EuroCircol - Cosine Theta

Design and protection of the EuroCirCol costheta bending dipole for the Future Circular Collider

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Outline:

1. Main design parameters
2. 2D Magnetic design
3. 3D coil ends
4. Protection
5. Conclusions
## 1.1 Main design parameters

<table>
<thead>
<tr>
<th>Constraints for the magnet design</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore inner diameter</td>
<td>50 mm</td>
</tr>
<tr>
<td><strong>Beam distance</strong></td>
<td>204 mm</td>
</tr>
<tr>
<td>Bore nominal field</td>
<td>16 T</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Operation on the load line</td>
<td>86 %</td>
</tr>
<tr>
<td>Maximum strand number per cable</td>
<td>40</td>
</tr>
<tr>
<td>Cable insulation thickness</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Cu/NCu</td>
<td>≥ 0.85</td>
</tr>
<tr>
<td>Field harmonics (geometric/saturation)</td>
<td>≤ 3/10 units</td>
</tr>
<tr>
<td>Peak temperature (105% of operating current)</td>
<td>≤ 350 K</td>
</tr>
<tr>
<td>Yoke outer radius</td>
<td>400 mm</td>
</tr>
</tbody>
</table>

- Magnetic design for a **double aperture** magnet
Why is beam distance \textbf{204 mm}? 

- It is an \textbf{advantage} in terms of electromagnetic design
  - Bore field increase
  - More copper in conductors

- It is an advantage in terms of mechanics
  - More \textbf{symmetric}
  - More efficient
  - Details in the talk on mechanics (B. Caiffi, this morning)

- It is less far from hypothetic compatibility of the magnet with \textbf{HE-LHC} (194 mm)
Design strategy

- Design as **compact** as possible
  - Reduce amount of conductor
  - Reduce complexity of the magnet

- Maintain the feasibility of the protection
  - HST < 350 K

- Consider the possible construction issues
  - Wedges
  - Connections
## 2.1 2D Magnetic design – cross section

### Grading

- **B peak**: 16.36 T

### Number of turns:
- Layer 1: 13
- Layer 2: 19
- Layer 3: 29
- Layer 4: 39
- **Tot: 200/ap.**

### Cable Specifications

<table>
<thead>
<tr>
<th></th>
<th>Cable 1 (inner)</th>
<th>Cable 2 (outer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand number</td>
<td>22</td>
<td>37</td>
</tr>
<tr>
<td>Strand diameter</td>
<td>1.1 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Bare width</td>
<td>13.2 mm</td>
<td>13.65 mm</td>
</tr>
<tr>
<td>Bare inner thickness</td>
<td>1.892 mm</td>
<td>1.204 mm</td>
</tr>
<tr>
<td>Bare outer thickness</td>
<td>2.072 mm</td>
<td>1.3231 mm</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.15 mm</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>0.5°</td>
<td>0.5°</td>
</tr>
<tr>
<td>Cu/NCu</td>
<td>0.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Operating current</td>
<td>11060 A</td>
<td>11060 A</td>
</tr>
<tr>
<td>Operating point on LL (1.9 K)</td>
<td>86 %</td>
<td>86 %</td>
</tr>
</tbody>
</table>

All the parameters are within the **design constraints**.
2.2 2D Magnetic design – wedges

- Minimum wedge thickness: 0.86 mm
- In LHC main dipole: 0.7 mm
- Number of wedges: 8
- In LHC main dipole: 4 (with one half of layers)

Design comparable with LHC main dipole
2.3 2D Magnetic design – iron yoke

- Outer radius: 375 mm
- Fringe field: 0.1 T at 410 mm

More details in the talk on the mechanics (B. Caiffi, this morning)
2.4 2D Magnetic design – inductance and energy

Double aperture

<table>
<thead>
<tr>
<th>Inductance @ $I_{op}$</th>
<th>Stored energy @ $I_{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.2 mH/m</td>
<td>2.6 MJ/m</td>
</tr>
</tbody>
</table>
2.5 2D Magnetic design – field quality

NORMAL RELATIVE MULTIPOLES @ 16 T:

<table>
<thead>
<tr>
<th>Multipole</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b 1</td>
<td>10000</td>
</tr>
<tr>
<td>b 2</td>
<td>-27.6</td>
</tr>
<tr>
<td>b 3</td>
<td>-0.41</td>
</tr>
<tr>
<td>b 4</td>
<td>-0.69</td>
</tr>
<tr>
<td>b 5</td>
<td>0.99</td>
</tr>
<tr>
<td>b 6</td>
<td>-0.01</td>
</tr>
<tr>
<td>b 7</td>
<td>1.72</td>
</tr>
<tr>
<td>b 8</td>
<td>-0.00</td>
</tr>
<tr>
<td>b 9</td>
<td>1.4</td>
</tr>
<tr>
<td>b 10</td>
<td>0.00</td>
</tr>
<tr>
<td>b 11</td>
<td>1.03</td>
</tr>
<tr>
<td>b 12</td>
<td>0.00</td>
</tr>
<tr>
<td>b 13</td>
<td>-0.18</td>
</tr>
<tr>
<td>b 14</td>
<td>0.00</td>
</tr>
<tr>
<td>b 15</td>
<td>0.01</td>
</tr>
</tbody>
</table>

- b2 optimization **not yet performed**
- b3 saturation to be contained
- Persistent currents **not** considered

Acceptable field quality
2.6 2D Magnetic design – strand area

**Conductor 1:**
- 22 strands
- $\varnothing = 1.1$ mm
- Cu/NCu = 0.9
- $J_{cu} = 1116$ A/mm$^2$
- Strand Area = 26.8 cm$^2$/apert.
- Weight (FCC) = 3.05 ktons

**Conductor 2**
- 37 strands
- $\varnothing = 0.7$ mm
- Cu/NCu = 2.2
- $J_{cu} = 1129$ A/mm$^2$
- Strand Area = 38.7 cm$^2$/apert.
- Weight (FCC) = 4.41 ktons

High Cu content for protection reasons!

COND. AREA (double ap.): = 131 cm$^2$

FCC dipoles extrapolation:

- COND. MASS: = 7.46 ktons

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**Data for FCC extrapolation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipole units</td>
<td>4578</td>
</tr>
<tr>
<td>Dipole length</td>
<td>14.3 m</td>
</tr>
<tr>
<td>Conductor density</td>
<td>8.7 kg/dm$^3$</td>
</tr>
</tbody>
</table>
2.7 2D Magnetic design – alternatives

Same design can be proposed with 250 mm beam-beam distance, but with:

- More current
- Less copper
- More difficult to protect
- Extreme IL conductor

Same design can be proposed with iron pad, leading to advantages such as:

- Less current
- More copper
- Easier to protect
- “Standard” IL conductor

➢ To be understood if iron pad can sustain mechanical stresses
3.1 3D coil ends – layout

- Work in progress
- Based on a two double pan-cakes configuration
- Harmonic analysis performed
- Peak field to be computed yet

Designed by A.M. Ricci, INFN-Genova
3.2 3D coil ends – field quality (opposite connections)

NORMAL 3D INTEGRAL RELATIVE MULTIPOLES

\( (10^{-4}) \)

\[
\begin{align*}
    b_1 &= 10000.00 \\
    b_2 &= -39.36 \\
    b_3 &= 2.59 \\
    b_7 &= 1.96 \\
    b_9 &= 1.39 \\
    \text{Others} &< 1
\end{align*}
\]
3.3 3D coil ends – field quality (opposite connections)
NORMAL 3D INTEGRAL
RELATIVE MULTIPOLES
\((10^{-4})\)

\(b_1 = 10000.00\)
\(b_2 = -42.85\)
\(b_3 = 5.45\)
\(b_5 = -2.76\)
\(b_7 = 2.08\)
\(b_9 = 1.49\)
Others < 1
4.1 Protection

- Main assumptions:
  - No energy extraction
  - Quench induced in the whole magnet 40 ms after initial quench start
  - Inductance dependence on the current
  - Material properties from MATPRO

- Result (105 % of $I_{op}$):
  - Hot spot temperature: $\sim 340$ K

More detailed quench protection studies in the Tiina Salmi talk (this morning)
5.1 Conclusions

The presented 16 T cosine-theta **accomplishes** the **EuroCirCol** design constraints

- Able to produce **16 T** bore field
- Margin on the load-line is **86%** at 1.9 K
- **Good** field quality
- Hot spot temperature **below 350 K** @ 105% $I_{op}$
- Possibility of using **iron pad** to improve the magnet is under exploration
- Possibility of adapting the magnet for **HE-LHC**?

We have began the design of 3D coil ends

- Two **double-pancakes** (well-known technology)
- **Acceptable** field quality
- Peak field to be computed