Design of the resistive insert coils for the HFML 45 T Hybrid Magnet

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28-08-2017
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Outline

• Short introduction of the 45 T hybrid magnet in Nijmegen
• Insert design requirements
• Coil design
• Housing design
• Clamping of the coil set
Hybrid System Overview

1. Hybrid magnet
2. Valve box
3. Cold box He refrigerator
4. 2 m$^3$ LHe storage dewar
5. 6 m$^3$ LN$_2$ storage tank
6. Main helium compressor

7. 3 kV/20 kA circuit breakers and thyristor switches
8. 20 kA/10 V power convertor
9. 55 MJ fast and slow dump resistor
Hybrid magnet requirements

• Combined on-axis field 45+ T
  - Resistive insert 32.7+ T @ 22 MW
  - Superconducting outsert 12.3+ T
• Free bore
  - Resistive insert: 32 mm
  - Superconducting outsert: 620 mm
• Technically robust design: user magnet

• Design a user magnet
  - Friendly access
  - Clear top side => connections on bottom
  - Reliable performance
  - As quiet as possible (acoustics)
• Fit in outsert bore => Housing OD 618 mm
• Max power 22 MW
• Worst-case fault force ≤ 2.5 MN
Coil Design – inner coils

- Used the design of our 38T magnet (commissioned 2014) as starting point

- Copper-Silver inner coils A1-A2 and B
  - OD limited to 240 mm (material manufacturing)
  - Radial division of space of the 38T is unsuitable for hybrid insert

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>B</th>
<th>38A1</th>
<th>38A2</th>
<th>38B</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID [mm]</td>
<td>38</td>
<td>70</td>
<td>140</td>
<td>38</td>
<td>68</td>
<td>152</td>
</tr>
<tr>
<td>OD [mm]</td>
<td>68</td>
<td>134</td>
<td>238</td>
<td>66</td>
<td>146</td>
<td>238</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>352</td>
<td>353</td>
<td>519</td>
<td>242</td>
<td>243</td>
<td>385</td>
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<tr>
<td>(J_0) [A/mm²]</td>
<td>600</td>
<td>402</td>
<td>260</td>
<td>653</td>
<td>477</td>
<td>337</td>
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<tr>
<td>(B_{self}) [T]</td>
<td>5.8</td>
<td>7.8</td>
<td>8.7</td>
<td>5.9</td>
<td>9.9</td>
<td>7.7</td>
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<tr>
<td>Stress [MPa]</td>
<td>700</td>
<td>720</td>
<td>700</td>
<td>620</td>
<td>660</td>
<td>650</td>
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</table>
Preliminary ANSYS Analysis – A1
Coil design – outer coils

- Initial design based on a double hull housing, i.e. return path for water in a separate channel.
  - Consumes space that does not contribute to field generation

- Investigated the possibility of alternative hydraulic path
  - Inner coils A-B-C in parallel, water flowing up
  - In series with coil D, water flowing down

- Benefits:
  - OD of the largest coil grows from 520 to 590 mm
  - More space to generate field
  - Larger coils are more efficient

<table>
<thead>
<tr>
<th>Variant</th>
<th>Field Factor</th>
<th>Power Efficiency</th>
<th>Space Factor</th>
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<tbody>
<tr>
<td>Classical</td>
<td>0.2587</td>
<td>0.1268</td>
<td>0.964</td>
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<tr>
<td>Return flow through D-coil</td>
<td>0.3558</td>
<td>0.1462</td>
<td>0.854</td>
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<tr>
<td>Change</td>
<td>+ 37 %</td>
<td>+ 15 %</td>
<td>-11 %</td>
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</table>
Preliminary ANSYS Analysis – D
Design of the housing

• Housing split into two segments
  - Top contains coils
  - Bottom for services
  - Both connect to bottom outsert
    – Keeps fault force path as short as can be

• Double hull housing
  - Return water flows around coil
  - Reynolds number: \( N_R \sim 10^5 \)
    – on-set turbulence: \( 4 \times 10^3 \)
    – typical \( N_R \) coil cooling: \( 4 \times 10^4 \)
Connections for power & cooling
Improving clamping conditions

- Use of a water-filled bellow
- Pressurised to 40-60 bar
- Use of a rubber filler to accommodate compressive stroke
A novel clamping method for resistive magnets

Introduction
Bitter magnets are constructed by stacking hundreds of individual Bitter plates together in a coil. This loose stack of disks needs to be clamped together with tie rods that are pretensioned for several reasons:

1. the coil should be a ‘rigid’ object that can be handled
2. the coil should have a stiffness against internal rotations
3. to keep the end turn disks in position despite the large forces on these turns
Summary

• Mechanical design of the insert is well on track
  - Validation of the bellow within a month
  - When successful it should improve stability & lifetime of the coils
  - Bellow can help in the end turn issue

• Preliminary Bitter disk design done
  - We have developed a self-consistent set of design tools
  - Final tuning of cooling hole distribution still needed
  - End turn analysis to be completed