Experience With Nb$_3$Sn CCT Magnets at LBNL


TRIUMF 2021 EIC Accelerator Partnership Workshop
10/26/2021
• Introduction
• CCT concept
• CCT fabrication methods
• Analysis methods
• Experience at LBNL with Nb₃Sn CCT dipoles
• Conclusions
• Nb$_3$Sn CCT work is part of the US MDP Nb$_3$Sn 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
  o Periodic models
  o Full 3D models
  o 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

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

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 $\text{Nb}_3\text{Sn}$ magnet
  - Additional features for instrumentation and alignment
  - Gaps for cable expansion are used for $\text{Nb}_3\text{Sn}$
- Winding performed by placing conductor in the groove with minimal tension

Machined Mandrel

Coil Winding

- Instrumentation Pocket
- Alignment Groove
Nb$_3$Sn Coil Reaction Requires Minimal Tooling

- Minimal tooling has been used for reaction of Nb$_3$Sn 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
  o Fast Solution
  o Good for design & parametric studies
  o Results deviate near the pole

• 3D periodic models
  o Full 3D solution for straight section (infinitely long)
  o Faster solution than full 3D model

• Full 3D models
  o Full solution including end effects
  o Reasonable solution times with use of cluster
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 (Nb₃Sn) 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

<table>
<thead>
<tr>
<th></th>
<th>CCT3/4</th>
<th>CCT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Nb₃Sn</td>
<td>Nb₃Sn</td>
</tr>
<tr>
<td>RRP</td>
<td>54/61</td>
<td>108/127</td>
</tr>
<tr>
<td>Cu:non-Cu ratio</td>
<td>0.85</td>
<td>1.2</td>
</tr>
<tr>
<td>Inner Bore Diameter [mm]</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Cable Width [mm]</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Cable Thickness [mm]</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of Strands</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Cable Insulation</td>
<td>S-glass Braid</td>
<td>S-glass Braid</td>
</tr>
<tr>
<td>Iron Yoke</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Impregnation Material</td>
<td>CTD-101K</td>
<td>FSU Mix-61</td>
</tr>
<tr>
<td>Short Sample Current [kA]</td>
<td>19.3</td>
<td>17.8</td>
</tr>
<tr>
<td>Short Sample Bore Field [T]</td>
<td>10.5</td>
<td>9.7</td>
</tr>
</tbody>
</table>

### Magnet Load Line for CCT4

- Cond Field (Fe)  
- Bore Dipole (Fe)  
- R.W. 4.26 K ft  
- R.W. 4.5 K ft  
- 5% cable deg. 4.5 K ft  
- Short Sample (Round Wire)  
  - Short-Sample (Round Wire)  
    - Is=19.366 A  
    - Lay1 Cond 11.86 T  
    - Bore Dipole 10.45 T  
  - Short-Sample (5% Cable)  
    - Is=19.79 A  
    - Lay1 Cond 11.68 T  
    - Bore Dipole 10.31 T
Design Evolved Through This Series To Address A Number Of Issues

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

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

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

*Magnet Load Line*

*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

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

*Effort led by G. Vallone*
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
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?
  o Need better understanding of sources of training (e.g. interface stress, motion, stress on conductor)
  o Can modeling be used to improve prediction of stresses when failure of surfaces occurs?
  o 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)