Falcon Dipole
The INFN dipole model for the FCC

R. U. Valente

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Introduction

- **Who?**
  Agreement between CERN and INFN

- **What?**
  Construction of a demonstrator/model cos-theta dipole able to reach 14 T

- **When?**
  Next 5 years

- **Where?**
  INFN-LASA & INFN Genova (Italy)

- **Why?**
  Milestone technology for the FCC main dipole
Electromagnetic design - requirements

- **General magnet characteristics:**
  - Cos-theta dipole, 1.5 m long
  - One aperture of Ø 50 mm
  - Winding type: 1 double pancake

- **Rutherford cable:**
  - Nb$_3$Sn, $J_C$ (@ 4.2K, 16T) = 1500 A/mm$^2$
  - Minimum bending radius \( \geq 10 \text{ mm} \)

- **Magnet performance:**
  - 14 T bore field, with a margin \( \geq 14\% \)
  - All high order harmonics < 40 units
**Electromagnetic design - cable**

### Rutherford Cable Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting material</td>
<td>Nb&lt;sub&gt;3&lt;/sub&gt;Sn</td>
</tr>
<tr>
<td>( J_c ) @4.2K, 16T (A/mm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>1500</td>
</tr>
<tr>
<td>Filament diameter (μm)</td>
<td>20</td>
</tr>
<tr>
<td>Cu/non-Cu</td>
<td>1</td>
</tr>
<tr>
<td>Strand number</td>
<td>34 (2x17)</td>
</tr>
<tr>
<td>Strand diameter (mm)</td>
<td>1.1</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>19.8</td>
</tr>
<tr>
<td>Inner width (mm)</td>
<td>1.892</td>
</tr>
<tr>
<td>Outer width (mm)</td>
<td>2.065</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>0.5°</td>
</tr>
<tr>
<td>Twist pitch (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Insulation thickness (mm)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

![Cable Diagram](image)

Dimensions:
- Outer width: 2.065 mm
- Inner width: 1.892 mm
- Height: 19.8 mm
- 34 strands, Ø 1.1 mm
Electromagnetic design - coils

Minimum bending radius: 9.7 mm

<table>
<thead>
<tr>
<th>Blocks</th>
<th>Min. wedge thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>1.08</td>
</tr>
<tr>
<td>2-3</td>
<td>1.35</td>
</tr>
<tr>
<td>4-5</td>
<td>1.77</td>
</tr>
</tbody>
</table>

**Input Magnet Parameter**

- Aperture number: 1
- Aperture radius (mm): 25
- Current (A): 25000
- Operation temperature (K): 1.9

**FEM analysis results (ROXIE 10.2)**

- Bore field (T): 14
- Minimum margin: 14% (block 3)
- $J_{cu}$ (A/mm$^2$): 1547
- Stored energy (MJ/m): 0.68
Electromagnetic design – iron yoke

- **Square window** (180 mm x 180 mm) is needed to use bladder & keys technology.
- **Holes** (Ø 70 mm, Ø 20 mm) for the coolant system have no effect on the field quality.
Electromagnetic design – field quality

The field quality has been optimized keeping constructive parameters within safe limits:

- Minimum wedge thickness > 1 mm
- Minimum bending radius around 10 mm
- Minimum steel pad thickness around 20 mm

<table>
<thead>
<tr>
<th>Harmonics @ 25 kA</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>b₃</td>
<td>1.3</td>
</tr>
<tr>
<td>b₅</td>
<td>-6.2</td>
</tr>
<tr>
<td>b₅</td>
<td>18</td>
</tr>
<tr>
<td>b₉</td>
<td>2</td>
</tr>
</tbody>
</table>

(superconductor magnetization not considered)
Electromagnetic design – different conductor performances

**EuroCirCol target cable**
(actually reached only in short units)

<table>
<thead>
<tr>
<th>$B_0$ (T)</th>
<th>margin (%)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>14%</td>
<td>25.0</td>
</tr>
<tr>
<td>16</td>
<td>1.3%</td>
<td>28.9</td>
</tr>
<tr>
<td>16.2</td>
<td>0%</td>
<td>29.3</td>
</tr>
</tbody>
</table>

**Conductor in procurement**
(value requested in specs)

<table>
<thead>
<tr>
<th>$B_0$ (T)</th>
<th>margin (%)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.3</td>
<td>14%</td>
<td>23.7</td>
</tr>
<tr>
<td>14</td>
<td>9.5%</td>
<td>25.0</td>
</tr>
<tr>
<td>15.4</td>
<td>0%</td>
<td>27.8</td>
</tr>
</tbody>
</table>

Conductor used to design Falcon Dipole short model

Conductor now available
Quench analysis – short model protection

Quench heaters (outer radius only)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet length</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Dump resistor</td>
<td>35 mΩ</td>
</tr>
<tr>
<td>Max ground voltage</td>
<td>±400 V</td>
</tr>
<tr>
<td>Heater delay</td>
<td>40 ms</td>
</tr>
<tr>
<td>Voltage threshold</td>
<td>100 mV</td>
</tr>
</tbody>
</table>

Hot-spot temperature 175 K
Quench analysis – long magnet protection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet length</td>
<td>15 m</td>
</tr>
<tr>
<td>Dump resistor</td>
<td>0 mΩ</td>
</tr>
<tr>
<td>Heater delay</td>
<td>40 ms</td>
</tr>
<tr>
<td>Voltage threshold</td>
<td>100 mV</td>
</tr>
</tbody>
</table>

Hot-spot temperature 322 K

Quench analysis performed with QLASA
Mechanical design – requirements

- Coil in compression up to nominal field
- Stress in the conductor
  - Room temperature, < 150 MPa
  - Cryo temperature (1.9 K), < 200 MPa
- Stress on mechanical structure < yield strength (see Table below)

<table>
<thead>
<tr>
<th>Material</th>
<th>Stress limit (MPa)</th>
<th>E (GPa)</th>
<th>ν</th>
<th>α (mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>1.9 K</td>
<td>RT</td>
<td>1.9 K</td>
</tr>
<tr>
<td>Austenitic steel (316LN)</td>
<td>350</td>
<td>1050</td>
<td>193</td>
<td>210</td>
</tr>
<tr>
<td>Al7075</td>
<td>480</td>
<td>690</td>
<td>70</td>
<td>79</td>
</tr>
<tr>
<td>Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial dir.</td>
<td>150</td>
<td>200</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>Azimuthal dir.</td>
<td></td>
<td></td>
<td>25</td>
<td>27.5</td>
</tr>
<tr>
<td>Ferromagnetic iron</td>
<td>230</td>
<td>720</td>
<td>213</td>
<td>224</td>
</tr>
<tr>
<td>Ti6Al4V</td>
<td>800</td>
<td>1650</td>
<td>115</td>
<td>126</td>
</tr>
</tbody>
</table>
Mechanical design - ANSYS model

- **Cold mass:** Ø 800 mm
- **Steel pads:** 180 mm x 180 mm

- **AL alloy shell (50 mm thick)**
- **Iron yoke (Ø 700 mm)**
- **Stainless steel pad**
- **Titanium pole**
- **Copper wedge**
- **Conductor**
- **Horizontal key (interference: 0.1 mm)**
- **Vertical key (interference)**
**Simulation steps**

1. Assembly → keys insertion
2. Cool down → thermal contractions
3. Energization → Lorentz forces in the conductor element

### Load cases

<table>
<thead>
<tr>
<th>Load cases</th>
<th>Bore field</th>
<th>Margin</th>
<th>Required vertical key interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal field</td>
<td>14 T</td>
<td>14%</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Cable in procurement short sample</td>
<td>15.5 T</td>
<td>0%</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>EuroCirCol cable short sample</td>
<td>16 T</td>
<td>0%</td>
<td>0.7 mm</td>
</tr>
</tbody>
</table>
Mechanical design – contact pressure

ASSEMBLY

14 T
Key interference 0.5 mm

Gap (where contact pressure = 0 MPa) < 3.2 μm

COOL DOWN

15.5 T
Key interference 0.6 mm

Gap (where contact pressure = 0 MPa) < 11.3 μm

ENERGIZATION

16 T
Key interference 0.7 mm

Gap (where contact pressure = 0 MPa) < 10.6 μm
Mechanical design – Von Mises stress in conductors

**ASSEMBLY**

- **14 T**
  - Key interference 0.5 mm
  - $\sigma_{VM,max} = 72.4 \text{ MPa}$

- **15.5 T**
  - Key interference 0.6 mm
  - $\sigma_{VM,max} = 86 \text{ MPa}$

- **16 T**
  - Key interference 0.7 mm
  - $\sigma_{VM,max} = 99.5 \text{ MPa}$

**COOL DOWN**

- **14 T**
  - $\sigma_{VM,max} = 172 \text{ MPa}$

- **15.5 T**
  - $\sigma_{VM,max} = 192 \text{ MPa}$

- **16 T**
  - $\sigma_{VM,max} = 210 \text{ MPa}$

**ENERGIZATION**

- **14 T**
  - $\sigma_{VM,max} = 177 \text{ MPa}$

- **15.5 T**
  - $\sigma_{VM,max} = 201 \text{ MPa}$

- **16 T**
  - $\sigma_{VM,max} = 209 \text{ MPa}$

INFN-LASA & INFN Genova

27/06/2019
Conclusions

We designed a model dipole for FCC (named Falcon Dipole) with the goal of making the winding and assembly procedure as feasible as possible.

The results of our analysis satisfy the requirements:

- The magnet is able to reach 14 T in the bore within the margin of 14%, using the conductor with EuroCirCol specs

- In principle the same target of 14 T may be reached using the specs of the conductor under procurement, but with a reduced margin of 9.5%

- All the stress in the magnet are always below the limits, in particular in the coil the maximum stress is 177 MPa at energization

Notice that:

- A bore field of 16 T theoretically may be reached with the current at the ‘short sample limit’ (EuroCirCol target cable)
Thank you for your attention
Mechanical analysis – gap at pole

**ASSEMBLY**

- **14 T**
  - interference 0.5 mm

**COOL DOWN**

- **15.5 T**
  - interference 0.6 mm

**ENERGIZATION**

- **16 T**
  - interference 0.7 mm


gap \[ \mu m \]