U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn Magnets – CCT Status and Next Steps

Diego Arbelaez (for the Nb_3Sn CCT Team)

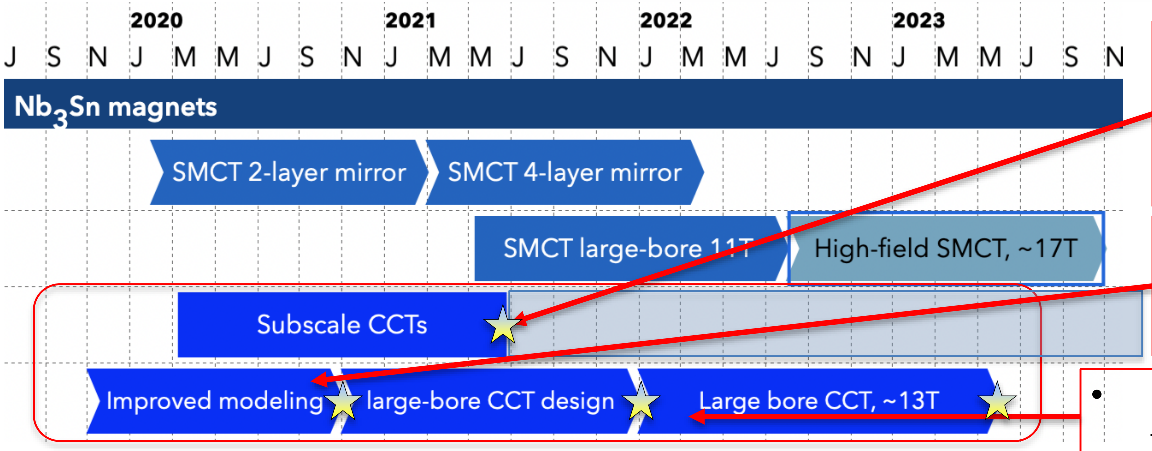
U.S. MDP Collaboration Meeting

03/21/2023

The Nb_3Sn Magnet Area Focuses On The Development Of Stress Management Techniques For High Field Magnets

- *“The updated Nb_3Sn magnet roadmap works to develop and demonstrate effectiveness of stress-managed (SM) approaches”*
- *“The program focuses on a) increasing magnet operational field and aperture, b) reducing potential for magnet degradation, and c) reducing magnet training”*
- *“The program furthermore considers means to minimize magnet cost”*
- *“Stress management approaches are also critical for HTS program elements, thus linking the aims of the Nb_3Sn program to those of the HTS program.”*

The Nb_3Sn CCT Road Map Focuses on Improving Training and Demonstrating High Field Performance for Large Bore Magnets



- Four magnets have been tested to date (Eight total tests)
- Two more magnets in preparation for FY23 (Full Wax and Full Stycast)

- Models have been developed & continuously improving – *see talk by G. Vallone*

- Basic Design complete – preparing for fabrication of first layer

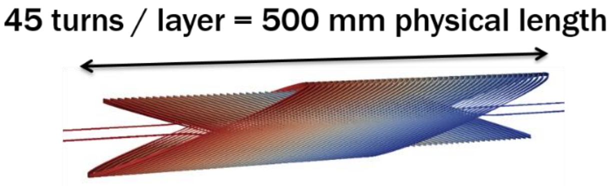
Task 1. Use CCT subscale program to increase understanding and improve training in stress managed magnets.
Task 2. Improve numerical modeling of magnet mechanics to accurately predict stresses when surface failure/delamination can occur.
Task 3. Design of CCT6 4-layer magnet with target field of 13 T and bore diameter of 120 mm (with feedback from desired diameter from HTS components of MDP). Design of CCT6 will profit from feedback provided by subscale testing and improved modeling methods.
Task 4. Fabrication and test of CCT6 4-layer CCT magnet.

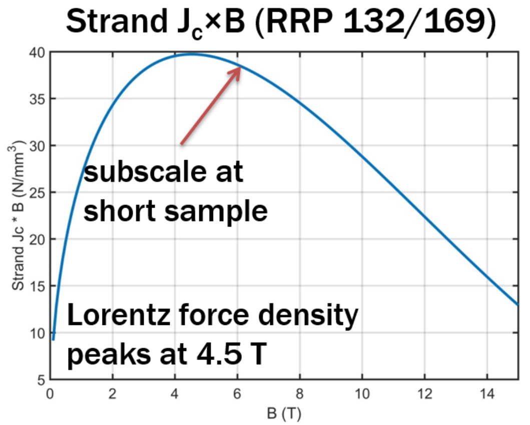
Task 1. Use CCT subscale program to increase understanding and improve training in stress managed magnets.

Subscale models can lead to faster turnaround for dedicated training experiments, for example:

- Epoxy (or other impregnation materials) influence on training (e.g. different epoxies, wax, filled resins)
- Structural influences (e.g. spar thickness)
- Interface conditions (e.g. inter-layer shim angle)

Subscale models are complementary to overall MDP program and will give feedback to design of future large stress managed magnets



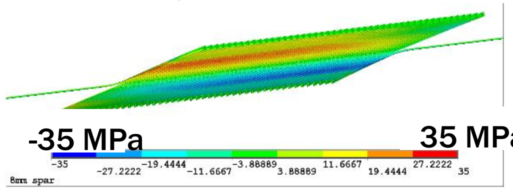


Four subscale magnets have been fabricated and tested

- First two magnets have inner layers with thin (Sub 2 / baseline) and thick spars (Sub 3)
  - Thin spar → reduced interface shear stress and increased normal stress due to bending
  - Thick spar → increased interface shear stress and reduced normal stress due to bending
- Third magnet (Sub 4) used new non-epoxy high toughness resin CTD-701x (*SBIR collaboration led by T. Shen at LBNL*)
- Fourth magnet (Sub 5) with wax impregnated inner layer (*Fabrication process covered in talk by J.L. Rudeiros Fernandez*)

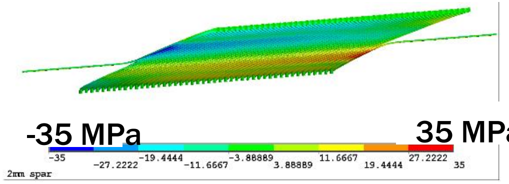
Sxy (radial-azimuthal)

8 mm spar



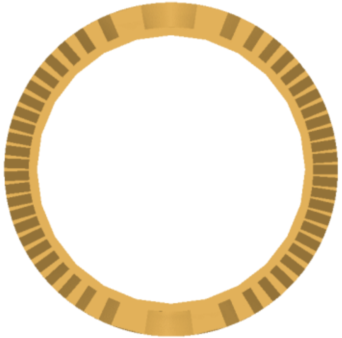
-35 MPa 35 MPa

2 mm spar

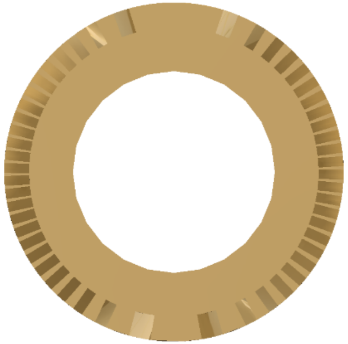


-35 MPa 35 MPa

Thin Spar (Baseline)



Thick Spar



A Total of Eight Magnet Tests Have Been Performed Until Now

CCT Sub2 (thin spar / baseline)

- Initial Test
- Test after thermal cycle
- Test after disassembly and reassembly **
  - Demonstrated magnet disassembly / reassembly without damaging the coils
  - Outer layers can be re-used for future tests

CCT Sub3 (thick spar)

- Initial Test
- Test after thermal cycle

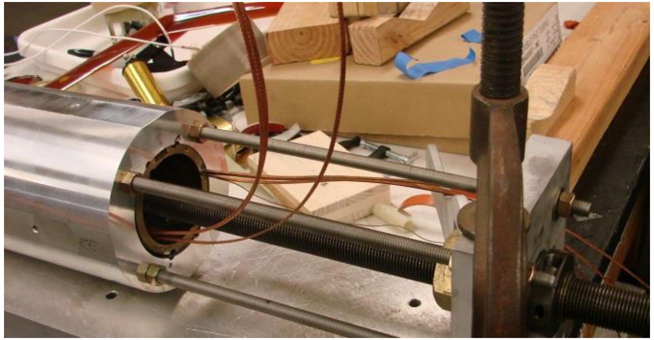
CCT Sub4 (CTD 701x impregnation)

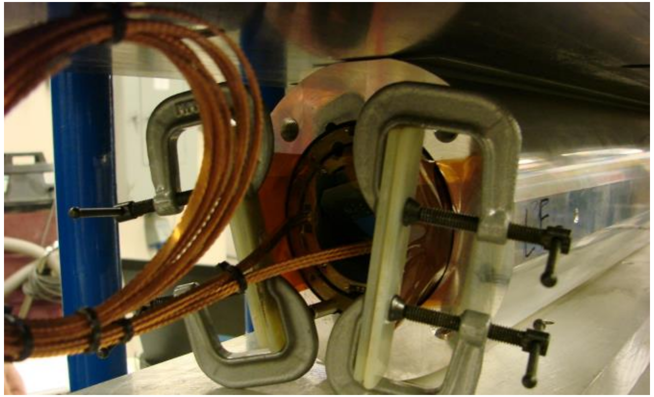
- Initial Test
- Test after thermal cycle*

CCT Sub5 (Inner layer wax impregnation)

- Initial Test **

Sub2 Disassembly / Reassembly

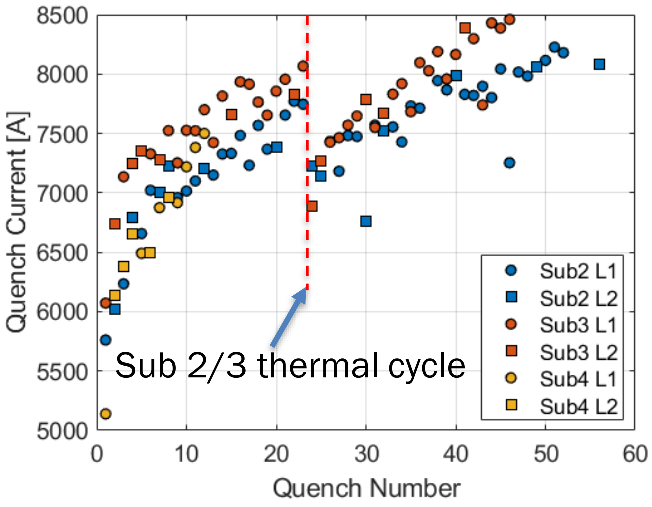


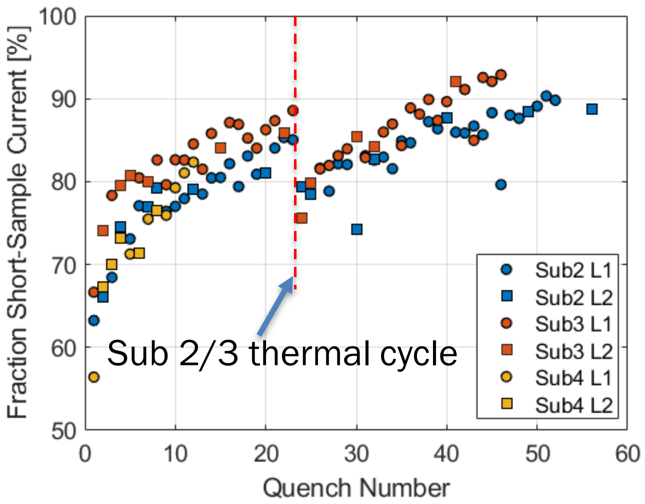


* *Magnet was limited at or near the internal splice*
** *Tests performed since last collaboration meeting*

CCT Subscale 2, 3, 4 Training Summary

- Subscale 3 starts at higher current quench current and trains faster initially
- Similar training rate is seen between subscale 2 and 3 after the fast training segments with ~ 4% offset before thermal cycle
- Some loss of memory in both magnets after thermal cycle (likely higher loss of memory in sub3)
- Sub3 has a higher training rate after the thermal cycle





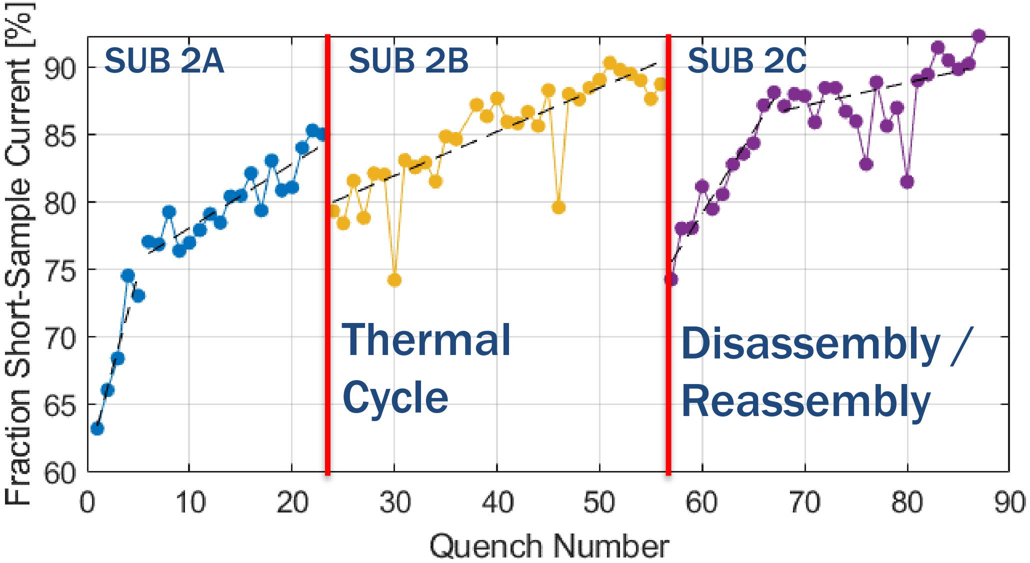
Sub2 – baseline
Sub3 – thick spar
Sub4 – CTD 701x resin

Stiffer structure seems to reduce training even with higher shear stress

Subscale 2 Reassembly Test

- Magnet Disassembly / Reassembly was succesful
- Outer layers can be reused for testing (may not always be desirable as shown later)

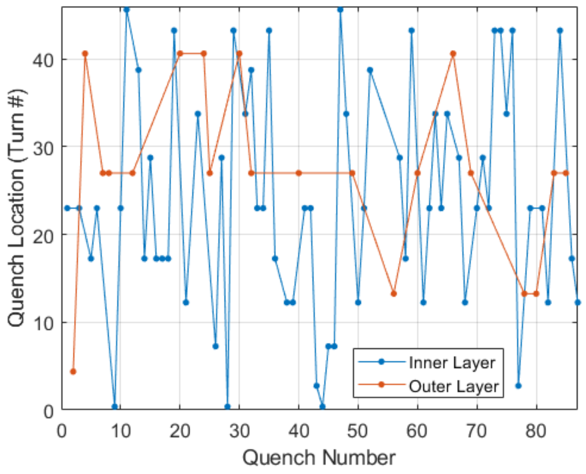
- *Magnet shows fast then slow training behavior (knee)*
- *Knee behavior is mostly gone after thermal cycle with some detraining*
- *Fast training reappears after disassembly / reassembly – global behavior*



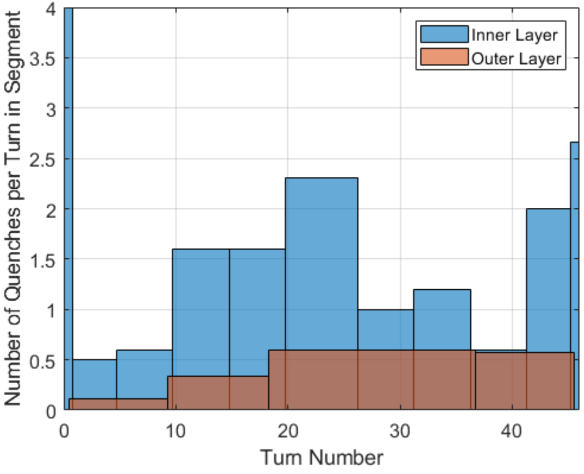
Subscale 2 Quench Location History Based on Voltage Taps

- Quench location is fairly evenly distributed as a function of turn number for all tests
- Quenching in a single segment (indicating SSL) is never reached for all SUB2 tests
- Approximately 75% of quenches are in the inner layer

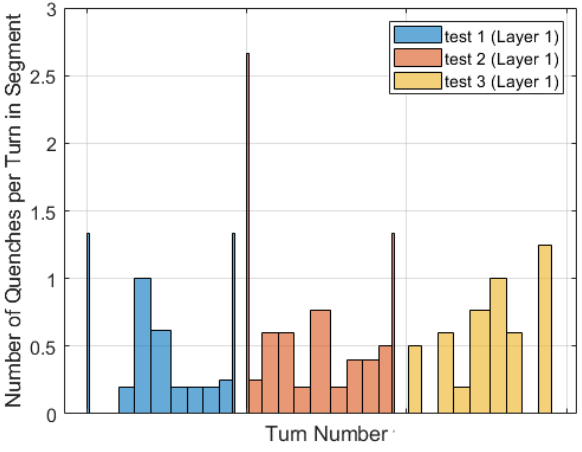
Quench Locations vs Quench Num



Quench Location Histogram



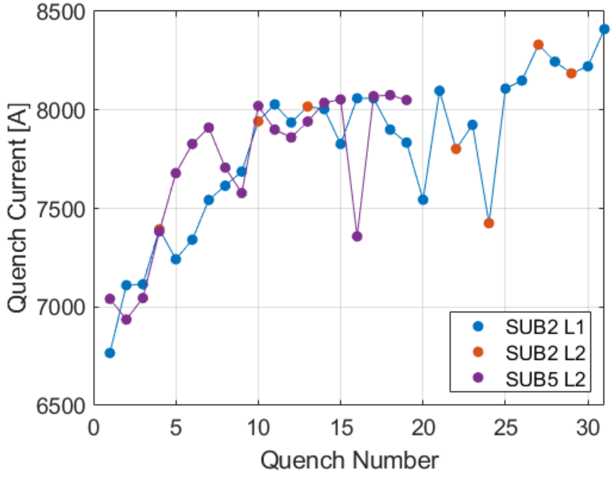
Quench Location Histogram per Test



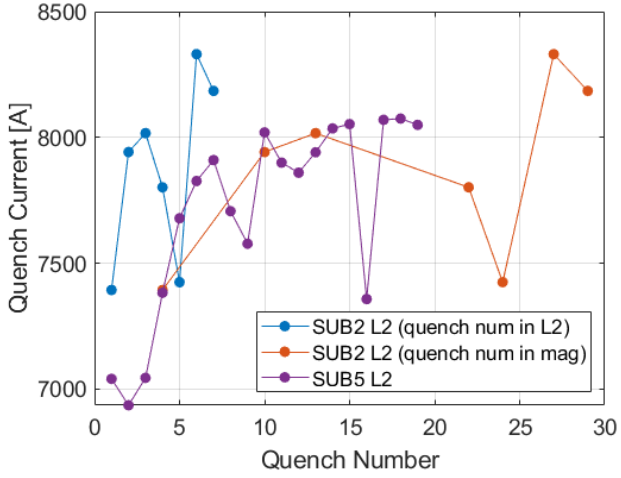
Wax Inner layer Shows Zero Training Quenches

- Wax magnet inner layer was fabricated and assembled along with epoxy outer layer
- Zero training quenches occurred in the wax inner layer
- Training of magnet behaves similar to the SUB 2 after disassembly / reassembly but all training occurs in outer layer
  - Could training behavior be possibly independent of quench location for subscale CCT ? (i.e. trains the same whether quench is in IL or OL)
  - Could increased inner layer training be due to changes in mechanics that affect outer layer? (i.e. L1 stiffness, inter-layer shim change)

Comparison Between SUB 5 and SUB 2C



Comparison Between Outer Layer Quenches

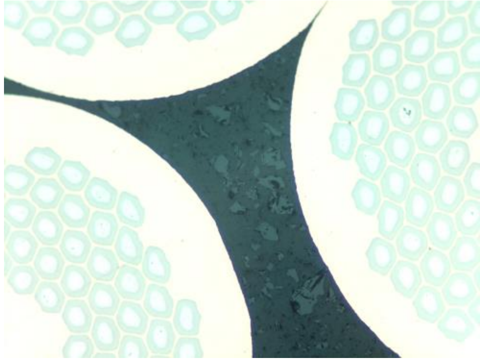


Next subscale Deliverables

Deliverables over the next 1 year

- **Test of all-wax subscale magnet**
  - Wax impregnated outer layer will be fabricated and assembled with wax inner layer from SUB 5
  - Explore if short sample limit can be reached as has been done in BOX experiments at PSI [1]
  - Exploring wax properties to understand reason for lack of training* – likely driven by low strength / friction which limits energy release
- **Test of Stycast impregnated subscale magnet**
  - Stycast BOX samples showed similar training to wax but may not have low strength limitations
  - Exploring material properties to understand quench behavior* - possible reasons include close match of thermal contraction of metals, high thermal conductivity, high toughness, perhaps lower adhesion strength to mandrel surfaces

Stycast Impregnated Cable in Groove



[1] Daly, Michael, et al. "Improved training in paraffin-wax impregnated Nb3Sn Rutherford cables demonstrated in BOX samples." Superconductor Science and Technology 35.5 (2022): 055014.

** See talk by Jose Luis Rudeiros Fernandez*

Subscale CCT Test With High Cp Tape

Motivation:

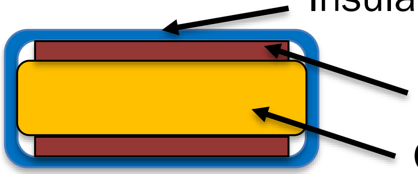
- Develop method to reduce training by absorbing energy released from different events (cracking, sliding, ….) with a high Cp material
- This solution has the potential to be independent of impregnation material / process and groove / interlayer interface conditions

Plan:

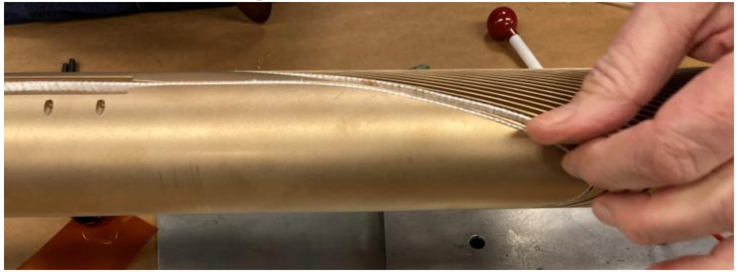
- Use subscale CCT platform to test effect of high Cp tapes being developed at FNAL on CCT magnet training
- High Cp tapes will be applied to each face of the subscale CCT cable inside of a glass tape wrap insulation

Current Status:

- Procedure to apply tapes and insulate cable currently ongoing at FNAL using Copper tapes
- LBNL providing support with windability and insulation testing

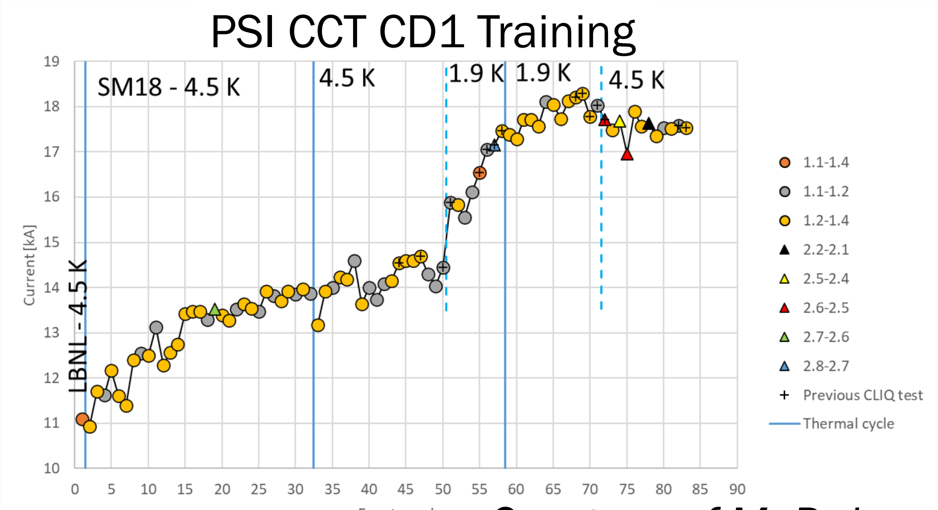


Winding of initial test cable



Subscale test at FNAL - 1.9K

- CD1 Magnet from PSI showed similar training behavior as CCT5 when tested at 4.2 K
- Training rate increased significantly when tested at 1.9 K and with the use of CLIQ
- Memory remains after returning to 4.5 K
- Motivates plan to send CCT SUB 2 to FNAL for testing at 1.9 K and possibly with QCD system if possible



Courtesy of M. Daly

CCT SUB 2

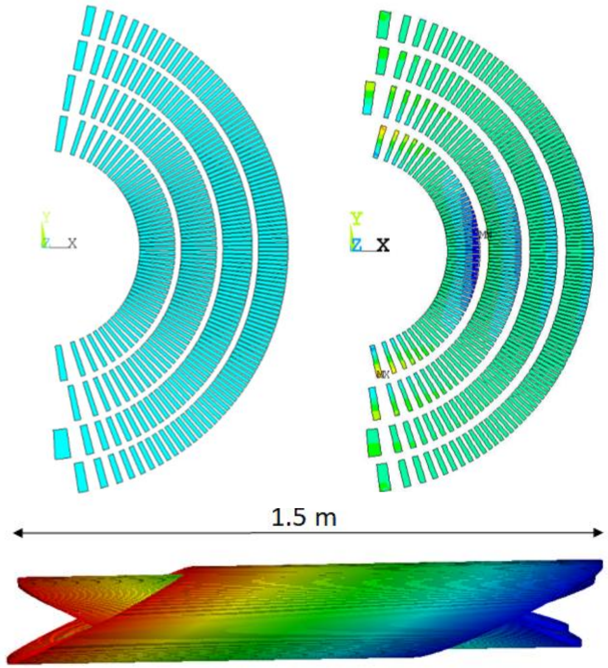
Task 3. Design of CCT6 4-layer magnet with target field of 13 T and bore diameter of 120 mm

- Target Parameters
  - 4 layers
  - Bore field of 12 T / 13 T for standalone operation (30+ % current margin at target fields of 12 T, 4.2 K and 13 T, 1.9 K)
  - Bore diameter: 120 mm
- Field strength and bore size needs are compatible with HTS programs for hybrid testing
- Use feedback provided by subscale testing and improved modeling methods in CCT6 design

Goals:

- Demonstrate scale up for more than two layers
- Demonstrate feasibility of CCT at higher field with a large bore

CCT6 Design



Current Status And Next Steps

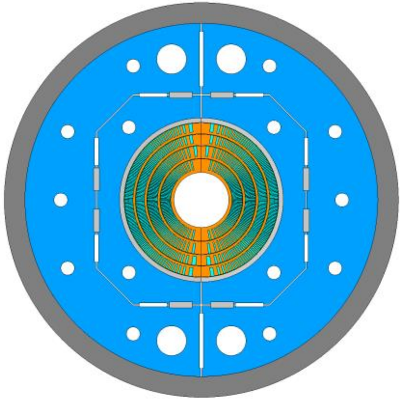
Current Status

- Current conceptual design assumes use of existing LD1 (in-hand) cable for inner layers and MQXF type (needed) cable for outer layers
- 3D analysis of mechanical structure is being performed
- Optimization of deep groove machining has been performed
- Winding, reaction, and impregnation tests have been performed on 7-turn Coil (demonstrated feasibility of winding wide cable)

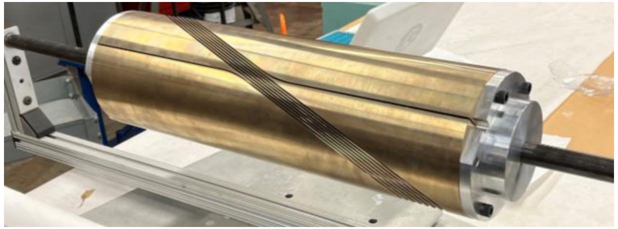
Upcoming Work

- Complete second 7-turn test mandrel to finalize coil geometry
- Machining of layer 1
- Winding, Reaction, and Impregnation of layer 1

4 Layer CCT Magnet



Test Mandrel



** See talks by Lucas Brouwer (CCT6) and Mariusz Juchno (Utility Structure)*

Next “Large” CCT Model Milestones & Deliverables

Deliverables

- Design, fabrication, and test of 4-layer CCT magnet

Milestones

- Original milestone: Design completed at the end of Q1 FY2022 (with input from modeling and subscale work)
  - Currently working on finalizing structure design
  - Ready for detailed design of coils
- Original Milestone: Full magnet assembly and testing Q3 FY2023
  - Fabricate layer 1 by end of 2023
  - Current plan is to test two inner layers ~ Q3 FY 2024 ***(requires utility structure)***
  - Full magnet test would be approximately 1 year later

Conclusions

- **Subscale plan is being carried out to further probe training causes and to test methods that can lead to improvements in training at a faster rate**
- **Subscale program has led to improvement in fabrication techniques and development of new methods (synergistic with HTS programs)** * *See talk by Jose Luis Rudeiros*
- **Design and optimization is being performed for 120 mm bore 12 - 13 T 4 layer CCT dipole** * *See talks by Lucas Brouwer (CCT6) and Mariusz Juchno (Utility Structure)*
- **Subscale program is testbed to test / improve diagnostic methods and analysis / interpretation** * *See talk Maxim Marchevsky and Reed Teyber*
- **Improved modeling efforts to better understand the interfaces in stress managed magnets are ongoing** * *See talk by Giorgio Vallone in Modeling Section*

Focus for next step in road map

- **Continue working on understanding and improving training in stress-managed Nb_3Sn magnets**
- **Demonstration of higher field model magnets (4 layers) and HTS hybrid magnet operation**
  - **Plan to test CCT5 for future use as an outsert in this calendar year (CCT5 has been reassembled and is ready for testing) –** ***See talk by Laura Garcia Fajardo***
  - **Continue work on design and fabrication of CCT6**