Ultra-light 2T/4m bore Detector Solenoid for FCCee
- the Solenoid in the IDEA detector -

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for the FCC detector magnets design team

1. Motivation
2. 2T IDEA Solenoid
   Conductor, coil windings, Quench protection
3. Cryostat
   Optimized conventional, Honeycomb-like
4. Conclusion

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For FCC-ee two detector designs are proposed:

- **a conventional 2T solenoid around the calorimeter**, essentially a downscaled CLIC design, not further presented here

- **a challenging 2T solenoid “ultra-thin & transparent” around the tracker**, proposed by the magnet team and accepted as baseline
Motivation:
• Magnetic field is only required in the tracker + muon chambers, but most stored magnetic energy (some 80%) is wasted in the calorimeter space!

Obvious savings when coil is positioned inside:
• Factor $\approx 4.2$ in stored energy
• Factor $\approx 2.1$ in cost!

But design is not obvious and requires R&D and a demonstrator

Solenoid **outside** or **inside** calorimeter?
Crucial technologies to be developed:

- High YS Super-Conductor allowing self-supporting cold mass
- Maximum energy extraction at quench to minimize cold mass hot spot temperature

- New ultra-light cryostat design following two routes:
  - high level of thermal insulation and mechanical support through metal foil sealed glass spheres or permaglass under vacuum (not presented here)
  - lightest possible metallic-vacuum cryostat using honeycomb structures or corrugated plate-sandwich panels

1\textsuperscript{st} design shows that it is feasible; would be a breakthrough towards lighter and smaller detector magnets, and significant cost savings
2. Solenoid for IDEA detector

Requirements:

- 2T in thin Solenoid with radiation length $X_0 < 1$ in radial direction!
- Radial envelope <300 mm
- Magnetized iron for muon detection

Strategy:

- Reduce thickness of cold mass
- Reduce thickness of cryostat
- Magnetic flux return by a light return yoke

IDEA detector (International Detector Electron Accelerators), innovative thin solenoid around tracker
Scaling from ATLAS Solenoid to FCC-ee IDEA Solenoid

ATLAS Solenoid:
2T in $\varnothing 2.51 \text{ m} \times 5.4 \text{ m}$

IDEA Solenoid:
2T in $\varnothing 4.4 \text{ m} \times 6$

$\approx 1.1 \times \text{in length}$

and

$\approx 1.8 \times \text{in diameter}$
Self-supporting single layer coil
  - high yield strength conductor fully bonded
  - thin Al support cylinder for conduction cooling

Coil composition:
  - Aluminum (77 vol.%)  
  - NbTi (5 vol.%) / copper (5 vol.%)  
  - glass/resin/dielectric film (13 vol.%)

Radiation thickness:
  - Cold mass: $X_0 = 0.46, \lambda = 0.09$
  - Cryostat (25 mm Al): $X_0 = 0.28, \lambda = 0.07$

1st design shows that achievable is a total $X_0 = 0.74 < 1$ (at $\eta = 0$)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field in center [T]</td>
<td>2</td>
</tr>
<tr>
<td>Free bore diameter [m]</td>
<td>4</td>
</tr>
<tr>
<td>Stored energy [MJ]</td>
<td>170</td>
</tr>
<tr>
<td>Cold mass [t]</td>
<td>8</td>
</tr>
<tr>
<td>Cold mass inner radius [m]</td>
<td>2.2</td>
</tr>
<tr>
<td>Cold mass thickness [m]</td>
<td>0.03</td>
</tr>
<tr>
<td>Cold mass length [m]</td>
<td>6</td>
</tr>
</tbody>
</table>
Conductor & Windings

Conductor:

- NbTi/Cu Rutherford cable, Al 0.1%Ni stabilizer, welded Al-7XXX alloy bar reinforcements
- 20 kA operating current, 0.85 H self-inductance
- 6.5 K current sharing temperature (at 3.2 T peak):
- 2.0 K temperature margin at 4.5 K cooling
- 100 MPa combined Yield Strength of Al-Ni + NbTi core + G10 insulation
- 280 MPa local peak stress

Winding scheme:

- 1 layer coil, 595 turns, conductor length 8.3 km
- Energy over mass density: 24 kJ/kg
Quench Protection and Hot-spot temperature

Quench protection:

• Relies on high percentage of extraction to reduce cold mass enthalpy
• And relies on quench heaters
• 1000 V peak extraction voltage accepted to yield 76% extraction
• Required conductor RRR> 400
• Normal quench scenario:
  $T_{\text{hotspot}} < 100 \, \text{K}$
• Extreme fault scenario hot spot can be improved by using axial quench propagation strips.

Scenario | Hot spot temperature [K]
--- | ---
Regular | 87
Malfunctioning heaters | 150
Malfunctioning extraction | 118

$R_{\text{fastdump}} = 50 \, \text{mΩ}$

$R_{\text{fastdump}} = 50 \, \text{mΩ}$

$I_{\text{op}} = 20 \, \text{kA}$, $L = 0.85 \, \text{H}$
3. Cryostat – using thin reinforced outer shell

Main features:
- CAL is supporting the cryostat
- Cold mass supports to end flanges
- Solid plate inner shell
- Outer shell reinforcement rings to prevent buckling
- Material Al 5083-O

<table>
<thead>
<tr>
<th>Loads</th>
<th>Inner shell</th>
<th>Outer shell</th>
<th>Flanges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker mass [t]</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External pressure [MPa]</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self mass [t]</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold mass + rods thermal shrinkage [kN]*</td>
<td>215</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Initial estimate is 3 times the weight of the cold mass

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<tbody>
<tr>
<td>Material</td>
<td>Al 5083-O</td>
<td>Al 5083-O</td>
<td>Al 5083-O</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>3</td>
<td>15*</td>
<td>12</td>
</tr>
<tr>
<td>Min thickness [mm]</td>
<td>3</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Max thickness [mm]</td>
<td>3</td>
<td>73</td>
<td>12</td>
</tr>
<tr>
<td>Shield thickness [mm]</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Volume [t]</td>
<td>0.5</td>
<td>1.7</td>
<td>2 x 0.13</td>
</tr>
<tr>
<td>Mass [t]</td>
<td>1.4</td>
<td>5.2</td>
<td>2 x 0.4</td>
</tr>
<tr>
<td>Total mass [t]</td>
<td></td>
<td>7.4</td>
<td></td>
</tr>
</tbody>
</table>

Stress limits: According to EN 13458
Option for the external shell, use corrugated plate:

- More uniform thickness seen by particles
- Thickness of outer shell is very dependent on the period and amplitude of the corrugation
- Flat flanges may not be suitable in this case

<table>
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<th>Flanges</th>
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<tbody>
<tr>
<td>Material</td>
<td>Al 5083-O</td>
<td>Al 5083-O</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Sin Amplitude [mm]</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Wave period [mm]</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Volume [t]</td>
<td>1.4</td>
<td>2 x 0.16</td>
</tr>
<tr>
<td>Mass [t]</td>
<td>3.8</td>
<td>2 x 0.5</td>
</tr>
<tr>
<td>Mass cryostat [t]</td>
<td>6.2</td>
<td></td>
</tr>
</tbody>
</table>

1 Including thermal shield  
2 EN13456 standard
Cryostat option – use honeycomb-like plate

Option for the external shell, use honeycomb plate or sandwich panels:

- Drastic effective thickness reduction possible by using two separated plates with filling structure in between

When comparing the 4 solutions, honeycomb delivers the best radiation thickness!

<table>
<thead>
<tr>
<th></th>
<th>Uniform plate</th>
<th>Corrugated plate</th>
<th>Reinforcement rings</th>
<th>Honeycomb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plate thickness [mm]</strong></td>
<td>20.5</td>
<td>7.0</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Radiation length [X₀]</strong></td>
<td>0.23</td>
<td>0.11 (mean)</td>
<td>0.05 (1.0)</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>20.5</td>
<td>57</td>
<td>92</td>
<td>44</td>
</tr>
<tr>
<td><strong># support rings</strong></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong># corrugations</strong></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

- For the FCCee IDEA detector, a conceptual design of a 2T / 4m free bore / 6m long Solenoid surrounding the tracker was developed.
- The acceptance of the solenoid depends on the radial space the cryostat needs and effective Al thickness of the total radial build.
- A design using 300 mm radial space and 1 Xo radiation length is doable.
- Further, aggressive design may lead to another 20% reduction but requiring thickness-reducing engineering driving all sizes to minimum values.
- This may also lead to important innovations in thin-coil technology with spin-off to other magnet projects.