US-MDP Nb$_3$Sn Cos-theta Magnets

FCC Week in Amsterdam, April 9-13, 2018

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Outline

**Nb$_3$Sn Cos-theta dipole program plan and steps**

- **Step 1:** 15 T dipole demonstrator
- **Step 2:** 15 T dipole demonstrator + utility structure
- **Step 3:** 16-17 T dipole with stress management
- Large-aperture Nb$_3$Sn dipoles: 120-mm aperture dipoles with stress management for HTS coil test
- **Conclusions**
• **Step 1: 15 T dipole demonstrator design.**
  • Explore target field and force range.
  • Serve as technical and cost bases for comparison with new concepts.
  • Is an opportunity for program integration, particularly in the area of support structure design, and for exploration of different mechanical structures.
  • Most cost effective way to exceed the field obtained 20 years ago in the LBNL D20 dipole.
MDP 15 T Dipole Demonstrator Design

- **Mechanical structure:**
  - Thin StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - Thick end plates and StSt rods
  - Cold mass OD<610 mm

- **Coil:**
  - 60-mm aperture, 4-layer graded coil
  - \( W_{sc} = 68 \text{ kg/m/aperture} \)

- **Cable:**
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - 0.025 mm x 11 mm SS core
  - Insulation: E-glass tape
SSL and Design Field (or Magnet Design Limit)

Magnet design limit is determined by the mechanical constraints and it is 15 T.

- **300K**
  - $S_{eqv} = 133$ MPa

- **4K**
  - $S_{eqv} = 176$ MPa

- **4K+15T**
  - $S_{eqv} = 168$ MPa

**Magnet SSL:**
- $B_{ap} = 15.3$ T @ 4.5K
- $B_{ap} = 16.7$ T @ 1.9K

**J_c (4.2K, 12T) ~ 2600 A/mm^2**

Gaps between poles and pole turns
# Magnet Parameters at 4.5 (1.9*) K

<table>
<thead>
<tr>
<th>Parameter</th>
<th>D20 (LBNL)</th>
<th>HD2 (LBNL)</th>
<th>FRESCA2 (CERN)</th>
<th>HFDD (MDP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test year</td>
<td>1997</td>
<td>2008</td>
<td>2017</td>
<td>2018 (plan)</td>
</tr>
<tr>
<td>Max bore field [T]</td>
<td>13.35 (14.7*)</td>
<td>15.4</td>
<td>16.5 (18*)</td>
<td>15.2 (16.5*)</td>
</tr>
<tr>
<td>Design field $B_{des}$ [T]</td>
<td>13.35</td>
<td>15.4</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Design margin $B_{des}/B_{max}$</td>
<td>1.0 (0.9*)</td>
<td>1.0</td>
<td>0.8 (0.7*)</td>
<td>0.96 (0.89*)</td>
</tr>
<tr>
<td>Tested $B_{max}$ [T]</td>
<td>12.8 (13.5*)</td>
<td>13.8</td>
<td>~13</td>
<td>TBD</td>
</tr>
<tr>
<td>St. energy at $B_{des}$ [MJ/m]</td>
<td>0.82</td>
<td>0.84</td>
<td>4.6</td>
<td>1.7</td>
</tr>
<tr>
<td>$E_x$/quad at $B_{des}$ [MN/m]</td>
<td>4.8</td>
<td>5.6</td>
<td>7.7</td>
<td>7.4</td>
</tr>
<tr>
<td>$E_y$/quad at $B_{des}$ [MN/m]</td>
<td>-2.4</td>
<td>-2.6</td>
<td>-4.1</td>
<td>-4.5</td>
</tr>
<tr>
<td>Coil aperture [mm]</td>
<td>50</td>
<td>45</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Magnet (iron) OD [mm]</td>
<td>812 (762)</td>
<td>705 (625)</td>
<td>1140 (1000)</td>
<td>612 (587)</td>
</tr>
</tbody>
</table>
• All coil parts and structural components are available.
• Coil and mechanical structure fabrication is in progress.
Mechanical Structure

Iron Laminations

StSt Skin

AL I-Clamps

End Plates

Fillers

Axial Rods
Coil Components

Cable (FNAL)
- 420 m of 28-strand cable (4UL)
- 350 m of 40-strand cable (3UL)

L3/4 parts (FNAL)
- 3 sets

Traces (LBNL/FNAL)
- L2
- L4

L1/2 parts (CERN)
- Ti and Glidcop Wedges
- Ti poles and spacers, SS saddles
Fabrication of coil reaction/impregnation tooling was delayed => impact on coil fabrication schedule

- Reaction/impregnation (2 sets)
  - L1-L2
  - L3-L4
- Yoking
Mechanical Models

Models:
• 5 cm long
• 1 m long

MM components:
• Iron laminations
• Al l-clamps
• Coil-yoke shim
• Instrumented “dummy” Al coils (short and full-size)

Goals:
• To test all main components of the mechanical structure and tooling.
• To develop a coil assembly plan and pre-stress targets.
• To check instrumentation.
• For FEA validation.
Coil #1
- Coil **winding-curing-reaction-impregnation** is complete
  - 8 witness samples tested
- Coil size was measured
- Damaged due to shell buckling

Coil #2
- Coil **winding-curing** is complete
- Short in the transition cable has been found and repaired
- Strand damage was found in transition area

Coil #3
- Coil **winding-curing-reaction-impregnation** is complete
  - 7 witness samples tested
- Coil size measurements in progress

Coil #4 (to replace coil #1)
- Coil **winding** in progress
  - Coil parts from coil #2
  - Cable is available

Coil #5 (spare coil)
- Need coil parts and cable
Coil #1
- Coil winding-curing-reaction is complete
- Preparation to impregnation in progress

Coil #2
- Coil winding-curing is complete
- Preparation to reaction in progress

Coil #3 (spare coil)
- Coil winding-curing is complete
- Coil stored in holding fixture
Coil Heat Treatment Optimization

**0.7 mm RRP108/127**
40-strand cable with SS core

**1 mm RRP150/169**
28-strand cable with SS core

**L3-L4 witness samples:**
Location: tooling – 1 Rd+3 Ext, retort – 2 Rd+6 Ext
- $I_c (12 \text{T}) = 504 \text{ A (tooling)}$
- $I_c (12 \text{T}) = 498 \pm 3 \text{ A (retort)}$
- $RRR = 108 \pm 22 \text{ (tooling)}$
- $RRR = 74 \pm 6 \text{ (retort)}$
Step 2: A successful series of magnets will provide a platform for performance improvement.

- Utility structure parameters:
  - Al shell OD: 750 mm
  - Al shell thickness: 75 mm
  - Coil-pack horizontal and vertical size: 320 mm

- Next steps:
  - Design studies are complete (M. Juchno)
  - Engineering design – FY2018
  - Fabrication – FY2019

- 15 T demonstrator assembly and test in FY2019
Step 3: 60-mm aperture 16 T Dipole

Step 3: **16 cos-theta design to explore the limit of Nb$_3$Sn in this geometry.**

### Table 3: Magnet parameters at SSL and 4.2 K

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BL IC</th>
<th>BL OC</th>
<th>SM IC</th>
<th>SM OC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore field, T</td>
<td>15.61</td>
<td>16.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak field, T</td>
<td>16.25</td>
<td>16.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current, A</td>
<td>11.34</td>
<td>10.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductance, mH/m</td>
<td>25.61</td>
<td>35.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored energy, MJ/m</td>
<td>1.65</td>
<td>2.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_x$, MN/m/quadrant</td>
<td>5.8</td>
<td>1.6</td>
<td>4.8</td>
<td>4.7</td>
</tr>
<tr>
<td>$F_y$, MN/m/quadrant</td>
<td>-1.2</td>
<td>-3.3</td>
<td>-0.5</td>
<td>-3.6</td>
</tr>
<tr>
<td>Number of turns</td>
<td>44</td>
<td>65</td>
<td>38</td>
<td>102</td>
</tr>
</tbody>
</table>

**Figure 2:** Bore (quench) field vs. the short sample limit.
Next steps: 120 mm 2-layer and 4-layer dipoles

11 T
Structure: 556 MPa

170 MPa
Equivalent Stress

15 T
Structure: 575 MPa

190 MPa
Equivalen Stress

Coil-structure gaps

Δmax ~ 13 μm
Coil Stress Management Technology

- Two possible end designs and technologies:
  - Design 1: winding with spacers;
  - Design 2: winding into slots.
Cos-theta Dipole Test in Utility Structure

60 mm aperture
B_{des} \sim 15 T

60 mm aperture
B_{des} \sim 17 T

Utility structure

120 mm aperture
B_{des} \sim 11 T

SM

Support structure has to keep iron yoke closed
Conclusions

• Fabrication of 15 T dipole demonstrator is in progress:
  o Design and procurement are complete.
  o Coil fabrication is in progress.
  o Mechanical structure is being tested.
  o Magnet test is scheduled for September of FY18.
• Design study of 16 T dipole with small aperture is complete:
  o Ready to start SM coil technology development.
• Design studies of magnet Utility Structure are complete:
  o Engineering design is next.
• Design studies of large-aperture 15 T dipole continue.
• **FNAL**: J. Carmichael, V.V. Kashikhin, S. Krave, I. Novitski, C. Orozco, S. Stoynev, D. Turrioni, G. Velev, A.V. Zlobin, **Techs**: A. Rusy, L. Ruiz, S. Johnson, J. Karambis

• **LBNL**: S. Caspi, M. Juchno, M. Martchevskii et al.

• **CERN**: D. Schoerling, D. Tommasini et al.

• **FEAC/UPATRAS**: C. Kokkinos et al.