[Thu-Mo-Or33]

Multiphysics FEA Led Design of Bi-2212 Round Wire Prototype Coils

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NATIONAL MAGLAB

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

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Overview

- Bi-2212 RW: Performance limits
- Multiphysics FEA
  - Introduction to the modeling effort
  - Principal assumptions and definitions
  - Analysis led design of prototype coils
- The Prototype Coil Program
  - Approaching operational limits
  - Experimental validation of the modeling
- Summary

Bi-2212 RW: A brief word on the wires

- Advancing wire and OP-HT processing

- Macroscopically isotropic, twisted round wire:
  - Minimal field drift; appropriate for NMR
  - Magnetization even smaller than LTS

J.Jiang, *et al.*

D.Larbalestier *et al.*, Nature Materials 2014

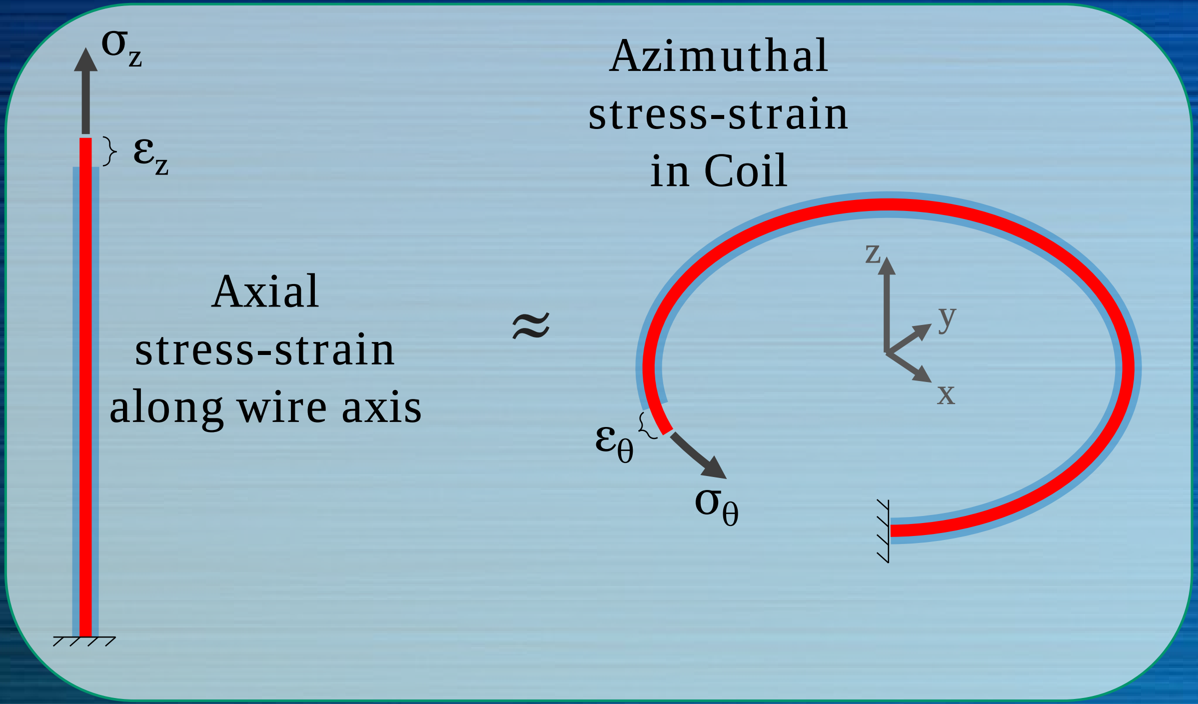
P.Chen

D.Davis, *et al.*

Bi-2212 RW: Performance limits

R.Bjoerstad *et al.*, CERN EuCARD-2 2015

- $I_c(B)$ field dependence
- $I_c(\varepsilon)$ strain along wire axis
  - MTS stress-strain data taken from single wires
  - Coil analogy ≈ azimuthal (hoop) strains in coils

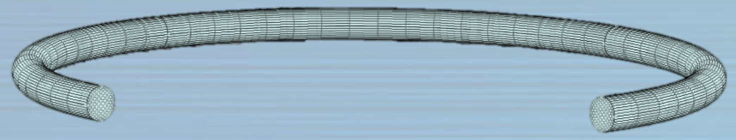


N.Cheggour, U.Colorado-Boulder

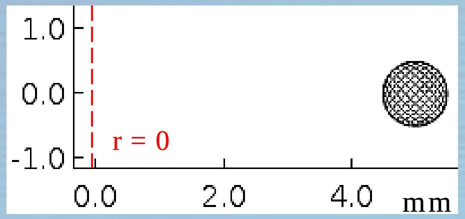
Multiphysics FEA: Addressing primary concerns

Models studied on a wire-by-wire level

- 4.2 K thermal strain
- Computation of magnetic fields
    - ($J \cdot B \cdot R$) Lorentz Forces → coil source stresses

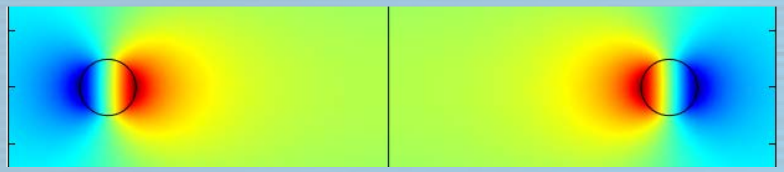


2D-axisymmetric



Field computed [T]

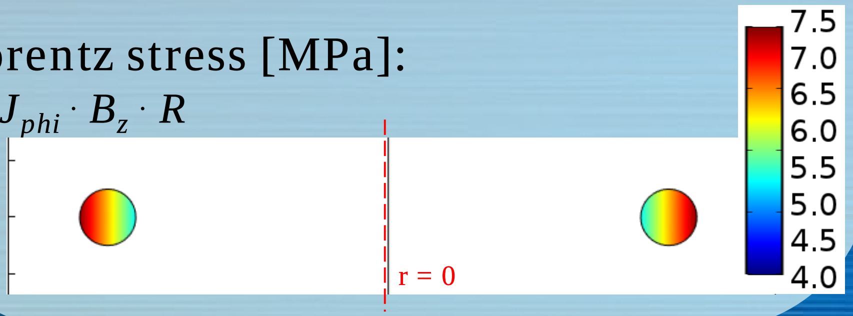
$\nabla \times H = J$



Above: Field generated by running 100 A/mm^2 in a single loop (1 mm dia wire; 10 mm dia loop) placed within a 10 T background field (range 9.97 *[blue]* to 10.05 *[red]* T).

Lorentz stress [MPa]:

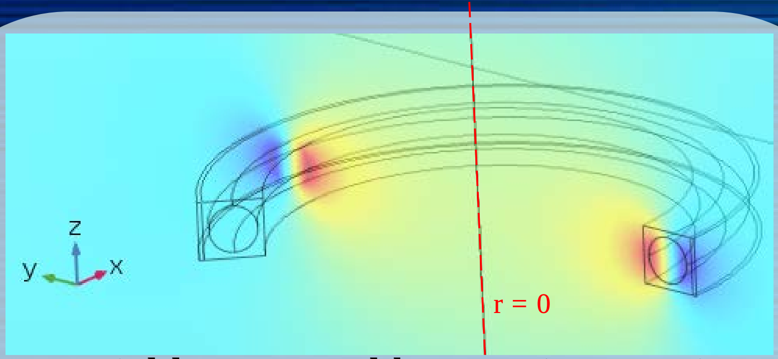
$J_{phi} \cdot B_z \cdot R$



Multiphysics FEA: Addressing primary concerns

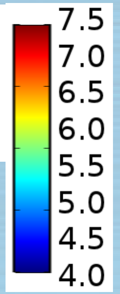
Models studied on a wire-by-wire level

- 4.2 K thermal strain
- Computation of magnetic fields
  - ($J \cdot B \cdot R$) Lorentz Forces → coil source stresses
- Coupling the $J \cdot B \cdot R$ to structural mechanics
  - These coils epoxy impregnated; so stresses are redistributed across all materials within the coil pack
  - Allows for reinforcement on coil level
  - Each material defined with its own material properties

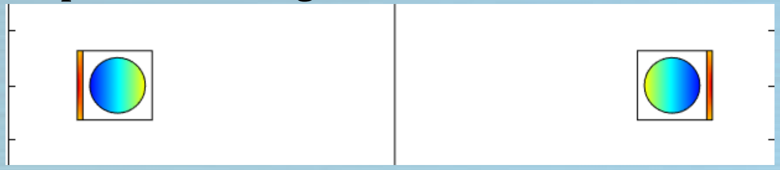


Above: Field generated by running previous slide example after epoxy impregnating and over-banding

Lorentz stress [MPa] is identical (J only in wire)



Below: Structural mechanics – coupling the Lorentz load with reinforcement lowers the hoop stress along the conductor.



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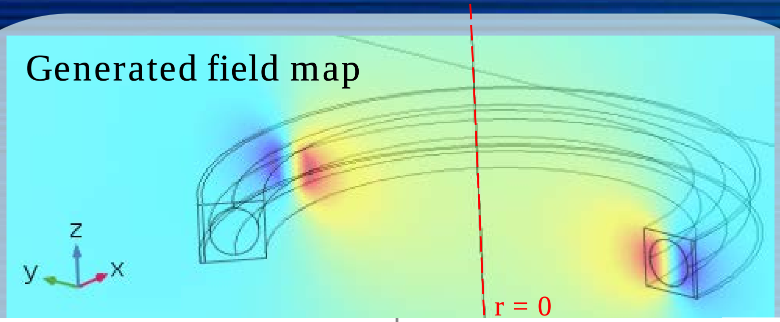
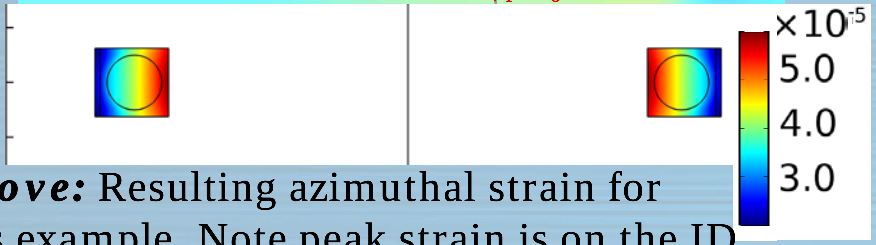
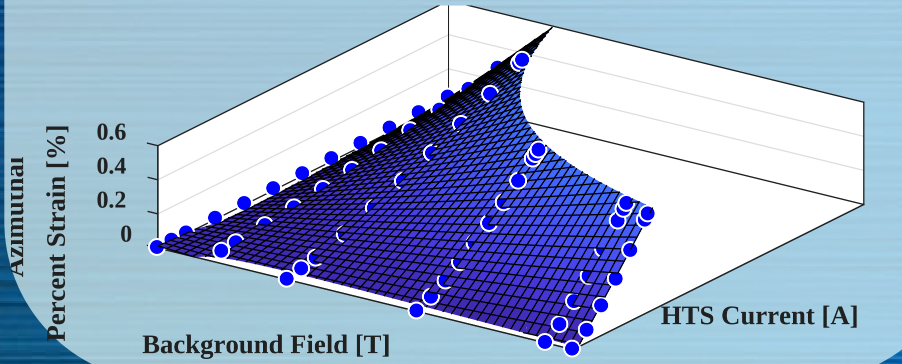
  - These coils epoxy impregnated; so stresses are redistributed across all materials within the coil pack
  - Allows for reinforcement on coil level
  - Each material defined with its own material properties
  - Conductor elasticity modulus based on non-linear stress-strain data from short samples
  - Fully coupled model accounts for movement of each conductor
- Parametric sweeps
  - Input current and LTS Outsert fields are real 'knobs'
  - Strain-based performance envelopes





Above: Resulting azimuthal strain for this example. Note peak strain is on the ID of loop

Below: Strain-limited performance envelope, increase of either background field and/or HTS current lead to 0.6% strain limit



Multiphysics FEA: Analysis led design of prototype coils

- Performance requirements for High Field Demonstration Magnet
  - IMPDAHMA Outsert: geometry and field
  - Demonstration design

    Thermal contractions – T_{op} = 4.2 K

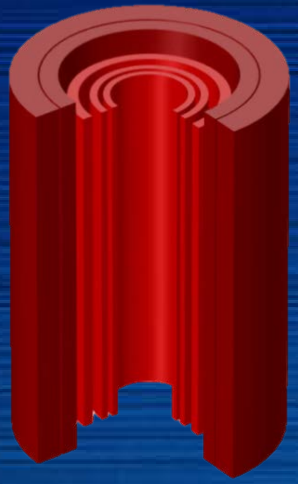
    Generated loads – targeting ~1 GHz (23.5 T)

    Homogeneity – targeting ~1 ppm

- Prototype design constraints
  - Geometry and background fields of the available LTS test beds
  - Working hot zone of the furnace (OPHT facility) – inner diameter of 130 mm; 450 mm height

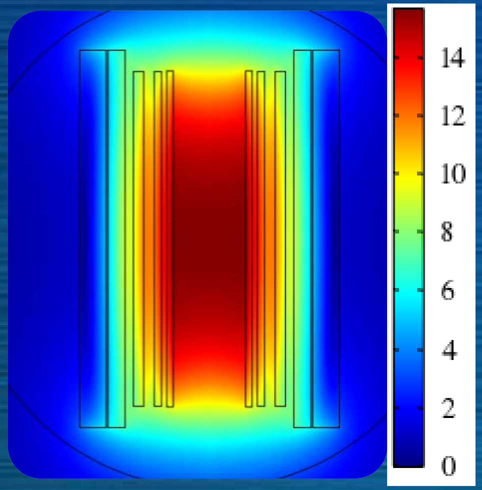
- Desire to drive Bi-2212 RW technology

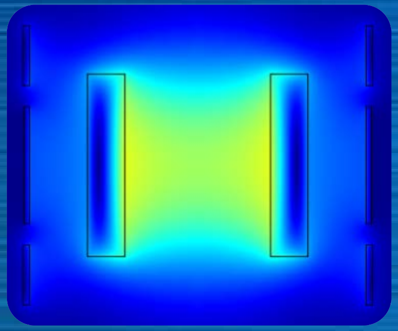
  Test plans to reach ultimate conductor limits



IMPDAHMA 16 T
110 mm cold bore

Cyocooled 8 T
242 mm magnet ID
140 mm cryostat





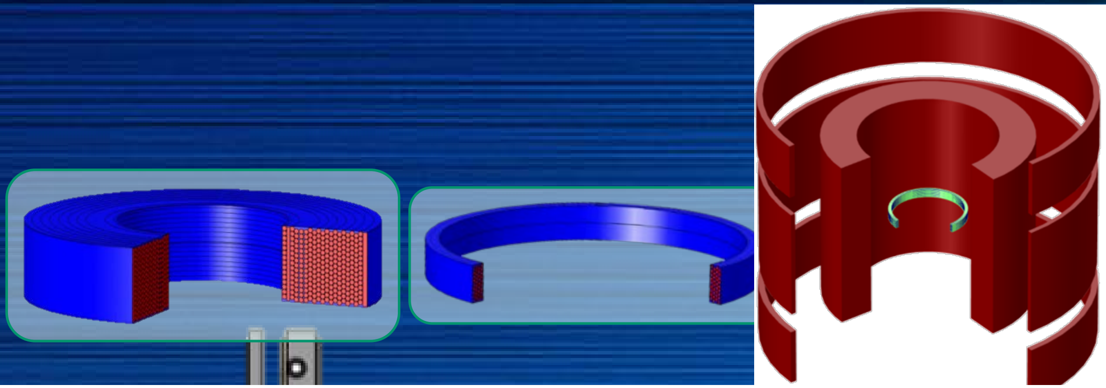
The Prototype Coil Program

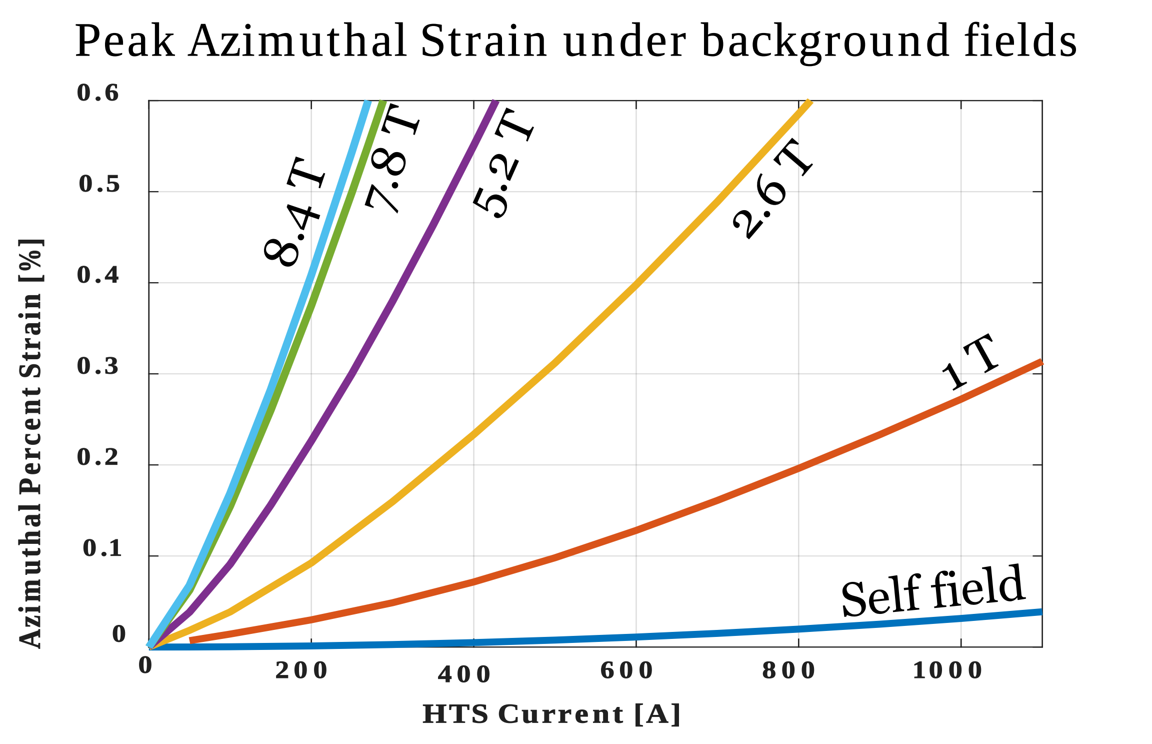
Motivation for each prototype:

- First set of prototypes were scaled versions of a larger (high field NMR) demonstration coil (18 layers, ~10 turns)
  - intended to test manufacturing
  - designed for a now decommissioned 17 T testbed

- Second set of prototypes were designed to approach the strain limits of a coil wound with Bi-2212 RW conductor
  (4 layers, 10 turns)
  (limited to the available 8 T background)
  - validating the FEA modeling efforts;
    qualification & quantification
  - examining reinforcement techniques

- Now using either prototype to target specific hurdles as we further develop Bi-2212 RW for high field NMR applications



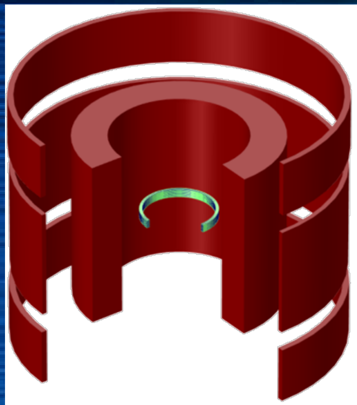


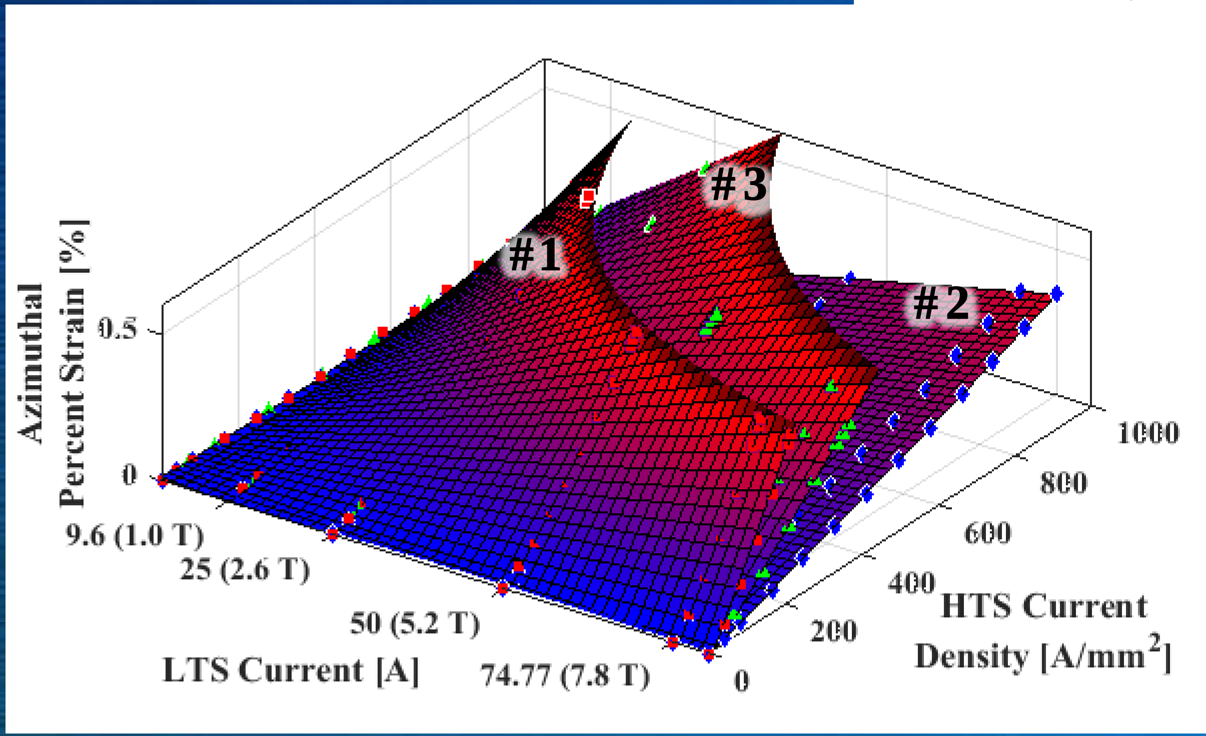
Prototype Coils: Experimental validation of modeling

Second set of prototypes predictions

- First coil (not reinforced) was predicted to reach 0.6% azimuthal strain near ~280 A (231 A/mm^2) within an ~8 T background
- Second coil built with full reinforcement
- Third coil includes moderate reinforcement to reach 0.6% near ~350 A (489 A/mm^2)

The third prototype was constructed with 1.0 mm wire; first and second had 1.3 mm wire. Roughly, B and R were held constant while increasing J_e. The added strain was thus managed with the inclusion of moderate reinforcement.





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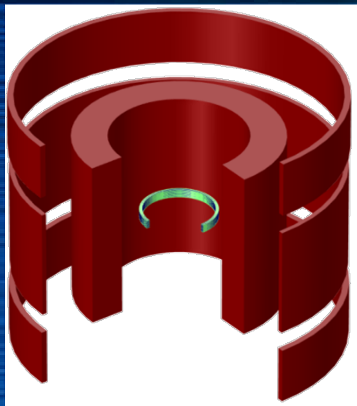
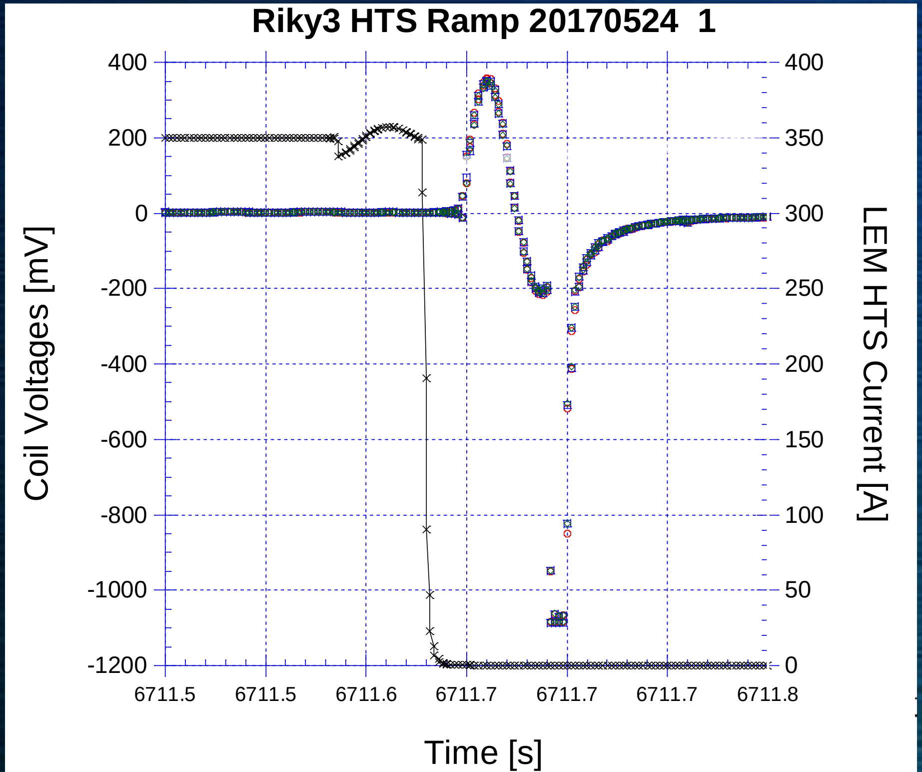
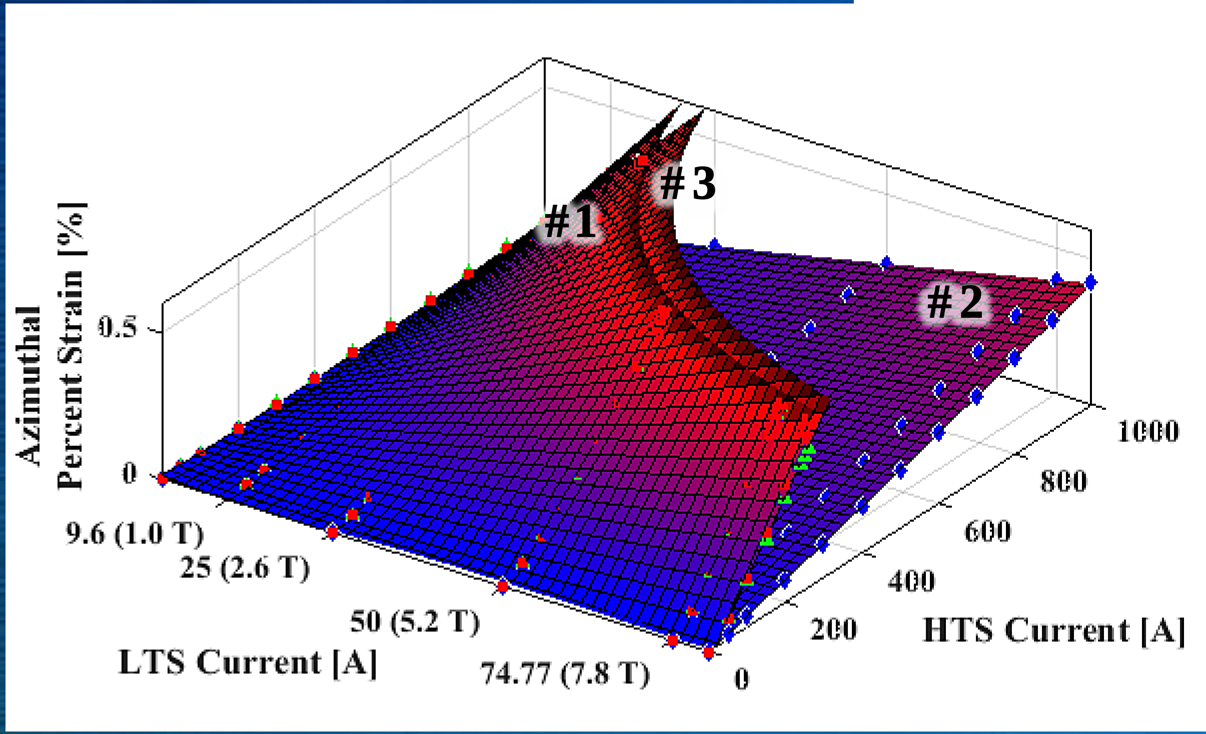






A Bi-2212 Insert for High Field NMR

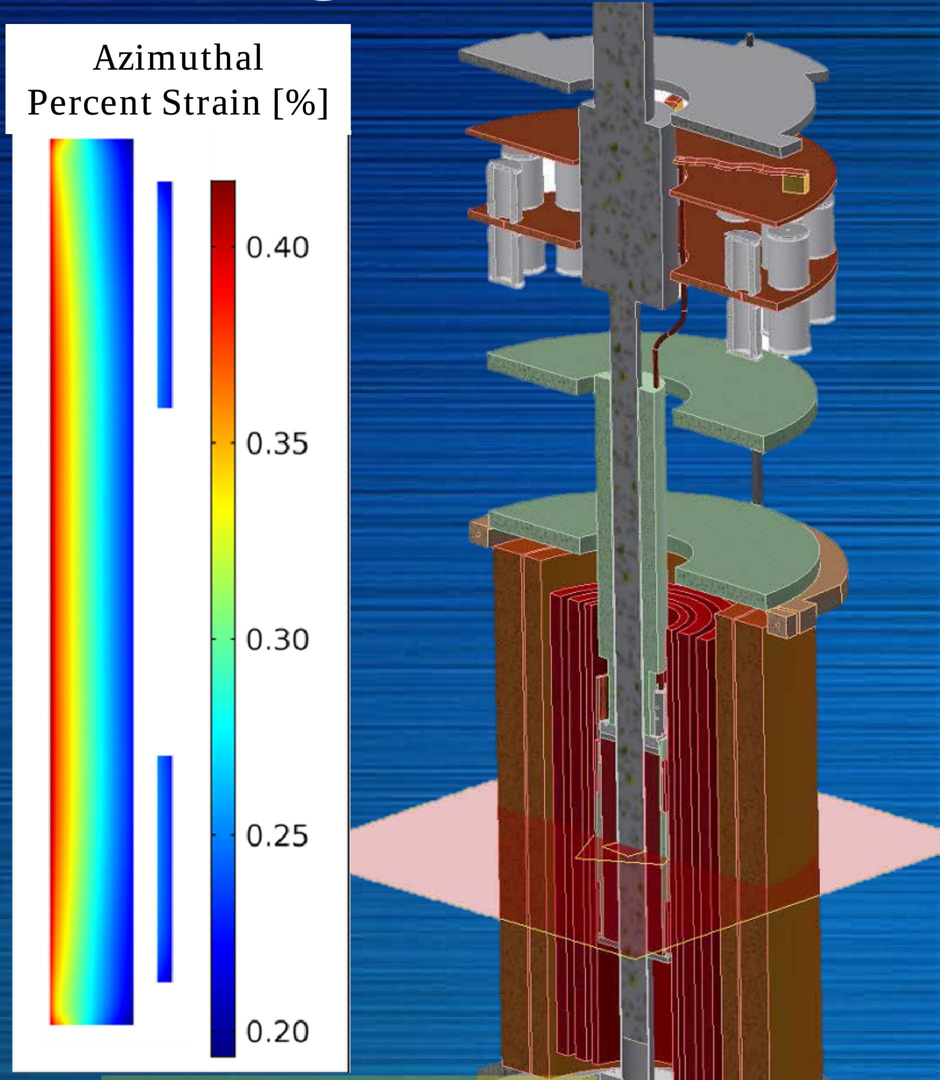
Next up: the NMR demonstration coil

- Coil parameters
  Wire diameter: 1.0 mm wire
  I_{op}: 310 A
  ID: 44.45 mm
  Background: 16 T (Adding: 5.3 T)

- Computation
  16.7 million degrees of freedom (10 hrs to mesh)
  45 minutes to compute (89 GB ram)

- So what?
  Confidence from the prototypes predicts:

  21.3 T [909 MHz] is achieved at 0.4% azimuthal strain;
  23.5 T [1^{+} GHz] is plausible even with this demo coil
  - 2212 macroscopically isotropic and should prove to have better field temporal stability



Platypus nested in *IMPDAHMA*
G.Miller

Summary

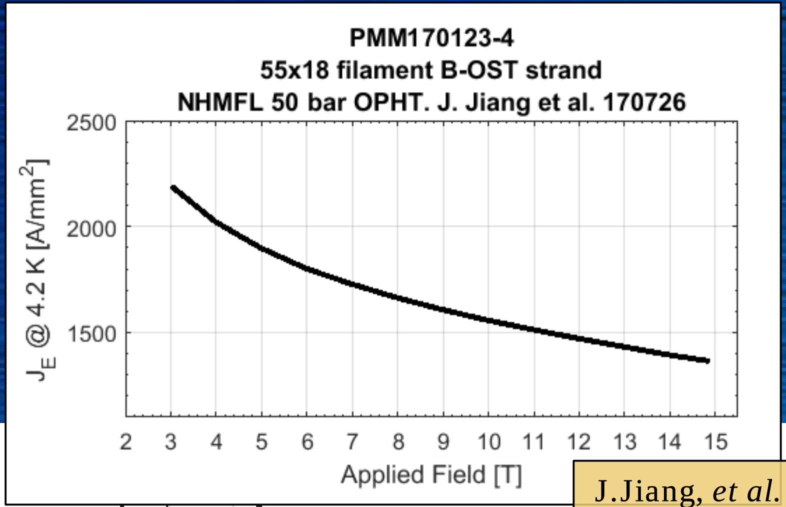
FEA tools have been developed to confidently build Bi-2212 coils that approach the conductor operating limits

- This conductor was once I_c limited
- Now it is strain limited

- Newest short sample shows at least 50% J_c improvement over wires used in these prototype coils

- Coil reinforcement allows for more use of this higher $I_c(B)$ limit, and otherwise provides tolerance to approaching $\varepsilon_{critical}$ = 0.6%

- Bi-2212 coil reinforcement is developing well, and Bi-2212 technology is ever advancing



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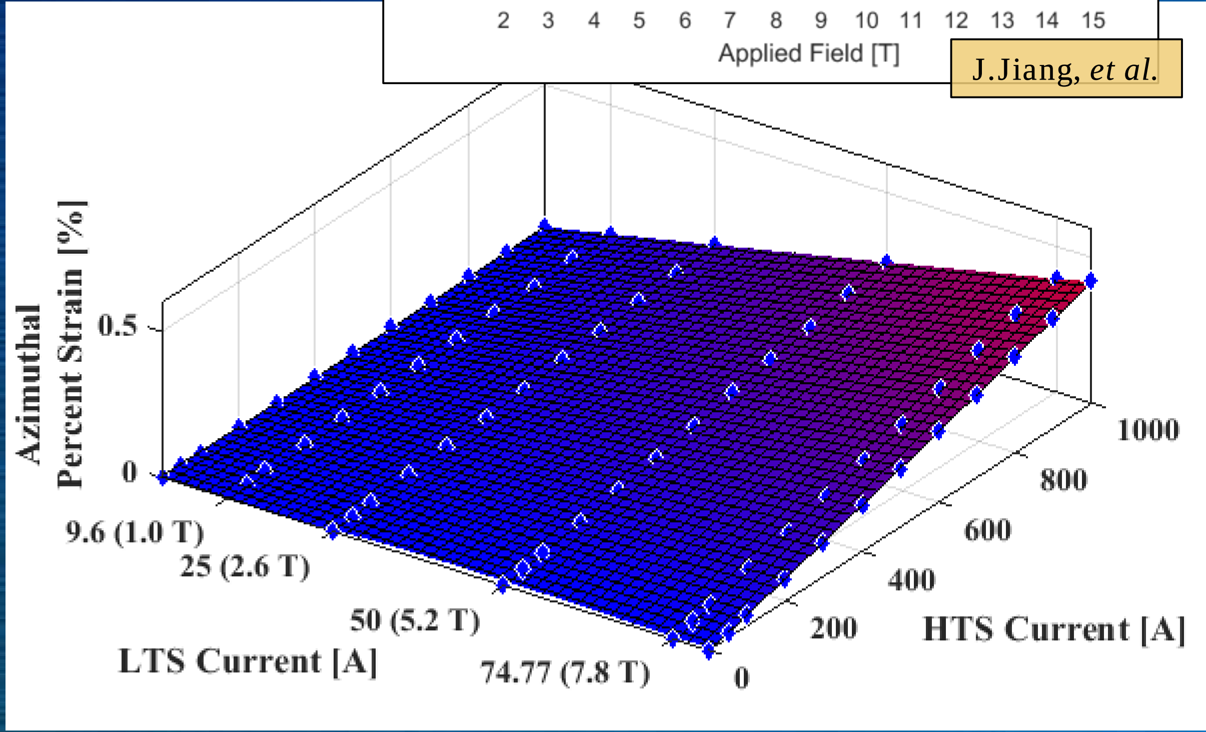

Acknowledgements

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