Experience With Nb_3Sn CCT Magnets at LBNL

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Outline

- Introduction
- CCT concept
- CCT fabrication methods
- Analysis methods
- Experience at LBNL with Nb_3Sn CCT dipoles
- Conclusions

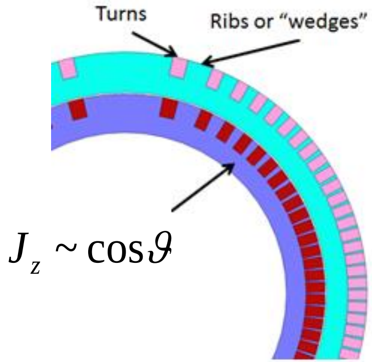
Nb_3Sn CCT Magnet Program at LBNL

- Nb_3Sn CCT work is part of the US MDP Nb_3Sn magnets area with a focus on stress management approaches for high field magnets
- Early focus in the program consisted of design, fabrication, and testing of 2 layer dipole magnet series with ~10 T short sample bore field and 90 mm clear aperture (CCT3 / CCT4 / CCT5)
- Currently undertaking subscale CCT program to understand and improve training in CCT magnets
- Currently working on design of CCT6 (120 mm bore diameter, 11 T dipole) that can serve as an outsert for hybrid configurations
- Advanced modeling effort
  - Periodic models
  - Full 3D models
  - Interface modeling including damage

The CCT Concept Can Offer Several Advantages Over Other Magnet Designs

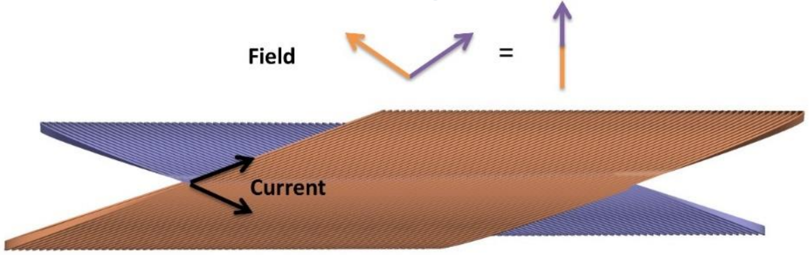
- **Canted windings in opposing directions produce dipole field (excellent field quality)**
- **Windings are placed in a mandrel with grooves - Ribs in mandrel intercept Lorentz force leading to substantially reduced azimuthal stress**
- **Ease of fabrication and minimal tooling**
- **Fabrication methods and modularity of approach leads to natural extension for HTS materials**

Ribs Intercept Lorentz Force

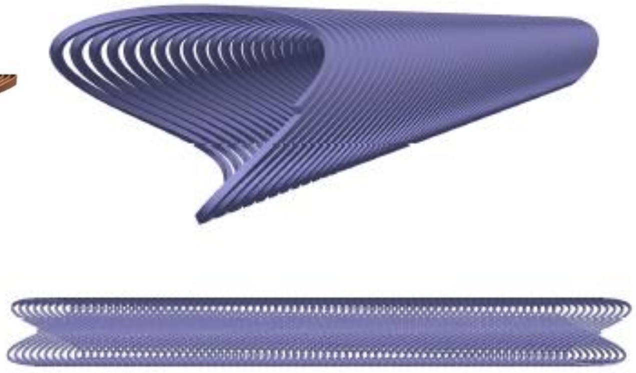


Transverse current density with cos-theta distribution approaches a perfect dipole current density distribution

Dipole Winding Geometry



Quadrupole Winding Geometry

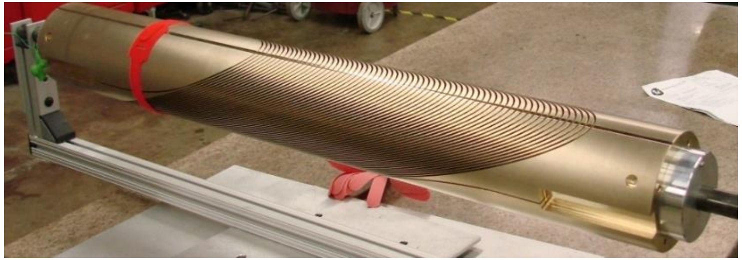


L. Brouwer, PHD Thesis

All Features Required For The CCT Winding Geometry Are Contained In The Machined Mandrels

- Mandrels are machined on 4-Axis CNC mill
  - Groove is machined normal to the mandrel surface
  - Splice pockets are included for Nb_3Sn magnet
  - Additional features for instrumentation and alignment
  - Gaps for cable expansion are used for Nb_3Sn
- Winding performed by placing conductor in the groove with minimal tension

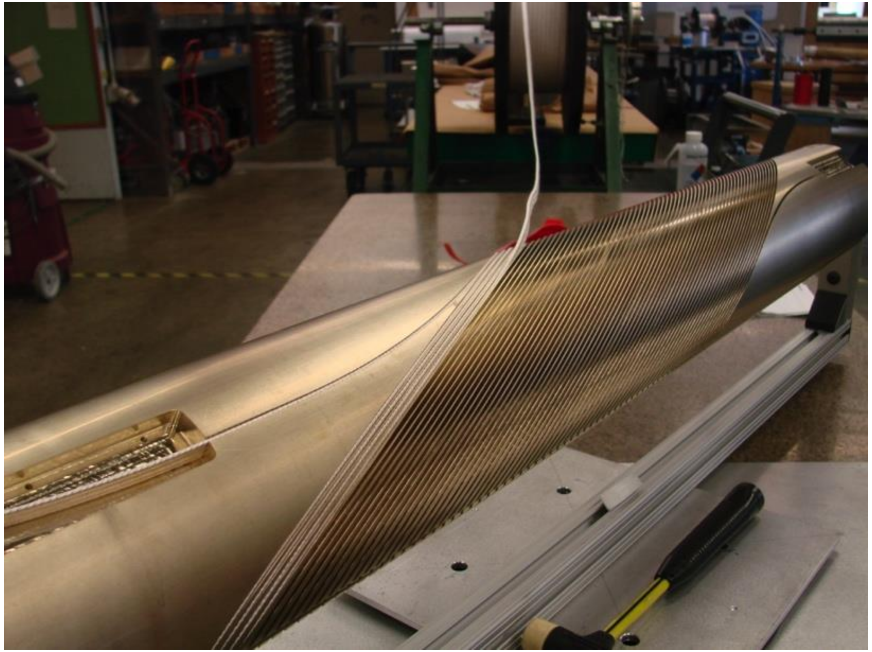
Machined Mandrel



Instrumentation Pocket

Alignment Groove

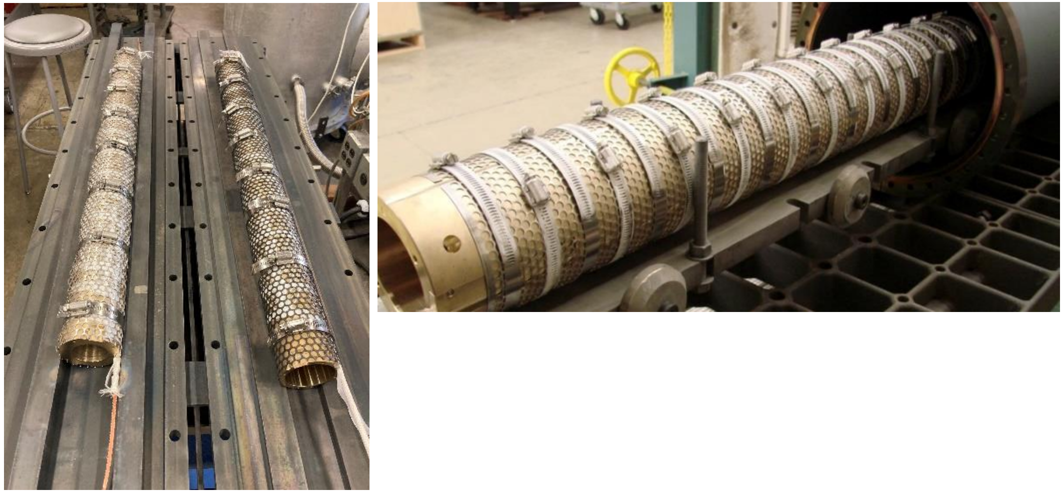
Coil Winding



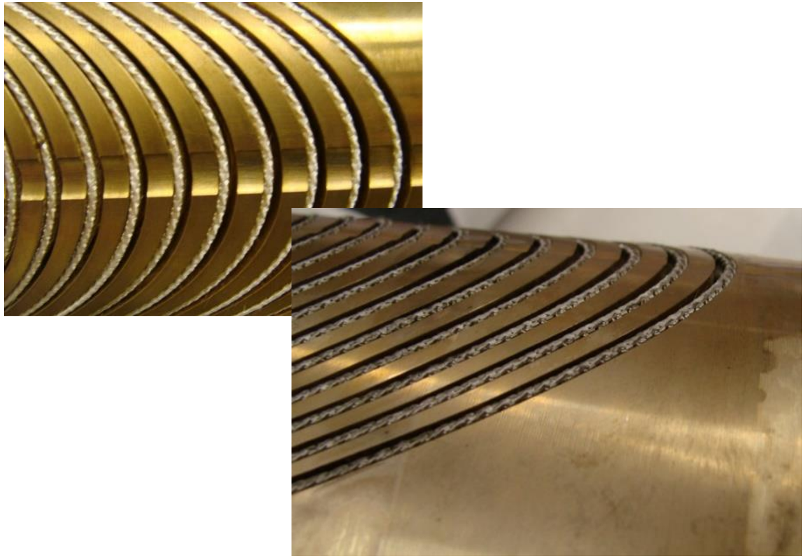
Nb_3Sn Coil Reaction Requires Minimal Tooling

- Minimal tooling has been used for reaction of Nb_3Sn coils
    - Clamped perforated stainless steel sheet around coils
    - Splice block fillers
- Reaction gaps are critical to avoid conductor damage

Heat Treatment Tooling



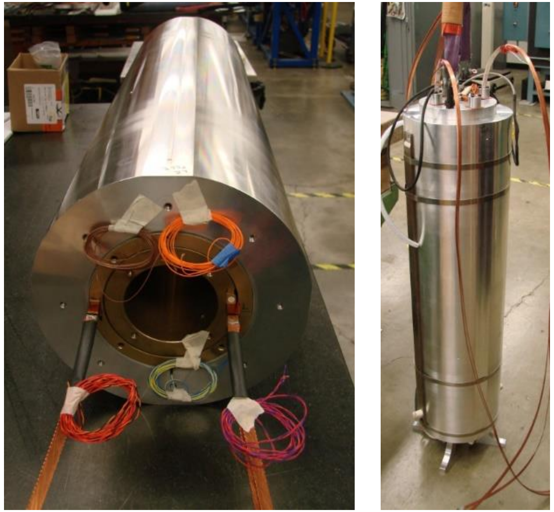
Cable Position Before and After Heat Treatment



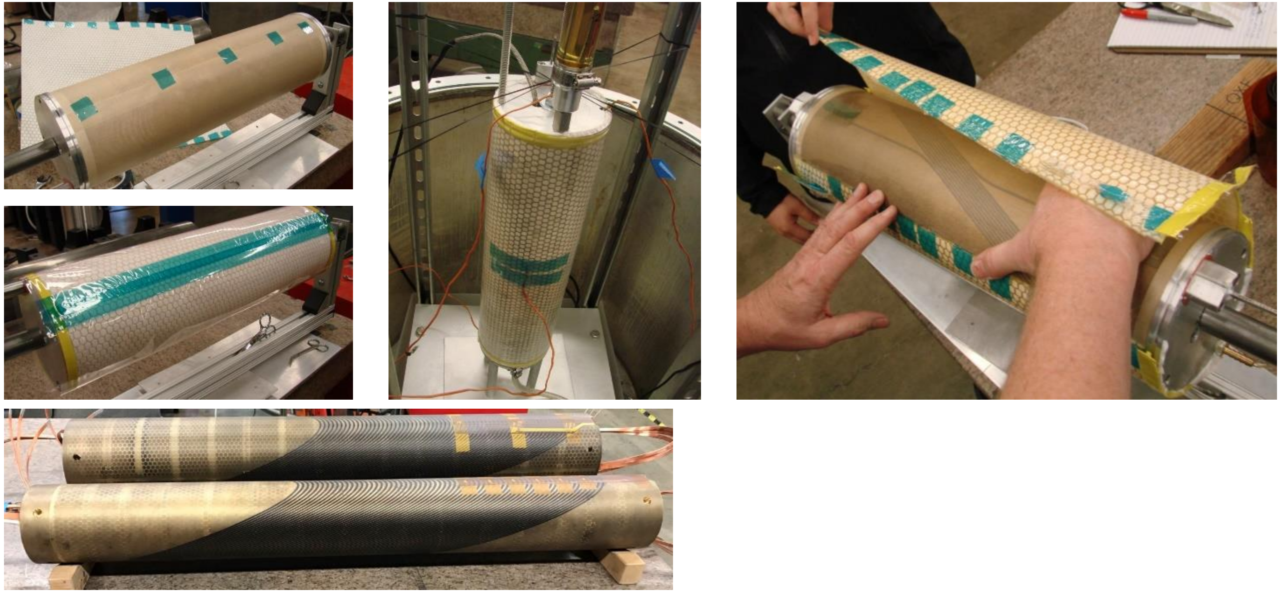
Epoxy Impregnation Requires Minimal Tooling

- **For early magnets the coil pair was assembled into an Aluminum shell and impregnated**
- **For later magnets the coils are impregnated individual and then assembled into the magnet**

Full Magnet Impregnation

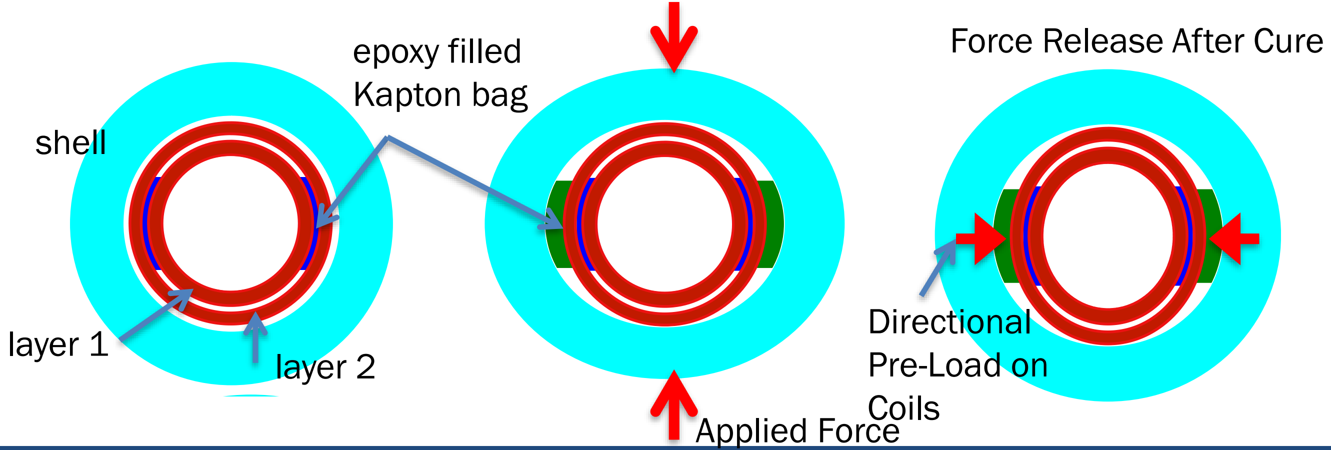


Individual Coil Impregnation



For Recent Magnets The Layer to Layer Assembly Has Been Preformed With The Bend-And-Shim Method

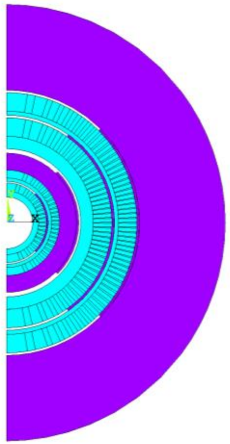
- Contact location between layers is controlled by using shims and Kapton bags that are filled with glass and epoxy
  - Allows for control of contact location
  - Fracture in interface epoxy does not propagate to the coil
  - Improved cooling at the pole regions from direct contact with LHe
- Directional preload to reduce energized stress can be applied by bending layers or shell, filling and curing epoxy in bent state, releasing bending pressure



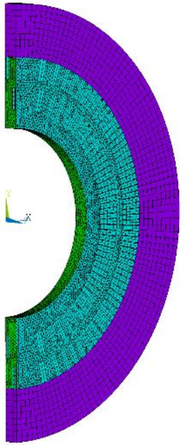
Modeling Approaches

- **2D models**
  - Fast Solution
  - Good for design & parametric studies
  - Results deviate near the pole
- **3D periodic models**
  - Full 3D solution for straight section (infinitely long)
  - Faster solution than full 3D model
- **Full 3D models**
  - Full solution including end effects
  - Reasonable solution times with use of cluster

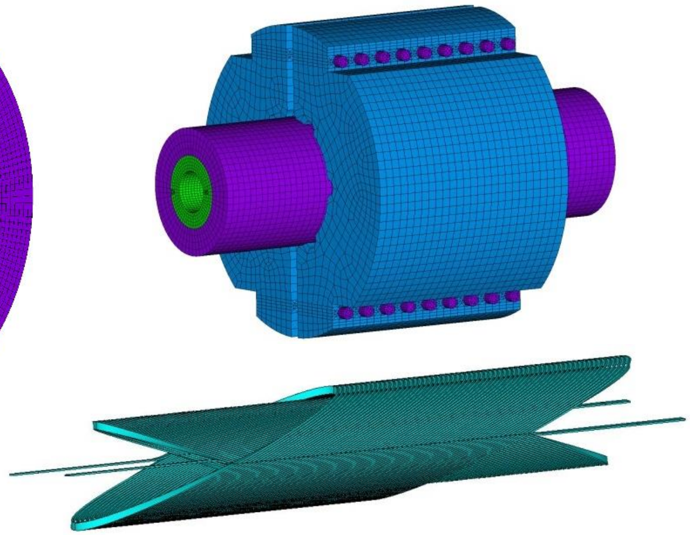
2D



3D Periodic



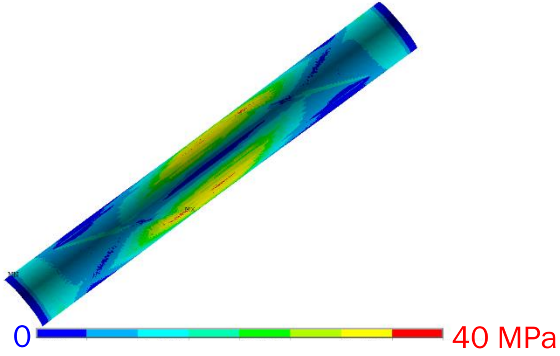
Full 3D



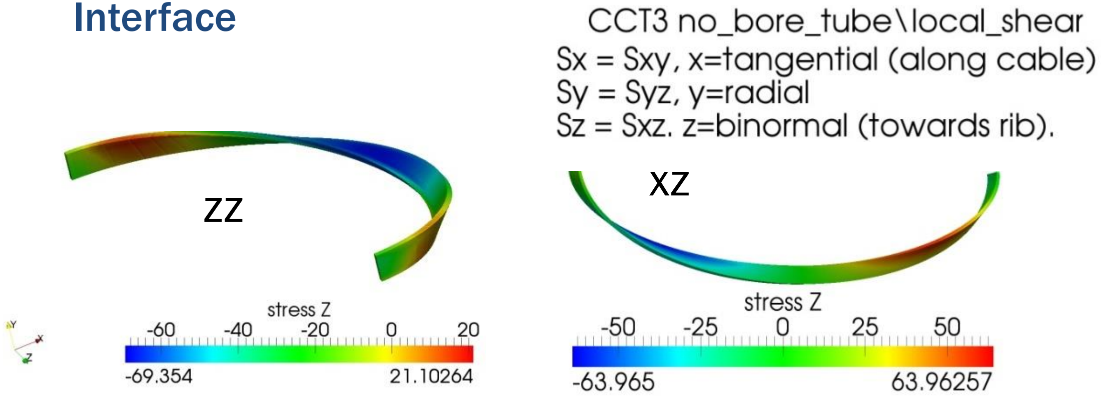
Stress Interception and Interfaces

- CCT approach leads to reduced Azimuthal stress on the dipole midplane
    - Lorentz force is intercepted by rib and transferred to spar
    - Interface shear stress is created at rib/cable and spar/cable interfaces
- Interface stress between layers is also possible training source

Shear Stress at Interface Between Layers 1 and 2



Normal and Shear Stress at the Cable/Rib Interface



CCT3 no_bore_tube\local_shear
Sx = Sxy, x=tangential (along cable)
Sy = Syz, y=radial
Sz = Sxz. z=binormal (towards rib).

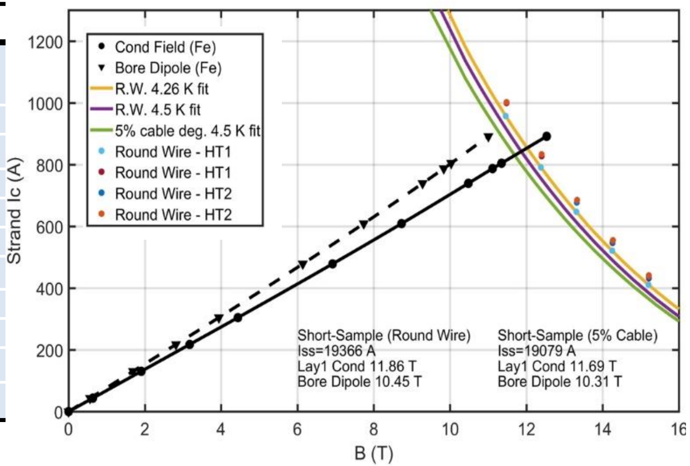
A Number Of Technology Issues Were Addressed With CCT 2-layer Magnet Series (~9T, 90 Mm Bore)

- **CCT3/4/5 (Nb_3Sn) 2-layer CCT dipole magnets have been designed, fabricated, and tested at LBNL**
- **CCT3 was limited by conductor damage**
- **CCT4 reached 86% of round wire short sample with significant training**
- **CCT5 showed some training improvement and reached 88% of round wire short sample**

Magnet Parameters

	CCT3/4	CCT5
Conductor	Nb_3Sn RRP 54/61	Nb_3Sn RRP 108/127
Cu:non-Cu ratio	0.85	1.2
Inner Bore Diameter [mm]	90	90
Cable Width [mm]	10.1	10.1
Cable Thickness [mm]	1.4	1.5
Number of Strands	23	21
Cable Insulation	S-glass Braid	S-glass Braid
Iron Yoke	Yes	Yes
Impregnation Material	CTD-101K	FSU Mix-61
Short Sample Current [kA]	19.3	17.8
Short Sample Bore Field [T]	10.5	9.7

Magnet Load Line for CCT4

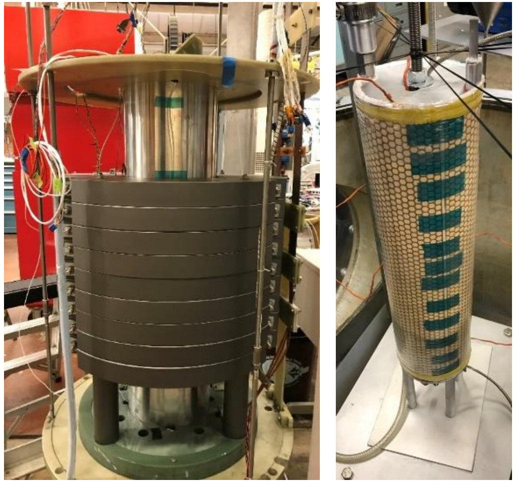


Design Evolved Through This Series To Address A Number Of Issues

	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	675
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer interface	bonded	mold released	bend and shim process

- Field quality
- Conductor damage/stability
- Cost and scalability
- Training

- *Red arrows represent significant changes*
- *Green arrows represent less significant*

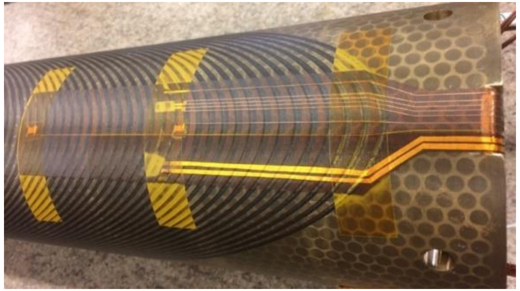


CCT5 Shows Initial Improvement in Training Followed by Similar Behavior to CCT4

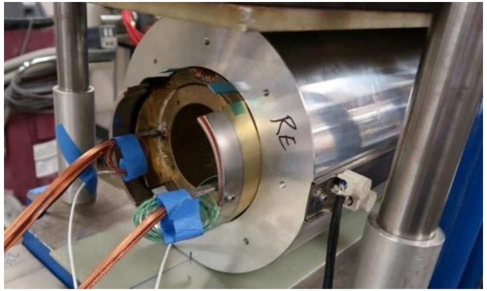
CCT4
- Coils and shell impregnated together
- CTD101K epoxy

CCT5
- Bend-and-Shim assembly of individually impregnated coils
- Mix61 epoxy from FSU

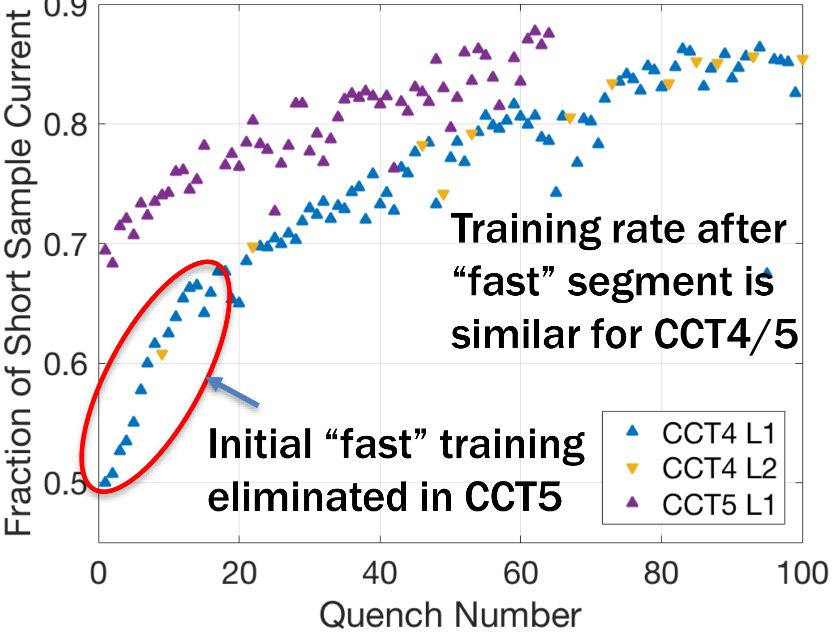
Individually Potted Coil



Bend and Shim Assembly



Quench Current Relative to SSL

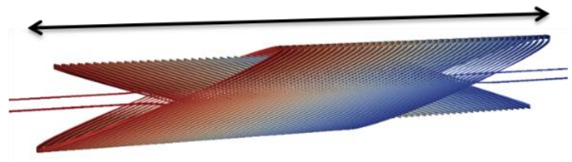


Training rate after “fast” segment is similar for CCT4/5

Initial “fast” training eliminated in CCT5

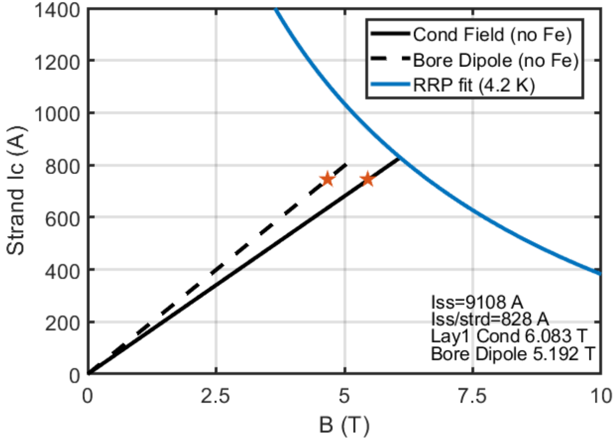
Subscale CCT Magnet Program Was Introduced to Further Understand / Improve Training In Stress Managed Magnets

- 11 strand Nb3Sn cable
    - Strand diameters is 0.6 mm
    - Cable dimensions (1.1 x 4.0 mm)
    - 9100 A short sample current
    - Cable length ~ 50m
- Nominal inner bore diameter is 50 mm (thin spar)
- Bore dipole field is approximately 5.2 T as short sample current
- Peak conductor field is approximately 6.1 T at short sample current

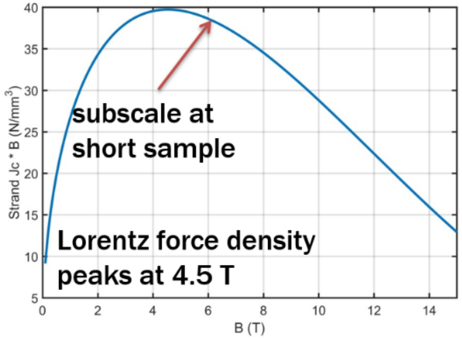


45 turns / layer = 500 mm physical length

Magnet Load Line*



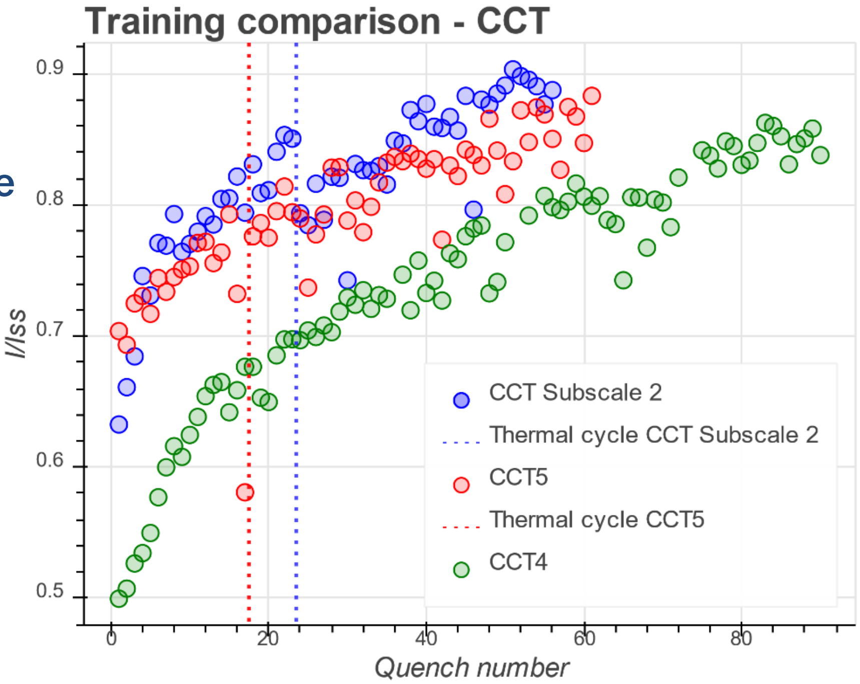
Strand J_c×B (RRP 132/169)



* Short sample measurements are based on similar wire used for superconducting undulators

Baseline Test Demonstrates That Subscale CCTs Can Reproduce Training Behavior Seen In Larger CCT Magnets

- Training slope for subscale (relative to SSL) is slightly higher when compared with CCT5 but overall training behavior is similar
  - Reach 80% of SSL after 14 quenches in subscale
  - Reach 80% of SSL after 22 quenches in CCT5
- Baseline subscale CCT has similar normal stress to CCT5 but lower shear stress
- Some detraining in the subscale CCT after the thermal cycle which was not seen in CCT5
- Fast training segment is seen for first several quenches as was the case for CCT4

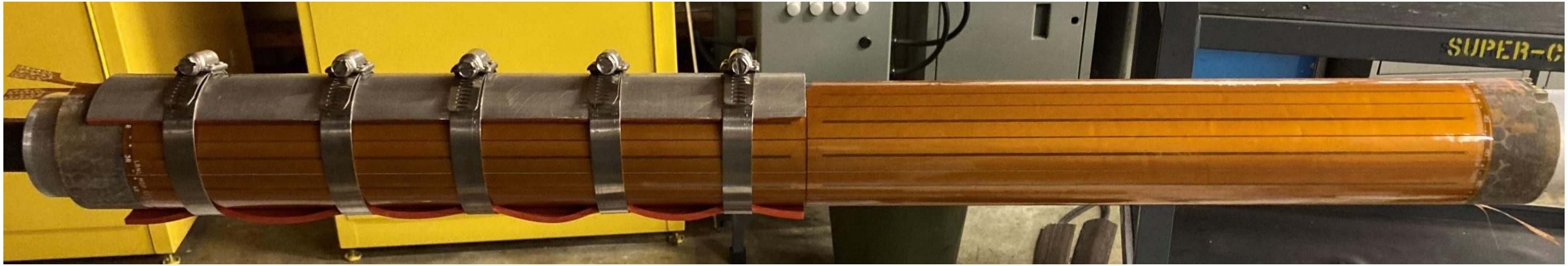


Several Instrumentation Approaches Are Used To Improve Understanding Of Training Sources

Subscale tests are used to test novel instrumentation methods and can lead to improved interpretation of measurement data

- Voltage taps
- Strain gages on shell and/or coils
- Acoustic sensors at coil ends and inside of magnet bore
- Quench antennas in bore and between layers

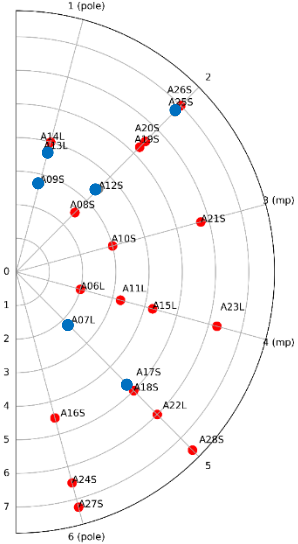
Interlayer Quench Antennas



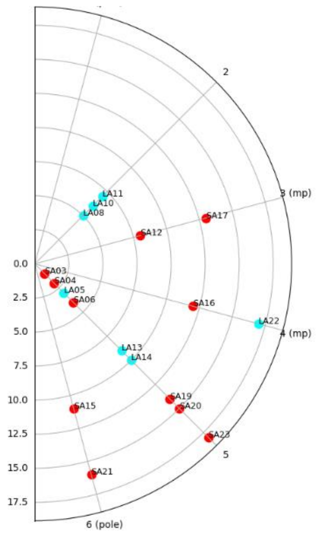
Flexible Quench Antenna

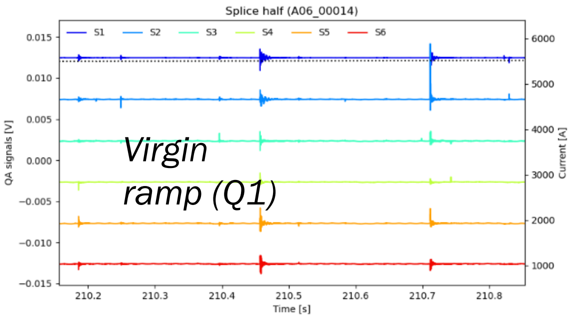
- Inter-layer antennas producing spatially resolved measurements of ramp activity and quench locations
    - Quench locations more evenly distributed in thin spar
    - Quench locations largely from 45 degrees / pole in thick spar
    - Focus has been largely experimental – detailed analysis to resume in October
- Moving forward:
    - Higher speed acquisition & increased spatial resolution
    - Simplified analytic modeling & quench heaters for validation

Thin spar (SUB2)

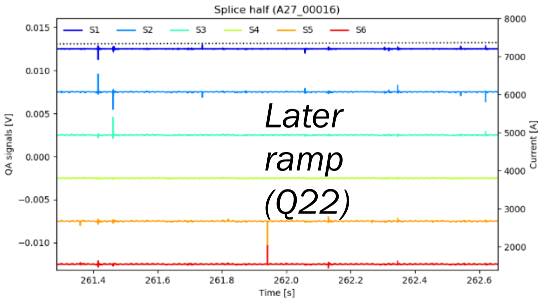


Thick spar (SUB3)





Virgin ramp (Q1)



Later ramp (Q22)

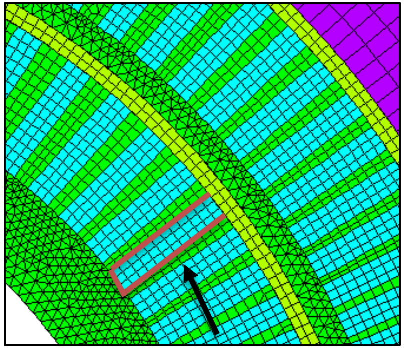
Effort led by R. Teyber, M. Marchevsky

Interface Damage Models Are Being Developed To Better Understand CCT Magnet Mechanics

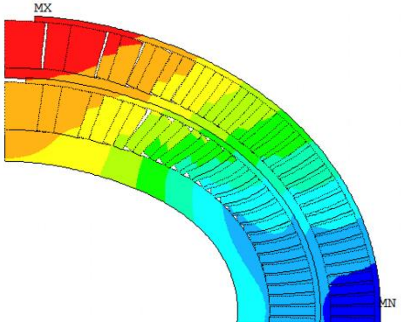
- **Aim**: study the **differences** between the **subscale** magnets (***qualitative***). Ideally, would like to **predict/match** the behavior starting from the **measured** interfaces' properties (***quantitative***)

- **Contact** elements (bonded/frictional/**CZM**) around the cable (**cable/spar**, **cable/rib**)
    - **Bonded** model, to evaluate tension/shear loads at the interfaces
    - **Frictional** model, to evaluate potential motion with failed interfaces
    - **Cohesive** model, to model progressive failure during training

- **Load steps**: 0: **prestress**, 1: **cooldown**, 2: **powering** to final current



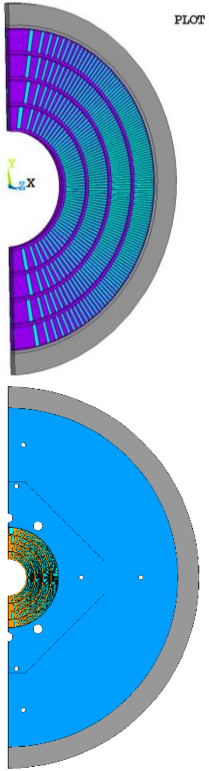
CZM elements



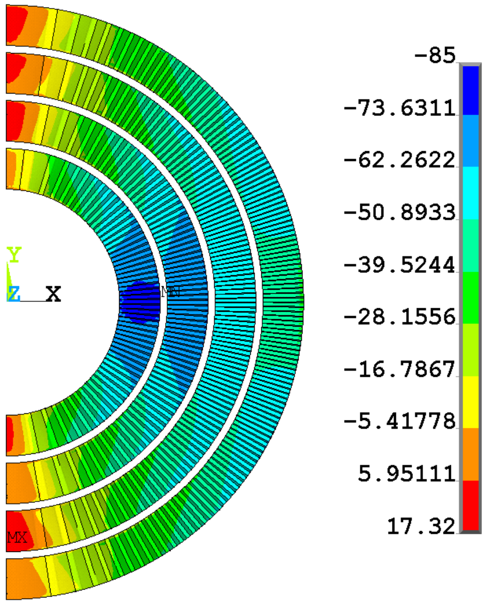
Effort led by G. Vallone

CCT6 Is Currently In The Design Phase

- **CCT6 is a four layer dipole magnet designed with bore field of 11 T (at 4.2 K) in a 120 mm bore**
  - Next step in CCT development with large bore, wide cable, and 4 layers
  - Allow for hybrid magnet testing with HTS inserts
  - Will use external key and bladder structure
- **Currently performing analysis and design optimization**
  - 2D and 3D periodic analysis
  - Structure optimization
- **Will fabricate test mandrel to test winding and reaction with a "wide" cable**



Azimuthal Stress at 12.2 T



Conclusions

- CCT magnets can provide reduced conductor stress by force interception
- CCT magnets use minimal tooling which can greatly reduce the design and fabrication complexity
- Winding geometry naturally produces excellent field quality
- Additional interfaces between the cable and mandrel can be possible sources of training
- Less efficient use of conductor when compared with other designs

Focus for next steps for LBNL CCT Program within MDP

- Can training be further improved in CCT magnets?
  - Need better understanding of sources of training (e.g. interface stress, motion, stress on conductor)
  - Can modeling be used to improve prediction of stresses when failure of surfaces occurs?
  - New approaches to reducing training can be tested in subscale setting (e.g. improved impregnation materials, engineered interfaces, non-impregnated coils, introduce high heat capacity materials)
- Hybrid magnet design and testing
- Design and Fabrication of CCT6 (11 - 12 T 4 layer dipole with 120 mm bore)