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
• $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ (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:

Coil terminal and lead interface

Thermal contraction compensation

Foot
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)
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
Comparison of Ideal vs Real:
PDE Assumptions

**Magnetic Fields (mf):**

- General PDEs
  \[ \mathbf{\nabla} \times \mathbf{H} = \mathbf{J}_e \]
  \[ \mathbf{B} = \mathbf{\nabla} \times \mathbf{A} \]

- \( J_e \) defined as \textit{Current / Area of Each Wire}

- Far field evaluated with perfect conductor

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![Computed Magnetic Flux Density [T] of Platypup1 (Running 400 A)](image)
Platypup1: Solid Mechanics

\(- \nabla \cdot \sigma = F_v \quad [I = 400 \, A]\)

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

For reference: 
L01_T8 = 278 MPa; L18_T8 = 122 MPa
Unreinforced test coil
External field = 17 T

Test 1, Test 2, Test 3, Test 4, Test 5, Test 6

Voltage [mV] vs. Current [A]
**Platypup3: Structural Reinforcement**

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

- Ceramic Fiber

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**Current vs. Field Operation Bounds**

- Platypup3
- 0.4%, 0.5%, 0.6%

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**Azimuthal Strain**

- Analysed by D.K. Hillen
Experimental results show that Platypup3 was NOT Strain Limited
Unfortunately, the results are hindered by low \( I_c \) 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