Status of the HFML-Nijmegen 45 T Hybrid Magnet

Andries den Ouden

27th International Conference on Magnet Technology
18 November 2021
1000 W @ 80 K Stirling cooler for radiation shields
20 kA current leads
20 kA sc bus bars
main cryo-line
Outsert magnet & cryostat
Insert magnet & housing
DAQ, control & HMI

Liquid helium plant & 200 W @ 4.5K refrigerator
20 kA/10 V POC
4.5 K valve box & sub-cooler
Liquid nitrogen supply
45 T Hybrid Magnet: a compact system

- LiN phase separator
- Quench detection cabinet
- Liquid helium plant & 200 W@4.5K refrigerator
- Outsert magnet & cryostat
- 20 kA current leads
- 20 kA sc bus bars
- 4.5 K valve box & sub-cooler
- main cryo-line
- Insert magnet & housing

Dimensions:
- 2 m
- 4 m
45 T Hybrid Magnet: nested solenoids

<table>
<thead>
<tr>
<th></th>
<th>Insert</th>
<th>Outsert</th>
</tr>
</thead>
<tbody>
<tr>
<td>conductor type</td>
<td>Cu alloy Florida-Bitter disks</td>
<td>Nb₃Sn/Cu-CICC</td>
</tr>
<tr>
<td># of nested coils</td>
<td>5</td>
<td>1 (5 sections)</td>
</tr>
<tr>
<td>operating current (A)</td>
<td>40,000</td>
<td>20,000</td>
</tr>
<tr>
<td>field contribution (T)</td>
<td>32.8</td>
<td>12.3</td>
</tr>
<tr>
<td>cooling medium</td>
<td>forced flow water (~ 140 ℓ/s)</td>
<td>forced flow supercritical helium (~ 10 g/s@6 bar)</td>
</tr>
<tr>
<td>operating temperature (K)</td>
<td>&lt; 350</td>
<td>4.5</td>
</tr>
<tr>
<td>required power (MW)</td>
<td>21</td>
<td>0.2</td>
</tr>
<tr>
<td>stored energy (MJ)</td>
<td>5</td>
<td>55</td>
</tr>
<tr>
<td>free bore diameter (mm)</td>
<td>32</td>
<td>620</td>
</tr>
</tbody>
</table>

Handling Lorentz forces between insert and outsert coils

Destabilising Radial body force due to misalignment magn. axes (manufacturing tolerances): \[ \frac{dF_r}{dr} = 22.5 \text{ kN/mm} \]

Stabilising Axial body force due to mid-plane misalignment (manufacturing tolerances): \[ \frac{dF_z}{dz} = 38.5 \text{ kN/mm} \]

Destabilising Axial (up or down) body force during fault insert coils (e.g. mid-plane short): \[ F_{fz} < 1.3 \text{ MN} \]

Force path of support structure between insert and outsert coils as short as possible
Handling axial (fault) forces outsert

A nearly constant compressive force on the coils at 4.5 K is maintained with a pressurised helium gas ‘bellow’ ($p_{op} < 20$ bar)

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

**Diagram:**
- Magnet vessel
- 800 mm
- 18 bar
- 17 bar
- 18 bar
- Force on insert coils

**Force on insert coils:**
- Cool down, maintain pressure, tension MV shells 4 K
- Full field operation 4K
- Fault down < 1.3 MN fault-force 4K
- Fault up

**Key components:**
- G10 coil support cylinder
- Common base plate
- Insert/outsert housing
- Magnet axis

Radboud University
Coil manufactured by NHMFL
Integration in cryostat well underway
All parts of cryostat manufactured

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 kΩ) voltage tap wiring
- Section joint box
- Bottom plate magnet vessel
- Pillow plate bottom radiation shield
- 8 mm thick G10 coil support cylinder (not shown here)
- Bottom plate vacuum vessel

Coil manufactured by NHMFL
32.8 T Florida-Bitter insert magnet (40 kA, 21 MW)

100 bar hydraulic pre-compression ‘bellow’

- Mitigates end-turn issues
- Sustains axial fault forces

All insert coil and housing components manufactured

Mock-up test hydraulic bellow

Axial fault forces (e.g. B-C mid-plane short after insert’s coil failure)

<table>
<thead>
<tr>
<th>PROPERTIES 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>40</td>
</tr>
<tr>
<td>current density (A/mm²)</td>
<td>603</td>
<td>345</td>
<td>214</td>
<td>111</td>
<td>95</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>
</tr>
<tr>
<td>uncooled heating rate (K/s)</td>
<td>2868</td>
<td>900</td>
<td>338</td>
<td>67</td>
<td>50</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>2.1</td>
</tr>
</tbody>
</table>

Ultimate static fault forces
shorted B-C coils at mid-plane (kN)
(No protective actions)

- **A1**: 83
- **A2**: 600
- **B**: -1032
- **C**: -1829
- **D**: 1274
- **Outsert**: 903

Provided coil protection systems work properly:
- Axial fault forces stay within 50% of ultimate
- Fault forces change sign = direction

Handling radial misalignment forces

Very compact radial support structure, 6 spokes inside cryostat at top plate magnet vessel

Radial stiffness 6 spokes = 381 kN/mm (angle independent)
Radial off-set force /mm misalignment: 22.8 kN/mm
Heat loads 6 spokes: 24 W @ 80 K, 1.2 W @ 4.6 K
Fixation to insert’s housing at outsert T = 90 K (pre-cooled state)

Radial support at bottom plate magnet vessel: G10 support cylinder (radial stiffness > 780 kN/mm)
Cryogenic systems operational

Cryo-room with main cryogenic equipment, control cabinets, current lead cryostat

Stirling cryo-cooler and distribution box
(1000 W @ 80 K, 20 bar gHe, cryo-fan forced flow)
Test & commissioning valve box - refrigerator - cryogenic control

Supercritical helium circuits (4.5 K)

Linde LR140

Heater box and 4.5K LHe sub-cooler

Heater 1 (coil circuit)

Heater 2 (bus bar & current leads)

Test configuration valve box & sc He circuits
- cooling power @ constant level
- cool-down characteristics
- representative heat loads
- mode switching at quench (heat, pressure)
- safety & control system
Quench Detection System

Max. voltage to ground: 1.3 kV
Commercial Knick isolation amplifiers
Labview controlled NI-cRIO (FPGA, RT & HMI)
Test & commissioning well underway

QDS cabinet with isolation amplifiers and NI-cRIO & FPGA
Superconducting circuits connected

20 kA Cu/HTS current leads commissioned
Mounted & electrically connected current lead cryostat

20 kA sc bus bar
Mounted & electrically connected superconducting Al-stabilized NbTi bus bar

Soft soldered joints current leads-bus bar

Soft soldered joints bus bar-coil terminals
45 T Hybrid Magnet System readiness

- Liquid helium plant & 200 W@4.5K refrigerator
- Liquid nitrogen supply
- 1000 W @ 80 K Stirling cooler for radiation shields
- Outsert magnet & cryostat
- Insert magnet & housing
- Valve box & 4.5 K sub-cooler
- Main cryoline
- 20 kA current leads
- 20 kA SC bus bars
- Quench detection
- DAQ, control & HMI
- gHe recovery
- 20kA/10 V POC & control
- 45 T Hybrid Magnet System readiness

Status:
- All hardware delivered
- Under construction
- Integration stage
- Operational
Acknowledgements

Radboud Universiteit

EPSRC
Engineering and Physical Sciences Research Council

NATIONAL HIGH MAGNETIC FIELD LABORATORY

European Magnetic Field Laboratory
Superconducting outsert circuit 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)
(Al-stabilized NbTi-Rutherford cable)

20 kA Cu-HTS current leads
(HFML-NHMFL collaboration)
20kA power converter, protection breakers, dump resistors and bus bars to the magnet cell (Vonk B.V.)

Installed, tested and commissioned
Insert coils

\[ I_R = 0.5B \]

\[ I_R = 0.5C \]

\[ I_R = B \]

\[ I_R = C \]

\[ I_R = L_{0.5B} \]

\[ I_R = L_{0.5C} \]

\[ I_R = L_{0.5D} \]

\[ A1, A2 \]

\[ 0.5R_A, 0.5R_{A2} \]

\[ 0.5R_B, 0.5R_C, 0.5R_D \]

\[ 40 \text{kA, 550 V} \]

Sc outsert

\[ 20 \text{kA, 10 V} \]

\[ 0.5R_A, 0.5R_{A2} \]

\[ 0.5R_B, 0.5R_C, 0.5R_D \]

\[ Sw_R, Sw_O \]

\[ 40 \text{kA, 550 V} \]

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

Current in the coil sections after a B-C mid-plane short
### FPGA Kintex 325T

<table>
<thead>
<tr>
<th>Slot 1</th>
<th>Slot 2</th>
<th>Slot 3</th>
<th>Slot 4</th>
<th>Slot 5</th>
<th>Slot 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB 3.0</td>
<td>USB 3.0</td>
<td>USB 3.0</td>
<td>USB 3.0</td>
<td>USB 3.0</td>
<td>USB 3.0</td>
</tr>
<tr>
<td>10G Ethernet</td>
<td>10G Ethernet</td>
<td>10G Ethernet</td>
<td>10G Ethernet</td>
<td>10G Ethernet</td>
<td>10G Ethernet</td>
</tr>
<tr>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
</tr>
<tr>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
<td>100Base-TX</td>
</tr>
<tr>
<td>Slot 7</td>
<td>Slot 8</td>
<td>Slot 9</td>
<td>Slot 10</td>
<td>Slot 11</td>
<td>Slot 12</td>
</tr>
</tbody>
</table>

**cRIO-9049**

- Controller
- Ethernet Port 1
- Ethernet Port 2
- Port 1: USB 2.0 Host
- Port 2: USB 3.0 Host
- Port 3: USB 3.0 Device Port
- RS-232 Serial Port
- RS-422 Serial Port