Design of a superconducting magnet for proton therapy

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Outline

• Magnet specifications and design
• Thermo-mechanical calculations
• Quench scenario
Magnet technical specifications

- Racetrack geometry → manufacturing as easy as possible (+)

- Large aperture magnets → large $B_{\text{conductor}}/B_{\text{GFR}}$ (-)

- B-field ramp rate below 0.2 T/s → reduced AC losses (+)

- Cooling option: dry cooling system with cryocoolers, $T_{\text{op}} \sim 4.5$ K → limited heat removal (-)

- Superconducting material: $\text{Nb}_3\text{Sn}$ → comfortable temperature margin (+)
  → brittle and strain sensitive material (-)
  → expansive material (-).
Bending section layout

Superconducting dipoles with integrated quadrupole and sextupole components (DQS)

Superconducting focusing quadrupole with integrated sextupole components (QS)

Normal conducting focusing quadrupoles
Combined function magnet, dipole + quadrupole + sextupole: coils only

$I=1.7 \ kA \rightarrow \text{Rutherford cable}$

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<thead>
<tr>
<th>N. strand</th>
<th>Strand diameter (mm)</th>
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<th>Thickness (mm)</th>
<th>Twist pitch (mm)</th>
<th>Compaction (%)</th>
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<tbody>
<tr>
<td>12</td>
<td>0.82</td>
<td>4.7</td>
<td>1.5</td>
<td>70</td>
<td>~88</td>
</tr>
</tbody>
</table>

7.63 T

7.00
6.00
5.00
4.00
3.00
2.39

700

Tilt angle $\pm 17$ deg

Ciro Calzolaio
Operating margins: DQS magnets

Critical current as a function of magnetic B-field and temperature for a Rutherford cable made by 12 strands, Nb$_3$Sn EUTF6 ITER type

In red: DQS magnet load line and DQS operating point against operating temperature

Steady state load line current and temperature margins for the DQS magnet as a function of the strain experienced by the Nb$_3$Sn filaments inside the strands.

For a strain below 0.2%:
- Margin along the load line: 30-35 %;
- Temperature margin: 4.5-5 K
**Superconducting quadrupole-sextupole**

$I=1.7$ kA $\rightarrow$ **Rutherford cable**

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Operating margins: QS magnet

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Temperature margin: 4.5-5 K
Combined function dipole: main parts

Winding pack

316LN former

CuBe thermal anchor (steel to cut the eddy currents path.)

Cu shield anchored to the 1st stage of the cryocoolers (4 cold heads).

316LN cryostat + supports

[Y.S. Choi at al., Cryocooled Cooling System for superconducting magnet]
For the thermal analysis (also in case of quench) the following losses were considered:

**AC losses:**
- AC losses in the conductor
  - Within superconducting filaments (Hysteretic)
  - Between filaments and between strands (Coupling)
  - Eddy current in the matrix
- Eddy currents in the structures.
AC losses

Treatment cycle for a maximal target

Contributions to the total losses (integrated along the four cycles)
Temperature evolution in the winding pack (for the DQS)

$T_{\text{max}} < 7 \text{ K} \Rightarrow \text{Comfortable temperature margin}$
Mechanical analysis: the effect of the Lorentz forces

- COMSOL simulations results:
  - Cable Principal Strain < 0.05% \(\rightarrow\) Intrinsic strain \(\leq 0.1\%\) (upon cooldown)
  - Displacement: \(\leq 0.15\) mm
Quench protection

Mechanical switch:
- It opens in less than 50 ms;
- It sustains voltages up to 2 kV;
- It sustains currents up to 5 kA.

Dump resistor: 1.6 Ω (L=0.8 H → τ=L/R_{ex}=0.5 s)

Heat pulse location.
Heat pulse duration: 1 s.

Total current in the winding pack.
Quench protection

Dump resistor:
1.6 Ω (L=0.8 H → τ=L/R_{ex}=0.5 s)

Heat pulse location. Heat pulse duration: 1s.

Graphs showing temperature and voltage over time.
Quench scenario

Quench start ($v \approx \text{m/s}$)

Time=0 s  Surface: Temperature (K)

Time=50.5 s  Surface: Temperature (K)

Time=60 s  Surface: Temperature (K)

Time=51.5 s  Surface: Temperature (K)

Time=52 s  Surface: Temperature (K)

Time=53 s  Surface: Temperature (K)

Time=54.5 s  Surface: Temperature (K)

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Conclusions and outlook

- A design for a gantry magnet using a series of combined function racetrack Nb$_3$Sn coils for the bending section has been proposed.
- A bronze route Nb$_3$Sn strand has been selected for the winding. Small Rutherford cables will be used.
- The magnets will operate at 4.5 K cooled down by cryocoolers.
- Thermo-mechanical calculations showed that the magnets will operate with a comfortable temperature margin.
- Due to the low operating current density value, a classical quench protection scheme with extraction resistors should be sufficiently reliable.

Thank you for the attention
Back up slides
Mechanical analysis: cryostat buckling analysis
1st limitation: Stray field at patient location < 0.5 mT

3 mT @ isocenter without additional shielding

2nd limitation: GM cryocoolers:

- Drive motor: 50-80 mT;
- Displacer: 100 mT;
- Regenerator: 10% power reduction when in field above 1.5T.
Stray field
Stray field
Dipole dimensions

Tilt angle +/- 17 deg
Alignment

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Best dispersion matching @ isocenter

- RMS [mm] vs Longitudinal position [m]
- Proton energy (MeV) vs Angle (deg)

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Strand/cable specifications

Nb₃Sn bronze route

Strand composition

Hot spot temperature in case of quench below 150 K

Strand parameters

<table>
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<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Strand diameter (mm)</td>
<td>0.82</td>
</tr>
<tr>
<td>Filaments twist pitch (mm)</td>
<td>14</td>
</tr>
<tr>
<td>Filaments diameter (µm)</td>
<td>≈6-7</td>
</tr>
<tr>
<td>Filament number</td>
<td>8305</td>
</tr>
<tr>
<td>Cu to non-Cu ratio</td>
<td>0.93</td>
</tr>
<tr>
<td>RRR</td>
<td>&gt;100</td>
</tr>
<tr>
<td>$I_c$ at 4.5 T, 4.2 K and 0.2% strain (A)</td>
<td>200</td>
</tr>
</tbody>
</table>

Selected winding pack composition: 80% EUTF6 strands + 20% insulation