F2D2: the CEA Dipole Model for the FCC

F2D2 = FCC Flared-ends Dipole Demonstrator

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27/06/2019
**STRONG INTERACTION WITH MAGNET PROGRAMS**

### CEA-CERN Program

1. ECC block-coil design [1-2]
   - 16T Conceptual design
   - Double aperture


2. F2D2 short model [3]
   - Design/fabrication at CEA
   - Test at CERN
   - Single aperture
   - Same coil design as ECC


### CERN Programs

- SMC models
  - Technology development
  - Conductor qualification

- ERMC/RMM models [4,5]
  - 16T magnet R&D


   [5] See "Mechanical validation of the support structure of the eRMC and RMM, the 16-T R&D magnets for the FCC", this conference

### EPFL-CERN Program

- R&D on junction technology [6-7]


   [7] See “Soldered and diffusion-bonded splices between Nb3Sn Rutherford cables for graded high-field accelerator magnets “”, this conference
1. **Maximize central field with margins:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Current Inom</td>
<td>10378 A</td>
</tr>
<tr>
<td>Short sample current $I_{ss}$</td>
<td>12118 A</td>
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<tr>
<td>Bore field $B_{y0}$ at Inom ($I_{ss}$)</td>
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<tr>
<td>Loadline Margin at Inom (HF/LF)</td>
<td>14.0 / 15.4 %</td>
</tr>
<tr>
<td>Stored Energy Inom</td>
<td>1.4 MJ/m</td>
</tr>
</tbody>
</table>

2. **Harmonics representative of an accelerator magnet:**

![Diagram showing harmonics and load lines]

- **Legend:**
  - ↑: Increment
  - ↓: Reduction
  - Shim Y-Pad
  - Shim X-Pad
  - Y-Pusher
  - Y-Shim Coil
  - Coil X-Position
  - Yoke radius

- **Load Lines:**
  - 1200 A/m² Today
  - 1500 A/m² Tomorrow

- **Harmonics:**
  - $b_3$, $b_5$, $b_7$, $b_9$
  - +/- 3 units
  - 15 units
1. Provide coil-pole contact during nominal operation
2. Keep peak stress below (reversible) degradation limits
Field map \( B(x,y) \)

Stress map \( S(x,y) \)

\( I_{SS\,\text{limit}} = I_c(B_{\text{max}}) \)

Traditional approach

\( S_{\text{limit}} = 150 \, \text{MPa} \)
2D MAGNETO-MECHANICAL DESIGN - FINALIZED

Field map $B(x,y)$

Stress map $S(x,y)$

$I_c(B,S)$ for a cable [8]

Map of $I_c$ reduction $I_c(x,y)$

$S_{\text{limit}} = 150 \text{ MPa}$

$I_{\text{SS limit}} = I_c(B_{\text{max}})$

Stress induced current limit of the magnet [9] ≤ short sample

- **Trade-off on the pre-stress** (interference):
  - Minimize $I_c$ reduction
  - Provide sufficient pre-stress

At nominal current:

- Negligible $I_c$ reduction $\Rightarrow I_{\text{limit}} = 99\% I_{\text{ss}}$
- 100 % coil in contact with the post

[8] See “Electro-mechanical properties of Nb3Sn conductors for application to high-field magnets”, this conference
Protection Criteria (same as ECC):
- Every coil has a quench heater
- Detection delay = 20 ms
- Detection voltage = 5 mV
- Heater activation delay = 20 ms
- Max hot spot temperature = 350 K
- Max $\Delta V$ to ground = 1200 V

Model Hypotheses:
- Adiabatic Regime
- Cryocomp material database
- Magnetoresistivity included
- Transverse+longitudinal propagations considered

→ Magnetic, electrical, thermal models validated
1. Turn-by-turn coil model
   → External joints option
   → Define path for cable exits

2. Coil components
   → Study concepts for external joints

3. Coil fabrication tooling
   → Winding + reaction + splicing + impregnation
   → Study compatibility with the fabrication process
WINDING MOCKUPS - FINALIZED

- 2 options for cable exits:
  
  A: → Hard-way only
  → 1 layer jump shim

  B: → Easy-way + Hard-way
  → 2 layer jump shims

- Winding trials with SMC-11T cable:
1. Preliminary CAD model of the coils

2. 3D simplified Opera FEM:
   
   b. Central field:
      • Magnetic Length = 1042 mm
      • Uniform field region (±1%) = 249 mm

   c. Field in critical areas:
      • Peak field in straight section
      • Field in the layer jumps < 14 T
1. **Preliminary CAD** model of the structure

2. **3D simplified Ansys FEM:**
   a. Optimize the transverse preload
   b. Stay below the stress limits:
      - Coil
      - Components
- Verified consistency with 2D model at z=0
- Coil peak stress within targets at z=0
3D Mechanical Design - Ongoing

- Peak stress in coil and critical components within targets
- Next step: optimize longitudinal pre-load
Goal: Demonstrate some key concepts for FCC block-coil dipoles:

- Grading between blocks
- Joint technology

How?
- Relying on proven technology:
  - Block-coil
  - Bladders and keys structure
- Using state of the art conductors
- Developing engineering solutions for joints
  - 2 proposed solutions: internal and external
  - External joints selected to reduce the risks
  - Room to implement internal joints

With today’s state of the art conductors:
- 15.5 T achievable at 14 % margin
- ~18 T at short sample
• Status:
  → Integrated magnetic and mechanical design:
    • 2D magnetic + 2D mechanical completed
    • Protection ongoing
    • 3D magnetic completed, 3D mechanical ongoing
  → Engineering design:
    • Conceptual design of the coil ends and structure finalized
    • Technical solution validated with mock-ups

→ Challenging magnet!

• Future plans: preserve complexity and mitigate risks
  1. 1st stage: Proof-of-concept graded racetrack coils
     → Assembly and test in the F2D2 structure
  2. 2nd stage: F2D2 graded flared-end coils
     → Assembly and test of the final F2D2 magnet
**Grading Concept in Block-Coils**

- 2D: “grading” needed for FCC [3]
  - 2 cable sizes, same current
  - Optimizing the current density
  - Compact coils = less conductor

- 3D: need “joints” between the cable grades
  1. Internal joints explored within EPFL-CERN Program
  2. External joints explored at CEA

High Field “HF” blocks, low current density

Low Field “LF” blocks, high current density

3D integrated design
- CAD
- Magnetic
- Mechanical
V1.1.1: FROM DOUBLE TO SINGLE APERTURE

ECC double aperture

\[ \Omega_{770} \text{ mm} \]

\[ \rightarrow 16,1 \ T @ 86 \% \]

Peak stress: 186 MPa

Min contact: -3 MPa

Translation in a single aperture

\[ \Omega_{576} \text{ mm} \]

\[ \rightarrow 15,8 \ T @ 86 \% \]

Peak stress: 193 MPa

Min contact: 36 MPa

97 mm interbeam

100 mm

0 mm interbeam

IRFU/DACM/LEAS

F2D2 Project Status
MAIN DESIGN FEATURES

- Rectangular Block-coils
- Shell-based structure with Bladders & Keys
- Conductor with present performances

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<td>MJ/m</td>
</tr>
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</table>
### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial (Clément) V1</th>
<th>Updated (Jerôme)</th>
<th>Proposed v4</th>
<th>Unit</th>
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<tbody>
<tr>
<td>HF</td>
<td>LF</td>
<td>HF</td>
<td>LF</td>
<td>HF</td>
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<tr>
<td>HF</td>
<td>LF</td>
<td>HF</td>
<td>LF</td>
<td>HF</td>
</tr>
<tr>
<td>Strand diameter</td>
<td>1.1</td>
<td>1.1</td>
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<td>1.1</td>
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<tr>
<td>Number of strands</td>
<td>21</td>
<td>21</td>
<td>21</td>
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<tr>
<td>Unreacted width</td>
<td>12.47</td>
<td>12.310</td>
<td>12.579</td>
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<tr>
<td>Unreacted thickness</td>
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<tr>
<td>Reacted width</td>
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<tr>
<td>Reacted thickness</td>
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<td>2.028</td>
<td>2.06</td>
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<tr>
<td>Copper/non-Copper ratio</td>
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<tr>
<td>Insulation thickness</td>
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<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Bare cable compaction</td>
<td>11.8</td>
<td>10.5</td>
<td>10.5</td>
<td>%</td>
</tr>
<tr>
<td>Packing factor</td>
<td>85.4</td>
<td>85.9</td>
<td>84.9</td>
<td>%</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>15</td>
<td>16.5</td>
<td>16.5</td>
<td>°</td>
</tr>
<tr>
<td>Transposition pitch</td>
<td>93</td>
<td>83.1</td>
<td>84.0</td>
<td>mm</td>
</tr>
</tbody>
</table>

\[
T_{\text{th target}} = 2d(1 - \text{comp})
\]

\[
W_{\text{target}} = \frac{Nd}{2 \cos(PA)} + 0.24d
\]

\[
\text{Packing} = \frac{A_{\text{strands}}}{A_{\text{bare cable}}} = \frac{N \pi d^2}{4 \cos(PA) T_{\text{th bare}} W_{\text{bare}}}
\]
CABLE DIMENSIONS V4

- Cable does not exist, baseline defined as:
  1. Thickness compaction after cabling: 9 to 12 % → **baseline 10.5 %**
  2. Expansion during reaction → ECC baseline: +3 % **thickness** / +1 % **width**
  3. Insulation → ECC baseline: **150 µm**

- Strategy: **fixed insulated reacted cable dimensions** for the CAD design
  - Baseline cable with increased room for expansion
    → compensation of thicker cables
  - Insulation used to compensate thinner cables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HF: 1.1mmx21 strands</th>
<th>LF: 0.7mmx34 strands</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Thick.</td>
<td>Width</td>
<td>Thick.</td>
</tr>
<tr>
<td>Bare Virgin</td>
<td>µm</td>
<td>1969</td>
<td>12579</td>
<td>1253</td>
</tr>
<tr>
<td>Insulation thick.</td>
<td>µm</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Room for expansion during reaction</td>
<td>%</td>
<td>4.6</td>
<td>1.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Insulated Reacted</td>
<td>mm</td>
<td>2.36</td>
<td>13.04</td>
<td>1.61</td>
</tr>
</tbody>
</table>
INTEGRATED 2D MAGNETIC AND MECHANICAL OPTIMIZATION

V1.1.1
ECC 2017 design single aperture

V4.1.1
+ F2D2 Cable V4

V4.4.1
+ Coil position from ECC 2018

V4.4.2
Structure optimized for harmonics
• Non ferromagnetic pad
• Ferromagnetic filler

V4.4.n
Magnetic optimization

V4.4.3
Mechanical optimization

IRFU/DACM/LEAS

F2D2 Project Status

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**Insulated Reacted Cable for the CAD**

**Insulation**

- Bare Reacted Cable
- Bare Virgin Cable

1st margin: to compensate the bare cable

Uncertainty due to cabling R&D

**Nominal 150 μm, 2nd possible margin**

**Fixed Ins. React. Th. for the CAD design**

\[
\text{Ins Reacted Th} = \text{Max Bare Virg Th} \times (1 + \text{Nom Exp}) + 2 \times \text{Nom Ins Th}
\]

\[
= 1.1 \times 2 \times (1 - 9\%) \times (1 + 3\%) + 2 \times 150 = 2362 \mu m \approx 2.36 mm
\]

3rd margin: variable shims (insulated fiberglass)
- Fixed value in the nominal drawings
- Free value in the as-built drawings
<table>
<thead>
<tr>
<th>Potential show-stoppers</th>
<th>Internal joints</th>
<th>External joints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• margin at high field</td>
<td>• room for support</td>
</tr>
<tr>
<td></td>
<td>• room for operations</td>
<td>• room for operations (placing parts, splicing)</td>
</tr>
<tr>
<td></td>
<td>• (placing parts, splicing)</td>
<td></td>
</tr>
<tr>
<td>Clues that it can work</td>
<td>Low joint resistances in FRESCA samples</td>
<td>Concept similar to FRESCA2 endshoes</td>
</tr>
<tr>
<td></td>
<td>and for EPFL joints</td>
<td></td>
</tr>
<tr>
<td>End harmonics</td>
<td>• Compact ends possible</td>
<td>• Ends longer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• « naturally » more homogeneous</td>
</tr>
<tr>
<td>Axial loads</td>
<td>Behavior under Lorentz forces ?</td>
<td>Impact of pre-load ? (sharp wedges, relative motion...)</td>
</tr>
<tr>
<td></td>
<td>(detachment, motions…)</td>
<td></td>
</tr>
<tr>
<td>Layer jumps</td>
<td>No LF layer jump</td>
<td>• Need additional room for LF layer jump</td>
</tr>
</tbody>
</table>
**1st Solution for F2D2: Internal Joints**

- Ideal solution for FCC
- Concepts:
  - $\text{Nb}_3\text{Sn}$-HF to $\text{Nb}_3\text{Sn}$-LF joint
  - Performed in an end-spacer
- Winding layout:
  - HF Double-layer pancakes + layer jump
  - LF single layer pancakes

- Status:
  - Joints under development by EPFL-SPC (See presentation “R&D on $\text{Nb}_3\text{Sn}$ cable splices”, P. Bruzzone and Poster “Preliminary investigations of Rutherford cable splicing techniques for high field accelerator magnets”, M. Kumar)
    - Several explored technical solutions
    - Test on joints in Sultan
  - Engineering implementation in coils remains an open question

→ High technical risk for F2D2
→ High risk for the schedule
**ALTERNATIVE SOLUTION FOR F2D2: EXTERNAL JOINTS**

- Decoupling grading and joints for the demonstrator
- **Goal:**
  - **Minimize risks in coil fabrication**
  - Each coil heat-treated and impregnated individually
  - Use a known joint technique outside of the coil
- **CAD Geometric investigation ongoing:**
  - **Large footprint outside of the coil**
  - **Routing and supporting the cable**

![Diagram](image)

<table>
<thead>
<tr>
<th>HF blocks</th>
<th>LF blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
</tr>
</tbody>
</table>

- 1 coil = 1 HF double pancake + 1 LF double pancake
- 1 pole = 2 coils
1. HF double-layer pancake with layer jump in the pole
2. Routing of the HF leads in an “inter-coil wedge” → take advantage of flared ends
3. LF double-layer pancake with layer jump in the end-spacer

4. LF leads in the end-shoe

5. Heat treatment and impregnation of the coil

6. Joints Nb3Sn-NbTi outside the coil in the inter-coil wedges
7. Same concept for the other coils
8. Assembly of the coils

9. NbTi-NbTi joints to connect LF and HF leads