Shielding magnetic fields of several Tesla: the FCC SuShi project

http://cern.ch/sushi-septum-project

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The Future Circular Collider

Baseline:

- 50+50 TeV proton-proton collider
- 100 km ring
- Using existing CERN infrastructure as injector

Targeted problem: extraction of the 50 TeV beam towards the beam dump
Extraction scheme

- Beam is dumped when:
  - Something misbehaves
  - At the end of the cycle

- Particle bunches

- Septum magnet: very sharp transition of B-field

- High field

- Dilution kickers

- Zero field

- Dump

- Kicker protection

- Abort gap
Doing it at the LHC: the Lambertson septa

Mu-metal layer on vacuum chamber

B < 1.2 T

Circulating & extracted beams

Coils

Iron yoke

Doing it at the LHC: the Lambertson septa

Mu-metal layer on vacuum chamber

Circulating & extracted beams

Using $\mu_r \gg 1$ to „suck out” the field lines from the circulating beam

Can't go above ~1.5 T due to saturation of iron

FCC parameters for extraction

At top energy (most difficult):

<table>
<thead>
<tr>
<th>Septum integrated field</th>
<th>190 T m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available space for septum</td>
<td>120 m</td>
</tr>
</tbody>
</table>

Need ≥ 2 T field (to accommodate gate valves, pumps, etc)

(Space would be even more tight in the „high-energy LHC” - LHC tunnel with FCC technology)

• B > 2 T (target: 3 Tesla)
  - Not easy with normal-conducting devices
  - need superconductors?

• Must follow the ring energy to be ready for beam-abort at any time (quasi-DC mode)

• Field homogeneity: ~1%

• Leakage field at circulating beam: < 10^{-4} relative
Doing it at the FCC: the SuShi idea

- If cooled down in 0 field, a superconductor can shield the outside field
- Persistent currents
  - Homogeneous high field
  - ~5-7 cm
- Concept is similar to eddy current septum, but can work in DC mode, (because the eddy currents are persistent)
Doing it at the FCC: the SuShi idea

- If cooled down in 0 field, a superconductor can shield the outside field.
- Persistent currents.

Concept is similar to eddy current septum, but can work in DC mode, (because the eddy currents are persistent).

Using $\mu_r \ll 1$ material to expel the field lines.
### Pros & cons

**Pros**
- Shielding currents arranged by nature (high precision zero field)
- Continuous 2D current distribution (unlike a winded magnet) → perfect shielding
- Bulk shield, better mechanical, and thermal stability
- Highest possible current density (critical state model) → thinnest shield

**Cons**
- Superconductor in high rad zone (quench)
- Hysteretic behavior, always have to start from virgin state
- To erase ‘memory’ of shield, temperature has to be increased
Combining $\mu_r \gg 1$ and $\mu_r \ll 1$

The „magnetic cloak”

- Ferromagnet absorbs the induction lines expelled by the superconductor
- Seems a natural choice, since it does not distort the external field

Does not work for FCC with realistic geometrical parameters:

field in ferromagnet would be too high: ~13-18 T
Homogeneity at various field strengths

Flat wall → homogeneity despite significantly different penetration depths

At injection

pos. winding

neg. winding

≤0.5 T

At top energy

3 T
CERN Bubble chambers

- In the '70ies: superconducting tube to shield high magnetic field
- To introduce low-momentum particles into the high field of the bubble chamber
- Different materials, and techniques could bring the shielded field strength from 2 T up to 5.9 T

- M.Firth, et.al.: Performance of the superconducting field shielding tube for the CERN 2m hydrogen bubble chamber
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
MgB$_2$

- Produced by the Reactive Liquid Magnesium Infiltration (RLI) process (G. Giunchi, Int.J.Mod.Phys.B17,453)

- Extra large boron grainsize (160 $\mu$m) to be stable against flux jumps (G.Giunchi et al, IEEE Trans. Appl. Supercond. 26, 8801005)
Testing of prototypes at SM18

- Shielding magnetic fields of several Tesla: the FCC Su Shi project,

This diagram shows a detailed view of the testing setup at SM18, including:

- Long aluminium support tube
- Hall sensors
- LHC corrector magnet MCBY
- Transverse alignments
- Delrin rod
- Transverse aligners

The diagram provides a clear visual representation of these components and their arrangements.
MgB$_2$ magnetization cycle

Field inside the shield

Field outside the shield
MgB$_2$ magnetization cycle

Ramp rate: 0.1 A/s $\rightarrow$ 5 mT/s on external sensors (realistic for FCC: 3 T/10 minute)

2 minute plateaus for relaxation measurement
MgB$_2$ magnetization cycle

Smooth penetration at 2.6 T

Complete shielding below 2.6 T
MgB$_2$ magnetization cycle

- No flux jump on the virgin curve up to the highest field.
- Flux jumps at low fields, after the shield has been exposed to high fields.
- Smooth penetration at 2.6 T.
MgB$_2$ magnetization cycle

![MgB$_2$ magnetization cycle graph](image-url)
MgB$_2$: field penetration

- 2.6 T plateau (full shielding)
- Significant creep on the plateaus (smooth, not an avalanche-like jump!)

64 A magnet current

H0, H1, H2 x 6
MgB$_2$: field penetration

- 2.6 T plateau (full shielding)
- Field penetration at open end of the tube
- Significant creep on the plateaus (smooth, not an avalanche-like jump!)
- Full shielding (<0.1 mT) deeper inside
- 88 mm from shield's end
MgB$_2$: linearity

Measured external magnetic field is non-linear as a function of magnet current!
**MgB$_2$: linearity**

- Increasing field $\rightarrow$ more penetration
- Effective shielding surface drifts away from Hall sensor
- Less field concentration at sensor

\[ J_c(B) = J_0 \cdot \exp(-\gamma B) \]

**COMSOL simulation in precise model of MCBY magnet**
MgB$_2$: linearity

\[ J_c(B) = J_0 \cdot \exp(-\gamma B) \]

J$_0$ and $\gamma$ are strongly correlated

COMSOL simulation in precise model of MCBY magnet

Hall sensor
**MgB$_2$: linearity**

- **MgB$_2$:** linearity
- **J$_c$(B) = J$_0$ \cdot \exp(-\gamma B)**
- **Hall sensor**
- **COMSOL simulation in precise model of MCBY magnet**
- **J$_0$ and $\gamma$ are strongly correlated**

**Graphs:**
- Graph showing $B_{\text{ext}}$ at sensor's position vs. magnet current.
- Graph showing $\gamma$ vs. $J_0$ with $\chi^2$ values.

**Equation:**
$$J_c(B) = J_0 \cdot \exp(-\gamma B)$$

**Text:**
- MgB$_2$ is a superconductor with a critical current density $J_c$ that is a function of the magnetic field $B$.
- $J_0$ and $\gamma$ are strongly correlated, indicating a realistic model for MgB$_2$ superconductors.
MgB$_2$: linearity

\[ J_c(B) = J_0 \cdot \exp(-\gamma B) \]

realistic MgB$_2$

COMSOL simulation in precise model of MCBY magnet

Hall sensor

\( J_0 \) and \( \gamma \) are strongly correlated
MgB$_2$: linearity

- From observed nonlinearity one can get some info on $J_c(B)$
- At 64 A different parameters give B penetration profiles with same, almost full depth
HTS tape covered tube

- 
  - Ø46.5 mm
  - 25 layers of helically wrapped SuperOx 2G HTS tape, soft-soldered
  - Copper support tube
  - 450 mm

Layers overlapping
Little current loops
Superposition
HTS: Shielding performance

- Shielding up to 0.25 T (not perfect, as we will see!)
- Smooth, full penetration above 0.25 T
- Due to limited $J_c$?
- No flux jumps!

Graph showing the magnetic field behavior with different curves for $H_0:H_4$, $H_1:H_5$, and $H_2:H_6$. The graph plots $B_{in}$ vs. $B_{out}$ with $B_{in}$ ranging from -1.5 to 1 and $B_{out}$ ranging from -1 to 1.5.
HTS: penetration at low field!

Continuous penetration from zero field!
Attenuation is about $10^{-3}$ here
Due to geometry? (non-continuous geometry, small gaps between tape layers, small current loops)
NbTi/Nb/Cu multilayer shield

- Consists of multilayer sheets of ~0.8mm, containing 30 layers of 9 µm NbTi
- From previous tests it seems possible to shield 2.5T field with 3 sheets (~2.4mm)
- A 4-sheet shield will be tested in the beginning of next year

Shielding performance

Exponential

\[ J_c(B) = J_0 \cdot \exp(-\gamma B) \]

leads to exponential increase of required thickness:

\[ d = d_0 \cdot \exp(\gamma B) \]

with \( d_0 = 1/\gamma \mu_0 J_0 \)

For MgB\(_2\): roughly \( \times 3 \) increase for +1 T

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Shielding performance

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For MgB\(_2\): roughly \( \times 3 \) increase for +1 T

\[ j_{\text{eng}} \left[ \times 10^9 \text{ A/m}^2 \right] \]

\( B \) [T]

Outlook

• Passive superconductors:
  – Perfect shielding if thickness is sufficient
  – Up to very high fields
  – DC and AC mode
  – Very attractive if space is tight
  – Very versatile:
    • MgB2: large bulk, complex shapes, EDM machining, cheap
    • NbTi multilayer: ductile, robust, formable

• Future plans:
  – Measurement of third prototype
  – Construct a full demonstrator
Thank you for your attention!

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Additional slides
Measurement possibilities

- Rotating coil to measure field quality (during tests only)
- Shield thick enough to ensure **perfect shielding** safely...
- Most important: detect flux-jumps (very quickly and reliably) → beam abort
- Hall sensors close to the shield (off the mid-plane) (tests & real app. ?)
- Hall sensor to measure the „zero field“ (during tests only)
- Pick-up coil to detect flux-jump (tests & real app.)

- Do not need to be high precision
MgB$_2$: long-term relaxation

- If external field at a safe level below full penetration...
- ...relaxation is small, can be compensated by the excitation current

Graph showing the change in $B_{\text{ext}}$ over time with annotations indicating that relaxation is small and can be compensated by the excitation current.