Progress in the Construction of the HFML 45 T Hybrid Magnet

Andries den Ouden


High Field Magnet Laboratory (HFML-EMFL), Radboud University, Nijmegen, The Netherlands
HFML 45 T Hybrid Magnet program

• Combined on-axis field 45 T

• Resistive Florida-Bitter type **insert** magnet generates 33 T at 40 kA, 22 MW

• Superconducting Nb$_3$Sn-CICC based **outsert** magnet delivers 12.3 T at 20 kA

• Insert bore 32 mm, outsert RT bore 620 mm

**Collaboration** with US-NHMFL (SCH program)

- common CICC design, outsert coil design & fabrication

- Cu-HTS current lead development
Hybrid Magnet SYSTEM

1000 W Stirling cooler for radiation shields

20 kA current leads

20 kA SC bus bars

The hybrid magnet

Valve box

DAQ, control & HMI

Liquid helium plant

gHe recovery

20kA/10 V POC

Liquid nitrogen supply
Superconducting outsert circuit HFML 45 T hybrid magnet

12.3 T, 620 mm bore Nb$_3$Sn-CICC outsert magnet
(fabricated at NHMFL)

4.5 meter superconducting bus bar (HFML)
(AI-stabilized NbTi-Rutherford cable)

20 kA Cu-HTS current leads
(HFML-NHMFL collaboration)
Outsert 20kA power converter
(protection breakers, dump resistors and bus bars to magnet cell)
(manufactured by Ampulz B.V., The Netherlands)

Installation, test and commissioning
July 2015
20kA, binary Cu-HTS (Bi2223), LiN cooled current leads
(in collaboration with NHMFL, USA)

HFML 77-300 K ‘chimney’-type Cu-plate heat exchanger
Calculated temperature profiles resistive section (RRR ~ 5, $T_{\text{warm}} = 300$ K)

**I = 0 kA**

- $P_{\text{cold}} = 167$ W/lead
- $P_{\text{warm}} = 335$ W/lead

**I = 20 kA**

- $V_{\text{resistive}} = 47$ mV
- $P_{\text{cold}} = 620$ W/lead (14 litre LiN/h)
- $P_{\text{warm}} = 2$ W/lead
20kA Cu-HTS, LiN cooled current leads

- BiSrCaCuO (2223) section
- Al stabilized NbTi jumper
- Supercritical helium cooling channel @ 6 bar, 5 K
- LiN vessel Cu-HEX

Test and commissioning 2018
Ready for integration into CL cryostat
Cryogenic components

- Aluminium 20 kA bus bars
- Cryo-line to Stirling cryo-cooler
- Current leads location
- Cryo-line valve box - magnet cryostat
- Valve & distribution box
- Helium refrigerator/liquefier in operation
- All components ready for testing and integration
Superconducting bus bars between current leads and cryostat

(in collaboration with Cryoworld B.V., the Netherlands)

Actively cooled Al-stabilized NbTi Rutherford cable
(CERN-ATLAS ECT grade, 5T, 4.2 K, 60 kA)

Thermal strain relief

Superconducting Quench Detector (developed at CERN)
12.3 T Nb$_3$Sn-CICC superconducting outsert magnet

Top plate magnet vessel (1 bar He gas @ 4.5 K)
4.5K and 18 bar helium filled pre-compression bellow
current limiting resistors (13 k$\Omega$) voltage tap wiring
Section joint box
Bottom plate magnet vessel
Pillow plate bottom radiation shield
Bottom plate vacuum vessel

Coil manufacturing by NHMFL completed in 2018
Integration in cryostat well underway
All parts of cryostat have been manufactured
Axial fault forces after insert coil failure (Presented Tue-Po2.15-03)

**Ultimate static fault forces**
shorted coils at mid-plane (kN)

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-C</td>
<td>83</td>
<td>-54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-D</td>
<td>600</td>
<td>-389</td>
<td>-1032</td>
<td>1694</td>
<td>2988</td>
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</table>

**PROPERTIES INSERT COILS**

<table>
<thead>
<tr>
<th>Property</th>
<th>Insert Coils</th>
<th>A1</th>
<th>A2</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating current (kA)</td>
<td>13</td>
<td>27</td>
<td>40</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current density (A/mm²)</td>
<td>603</td>
<td>345</td>
<td>214</td>
<td>111</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Power density (W/mm³)</td>
<td>9.9</td>
<td>3.1</td>
<td>1.2</td>
<td>0.23</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Uncooled heating rate (K/s)</td>
<td>2868</td>
<td>900</td>
<td>338</td>
<td>67</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Voltage drop (V/winding)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.7</td>
<td>1.6</td>
<td></td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Fault forces normalised to their ultimate values after a C-D mid-plane short**

If coil protection systems work properly:
- Fault forces stay well within 50% of ultimate
- Fault forces change sign = direction
Axial support handling fault forces outsert: HFML approach

During an insert fault a constant stress in inner & outer shell of Magnet Vessel at 4.5 K is maintained with a pressurised helium gas bellow (\( p_{\text{op}} < 30 \text{ bar} \))

- Force constant: 73 kN/bar
- Axial stiffness: 17 kN/mm
- Lateral stiffness: 1.2 MN/mm
- Minimum gas volume: 7 dm\(^3\)

**Magnet vessel**

- Cool down, increase pressure, tension MV shells
- Full field operation
- Fault down
- Fault up

COIL

800 mm
33 T Florida-Bitter insert magnet (40 kA, 22 MW)
(presented Tue-Po2.15-02)

- Mitigates end-turn issues
- Sustains axial fault forces

100 bar hydraulic pre-compression ‘bellow’

All insert coil components being purchased
Summary

Key components for the outsert magnet nearly ready for integration

Insert components are being purchases or manufactured

Control & monitoring systems in production
(quench detection, cryogenics, magnet operation)

Commissioning expected to start mid 2020
Acknowledgements

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HFML

NHMFL
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Technical Advisory Committee
H. ten Kate (UT-CERN), A. Bonito-Oliva (F4E), P. Bruzzone (EPFL/CRPP) and U. Wagner (CERN)
<table>
<thead>
<tr>
<th></th>
<th>Insert</th>
<th>Outsert</th>
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<tbody>
<tr>
<td>operating current $I_I, I_O$ (A)</td>
<td>40,000</td>
<td>20,000</td>
</tr>
<tr>
<td>contribution to central field $T$</td>
<td>32.7</td>
<td>12.3</td>
</tr>
<tr>
<td>free RT bore diameter (mm)</td>
<td>32</td>
<td>600</td>
</tr>
<tr>
<td>expected # powering cycles</td>
<td>30,000</td>
<td>3,000</td>
</tr>
<tr>
<td>cooling medium</td>
<td>forced flow water (~ 140 l/s)</td>
<td>forced flow supercritical helium (~ 11 g/s@5 bar)</td>
</tr>
<tr>
<td>operating temperature $T_{op}$ (K)</td>
<td>&lt; 360</td>
<td>4.6</td>
</tr>
<tr>
<td>self inductance (mH)</td>
<td>5</td>
<td>266</td>
</tr>
<tr>
<td>mutual inductance (mH)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>(dump) resistance $R_I, R_O$ (mΩ)</td>
<td>15</td>
<td>130/2.5</td>
</tr>
<tr>
<td>decay time constant $(L/R)$ (s)</td>
<td>0.3</td>
<td>2.0/106</td>
</tr>
<tr>
<td>required power (MW)</td>
<td>21.5</td>
<td>0.2</td>
</tr>
<tr>
<td>stored energy (MJ)</td>
<td>5</td>
<td>55</td>
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