US Magnet Development Program

Design And Test Results Of The Nb$_3$Sn Canted-Cosine-Theta Dipole Magnet CCT4

MT25 Conference
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US Magnet Development Program

Lawrence Berkeley National Laboratory
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

Transverse current density with $\cos \theta$ distribution approaches a perfect dipole current density distribution
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. Nb$_3$Sn 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 Nb$_3$Sn 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 (Jc > 3000 A/mm$^2$ at 12 T)**

### Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CCT3/4</th>
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</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Cu:SC ratio</td>
<td>RRP 54/61</td>
</tr>
<tr>
<td>Inner Bore Diameter [mm]</td>
<td>90</td>
</tr>
<tr>
<td>Cable Width [mm]</td>
<td>10.1</td>
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<tr>
<td>Cable Thickness [mm]</td>
<td>1.4</td>
</tr>
<tr>
<td>Number of Strands</td>
<td>23</td>
</tr>
<tr>
<td>Cable Insulation</td>
<td>S-glass Braid, 0.2 mm thick</td>
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<tr>
<td>Iron Yoke</td>
<td>Yes</td>
</tr>
<tr>
<td>Impregnation Material</td>
<td>CTD-101K</td>
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<tr>
<td>Short Sample Current [kA]</td>
<td>19.3</td>
</tr>
<tr>
<td>Short Sample Bore Field [T]</td>
<td>10.4</td>
</tr>
</tbody>
</table>

**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

* Tooling Required is Minimal
• 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 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
• 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
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
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.

\[ S_{zz} \]
\[ S_{xz} \]

Stress at 18 kA:
- 33 MPa
- 43 MPa max
- -54 MPa

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.

**Strain Gage and Modeling Results**

**Shear Stress Bonded**
- 40 MPa

**Shear Stress Sliding**
- 10 MPa

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