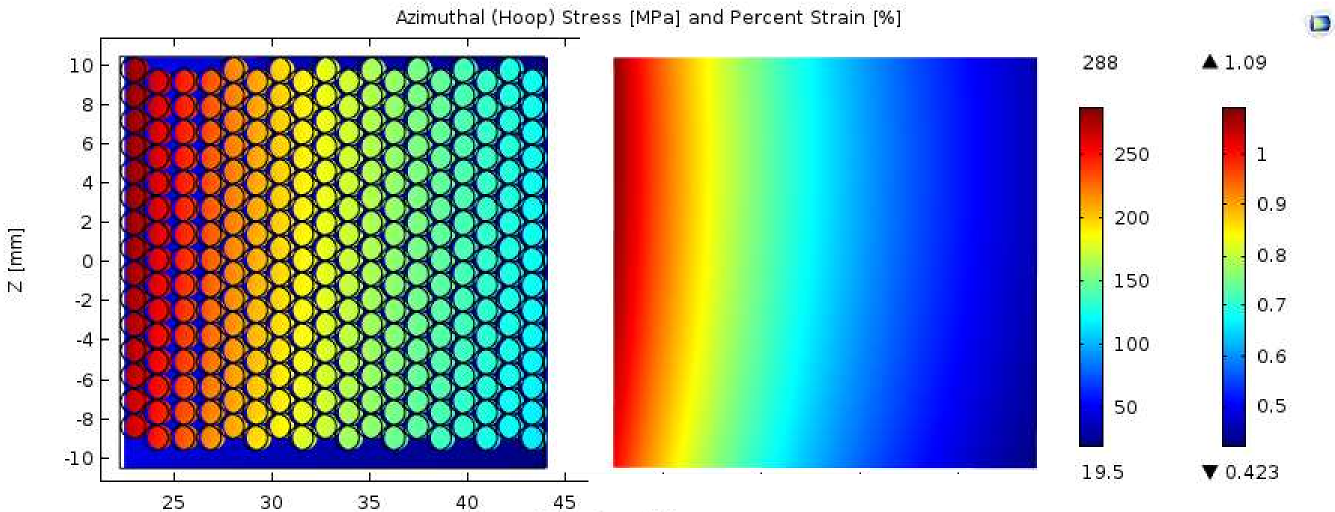
Platypup1: Solid Mechanics $-\nabla\cdot\sigma = \boldsymbol{F}_V$ $[I = 400\ A]$



For reference: L01_T8 = 152 MPa; L18_T8 = 230 MPa

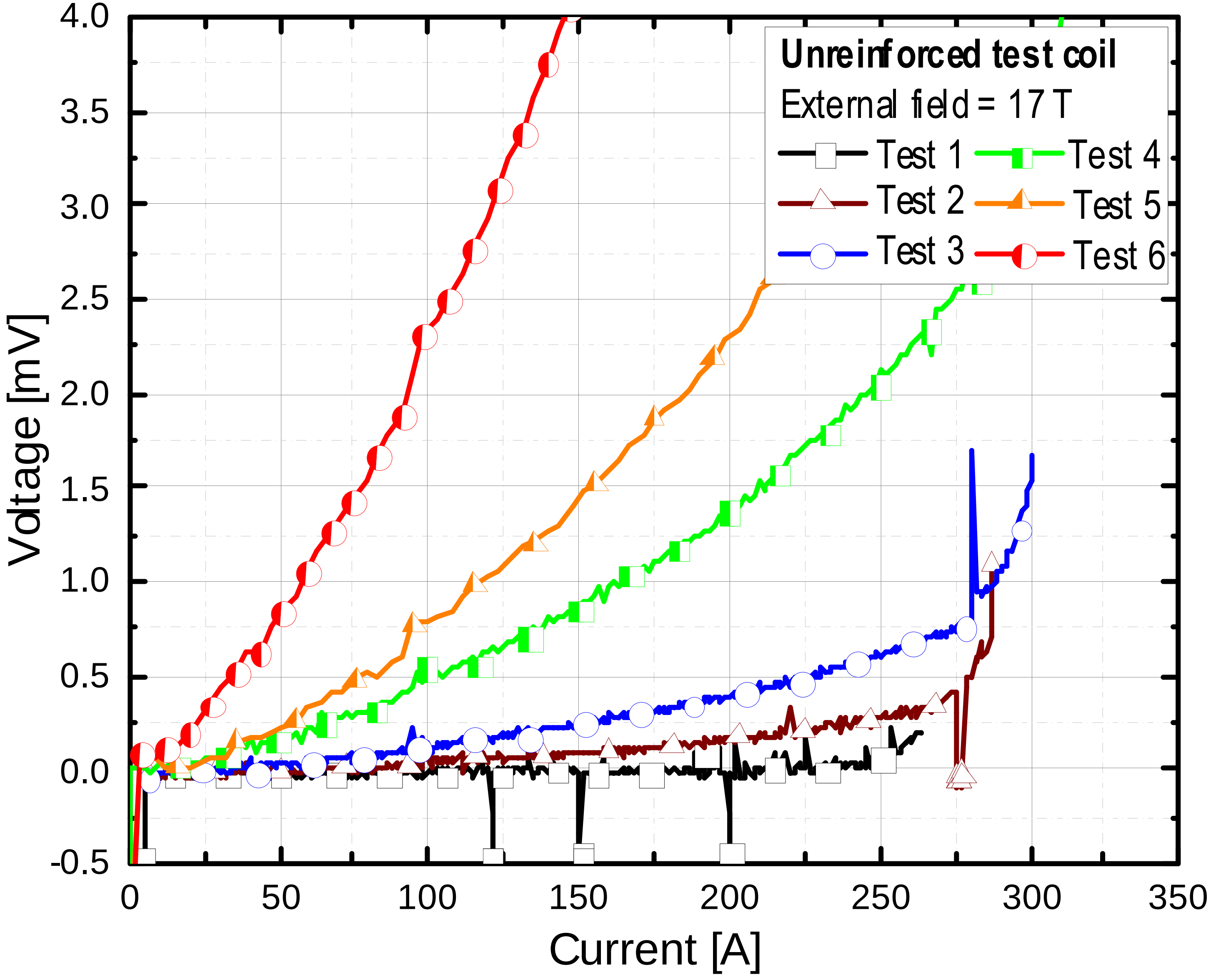




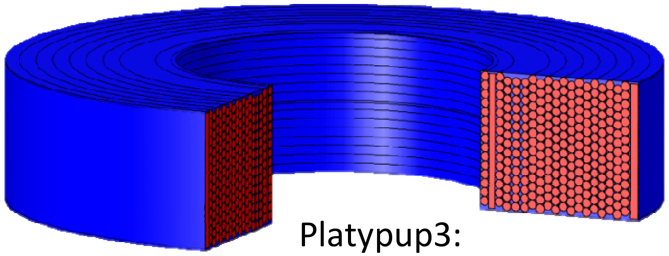


For reference: L01_T8 = 278 MPa; L18_T8 = 122 MPa

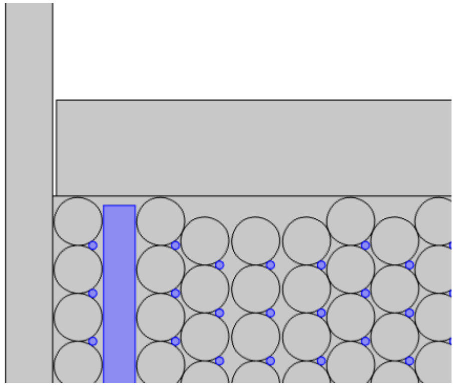
Platypup1: Experimental Results



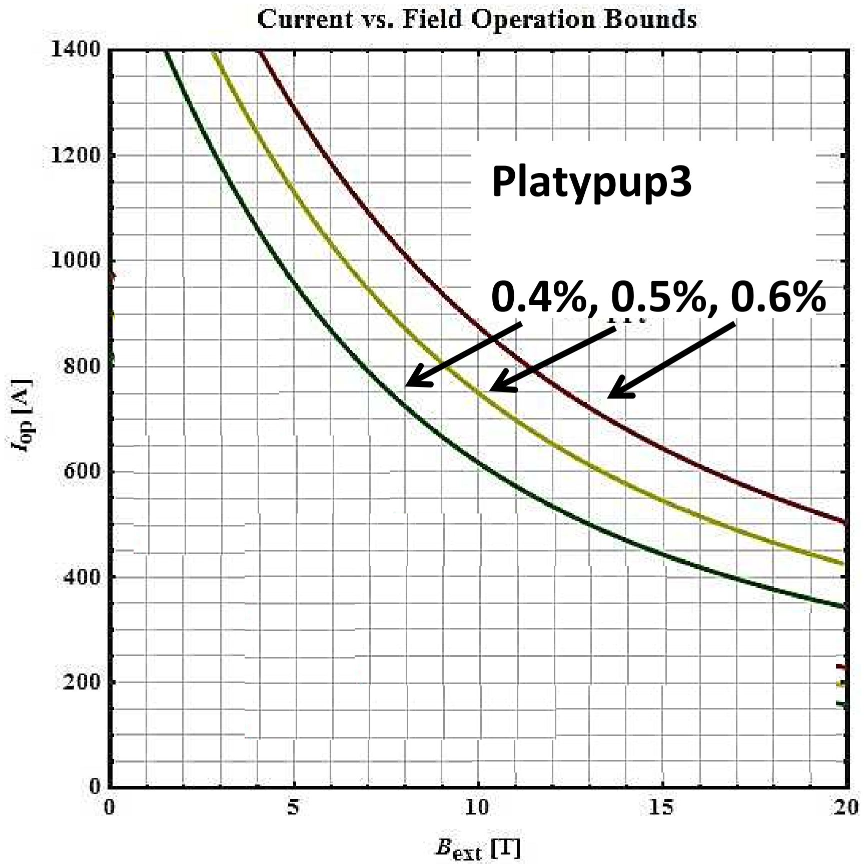
Platypup3: Structural Reinforcement

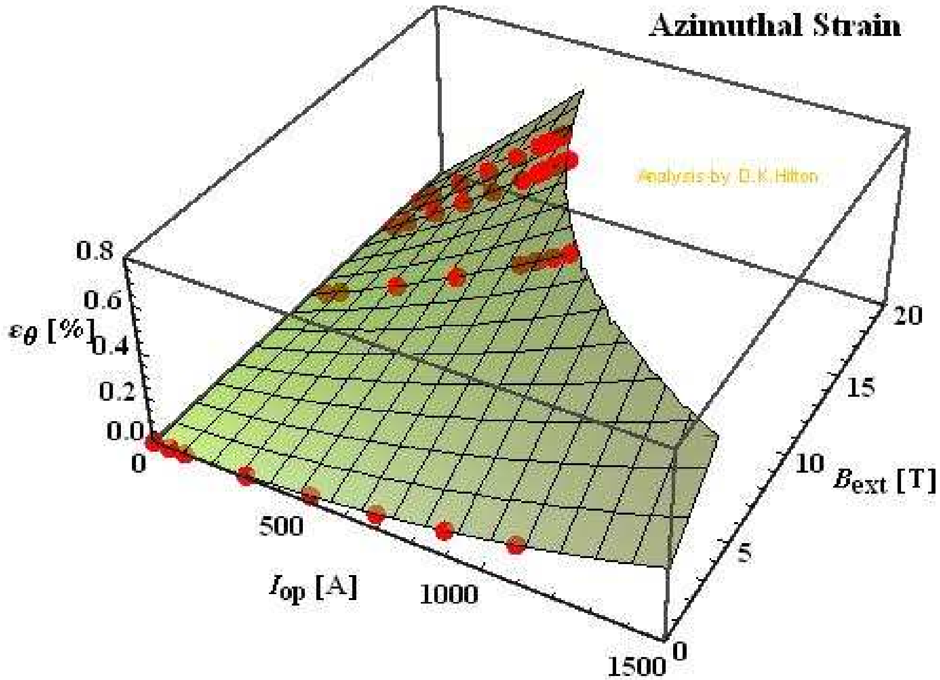


Platypup3:
Similar to Pup1, but includes innerband, co-wind, and overband

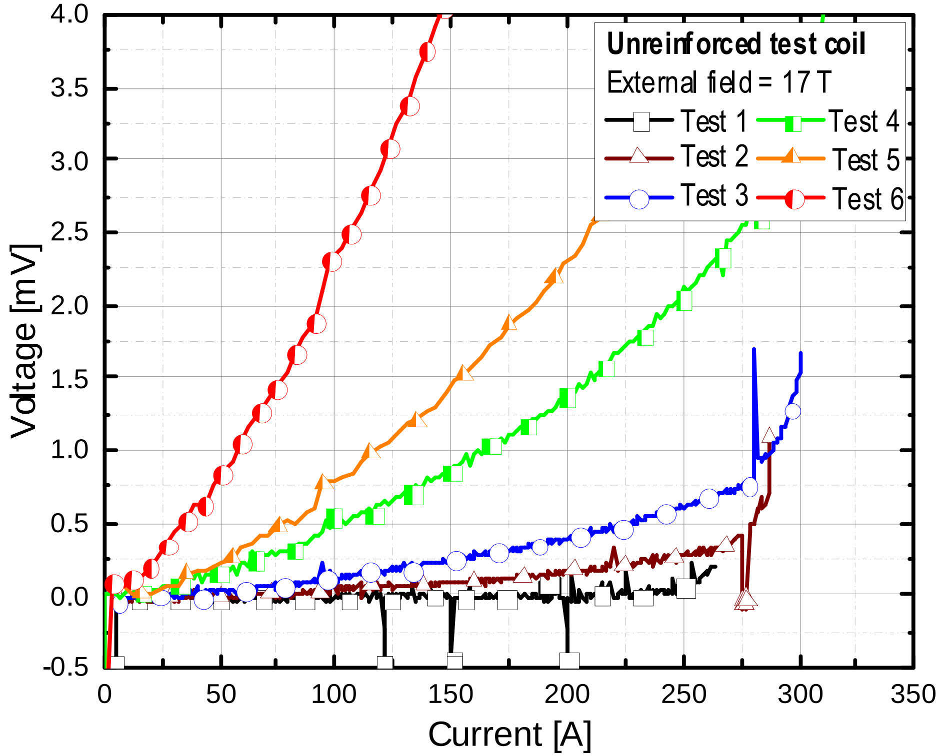


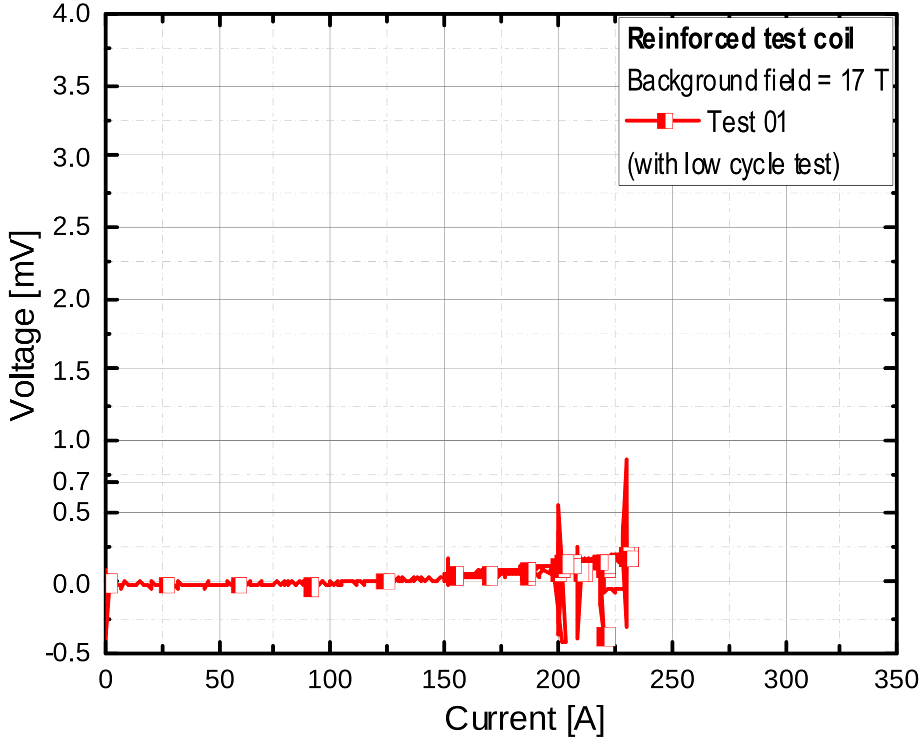
Ceramic Fiber





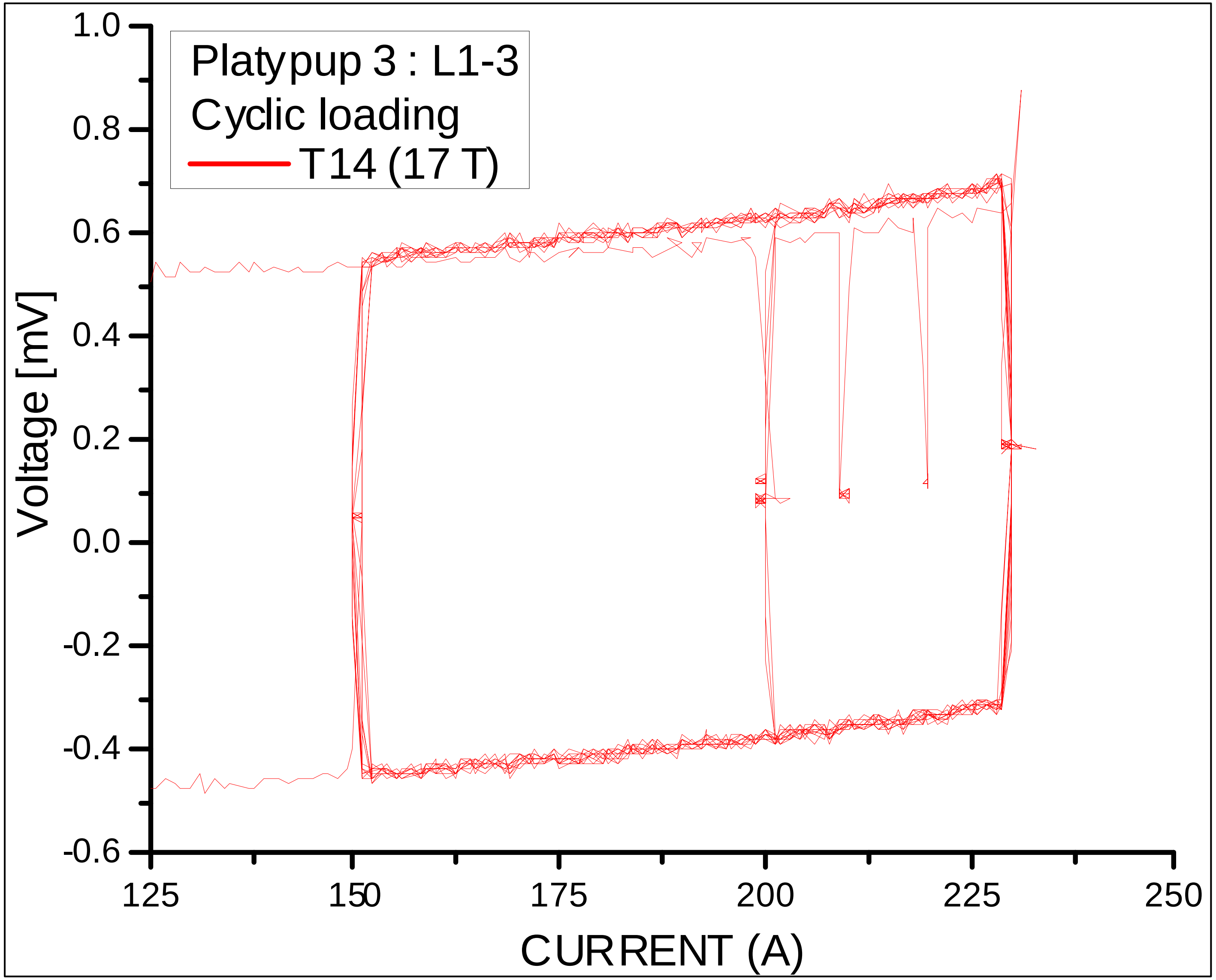
Platypup-1 and 3: Experimental Result Comparison



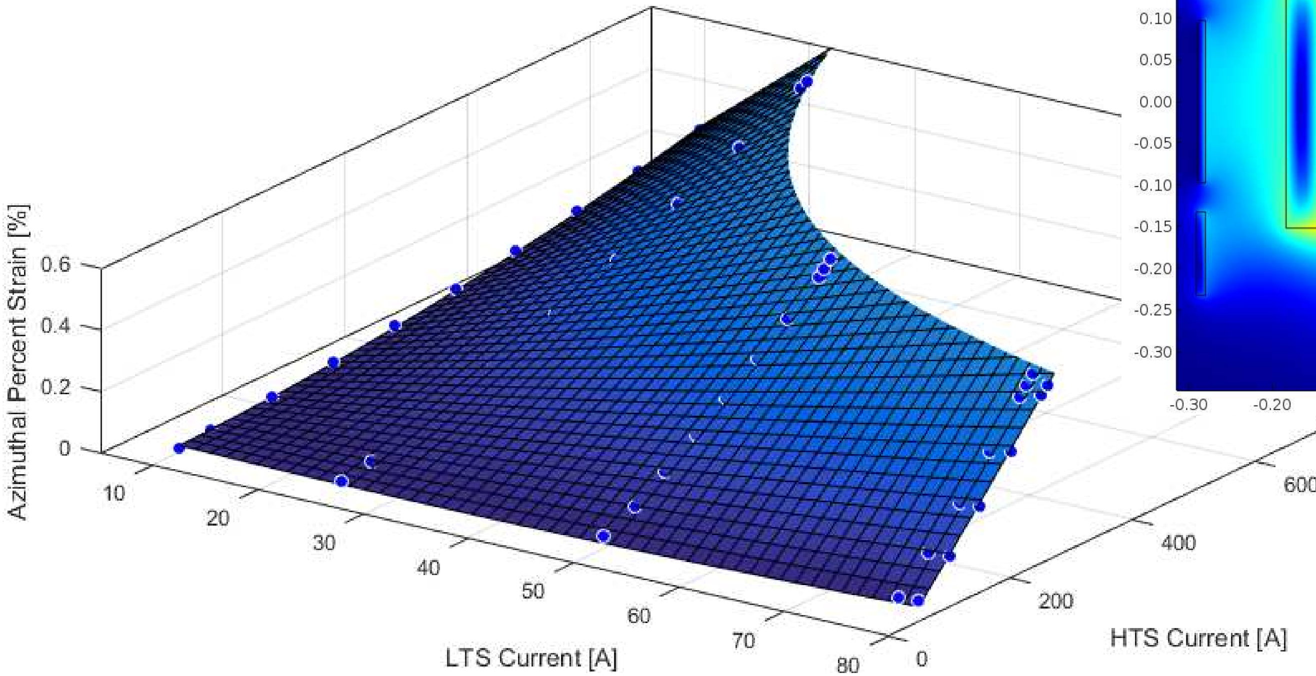


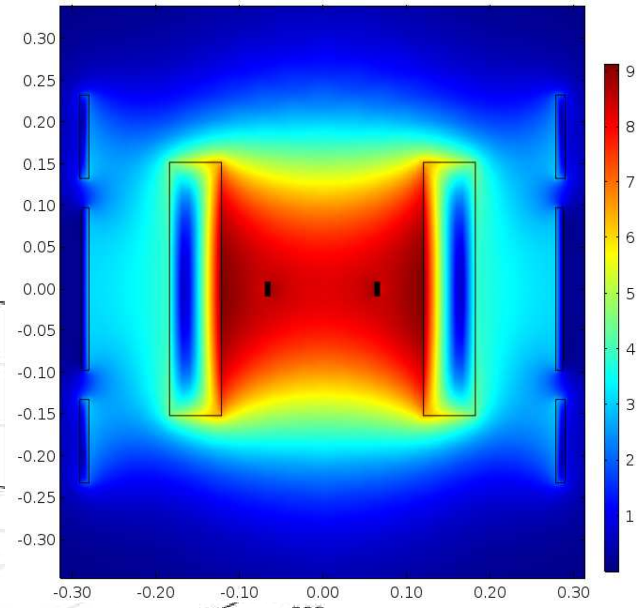
Experimental results show that Platypup3 was NOT Strain Limited
Unfortunately, the results are hindered by low Ic elsewhere in the coil, but after cyclic loading, the coil shows no systemic degradation – in contrast to what is seen in Platypup1

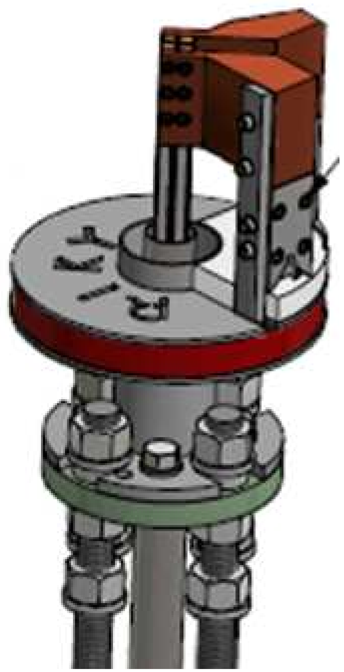
Platypup3: V-I Curve of Inner Layer During Cyclic Loading

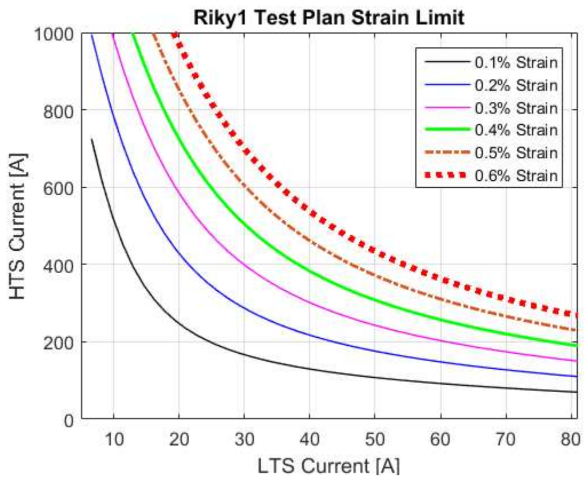


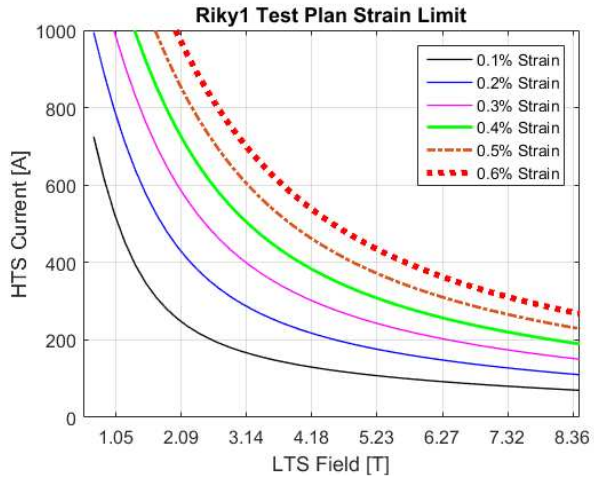
Riky1 Test Plan Inside of 8 T Cryo-cooled Magnet



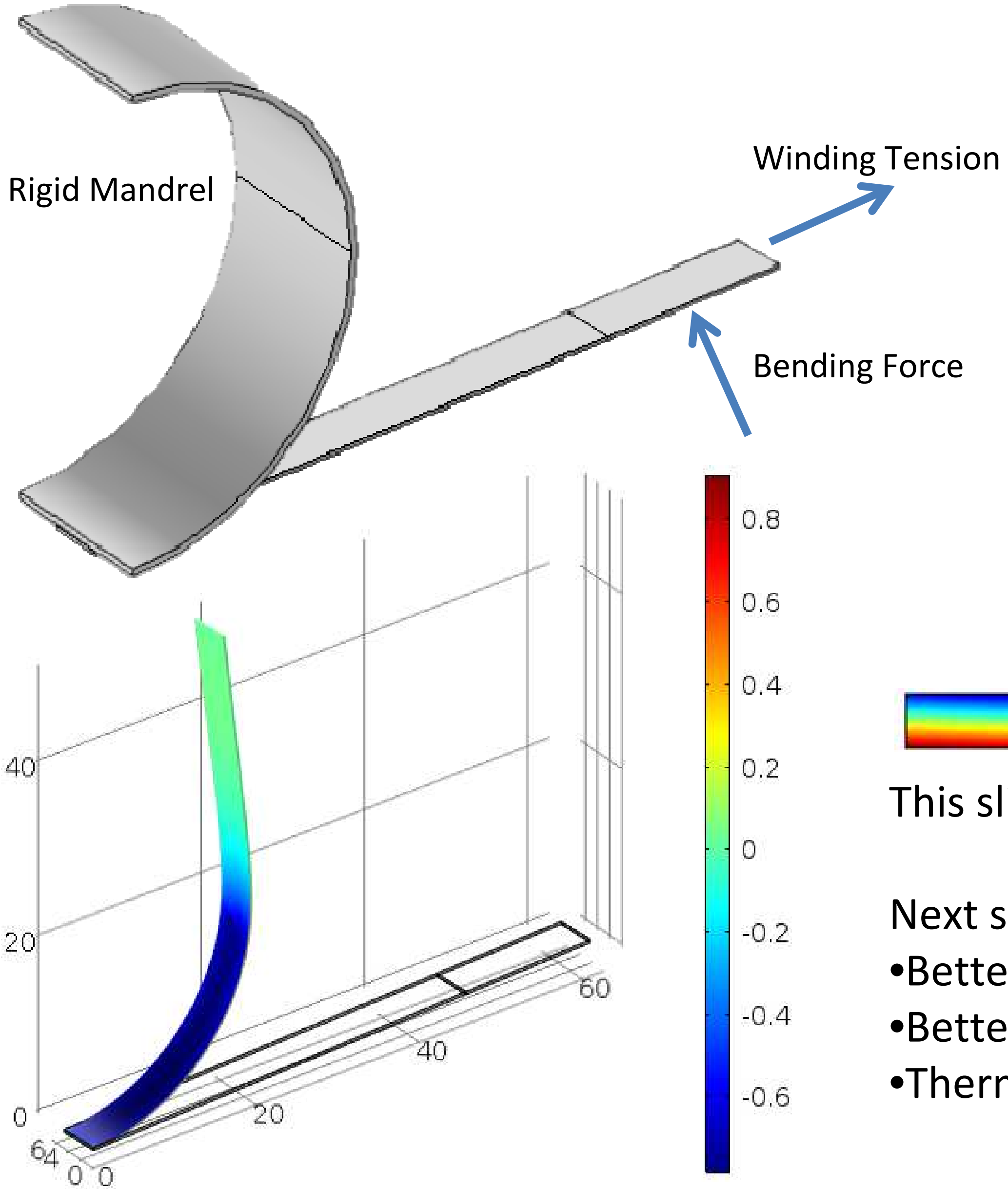


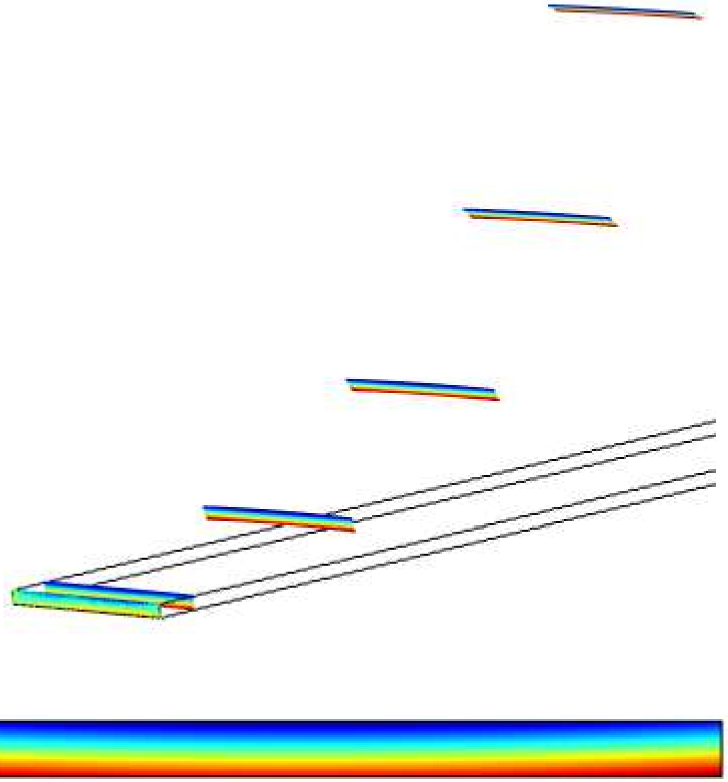






Current Work w.r.t Bending Strains
React-and-Wind Conductors / Laminated Bi2212





This slice corresponds to a 45 degree angle

Next steps aim to improve model:
- Better material properties
- Better geometry (including reinforcement)
- Thermal contraction

Conclusions

•Multiphysics FEA proving to be an invaluable resource in designing new prototype coils to investigate strain limits of conductors

•Development of test plans for experimentation give good validation of models with respect to real coil performance

•Confidence has been obtained to predict behavior of larger magnet systems – with obviously higher material and manufacturing costs

•Study of laminated, aspected conductors may help further push HTS technology toward High Field, High Homogeneity Magnet applications