Validation of COMSOL®-Based Performance Predictions of Bi-2212 Round Wire Prototype Coils

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05 October 2017

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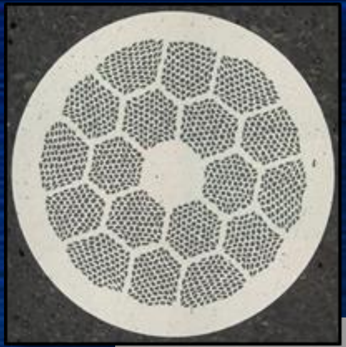
COMSOL CONFERENCE 2017 BOSTON

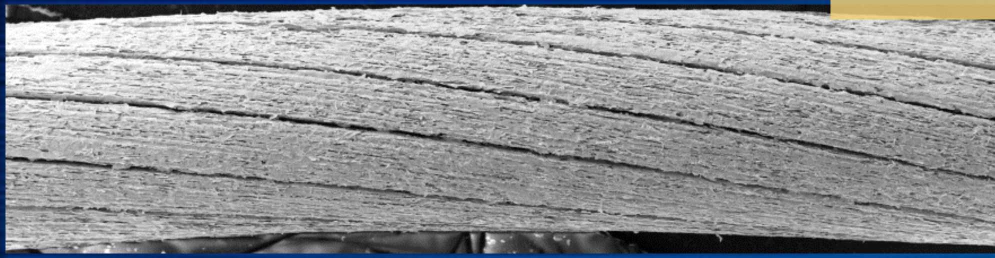
NATIONAL MAGLAB

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

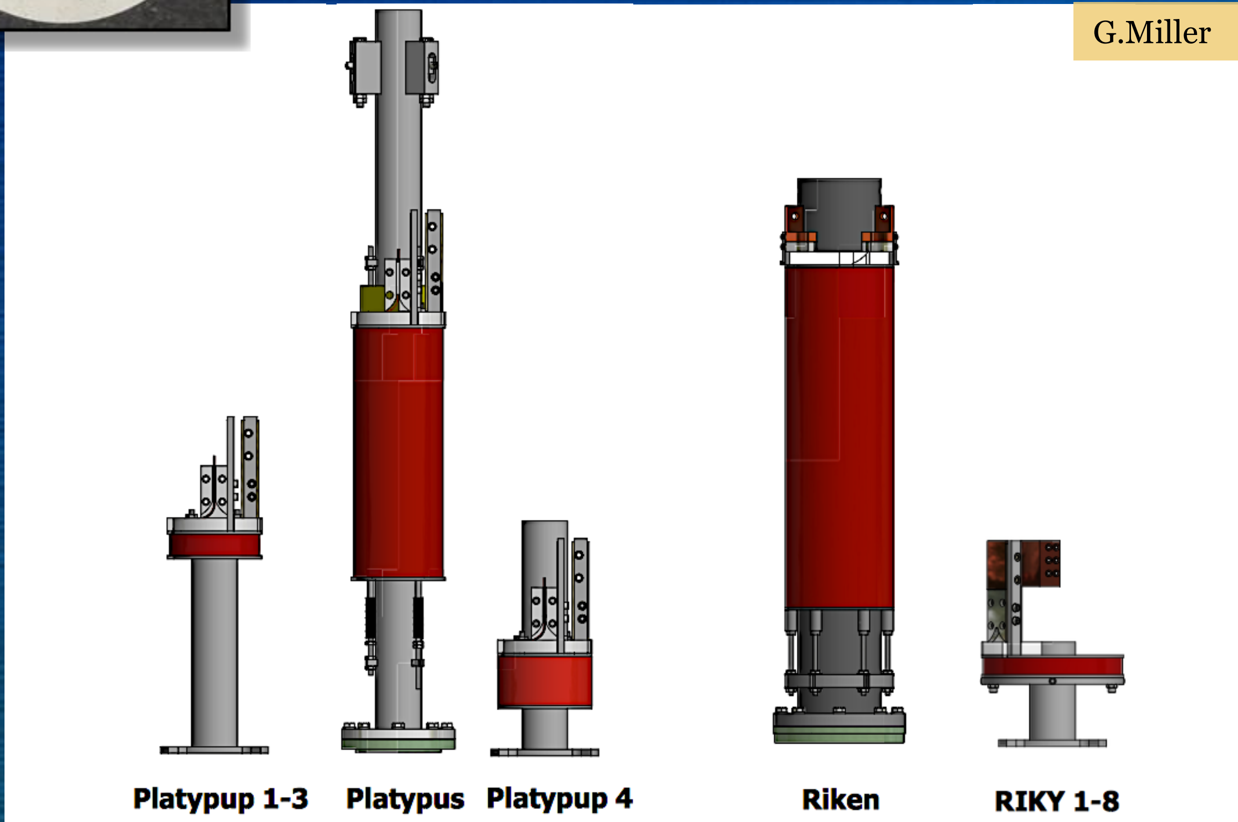
Overview

- Bi-2212 RW: Performance limits
  - $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (high temperature superconductor, HTS)
  - 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





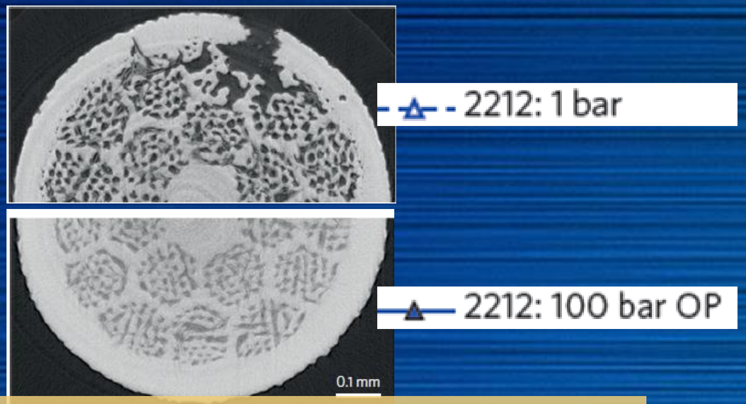
P.Chen



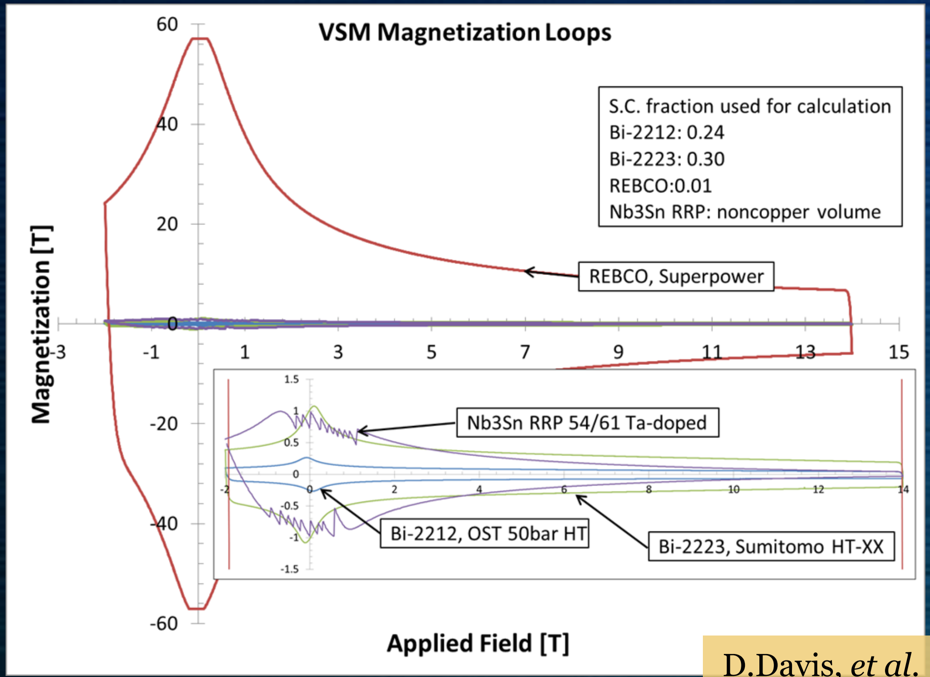
G.Miller

Bi-2212 Round Wire: A brief introduction

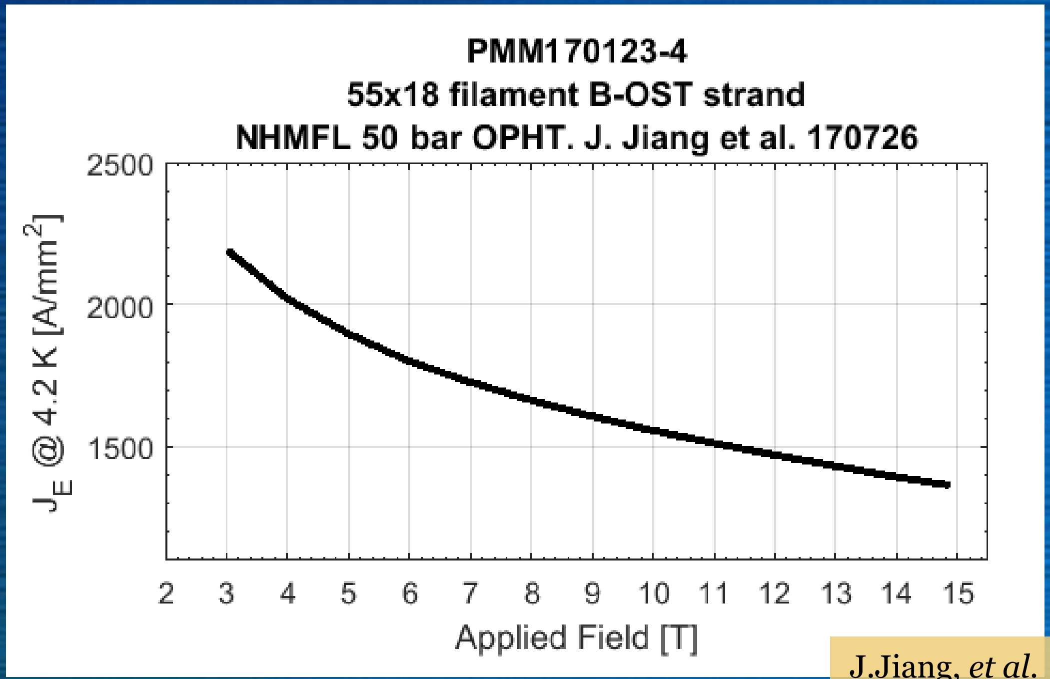
- Advancing wire and over-pressure heat treatment (OPHT) processing
- Macroscopically isotropic, twisted round wire:
  - Minimal field drift; appropriate for Nuclear Magnetic Resonance
  - Magnetization even smaller than low temperature superconductors



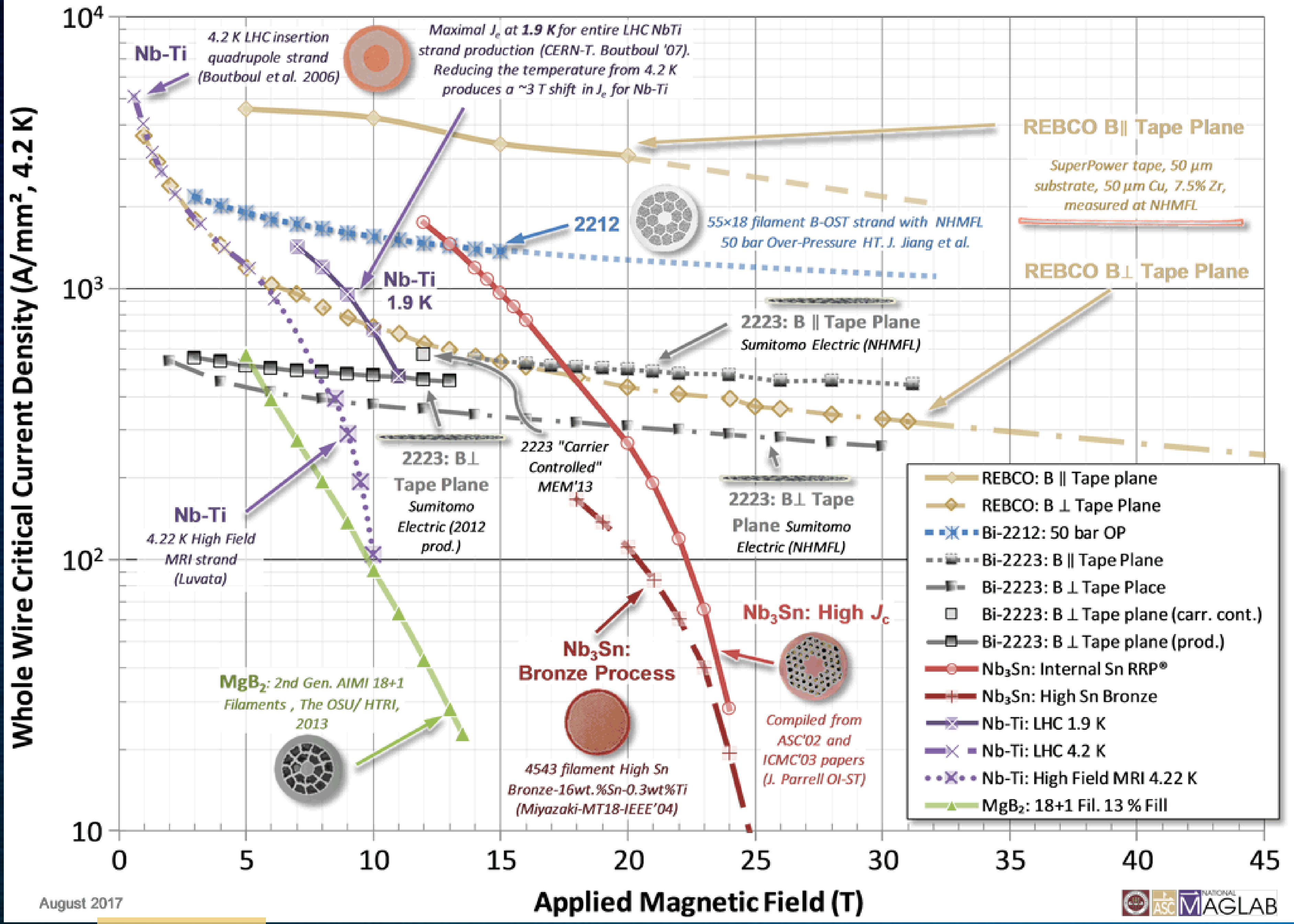
D.Larbalestier *et al.*, Nature Materials 2014



D.Davis, *et al.*



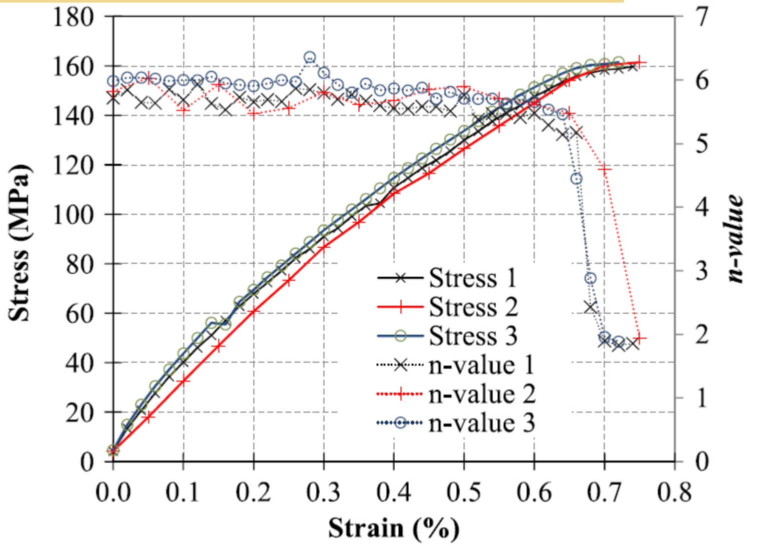
J.Jiang, *et al.*

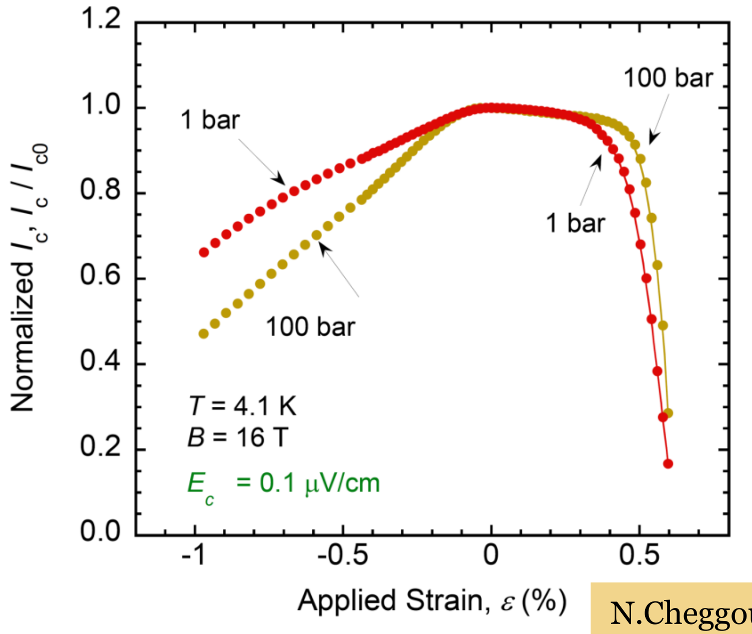

Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal J_e at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in J_e for Nb-Ti
REBCO B‖ Tape Plane
SuperPower tape, 50 µm substrate, 50 µm Cu, 7.5% Zr, measured at NHMFL
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
REBCO B⊥ Tape Plane
Nb-Ti 1.9 K
2223: B ‖ Tape Plane Sumitomo Electric (NHMFL)
2223: B⊥ Tape Plane Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti 4.22 K High Field MRI strand (Luvata)
Nb_3Sn: High J_c
Nb_3Sn: Bronze Process
MgB_2: 2nd Gen. AIMI 18+1 Filaments , The OSU/ HTRI, 2013
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B ‖ Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B ‖ Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
Nb-Ti: LHC 4.2 K
Nb-Ti: High Field MRI 4.22 K
MgB_2: 18+1 Fil. 13 % Fill
August 2017
MAGLAB

P.Lee

Bi-2212 RW: Performance limits

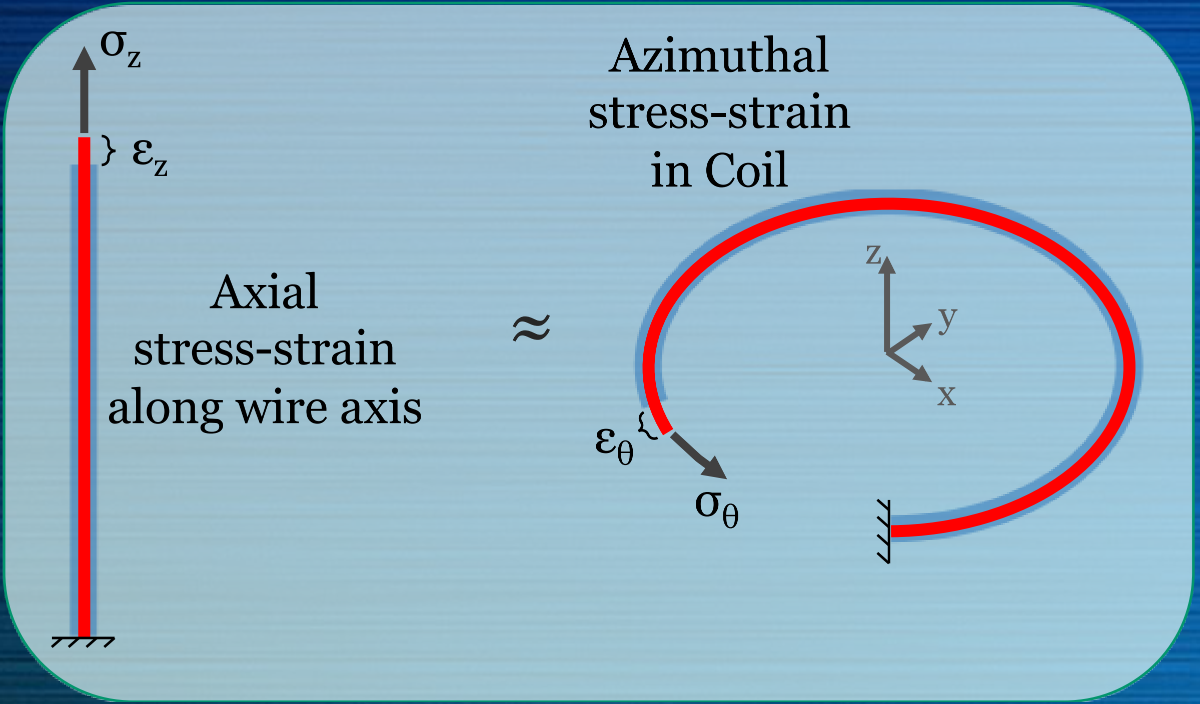
R.Bjoerstad *et al.*, CERN EuCARD-2 2015





N.Cheggour, U.Colorado-Boulder

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

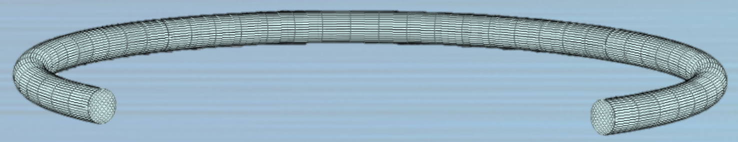


Multiphysics FEA: Addressing primary concerns

Models studied on a wire-by-wire level

- 4.2 K thermal strain

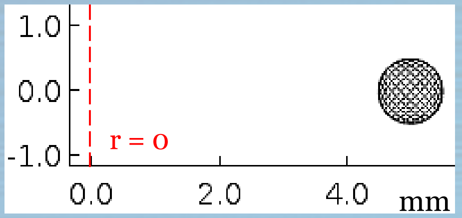
- Computation of magnetic fields
  - ($J{\cdot}B{\cdot}R$) Lorentz Forces → coil source stresses

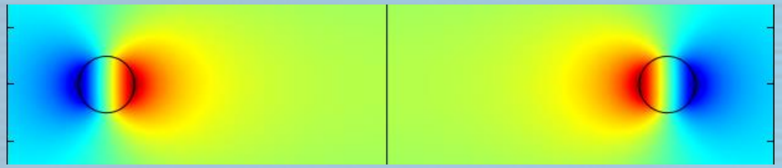


2D-axisymmetric

Field computed [T]

$\nabla \times H = J$

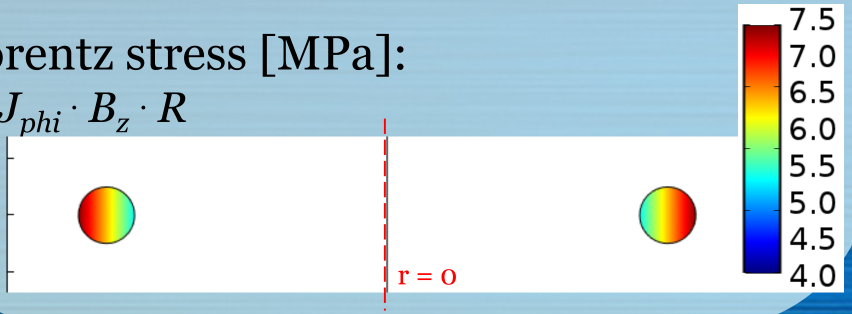




Above: Field generated by running 100 A/mm² in a single loop (1 mm dia wire; 10 mm dia loop) placed within a 10 T background field (range 9.97 *[blue]* to 10.05 *[red]* T).

Lorentz stress [MPa]:

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



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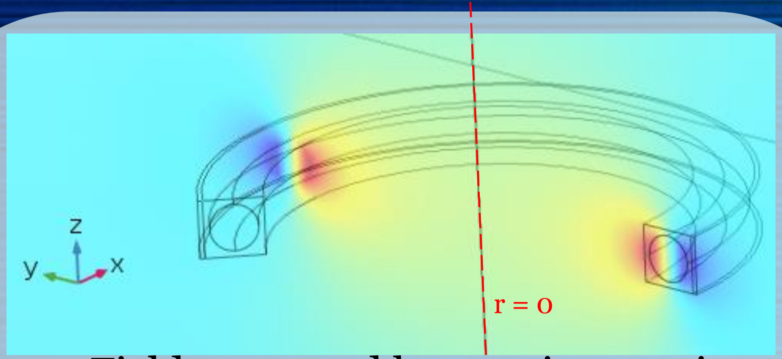
Models studied on a wire-by-wire level

- 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, experimentally tabulated 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.

Multiphysics FEA: Addressing primary concerns

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  - These coils epoxy impregnated; so stresses are redistributed across all materials within the coil pack
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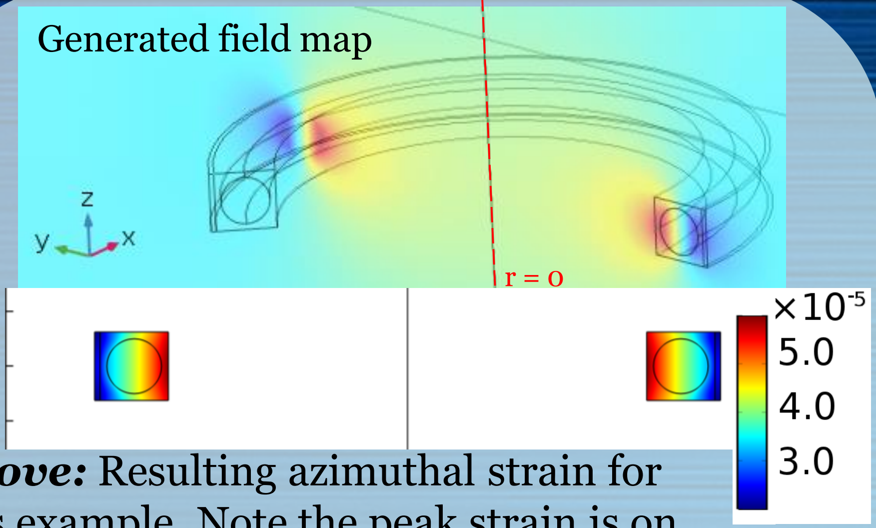
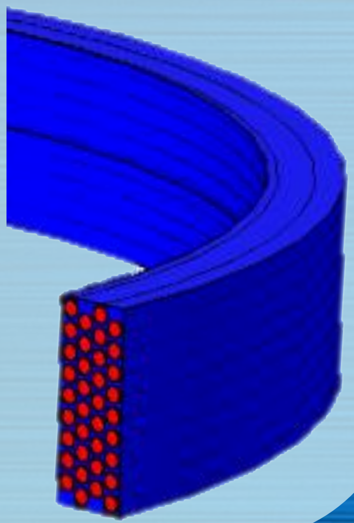
  - Each material defined with its own, experimentally tabulated material properties
  - Conductor elasticity modulus based on non-linear stress-strain data from short samples
  - Fully coupled model accounts for movement of each conductor



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

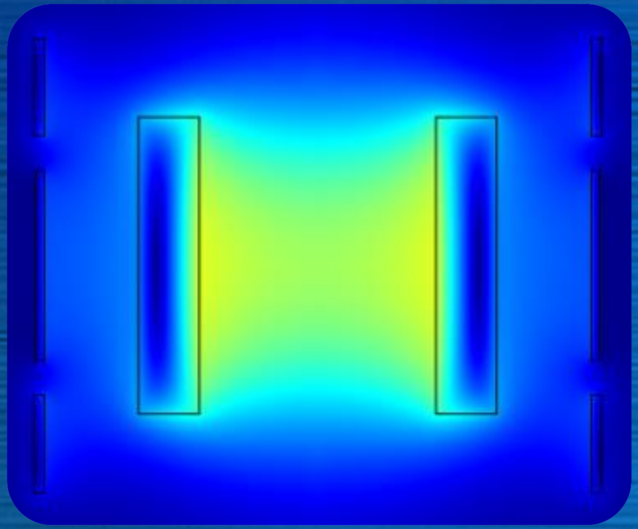


Right: A cross section of a prototype coil. Shown is Riky-1, a magnet would with Bi-2212 *[red]* wires and later epoxy *[blue]* impregnated but otherwise not reinforced coil.

Multiphysics FEA: Analysis led design of prototype coils

- 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; 890 degC; 50 atm

Cyocooled 8 T
242 mm magnet ID
140 mm cryostat



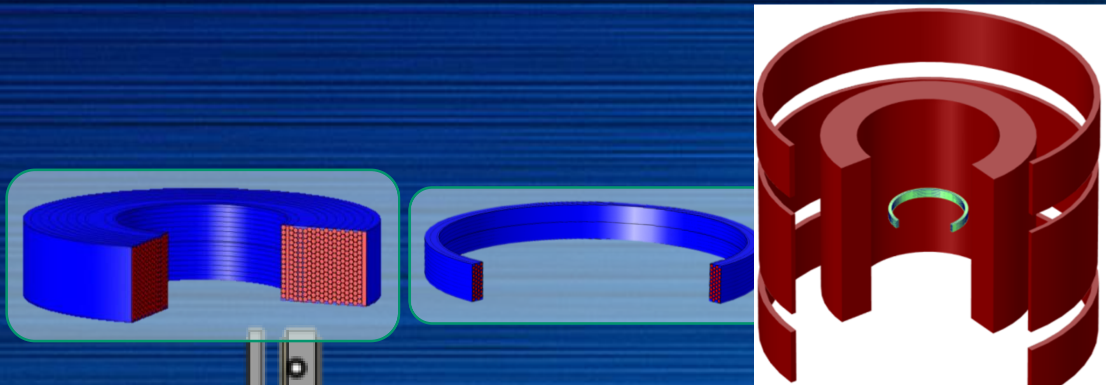
The Prototype Coil Program

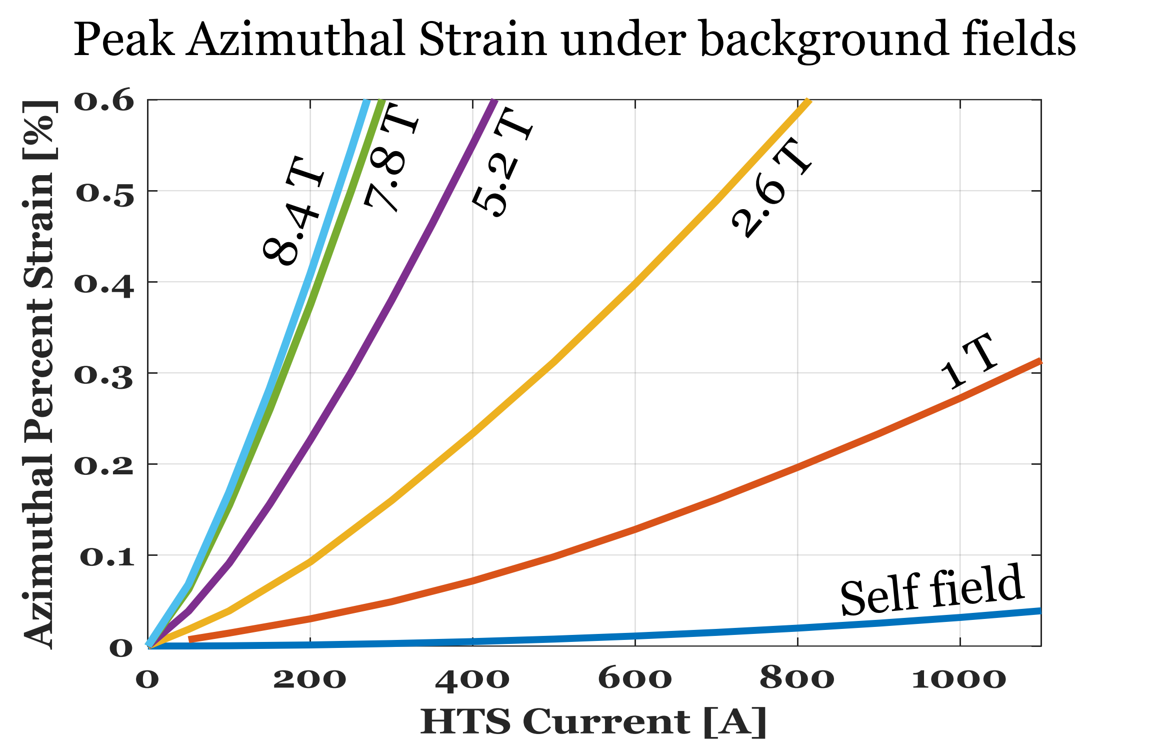
Motivation for each prototype:

- 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





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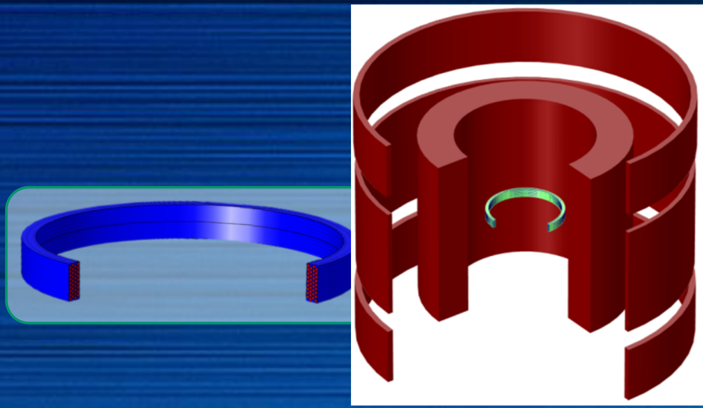

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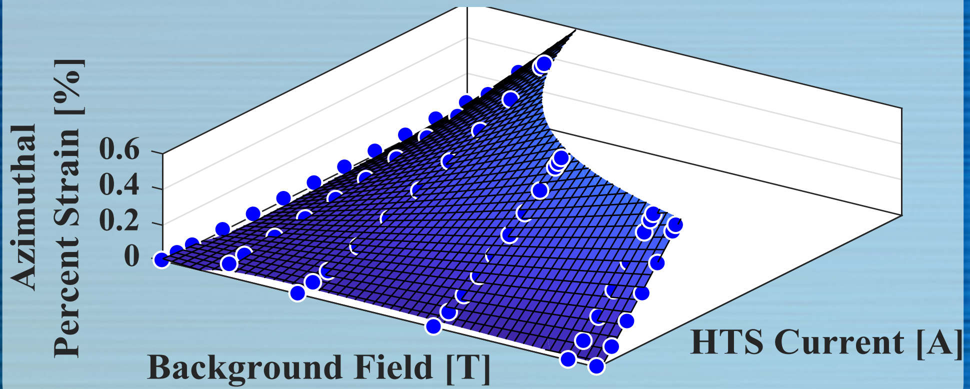
Below: Strain-limited performance envelope, increase of either background field and/or HTS current lead to 0.6% strain limit



Parametric sweeps

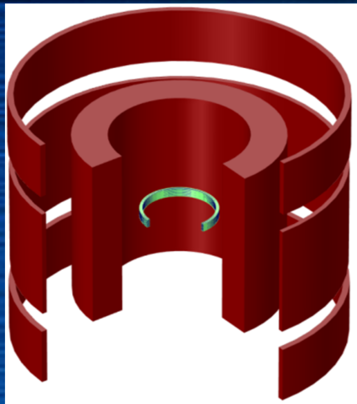
- Input current and LTS Outsert fields are real 'knobs'
- Strain-based performance envelopes

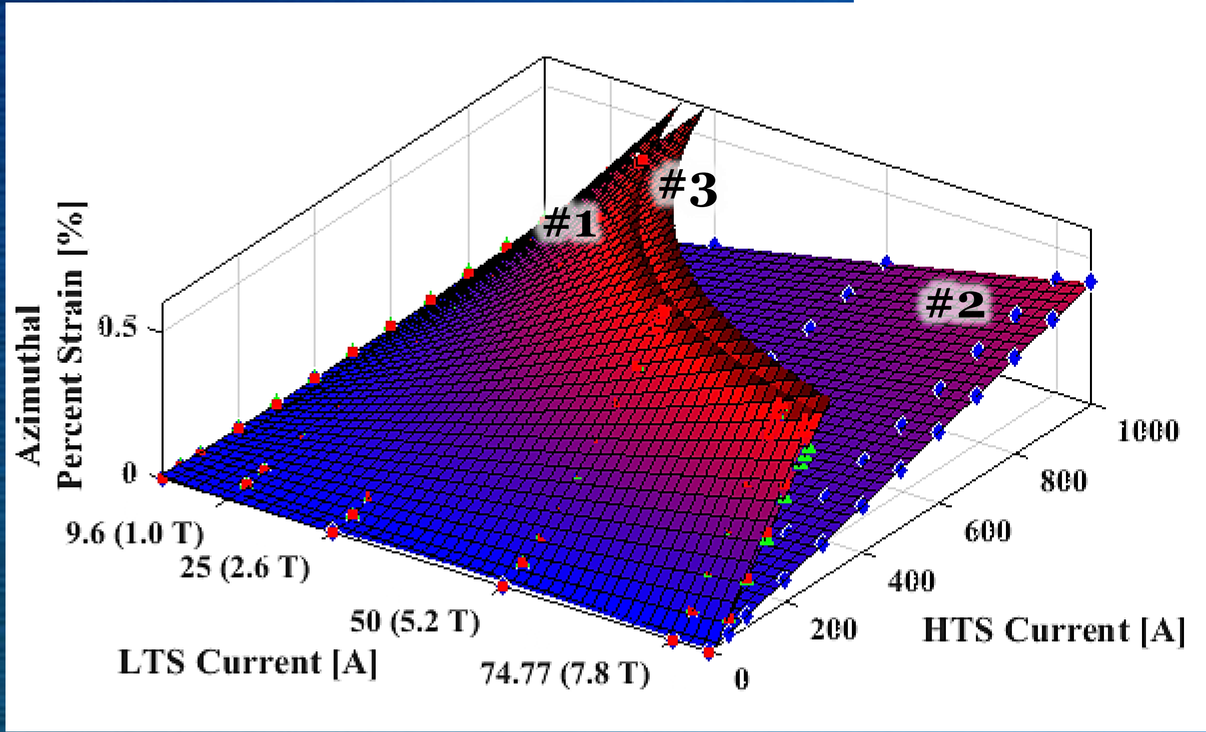
Prototype Coils: Experimental validation of modeling

Second set of prototypes predictions

- First coil (not reinforced) was predicted to reach 0.6% azimuthal strain near ~280 A (231 A/mm²) 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/mm²)

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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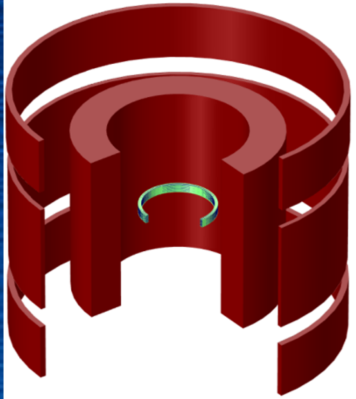
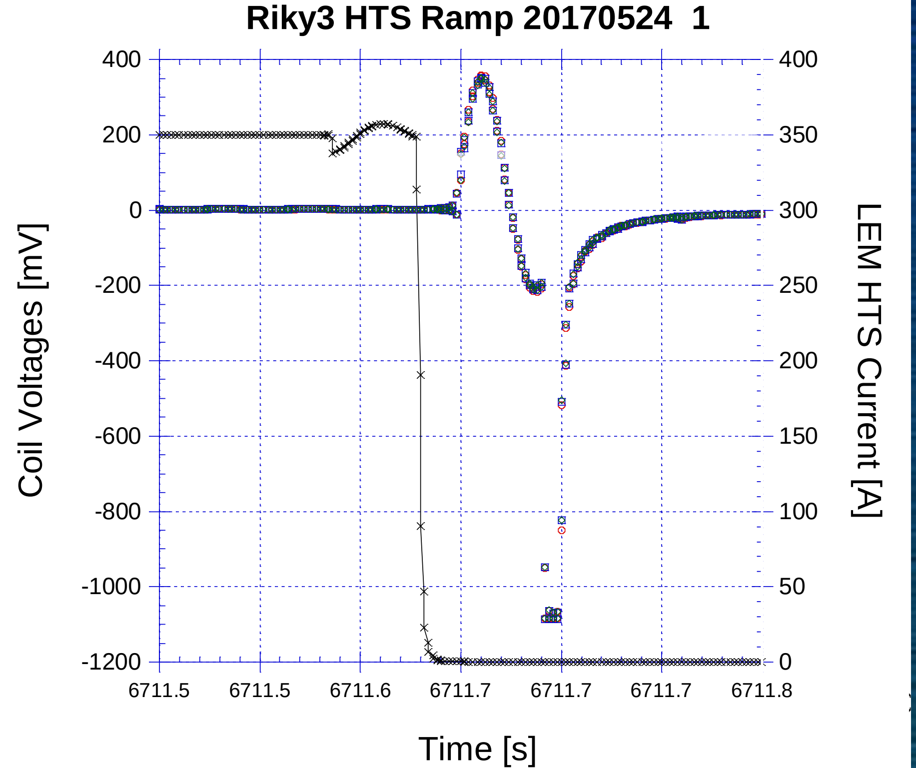
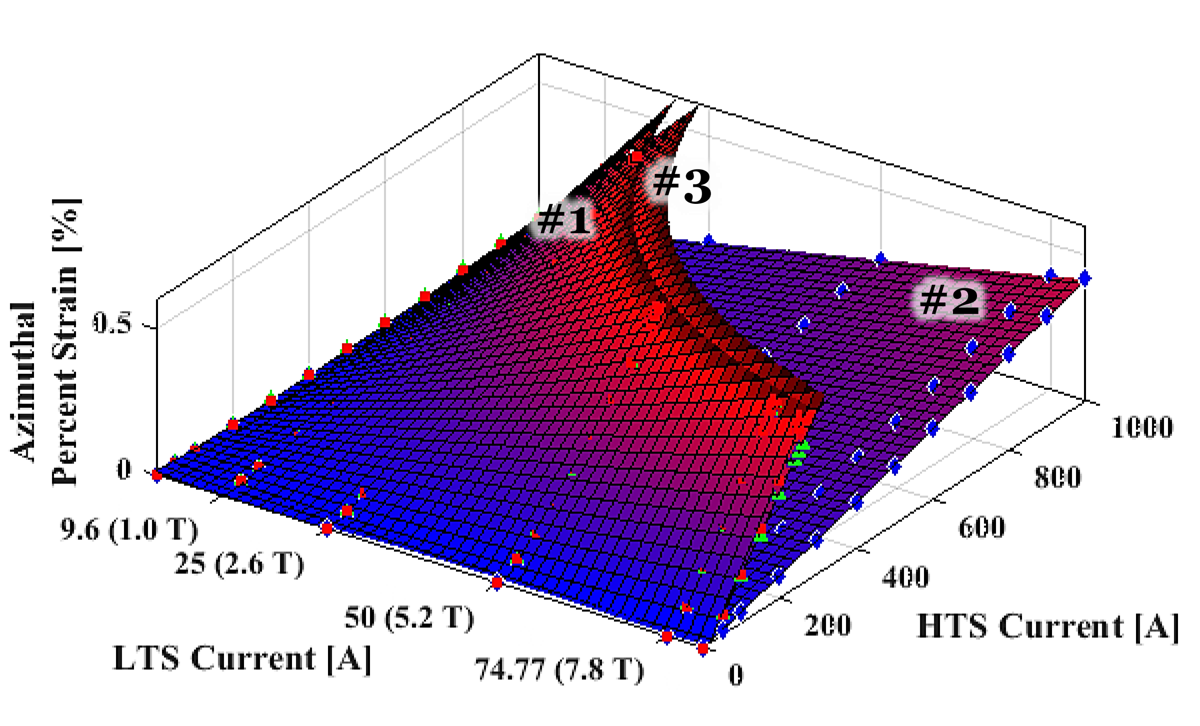




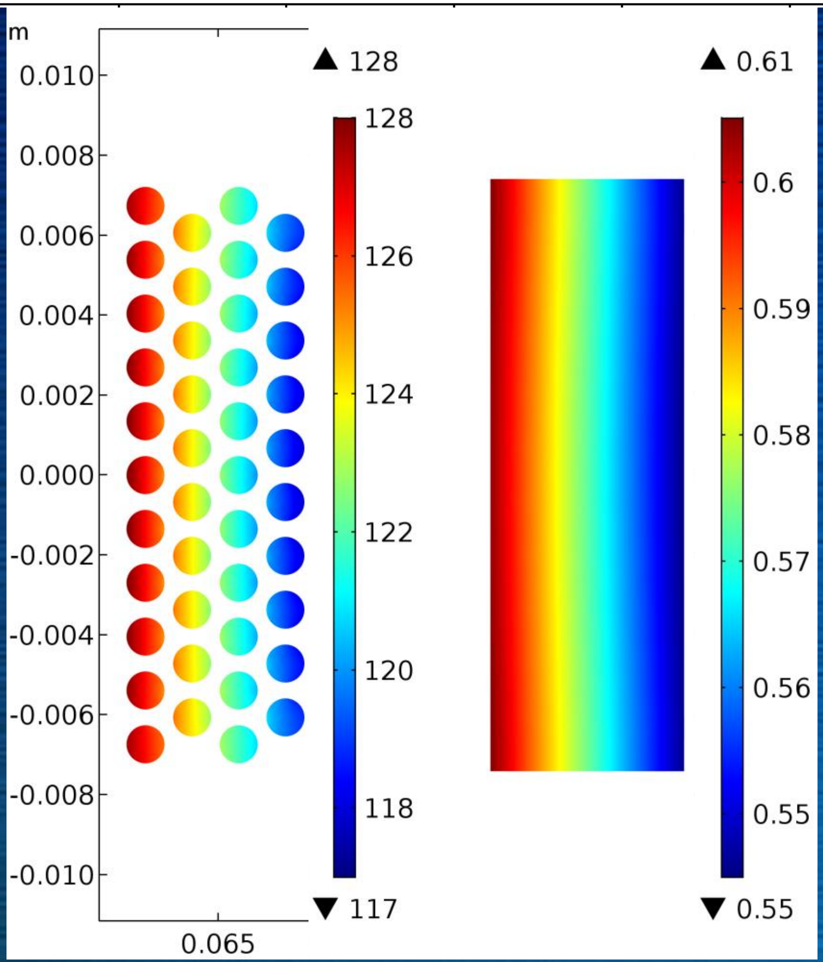


Prototype Coils: The next ones…

Another of the second set of prototype coils

Intended to further validate the model by including an incrementally larger amount of reinforcement. This coil is predicted to reach its critical strain at a current of ~450 A (628 A/mm²) within an ~8 T background.

Azimuthal (Hoop) Stress [MPa] and Percent Strain [%]

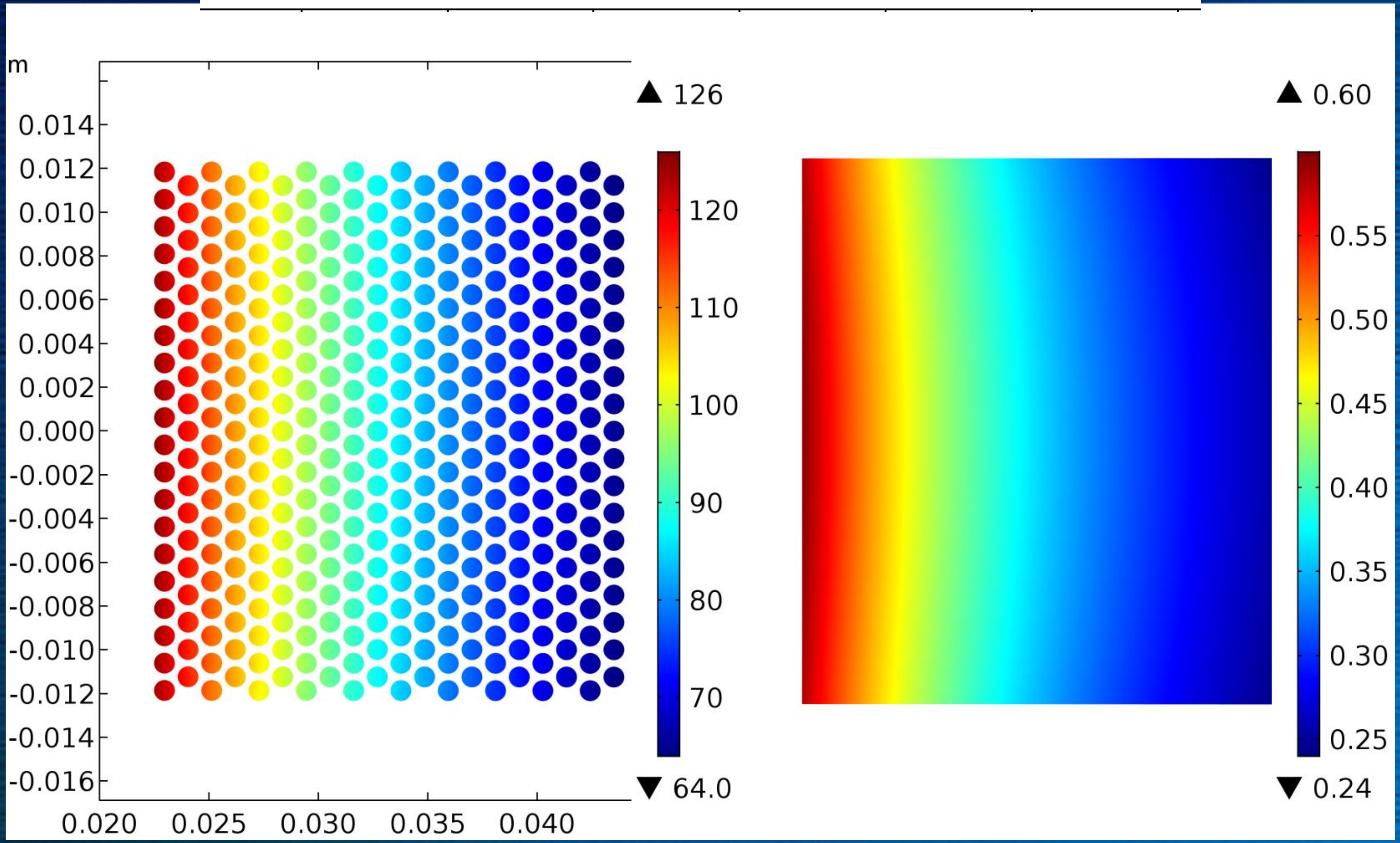


Prototype Coils: The next ones...

Another of the first set of prototype coils

As well as further validation, the first type of prototype coils were a thicker build. Hence, this cleverly designed coil should experimentally reveal a peak strain gradient with plenty of spatial resolution. The predicted strain limited performance for this coil peaks at a current of ~420 A (586 A/mm²) within an ~8 T background.

Azimuthal (Hoop) Stress [MPa] and Percent Strain [%]



A Bi-2212 Insert for High Field NMR

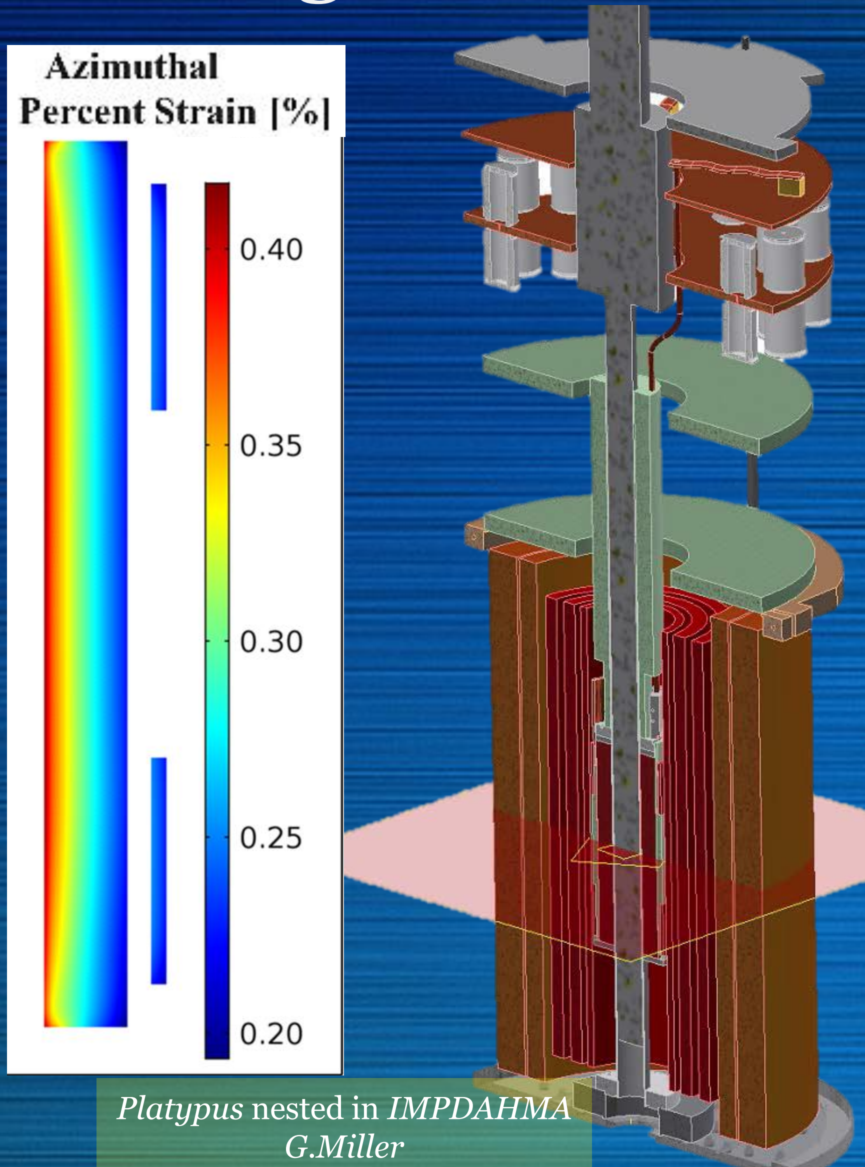
Next up: the NMR demonstration coil

- 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

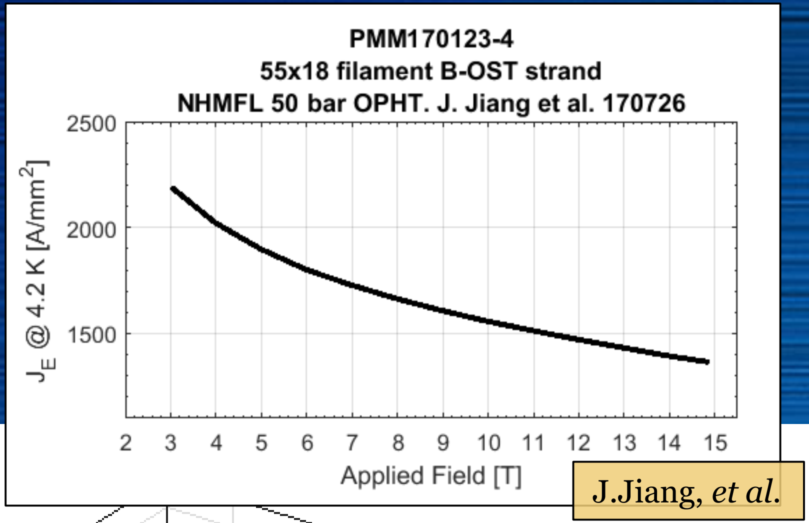
FEA tools have been developed to confidently build Bi-2212 coils that approach the conductor operating limits

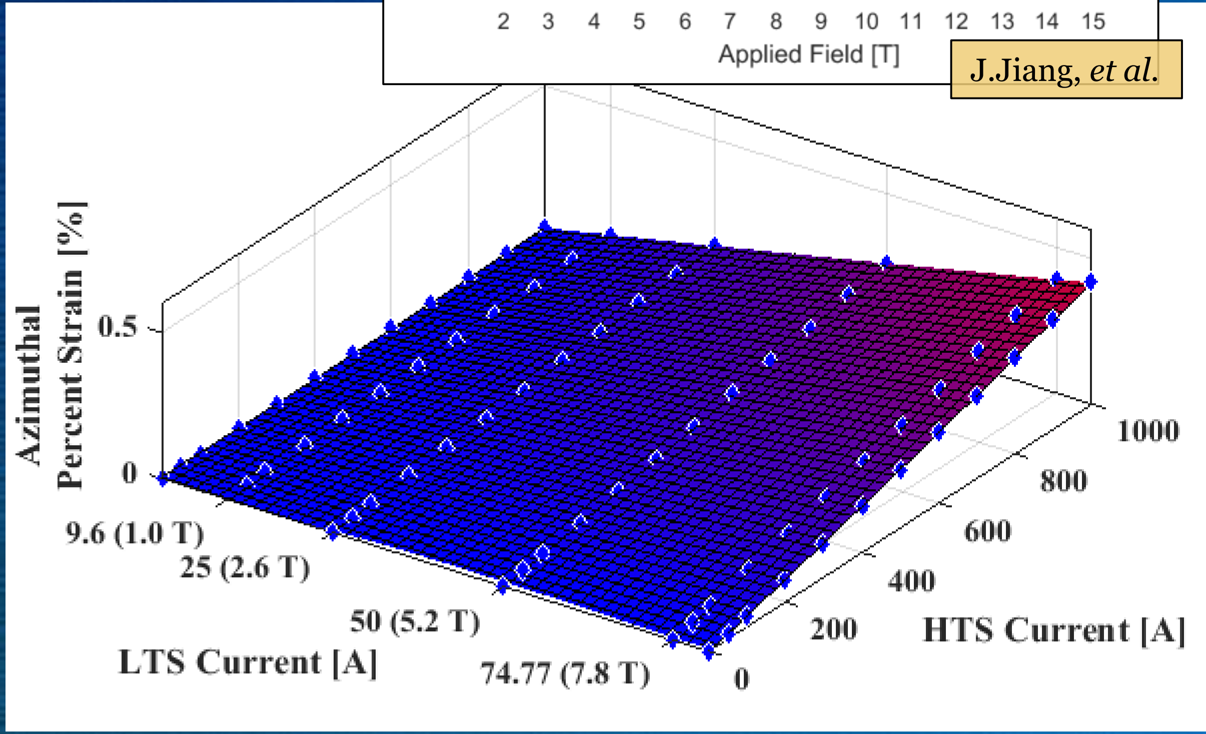
- This conductor was once I_c limited
- Now it is strain limited

- 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





Acknowledgements

This work is supported by the National Science Foundation under DMR-1157490, the State of Florida, and a grant from the National Institute of Health under 1 R21 GM111302-01.