Conceptual Design of a C-shaped 6.4 T Superconducting Dipole Magnet


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Introduction

Motivation
• Current non-superconducting magnets produce 3.2 T → Photons with critical energy 19 keV
• New high-energy x-ray tomography beamline → Need for critical energy of at least 39 keV
• CNPEM is entering the field of superconducting magnets → Design of a 6.4 T superconducting dipole (CERN-CNPEM agreement)

Design goals
• Match the integrated field and integrated gradient of the BC dipoles
• Use of warm bore vacuum chamber for NEG-coating → C-shaped magnet
• Use of NbTi wires → well-known and documented; widely employed; commercially available

Sirius arc layouts
Electromagnetic Design

**Studied coil designs**

- Single Coil
- ToH Coils
- Concentric Coils
- Conic Coil

**Studied coils magnetic field profile**

**Electromagnetic Design Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic gap</td>
<td>30 mm</td>
</tr>
<tr>
<td>Bare wire dimensions</td>
<td>0.80 mm</td>
</tr>
<tr>
<td>Cu/NbTi ratio</td>
<td>1.4</td>
</tr>
<tr>
<td>Engineering current density</td>
<td>254 A/mm²</td>
</tr>
<tr>
<td>Operating current</td>
<td>128 A</td>
</tr>
<tr>
<td>Critical current ($J_c$) @ 5 K, 7.6 T</td>
<td>772 A/mm²</td>
</tr>
<tr>
<td>Load-line margin</td>
<td>79% of $J_c$ @ 5 K</td>
</tr>
</tbody>
</table>

- Different coil designs were studied: Single Coil, ToH Coils, Concentric Coils and Conic Coil -> Similar results between designs -> Single Coil chosen due to its simpler design
- Single Coil -> dimensions and materials optimized. Best design chosen based on field’s intensity, peak’s FWHM and integrated field
Electromagnetic Design

- Permanent magnet low field dipoles added on each side of the superbend to match the integrated field of the BC dipoles.
- More studies are needed to match the integrated gradient of the BC dipoles and suppress the positive portion of the field.
- The stronger peak field and different longitudinal gradient would require a machine optics redesign.

<table>
<thead>
<tr>
<th></th>
<th>BC Dipole</th>
<th>Superbend (Single Coil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Field [T.m]</td>
<td>-0.7507</td>
<td>-0.7507</td>
</tr>
<tr>
<td>Integrated Gradient [T]</td>
<td>6.2508</td>
<td>1.8915</td>
</tr>
</tbody>
</table>
**Mechanical and Cryogenic Designs**

- Replace one BC dipole -> smaller than 900 mm
- C-shaped topology -> warm and disconnected beam chamber -> Good for NEG-coating
- LHe tank -> buffer in case of quench and speeds cooldown
- Vacuum pressure <= 10^{-6} mbar

**Half Section view of the magnet**

- Cryocooler
  - (2 stages -> 45W @ 50 K and 1.5 W @ 4.2 K)
- LHe Refilling Tube
- LHe Tank
  - (316L stainless steel)
- Yoke
  - (1006 carbon steel)
- Current Leads
  - (Hybrid-type: resistive part -> bronze; HTS part -> HTS-110 CryoSaver™)
- External Cryostat Vessel
- Recondenser
- 50 K Thermal Shield
- Holmium Pole
- Superconducting Coil
- Kevlar Support

**Dimensions:** 400 mm length, 740 mm width, 1012 mm height
Mechanical and Cryogenic Designs: Structural Analysis

- External vessel -> 12 mm thickness with reinforcement bars 20 mm thick -> max. deformation of 0.7 mm (lateral covers) and stress below material’s yield
- Bars also reinforce C-shaped region -> 4 mm thick (space constraints) -> max. deformation of 0.7 mm
- Yoke’s thickness chosen to be 180 mm -> max. deformation of 0.3 mm towards closing the gap

External vessel – total deformation

Yoke neck – thickness optimization
Mechanical and Cryogenic Designs: Thermal Analysis

- Steady state analyzes to determine the heat flux through components:
  - Thermal shield @ 50 K -> max. temperature of 53.4 K
  - LHe tank positioned on the top presented better results -> max. temperature of 4.9 K (bottom coil)

**Yoke and Coils – temperature distribution**

**Thermal Shield – temperature distribution**

**Summary of calculated heat loads**

<table>
<thead>
<tr>
<th></th>
<th>Inleak @ 50 K (W)</th>
<th>Inleak @ 4.2 K (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supports</td>
<td>1.60</td>
<td>200</td>
</tr>
<tr>
<td>Current leads</td>
<td>16.22</td>
<td>35</td>
</tr>
<tr>
<td>Radiation</td>
<td>4.12</td>
<td>51</td>
</tr>
<tr>
<td>Total</td>
<td>21.94</td>
<td>286</td>
</tr>
<tr>
<td>Cryocooler capacity (x2)</td>
<td>90.00</td>
<td>3000</td>
</tr>
</tbody>
</table>
Quench Protection Design

- Use of an external dump resistor to promote an active energy extraction in case of a quench event
- Monitor voltage across the coil and compare with pre-determined values -> imbalance bridge and over-voltage circuits -> further study for a final specification
- Hot-spot temperature during quench estimated by the MIITS calculation -> two scenarios studied -> temperatures below 40 K
Summary

- Different coil designs were studied -> Minor differences were found in the peak’s FWHM and integrated field -> Single Coil was chosen due to its simpler design
- Permanent magnet low field dipoles added on each side of the superbend to match the integrated field of the BC dipoles and suppress the positive portion of the field
- More studies are needed to match the integrated gradient of the BC dipoles
- The stronger peak field and different longitudinal gradient would require a machine optics redesign
- Mechanical and cryogenic designs are successful in maintaining structural integrity while keeping the temperature of the superconducting coils below 5 K. The estimated heat loads are within the capacity of the cryocoolers, but further studies with more components will be done. Based on the current results, the cryocoolers will have enough cooling power for the system, and maybe one of them can be used as a safeguard
- A first approach that uses an external dump resistor was proposed for the quench protection, but a deeper study needs to be done for the final solution