



**U.S. MAGNET
DEVELOPMENT
PROGRAM**

US Magnet Development Program

Design And Test Results Of The Nb₃Sn Canted-Cosine-Theta Dipole Magnet CCT4

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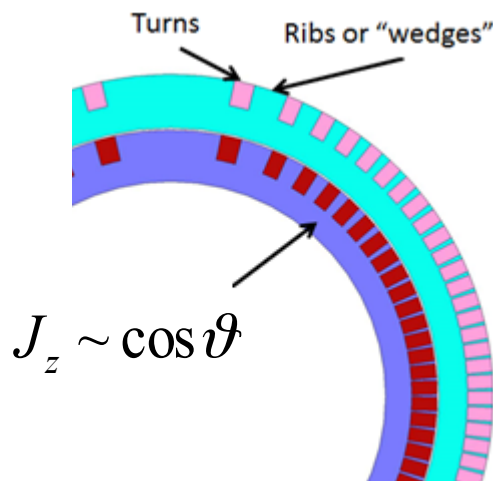




Concept – CCT Dipole Magnet

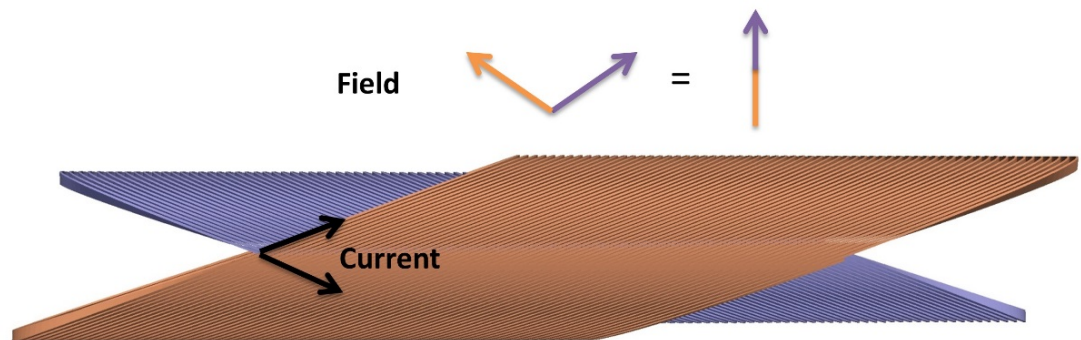
- Canted windings in opposing directions produce dipole field
- Layers in multiples of two are added to achieve higher fields
- Transverse current density has natural cos-theta distribution
- Windings are placed in a mandrel with grooves – Ribs and spars in mandrel intercept Lorentz force leading to substantially reduced azimuthal stress

Ribs Intercept Lorentz Force



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

Winding Geometry

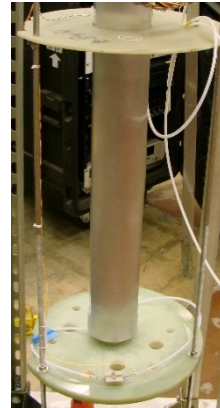




Summary of CCT Tests

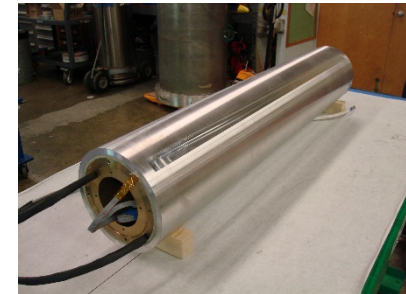
CCT1

- 2.5 T short-sample dipole
- 50 mm clear bore
- 8 strd. NbTi cable (0.65 mm SSC Outer)
- not impregnated
- 11/2013: tested up to 2.5 T



CCT2

- 5.3 T short-sample dipole
- 90 mm clear bore
- 23 strd. NbTi cable (0.8 mm SSC Inner)
- epoxy impregnated
- 5/2015: tested up to 4.7 T



CCT3

- 10.0 T short-sample dipole
- 90 mm clear bore
- 23 strd. Nb₃Sn cable (0.8 mm OST 54/61)
- 3/2016: tested up to 7.4 T
- Suspect Conductor damage as possible cause of current limit



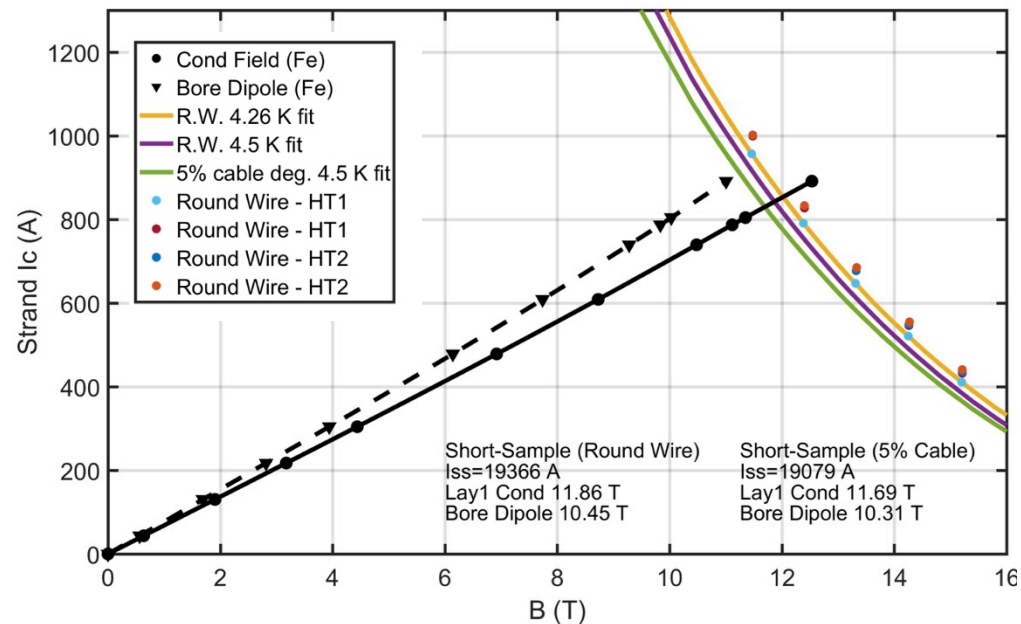


2-Layer Nb₃Sn CCT Dipole Magnet Series

- CCT 2-layer series has nearly identical geometry
 - 90 mm diameter inner bore and 1 m physical length
 - Mandrel grooves for 10 mm wide and 1.4 mm thick cable
- CCT3/4 use RRP 54/61 conductor ($J_c > 3000 \text{ A/mm}^2$ at 12 T)

Magnet Parameters	CCT3/4
	Nb ₃ Sn
Conductor	RRP 54/61
Cu:SC ratio	0.85
Inner Bore Diameter [mm]	90
Cable Width [mm]	10.1
Cable Thickness [mm]	1.4
Number of Strands	23
Cable Insulation	S-glass Braid 0.2 mm thick
Iron Yoke	Yes
Impregnation Material	CTD-101K
Short Sample Current [kA]	19.3
Short Sample Bore Field [T]	10.4

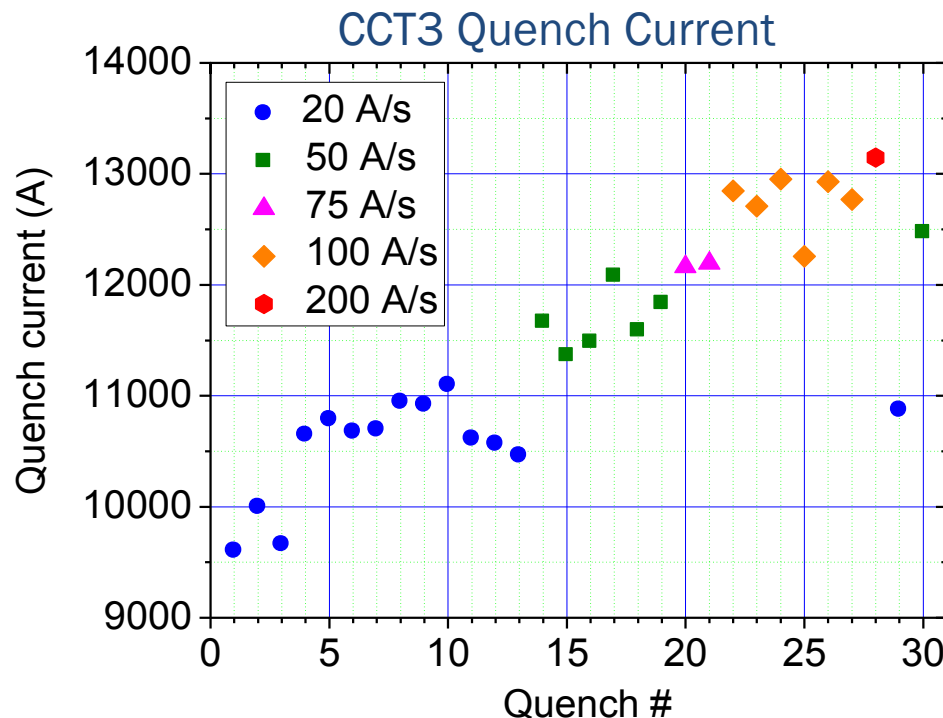
Magnet Load Line for CCT4





CCT3 Test Results

- CCT3 reached approximately 70% of short sample current after 28 quenches
- Higher current can be achieved at higher ramp rates
- Most quenches in the same region (within 5 turns from end in inner layer)
- Observed instability believed to be due to conductor damage

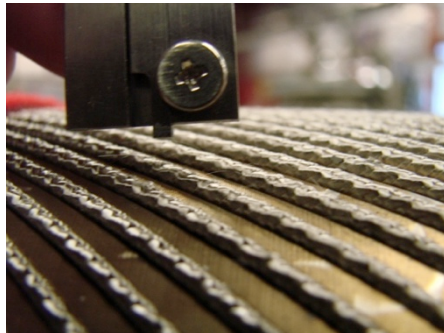




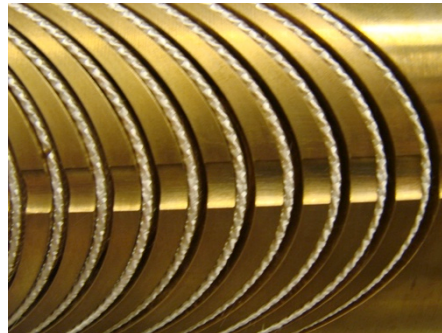
Conductor Expansion Problem Has Been Alleviated Through Mandrel Design Changes

- CCT3 Cable protruded from the surface of the mandrel after heat treatment
- Dedicated experiment was used to define the expansion gap that is needed to maintain the cable position after heat treatment
- Gaps were machined into mandrel to allow for dimensional changes of the cable

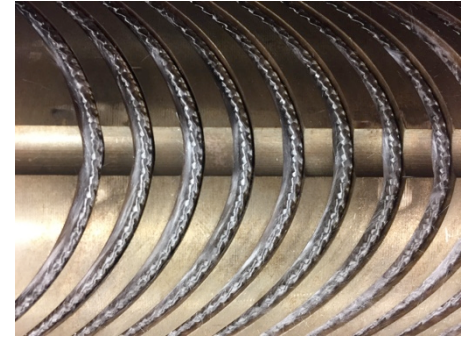
Cable Position After CCT3 HT



CCT 4 Before HT



CCT 4 After HT



Measured Gaps After Heat Treatment



Extracted Cable



Etched Cable Sample

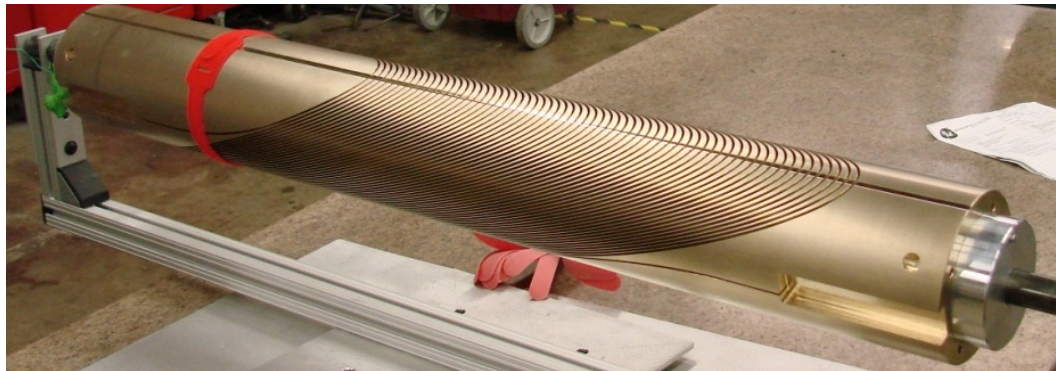




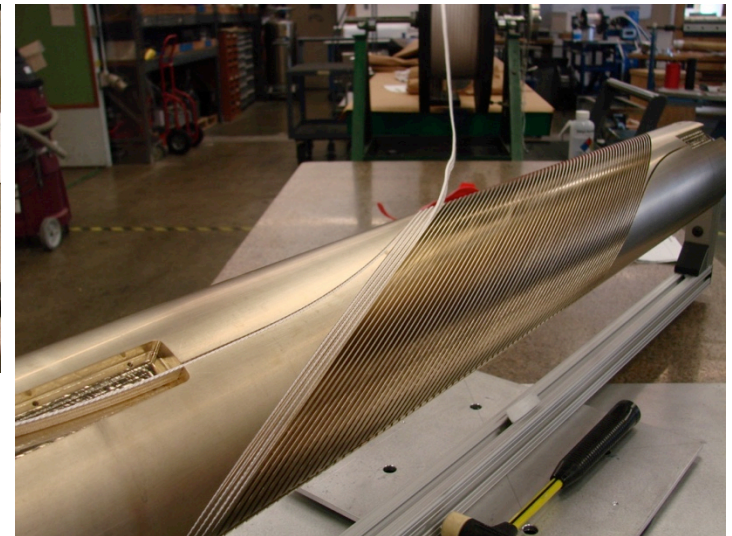
CCT Mandrels and Winding

- Aluminum Bronze mandrels are machined on 4-Axis CNC milling machine
- Conductor is placed into the groove without tension
- Pockets are machined into the mandrels for lead splices

Machined Mandrel



Coil Winding



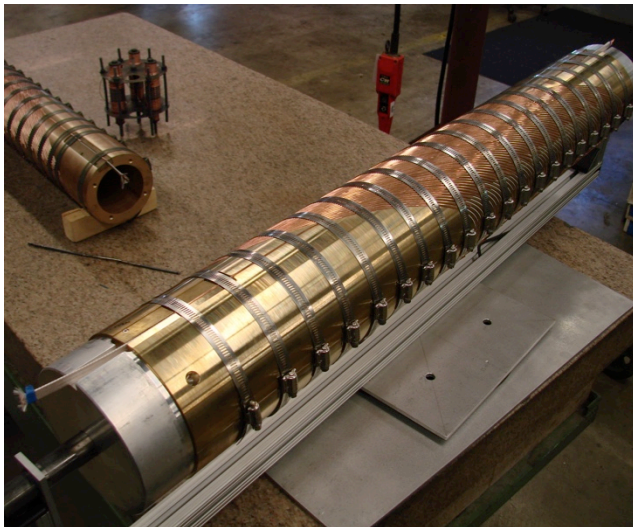
* Tooling Required is Minimal



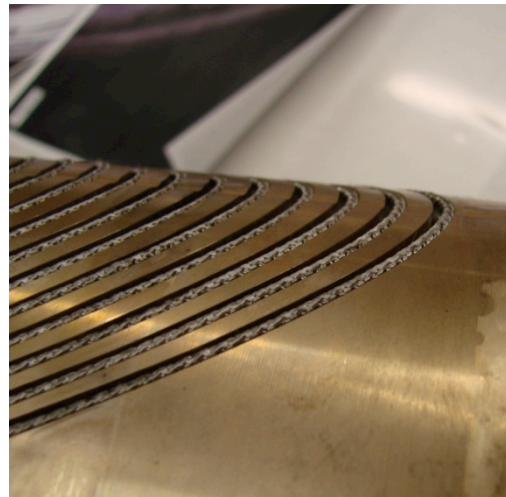
CCT4 – Heat Treatment and Assembly

- Copper wire is used to force the cable to the bottom of the channel
- Mandrel is secured with hose clamps
- Cable is below mandrel surface after heat treatment
- Layers are wrapped with G10 sheets and inserted into the outer layer and shell

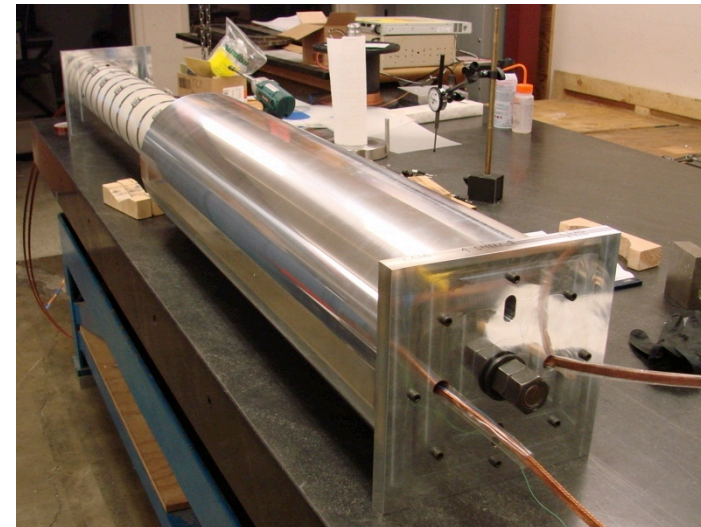
CCT4 Heat Treatment
Configuration



Cable Position After
Heat Treatment of CCT4



CCT4 Assembly

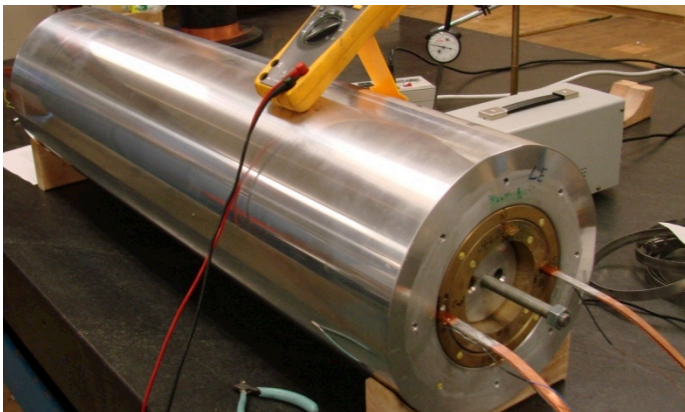




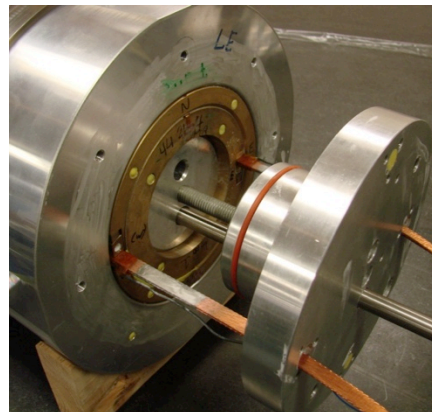
CCT4 Magnet Impregnation

- Coils and shell assembly is impregnated with epoxy
- Simple tooling is used to create a seal from the bore to the ends of the shell
- Inside of outer layer and shell were mold-released to avoid energy release from delamination at the interfaces
- Next Step: Development of individual layer potting and assembly is under way

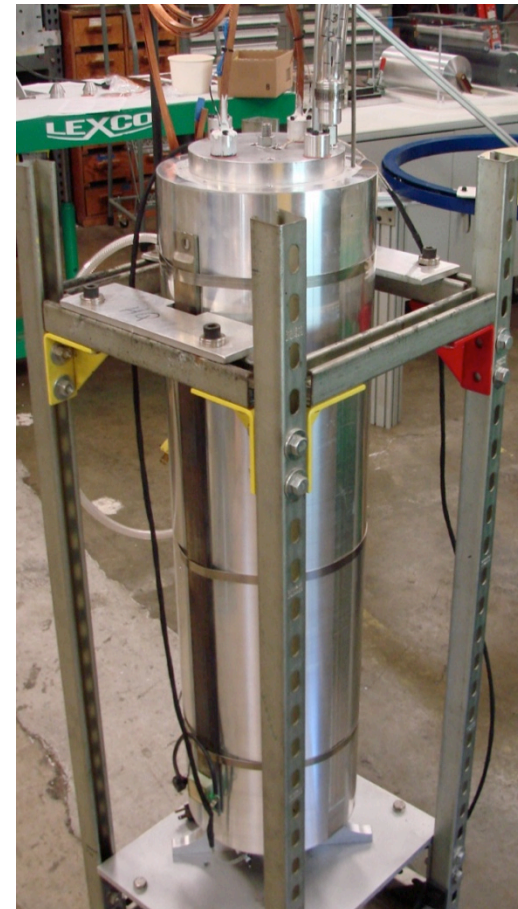
CCT4 Coil Assembly



Sealing End Caps



Potting Assembly





Instrumentation

- Voltage taps at various turns in the coil
- Acoustic Sensors at 10 locations on the shell
- Strain gages on Shell (Pole and Midplane)
- Spot Heater and Thermometer in Groove

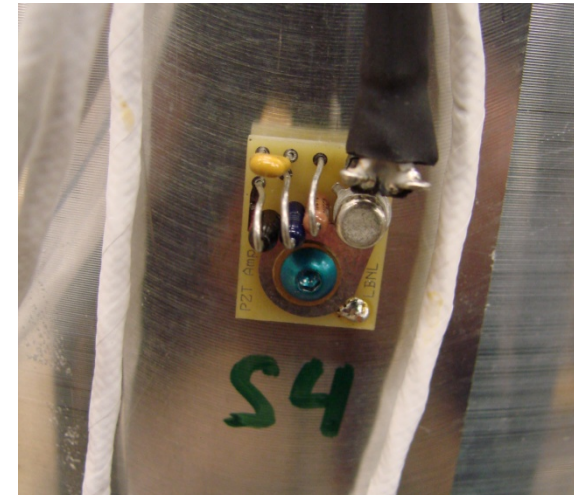
Spot Heater



Strain Gages



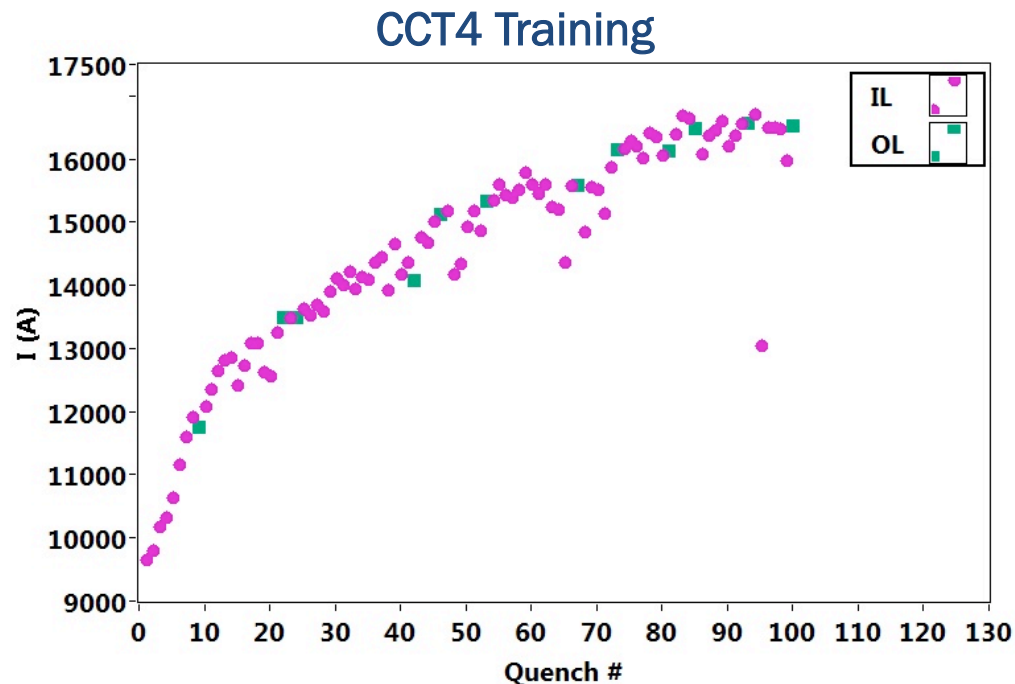
Acoustic Sensors





CCT4 Test Results

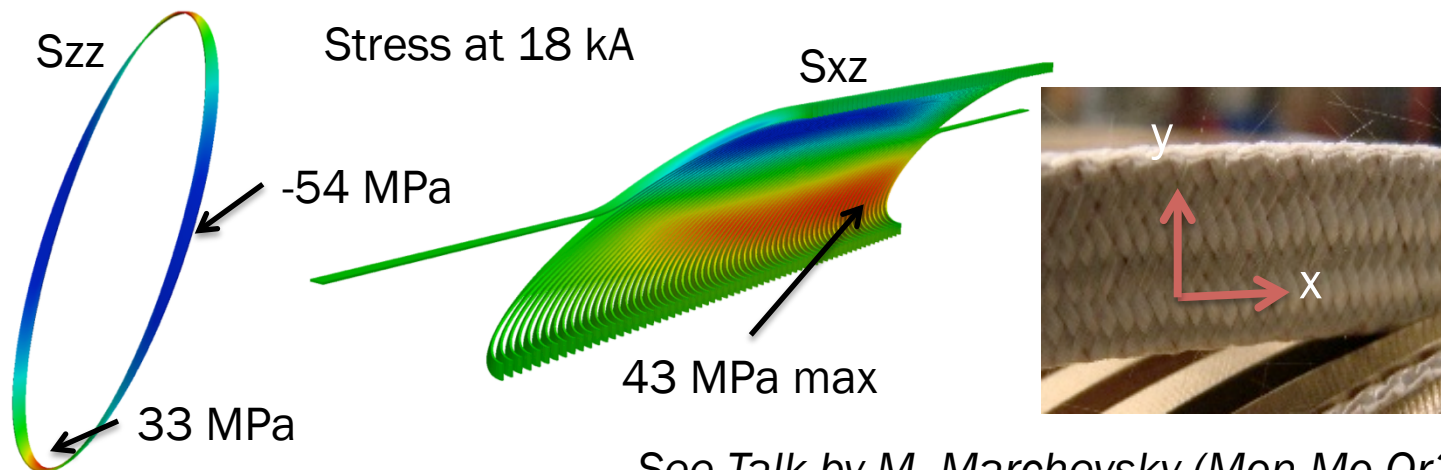
- Reached 86% of round wire short sample after 85 quenches
- Maximum current is 17.6 kA
- Maximum bore field is 9.14 T (90 mm aperture)
- Training behavior changes at around 13 kA



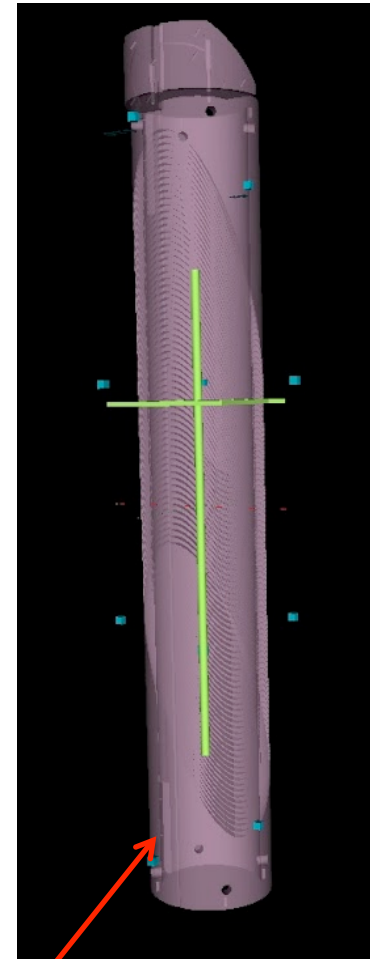


Critical Stress Regions

- Models are used to identify critical regions in the magnet where normal and shear stress is highest
 - Stress in cable
 - Shear stress in cable/groove interface
- Acoustic signal triangulation is used to determine location of mechanical events leading to a quench
- Data analysis is being performed to determine likely mechanisms for training



See Talk by M. Marchevsky (Mon-Mo-Or3)

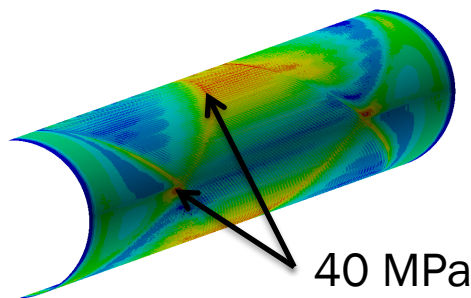




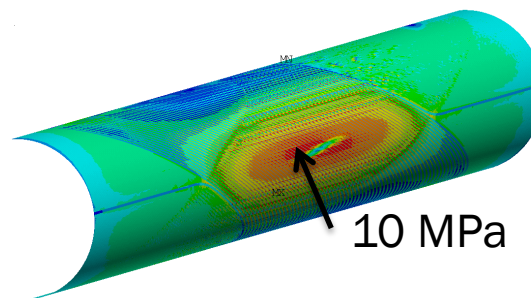
Critical Interfaces

- Different bonding assumptions (glued and sliding) are used to understand the behavior of the layer-to-layer interfaces
- Data is compared to strain gage response during test
 - Strain gage response remains linear during entire current ramp
 - Good agreement with finite element models
- Analysis of acoustic events is also used to understand behavior at the layer-to-layer interfaces

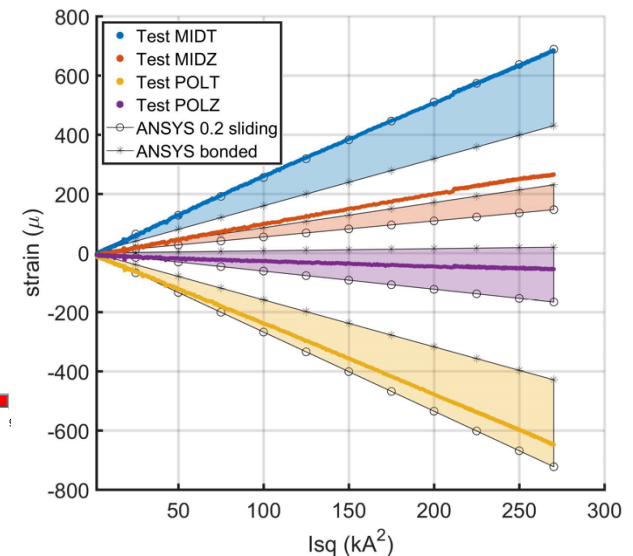
Shear Stress Bonded



Shear Stress Sliding



Strain Gage and Modeling Results



See Poster by L. Brouwer (Tue-Af-Po2.10)



Conclusions

- Cable damage problem that was exhibited in CCT3 has been solved
- CCT4 achieved a maximum field strength of 9.14 T in a 90 mm bore without pre-load
- Large number of training quenches were required to reach maximum field
- Currently analyzing acoustic data that could lead to better understanding of training sources
- Next Steps in CCT Program
 - Dedicated effort to understanding and reducing training
 - Development of impregnation and assembly methods that allow for modifying the stress state in the coils and for coil layer addition and replacement
 - Development of multi-layer magnets to demonstrate high field performance