FCC
SuShi septum prototype design report overview

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- Mathieu Canale (CAD models)
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- Matthias Mentink, Lorenzo Bortot (quench simulation)
- ... sorry for those not mentioned, too late at night
- FCC Study, EuCARD-2, Hungarian National Research, Development and Innovation office (grant #K124945)
Prologue

• The design presented here is based on the hi-lumi CCT corrector magnet designs
• We would not have been able to do it from scratch
• We tried to create a win-win situation, and contribute as well, not just benefit
  – mechanical simulations of deformations
  – quench simulation
  – help during winding/assembly, not just stand by and look
• Need to create our own infrastructure
• Dare to look critically, and come up with different (hopefully better) solutions, based on our experience during training.
Overview

- The superconducting shield (SuShi) septum concept
- Tests conducted so far
- Overview of the prototype design
  - Coil shape optimization
  - Magnetic simulations
  - Mechanical simulations
  - Quench protection studies
  - Overview of the CAD model and 3D design
The SUperconducting SHIeld (SuShi) septum concept
Extraction from the collider

LHC:
- normal-conducting Lambertson
  - $B < 1.5T \rightarrow$ long (need 190 Tm integrated)
  - normalconducting $\rightarrow$ energy consumption

Need high-field superconducting septum!
Superconducting shield to create sharp field jump

SC shield with permanent shielding currents

High field, extracted beam

We need a homogeneous field → see later

Zero field for circulating beam
Advantages

- Shielding currents are set up by Nature precisely
- Continuous shielding currents (in contrast to discrete wires), no leaking field
- Critical state model $\rightarrow$ shielding currents are automatically at their highest possible value (thinnest shield, automatically graded current density)
- Shield is bulk superconductor, no interleaving epoxy etc worsening thermal and mechanical stability
- Shield can be self-supporting (smaller total thickness)
Earlier examples: SLAC

F. Martin, S. J. St. Lorant, W. T. Toner: A four-meter long superconducting magnetic flux exclusion tube for particle physics experiments – NIM 103 (1972) 50

\[ \text{Nb}_3\text{Sn flux shield tube} \]

Field-free path within a 1.5 T field to guide out low-momentum forward particles from the magnet, avoiding detector saturation
Earlier examples: CERN

- Goal: field-free path to allow low-momentum particles enter a high-field bubble-chamber
- 5 mm Nb$_3$Sn: full shielding up to 4.2 Tesla

Earlier examples: BNL g-2 inflector

- Truncated cosine-theta
- SC shield used to **confine** the stray field of the septum

SuShi septum project
• Project history
• Shield tests
Project history

• 2016
  − Concept
  − CERN-Wigner Memorandum of Understanding for FCC
  − Addendum #1 to MoU to test SC shields

• 2017-2018
  − Successful shield tests
  − Detailed concept including magnet to create homogeneous field

• 2019
  − Addendum #2: design, construction & testing of a fully fledged proto
    • CERN: $, consultation, training (magnet manufacturing), know-how transfer, sharing of CAD models, etc
    • Wigner: simulation, design, project coordination, manufacturing, assembly, installation of necessary infrastructure
  − Trainings: 3 weeks in September 2019 (D. Barna, M. Novák – winding and assembly of LHCmCBRD), 3 days in October 2019 (D. Barna – impregnation)
SC shield tests: CERN SM18

Spare MCBY magnet

Semi-parasitic tests during the re-measurement campaign of these magnets
SC shield test: MgB$_2$
SC shield test: MgB$_2$

Results:
- 3 Tesla outside
- 0 Tesla inside
- Wall thickness: 8.5 mm
- BUT: flux jumps on the non-virgin curve

Szupravezető páncél tesztek: NbTi

- 30-30 layer NbTi & Cu (10 µm)
- SC shield
- 0.8 mm
Szupravezető páncél tesztek: NbTi

30-30 layer NbTi & Cu (10 µm)

Results:
- Shielded 3.1 Tesla field
- with 3.2 mm wall thickness (!)
- Very stable, no flux jumps at 4.2 K
- BUT: very expensive, availability uncertain

D. Barna, et al, IEEE TAS 29(2019), 4900108 (on front cover)
The magnet
Superconducting magnet

• Need to create the magnetic field
• Simultaneous optimization of magnet and shield shape to get homogeneous field
SuShi septum

SuShi = Superconducting Shield

circ. beam
extracted beam
circulating beam
extracted beam
SuShi septum

SuShi = **Superconducting Shield**

circulating beam, extracted beam

Goal: 3.2 Tesla
(≈ 2-3x LHC septum)
apparent septum thickness: <25 mm

daniel.barna@wigner.mta.hu – SuShi septum prototype review seminar – CERN, January 29, 2020
Coil & shield shape

- Flat wall for shield: helps to align B-lines straight
- Coil optimization in 2D: parametrize as $J_z(\theta) = \sum_n J_n \cos(n \theta)$ in two cylindrical shells
- Solve problem for each $n$ separately
- Calculate multipole composition of B field for each $n$ separately
- Invert the problem to calculate $J_n$
Coil shape: minimize $B$ @ backside center

- Best candidate: NbTi/Cu
- Would have a midplane “cut”
- Minimize $B$ field here to avoid big leakage fields to circulating beam
- ... by adding extra terms to the equation

Coil shape in 3D

\begin{align*}
\chi(\vartheta) &= R \cos(\vartheta) \\
\gamma(\vartheta) &= R \sin(\vartheta) \\
\zeta(\vartheta) &= \frac{T P R D_w}{n_1} \sum_{n} \frac{J_n}{n} \sin(n \vartheta) - P \frac{\vartheta}{2 \pi}
\end{align*}

- Unusual shape
- especially on the shield’s back side

(3x larger pitch for illustration)
Coil shape in 3D

\[ x(\vartheta) = R \cos(\vartheta) \]

\[ y(\vartheta) = R \sin(\vartheta) \]

\[ z(\vartheta) = \frac{TPRD_w}{n_1} \sum_n \frac{J_n}{n} \sin(n \vartheta) - P \frac{\vartheta}{2\pi} \]

radius, defined by aperture requirements

wire diameter 1 mm

number of wires (2) in a layer in the grooves
Coil shape in 3D

\[
\begin{align*}
\chi(\vartheta) &= R \cos(\vartheta) \\
y(\vartheta) &= R \sin(\vartheta) \\
z(\vartheta) &= \sum_{n} \frac{J_n}{n} \sin(n \vartheta) - P \frac{\vartheta}{2\pi} \\
\end{align*}
\]

transfer function, only free parameter

pitch: chose smallest which still respects rib thickness > 0.35 mm everywhere
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (SuShi)</th>
<th>Value (HL-LHC)</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>105.35</td>
<td>105.35</td>
<td>mm</td>
</tr>
<tr>
<td>Spar thickness</td>
<td>3</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Support tube thickn.</td>
<td>12</td>
<td>9.9</td>
<td>mm</td>
</tr>
<tr>
<td>Groove width/depth</td>
<td>2.1/5.1</td>
<td>2.1/5.1</td>
<td>mm</td>
</tr>
<tr>
<td># of wires</td>
<td>2 x 5</td>
<td>2 x 5</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>5.04</td>
<td>5.22</td>
<td>mm</td>
</tr>
<tr>
<td>Min. rib thickness</td>
<td>0.35</td>
<td>0.33</td>
<td>mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>102</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Shield length</td>
<td>800</td>
<td>N/A</td>
<td>mm</td>
</tr>
<tr>
<td>Average turn length</td>
<td>529/629</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Total wire length</td>
<td>1.2</td>
<td></td>
<td>km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (SuShi)</th>
<th>Value (HL-LHC)</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal field</td>
<td>3.2</td>
<td>2.6</td>
<td>T</td>
</tr>
<tr>
<td>Nominal current</td>
<td>464</td>
<td>434</td>
<td>A</td>
</tr>
<tr>
<td>Transfer function</td>
<td>0.0069</td>
<td>0.006</td>
<td>T/A</td>
</tr>
<tr>
<td>Inductance</td>
<td>146</td>
<td>103/820</td>
<td>mH</td>
</tr>
<tr>
<td>$I_0/I_c$ (short sample)</td>
<td>53-65</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Ramp rate (FCC ramp ~ 20 min?)</td>
<td>2.5</td>
<td></td>
<td>mT/s</td>
</tr>
</tbody>
</table>
“Block coil” model

- Meshing the complete geometry is difficult (rib thickness ~ 0.35 mm)
- Simulate coils as contiguous domains
- Introduce bulk current density giving same average (but without pitch)
- Shield = strong diamagnet ($\mu_r = 10^{-4}$)
2D model

- Build full 3D coil geometry (mesh only coil domain!)
- Solve current pattern in coil domain
  - Take x-section at z=0
  - Build other objects in 2D
  - Use current pattern of 3D solution in 2D
Homogeneity (2D)

Simulate the shield using Campbell’s model (finite penetration using $J_c(B)$ curve)
Linearity, homogeneity (2D)

\[
\frac{B_{\text{max}} - B_{\text{min}}}{B_{\text{average}}}
\]

Deviation from linearity

\[
\frac{B_{\text{ave}}}{I_0} \cdot T - 1\%
\]
Flat-top region

- Shield length: 800 mm
- Transfer function: 0.0069 T/A
- Variation of central field within 20 cm long region: 3%‰
- Enough to measure field quality
Field between the coils

For $B_0 = 3.2$ T

Sampled on X axis
Field between the coils

For $B_0=3.2$ T

Small transfer function $\rightarrow$ less tilt of coils $\rightarrow$ more azimuthal currents $\rightarrow$ more $B_z$ between coils $\rightarrow$ higher $B_{\text{peak}}$
Peak field, wire performance

For $B_0 = 3.2$ T

$B_{\text{peak}}$ vs. Transfer function [T/A]

$I_c$ vs. $B_{\text{peak}}$ [T]

Transfer function: $0.00725(\blacklozenge)$

$0.0069(\star) 0.0065(\bullet) 0.00625(\triangle) 0.00575(\circ) 0.00525(\circledast) 0.00475(\otimes)$

For $B_0 = 3.2$ T
Choose $T=0.0069\ \text{T/A},\ I_0=464\ \text{A}$ for $B_0=3.2\ \text{T}$
Alignment: torques

Shield misaligned

Restoring torque: 
-0.25 kN m / m / deg
Nominal position is stable

Outer former misaligned

Torque: 0.17 kN m / m / deg
Stable equilibrium position is offset
Alignment: field quality

Misalignment of the outer former

Misalignment of the shield

Relative weight vs. Multipole number
Alignment: required tolerances

- Azimuthal alignment of shield and/or formers: better than 1° seems sufficient
- 1° corresponds to ~1 mm circumferencial displacement for these former diameters
- Field quality is NOT driving machining tolerances, standard tolerances can be used.
Mechanical simulations (2D)

Continuity condition: wires in grooves

Contact conditions: objects can separate

epoxy-repellent coating
Thermal stresses

- Elastic support can absorb differential thermal expansions
- Compressed horizontally by about 0.25 μm
- Integrated thermal expansion of aluminium: 4 mm/m
- MgB2 thermal expansion: 7e-6/K (Giovanni Giunchi)
- NbTi shield (wrapped sheet on copper support) is closer to aluminium, less critical
Deformation under Lorentz forces

- Without thermal contraction yet
- (to be done)
Quench protection
Rough estimates

- Magnet inductance (block coil model): \( L = \frac{1}{I_0^2} \int B H d^3x = 146 \text{ mH} \)

- Hi-lumi CCT magnets: 103 mH (0.5m) and 820 mH (2.2m)
- Both can be protected by a simple external dump resistor
- Same coil pack geometry, etc
- Use the same protection system (save money, manpower)
Adiabatic hot-spot $T$

17 ms until trigger, 10 ms through 50 mΩ

$\int I^2(t) \, dt = 28100 \, A^2 \, s$

146 mH, 700 mΩ (325 V)

Coil current [A]

Time [s]

Adiabatic hot-spot temperature [K]

Quench integral $[A^2 \, s]$

M Mentink, J Van Nugteren, F Mangiarotti, M Duda, and G Kirby.
Quench Behaviour of the HL-LHC Twin Aperture Orbit Correctors.
IEEE TAS, 28(3):Art. no. 4004806, 2018
Adiabatic hot-spot $T$

17 ms until trigger, 10 ms through 50 mΩ

$\int I^2(t) \, dt = 24000 \, A^2 \, s$

146 mH, 862 mΩ (400 V)

M Mentink, J Van Nugteren, F Mangiarotti, M Duda, and G Kirby.
Quench Behaviour of the HL-LHC Twin Aperture Orbit Correctors.
IEEE TAS, 28(3):Art. no. 4004806, 2018

(a)

(b)
Describe eddy currents and main coil by coupled LR circuits

mutual inductance between any 2 loops
Calculating lumped-element values

- Use block-coil model
- Force long linear ramp of coil current, until eddy currents do not change
- Define equivalent current in each alu part:
  \[ I = \frac{1}{2} \int \int_{z=0} dx \ dy \ |J_z(x, y, 0)| \]
- Record the 3D eddy current pattern in each former
- Assume that 3D pattern is time-invariant, only changes in magnitude over time
Calculating lumped-element inductances

- Solve individual simulations for each former. Eddy current only in that former.

- Get field solutions: $B_i$, $H_i$

- Self-inductances:
  \[ \frac{1}{2} L_i I^2 = E_i = \frac{1}{2} \int B_i \cdot H_i \, d^3x \]

- Mutual inductances:
  \[ L_{ij} = k_{ij} \sqrt{L_i L_j} \]
  \[ k_{ij} = \frac{E_{ij} - E_i - E_j}{2 \sqrt{E_i E_j}} \]
  \[ E_{ij} = \frac{1}{2} \int (B_i + B_j) \cdot (H_i + H_j) \, d^3x \]
Calculating lumped-element resistances

- In the quasy-steady state (coil being ramped, eddy currents reached steady state), transformer equation:
  \[ L_{coil,i} \frac{dI_{coil}}{dt} = R_i I_i \]
- Inductances, ramp-rate and currents are defined
- Calculate \( R_i \)
Lumped element equations

- Coupled LR circuits:
  \[ \frac{dI}{dt} = L^{-1}U = L^{-1}R(t) \cdot I \]

  \[ R(t) = \text{diag} (R_i(t) | i = \text{coil, former1, former2, support}) \]

- Use time-dependent resistances:
  - \( R_{\text{crowbar}}, R_{\text{dump}} \) switched in following the realistic protocol
  - Quench propagation speed from Wilson’s book
  - Calculate adiabatic T in quenched section, calculate R
  - Calculate trigger/threshold conditions, follow same protocol
  - (calculate adiabatic T in formers approximatively – no effect)
Adiabatic hot-spot $T$

\[ \int I^2(t) \, dt = 21000 \text{ A}^2 \text{ s} \]

- Lumped, realistic couplings
- Lumped, no couplings
- Lumped, $10 \times$ strand resistance

Heat-transfer, cooling of hot-spot and quench-back is still not considered!
Adiabatic hot-spot T

Without coupling: same as exp. decay

Exp. decays —— Lumped, realistic couplings
Lumped, no couplings ---
Lumped, 10× strand resistance ---

RRR = 200, Cu/SC = 1.35, D_{wire} = 0.85 mm

Exp. decay, R_{damp}=700 mΩ
Exp. decay, R_{damp}=862 mΩ
Lumped element simulation

(a) Coi1 current [A] vs. Time [s]
(b) Adiabatic hot-spot temperature [K] vs. Quench integral [A^2 s]
Adiabatic hot-spot T

- Quench propagation in wire affects trigger time…

- But later on, it has very small effect

- Quench-back is more important (makes full wire NC), but is not taken into account here
CAD model
General layout
Connection box
Connection box

- Connection box bolted to outer former, rather than inner former
- No need to make holes through fiber glass, kapton
Layer jump

- Complicated groove path
- Coil pack not supported, falls apart
- Fiber glass wrap: additional complications

- Fiber glass has to be cut to liberate groove
- Unsupported ends after cutting
Layer jump

- Groove first comes parallel to Z axis
- and only then raises to former 1

Larger slot, wires can be bent outwards, to cut fiber glass tape

Increased groove width: 3.1 mm

Widening groove end

Clamping of cut tape ends

0.5 mm recess
Azimuthal alignment

- Tried to avoid the “alignment pins” of LHCMCBRD
  - Going through support tube, former2
  - Need extra seals for impregnation
  - Had to cut kapton layers through small holes
  - HV clearances
Azimuthal alignment: lock ring
Epoxy impregnation

Spring washers & nut absorb different thermal expansion

LHCMCBRD: leakage during impregnation above 2 bar.

Our goal: avoid problem due to diff. thermal expansion
Fix seals to magnet ends directly
Epoxy impregnation: fix end
Epoxy impregnation: loose end
Epoxy impregnation: loose end
Summary

- 3D coil shape optimized
- Field homogeneity within +/-1.5% for both MgB$_2$ and NbTi, in full ramp range
- No mechanical issues
- SC wire to be chosen:
  - Cu:SC=1.35 offers higher margin ($I/I_c = 56\%$), to be purchased
  - Cu:SC=1.9 (CERN) offers more protection, ($I/I_c = 65\%$), readily available (?)
- Quench protection: 160 K seems reasonable (check consistency of RRR and Cu:SC of available wire options)
- CAD model is ready for overview, implements concepts/features to avoid difficulties experienced during the winding/assembly of LHCMCBRD (September 2019)