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

Septum magnet: very sharp transition of B-field

zero field

Kicker

protection

high field

dilution kickers

ejected beam

dump

particle bunches

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

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

Can't go above $\sim 1.5$ T due to saturation of iron

FCC parameters for extraction

At top energy (most difficult):

Septum integrated 190 T m field
Available space 120 m for septum

Need $\geq 2$ 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: $\sim 1\%$

- 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...
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
  - Using $\mu_r \ll 1$ material to expel the field lines

- Concept is similar to eddy current septum, but can work in DC mode, (because the...
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: $\sim 13-18$ T
Challenges

• Max. physical septum width: 25 mm (including vacuum pipe walls etc!)

• Go against „common practice” of superconductors (very fine filaments to avoid flux jumps – thermomagnetic instability)
  
  Want to exclude B from a large area
  
  Need special measures to ensure stability

• Care about the excluded field's quality (homogeneity)

• „Reset cycle” (warm-up and zero-field-cool) to be on the „virgin curve” of magnetization
Homogeneity at various field strengths

Flat wall $\rightarrow$ homogeneity despite significantly different penetration depths

At injection

- pos. winding
- neg. winding

$\leq 0.5 \text{ T}$

At top energy

$3 \text{ T}$
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

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

Dimensions:
- Width: 450 mm
- Length: 1100 mm
- H3, H2, H1, H0, H7, H6, H5, H4
MgB$_2$ magnetization cycle

Field inside the shield

Field outside the shield

B [T]

Time [s]
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

- $B$ [T]
- time [s]
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

![MgB2 Magnetization Cycle](image)
**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**
MgB$_2$: field penetration

2.6 T plateau (full shielding)

Significant creep on the plateaus (smooth, not an avalanche-like jump!)

Full shielding (<0.1 mT) deeper inside

Field penetration at open end of the tube

88 mm from shield's end

Time [s]
MgB\textsubscript{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
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

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

\( J_0 \) and \( \gamma \) are strongly correlated

COMSOL simulation in precise model of MCBY magnet

Hall sensor
\( \text{MgB}_2: \text{linearity} \)

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

COMSOL simulation in precise model of MCBY magnet

\( J_0 \) and \( \gamma \) are strongly correlated

\( \chi^2 \)
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

Layers overlapping
Little current loops
Superposition
HTS: Shielding performance

Shielding up to 0.25 T (not perfect, as we will see!)

No flux jumps!

Smooth, full penetration above 0.25 T
Due to limited $J_c$?
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)

**HTS: penetration at low field!**
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

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Shielding performance

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

leads to exponential increase of required thickness:

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

with \( d_0 = \frac{1}{\gamma \mu_0 J_0} \)

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

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

\[ J_{c,\text{NbTi/Nb/Cu}} \] multilayer sheet (various conditions) [1]

Large-grain MgB\(_2\) (estimates from our tests, using simulation)

MgB\(_2\) cheaper

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
Thank you for your attention!

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Additional slides
Measurement possibilities

- Rotating coil to measure field quality (during tests only)
- Hall sensor to measure the “zero field” (during tests only)
- Pick-up coil to detect flux-jump (tests & real app.)
- 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. ?)

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

$B_{\text{ext}}$ [T]

Time [hour]

0 1 2 3 4 5 6 7

2.425
2.42
2.415
2.41
2.405

0.25%