1st Performance Test of the 25 T Cryogen-free Superconducting Magnet

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Collaborators

HFLSM, IMR, Tohoku Univ.
Toshiba (Magnet system)

Fujikura (Gd123 tapes)
Furukawa (LTS cables)

NIMS (R&D)

LNCMI-CNRS (R&D)

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25T Cryogen-free Superconducting Magnet (25T-CSM)

56 GdBCO single pancakes
(11.5T@144A, 407MPa) /
38 Bi2223 double pancakes
(11.5T@203A, 323MPa)

4LPo1D-01

3 CuNb/Nb3Sn Rutherford solenoid
(14T@854A, 251MPa)

3 NbTi Rutherford solenoid

Cooling system 3LPo2B-04

Conduction cooling using He circulation
Shield: 2 x 1 stg GM cryocooler
HTS: 2 x 4K-GM cryocooler
(3W@4.2K, 10W@8K)
LTS: 2 x GM/JT cryocooler (8.6W@4.3K)
### Design of a 25T-CSM (Final)

<table>
<thead>
<tr>
<th></th>
<th>Gd123</th>
<th>Nb3Sn</th>
<th>Nb3Sn</th>
<th>Nb3Sn</th>
<th>NbTi</th>
<th>NbTi</th>
<th>NbTi</th>
<th>Bi2223</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current</strong></td>
<td>A</td>
<td>144</td>
<td></td>
<td></td>
<td>854</td>
<td></td>
<td></td>
<td>203</td>
</tr>
<tr>
<td><strong>Inner radius</strong></td>
<td>mm</td>
<td>52</td>
<td>149.5</td>
<td>185.3</td>
<td>228.6</td>
<td>271.7</td>
<td>301.6</td>
<td>312.9</td>
</tr>
<tr>
<td><strong>Outer radius</strong></td>
<td>mm</td>
<td>131.42</td>
<td>182.4</td>
<td>226.4</td>
<td>270.1</td>
<td>301.6</td>
<td>311.9</td>
<td>356.3</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>mm</td>
<td>336</td>
<td>542.0</td>
<td>630.3</td>
<td>680.4</td>
<td>629.5</td>
<td>629.5</td>
<td>629.5</td>
</tr>
<tr>
<td><strong>Space current density</strong></td>
<td>A/mm²</td>
<td>129.8</td>
<td>67.6</td>
<td>67.4</td>
<td>66.7</td>
<td>68.9</td>
<td>84.7</td>
<td>86.7</td>
</tr>
<tr>
<td><strong>No of turns/layer</strong></td>
<td>-</td>
<td>56</td>
<td>80</td>
<td>93</td>
<td>93</td>
<td>95</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td><strong>No of layer</strong></td>
<td>-</td>
<td>435</td>
<td>18</td>
<td>22</td>
<td>22</td>
<td>16</td>
<td>6</td>
<td>26</td>
</tr>
<tr>
<td><strong>Total No of turns</strong></td>
<td>-</td>
<td>24360</td>
<td>1438</td>
<td>2043</td>
<td>2043</td>
<td>1518</td>
<td>641</td>
<td>2779</td>
</tr>
<tr>
<td><strong>Bmax</strong></td>
<td>T</td>
<td>25.6</td>
<td>13.8</td>
<td>11.3</td>
<td>8.4</td>
<td>6.8</td>
<td>6.2</td>
<td>5.9</td>
</tr>
<tr>
<td><strong>Br</strong></td>
<td>T</td>
<td>4.66</td>
<td>4.65</td>
<td>5.58</td>
<td>5.71</td>
<td>5.71</td>
<td>5.71</td>
<td>5.52</td>
</tr>
<tr>
<td><strong>B0</strong></td>
<td>T</td>
<td>11.5</td>
<td>2.43</td>
<td>2.91</td>
<td>2.73</td>
<td>1.91</td>
<td>0.78</td>
<td>3.25</td>
</tr>
<tr>
<td><strong>Width of conductor</strong></td>
<td>mm</td>
<td>5.00</td>
<td>6.45</td>
<td>6.45</td>
<td>6.45</td>
<td>6.30</td>
<td>5.57</td>
<td>5.57</td>
</tr>
<tr>
<td><strong>Thickness of conductor</strong></td>
<td>mm</td>
<td>0.13</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.50</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td><strong>Thickness of layer insulation</strong></td>
<td>mm</td>
<td>0.055</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Jcon</strong></td>
<td>A/mm²</td>
<td>129.8</td>
<td>106.2</td>
<td>106.2</td>
<td>106.2</td>
<td>106.2</td>
<td>138.6</td>
<td>138.6</td>
</tr>
<tr>
<td><strong>Tcs</strong></td>
<td>K</td>
<td>6.69</td>
<td>8.37</td>
<td>9.94</td>
<td></td>
<td>5.98</td>
<td>6.20</td>
<td>6.39</td>
</tr>
<tr>
<td><strong>Averaged compressive stress</strong></td>
<td>MPa</td>
<td>-32</td>
<td>-38</td>
<td>-50</td>
<td>-48</td>
<td>-47</td>
<td>-55</td>
<td>-92</td>
</tr>
<tr>
<td><strong>Hoop Stress BJR</strong></td>
<td>MPa</td>
<td>407</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Hoop stress Wilson</strong></td>
<td>MPa</td>
<td>–</td>
<td>252</td>
<td>244</td>
<td>202</td>
<td>138</td>
<td>113</td>
<td>52</td>
</tr>
<tr>
<td><strong>IEEE/CSC &amp; ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.</strong></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Mechanical design of the LTS coils
- strand in Rutherford cable-

**CuNb/Nb$_3$Sn Rutherford cable**

**Axial stress**
- 252 MPa

**Transverse stress**
- 50 MPa

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**Critical current (A)**

- 12T
- 14.5T

200
150
100
50
0

4.2K, 100 μV/m

**Extracted strand from Rutherford cable**

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**Transverse compression stress (MPa)**

14.5T, 4.2K, 100 μV/m

Δ$I_c$ = 4% @ 60 MPa

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**n-value**

0 20 40 60 80 100

0 50 100 150 200 250

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Design of LTS coils

CuNb/Nb$_3$Sn Rutherford cable solenoids (R&W)

Table 1. Specification of NbTi and Nb$_3$Sn strands.

<table>
<thead>
<tr>
<th>Strand</th>
<th>NbTi-a</th>
<th>NbTi-b</th>
<th>CuNb/Nb$_3$Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter (mm)</td>
<td>0.80</td>
<td>0.70</td>
<td>0.8</td>
</tr>
<tr>
<td>Cu/CuNb/superconductor</td>
<td>1.9/-/1</td>
<td>1.9/-/1</td>
<td>20/35/45</td>
</tr>
<tr>
<td>Filament diameter (µm)</td>
<td>17.9</td>
<td>15.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>690</td>
<td>690</td>
<td>6973</td>
</tr>
<tr>
<td>Barrier material</td>
<td></td>
<td></td>
<td>Ta</td>
</tr>
</tbody>
</table>

Load factor $\approx$ 90% @4.2K

Critical current of the CuNb/Nb$_3$Sn Rutherford cable at 4.2 K and 267 MPa

at 4.2 K and 330 MPa

Load line of the L1 coil

Load line and stress of Gd123

Fujikura Gd123 tape

$I_c$ vs $B$ graph

$B^0.66$

$B_z^{max}$

$B_r^{max}$

$B_{//c}$

$407$ MPa

Fujikura coated conductor
40 μm Cu plated
$T = 77.3$ K, $B = 1$ T

Critical current

n-value

Tensile stress (MPa)
Load lines and stress limit -Bi2223 tapes-
Quench protection

\[ I_c(\text{Gd123}) > 200 \ A @20K \]

Induced \( I \) would not become larger than \( I_c @20 \ K \).
Cooling and impregnation of HTS

All turns are separated but the edge part is connected to the cooling plate.

Cooling system

-> Takahashi 3LPo2B-04
Cooling the LTS coil in the 25T-CSM

Cooling modes
mode 1 (300–50 K)
mode 2 (50–20 K)
mode 3 (20–4 K)

Heat load to the GM/JT cryocoolers at 4 K

<table>
<thead>
<tr>
<th>Heat load</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-loss of the LTS coils</td>
</tr>
<tr>
<td>Joule loss of the junctions</td>
</tr>
<tr>
<td>Heat invasion from the support</td>
</tr>
<tr>
<td>Heat invasion from the support of the REBCO coil</td>
</tr>
<tr>
<td>Thermal radiation</td>
</tr>
<tr>
<td>Heat load from the cold stage of the power lead</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Cooling system -> 3LPo2B-04
LTS coil stand-alone test
TEST results of LTS coil

1st run

Shut down test

2nd run

Oguro et al, SuST 29 (2016) 084004
Gd123 insert coil
Gd123 insert stand-alone test

S. Awaji et al., SuST 29 (2016) 05510
25 T-CSM combination test

$B_{\text{cal}} = 24.01 \text{ T} \ (124.6A)$
$(B_{\text{meas}} = 23.61 \text{ T})$

Quench point

$B_{\text{cal}} = 23.94 \text{ T} \ (110A)$
$(B_{\text{meas}} = 23.55 \text{ T})$

Stable Operation!
25 T-CSM combination test (Gd) - IV properties -

0A -> 95A (0.018 A/s (2h mode))
94A -> 125A (0.010 A/s)

- 10 average
○ Average at constant $I$

$B_{LTS} = 14$ T (855 A)

Sweep at $B_{LTS} = 14$ T
Sweep at $B_{LTS} = 0$ T
○ Constant-$I$

Balance V (mV)

$I_{HTS}$ (A)
Quench was detected due to the thermal runaway of HTS coil.

650 V x 2 at HTS coil was generated after the quench.

Drop of $I_{\text{HTS}}$ at 6 s past after the quench protection mode.

Vacuum was deteriorated rapidly at the same time.

The quench protection seems to work well at least for 6 s after the quench?
Comparison to quench simulation

![Graph showing comparison of quench simulation](attachment:image.png)

- $I_{HTS}$
- $I_{LTS-middle}/10$
- $I_{Nb3Sn}/10$
- $I_{NbTi}/10$
- $I_{LTS-PS}/10$

- Quench Detector (HTS)
- Quench Detector ($\text{Nb}_3\text{Sn}$)

**Graph Details:**
- L1, L4a, L4b, L5 quench
- Elapsed time (s)
- Current (A)

**Circuit Diagram:**
- 240A/8V
- 5.5Ω (Bi)
- 11Ω (Gd)
- H1
- 0.795Ω
- 10kΩ
- 1Ω
- L1, L2, L3, L4, L5
Bi2223 insert coil
Bi2223 insert stand-alone test

\[
B_{\text{cal}} = 11.60 \text{T} \\
B_{\text{meas}} = 11.48 \text{T} \\
I_{\text{op}} = 204.8 \text{A}
\]

-> Hanai et al, 4LPo1D-01
25T-CSM-Bi combination test

$24.6 \, T$

$I_{HTS}=187.8A$

$I_{LTS}=854A$
Field hysteresis

**Gd123**

25T-CSM combination test (Gd123 insert)

**Bi2223**

25T-CSM combination test (Bi2223 insert)
Field monitor for 25T-CSM

Field monitor coil

$\phi 89$

$R (\Omega)$ vs. $B (T)$ for 25T-CSM combination test (Bi2223 insert)
25T-CSM at HFLSM Annex building

Experimental preparation room

Measuring equipment storage

Machinery

25T-CSM

Hall

Front door

Closet

WC

Sink

WC
**$J_c$ measurement using 25T-CSM**

![Graphs and Equipment Image]

No time limit! Small noise level!
Summary

• 25T-CSM was installed and tested at the HFLSM, IMR, Tohoku University.
  - CuNb/Nb₃Sn, NbTi Rutherford cable coils (LTS coils)
    • 1 hour ramping up to 14 T of the LTS outsert coil was confirmed without training quench.
    • High stress operation in 251 MPa was succeeded.
  - Gd123 insert coil (HTS-Gd coils)
    • 1 hour charging/discharging up to 10.5 T was confirmed by the single mode test.
    • 24.01T was generated but a thermal runaway of the HTS coil happened.
  - Bi2223 insert coil (HTS-Bi coils)
    • 1 hour charging/discharging up to 11.5 T was confirmed by the single mode test.
    • 24.6T was achieved successfully within one hour charging time by the simultaneous ramping of both HTS and LTS coils.