First experimental results with the SuShi septum prototypes

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Outline
- Motivation
- The SuShi concept
- Simulation
  - Field homogeneity
  - Massless septum
- Experimental results:
  - MgB$_2$
  - HTS
- Outlook

Kristóf Brunner, Anikó Német (Wigner RCP)
Miro Atanasov, Márta Bajkó, Hugues Bajas,
Carlo Petrone (CERN)
Giovanni Giunchi
Alexander Molodyk (SuperOx)
FCC extraction scheme & parameters

Injection is OK with LHC technology (Lambertson septa)
FCC extraction scheme & parameters

- Kicker angle $\alpha_k$: 0.045 mrad
- Septum angle $\alpha_s$: 1.2 mrad
- Septum integrated field: 190 T m
- Available space for septum: 120 m
## FCC extraction scheme & parameters

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Need $\geq 2$ T field (to accommodate gate valves, pumps, etc)
Motivation, requirements

- $B > 2 \, T$
  - Not easy with normal-conducting devices
  - need superconductors?
- Must follow the ring energy (quasi-DC mode)
- Field homogeneity: $\sim 1\%$
- Leakage field at circulating beam: $< 10^{-4}$ relative
SuShi = Superconducting Shield

- Put a superconducting shield around the circulating beam (or the inverse config)
- Cool below $T_c$ in zero field
- Ramp up an external field
- Induced persistent eddy currents cancel the field inside
- Like an eddy current septum, but can work in quasi-DC mode

For details: D. Barna, PRAB 20 (2017), 041002
http://cern.ch/sushi-septum-project
Pros & Cons

- **Pros**
  - Shielding currents arranged by nature precisely, not by us
  - Continuous 2D current distribution, with no leak (in contrast to a magnet's winding)
  - Critical state model: currents flow at $J_c$ (i.e. highest possible value, thinnest possible septum blade)
  - Bulk superconductor, no windings, no interleaving insulation (better mechanical and thermal stability)
  - No quench heater needed

- **Cons**
  - Superconductors in potentially high rad zone $\rightarrow$ quench? (for all SC solutions)
  - Passive shield - hysteretic behaviour
  - Shield's state is not a unique function of the controllable parameters $T$ and $B_{ext}$ $\rightarrow$ must start from a 'virgin' state for each accelerator cycle.
Challenges compared to usual shielding applications

- Aimed field is high: >2 T (3-4 Tesla for a more compact system?)
- Must simultaneously **shield** the circulating beam, and **shape** a homogeneous field outside
- Coupled optimization of superconductor's shape and external magnet's geometry
- Homogeneity must hold independently from field strength, spanning a range of a factor 15 between injection/extraction
How to make a homogeneous field

For details:
D. Barna, PRAB 20 (2017), 041002
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Field homogeneity: $\Delta B/B \sim 1\text{-}2\%$ up to 3 Tesla, over a 5 cm GFR

- despite different penetration depths
- with different SC materials

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Massless septum

For details: D. Barna, PRAB 20 (2017), 041002
“Quite good” up to ~1.5 T:
- Homogeneity: 1.5%

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Massless septum

“Quite good” up to ~1.5 T:
- Homogeneity: 1.5%
- Attenuation: $10^{-4}$

For details: D. Barna, PRAB 20 (2017), 041002

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3 planned prototypes

• Quick and simple experiments → cylindrical shield in an existing magnet
  - Check highest shielded field
  - Check flux creep (slow relaxation of shielding currents)
  - Identify best material/technology for more sophisticated tests/prototypes

• Prototypes:
  - MgB$_2$
  - HTS
  - NbTi/Nb/Cu multilayer

• Shield parameters:
  - 450 mm length (to exceed the originally planned LHC MQSX magnet's length)
  - 50 mm outer diameter (to easily fit into the 70 mm bore of the magnet)
Experimental setup

MQSX was not available. Used magnet: MCBY (length: 1100 mm, bore: 70 mm)

Asymmetric setup:
one end immersed in high field,
one end sticking out of magnet

Superconducting shield
Experimental setup

MQSX was not available. Used magnet: MCBY (length: 1100 mm, bore: 70 mm)

4 Hall sensors (0-3) inside,
4 Hall sensors (4-7) outside the shield

Full setup immersed in liquid helium, $T = 4.2$ K
The MgB$_2$ shield

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

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.

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

Breakdown proceeds from the end? End effect?

Outsider

Inside

Side view

8.5 mm

Front view

Sharper surface

Higher field

88 mm from shield's end

8.5 mm

88 mm

H0

H1

H2

Time [s]

B [nT]
MgB$_2$: linearity

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

Observed nonlinearity is not due to MCBY's iron

COMSOL simulation in precise model of MCBY magnet
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
$\text{MgB}_2$: linearity

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

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

![Graph showing linearity of MgB$_2$](image)

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

$J_0$ and $\gamma$ are strongly correlated

**Realistic MgB$_2$ simulation**

**Hall sensor**

**COMSOL simulation**

**Magnet current [A]**

**$\gamma$**

**CH2**

**$J_0$ [10$^9$ A/m$^2$]**

**$10^{-2}$**

**$10^{-3}$**

**$10^{-4}$**

**$10^{-5}$**

**$10^{-6}$**

**$B_{\text{ext}}$ at sensor's position [T]**

**Measurement**

**Perfect diamagnet**

**Sim. best fit:**

$J_0 = 7.5 \times 10^6$ A/cm$^2$, $\gamma = 1.4$

**Simulation:**

$J_0 = 3 \times 10^5$ A/cm$^2$, $\gamma = 1$
MgB$_2$: linearity

- From observed nonlinearity one can get some info on $J_c(B)$
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
- Small discrepancy – end effect?
- ..but ultimate limiting factor is thickness (and/or $J_c$)!

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

Small discrepancy – end effect?

..but ultimate limiting factor is thickness (and/or $J_c$)!
MgB$_2$: relaxation

- External field on the plateaus (magnet's current is constant)
- Same vertical scale on all plots

Interplay between geometry and shielding currents' dynamics (shielding currents decay → effective shielding surface drifting away from Hall sensor)
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
The HTS Shield

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

- SuperOx 2G HTS Critical Current: \( I_c = 250\text{-}500 \text{ A/cm} \) in self-field, \( T = 77 \text{ K} \)
- Our moderate B field does not change much...
- Lift factor (improvement at 4.2 K w.r.t. 77 K) > 4 for \( B < 1 \text{ T} \)
- \( n = 25 \) layers

\[ \Delta B = \mu_0 * I_c * n = 0.8 \text{ Tesla} \]
HTS: Shielding performance

No flux jumps!

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

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

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- Smooth, full penetration above 0.25 T
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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)
HTS: relaxation

Relaxation of external field on the plateaus (H5)

- Same absolute scale on all plots
- Negligible below full penetration, significant above it.
3rd prototype – stay tuned!

**NbTi/Nb/Cu multilayer sheet**

Deep-drawn seamless cups

- Seems very promising
- Sheet material waiting for shipment
- Some R&D to fabricate the prototype

3 mm (!!) could shield 2.5 Tesla
## Prototype comparison

<table>
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<th>MgB$_2$</th>
<th>HTS</th>
<th>NbTi/Nb/Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Price</strong></td>
<td>1</td>
<td>4 x MgB$_2$</td>
<td>5 x MgB$_2$</td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td>simple (baking 950 °C), diamond or spark machining</td>
<td>easy (from commercial tapes), scalable</td>
<td>heavy machinery (rolling &amp; heat treatments)</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td>hard and brittle</td>
<td>robust</td>
<td>most versatile, ductile, robust</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>good</td>
<td>insufficient</td>
<td>best (anticipated from literature)</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>manufacturing of long (2-3 m) tubes needs R&amp;D (can be joined...)</td>
<td>very wide tapes to avoid helical wrapping?</td>
<td>can the price be reduced drastically?</td>
</tr>
</tbody>
</table>
Conclusions

- Simulation: optimized geometry produces homogeneous field at different field strengths, with different superconductor characteristics
- Massless septum configuration is promising up to moderate levels (1 T)
- MgB$_2$ prototype ✔
  - No flux jumps on the virgin curve
  - Perfect shielding up to 2.6 T with 8.5 mm wall thickness
  - 0.25% relaxation of external field over 6 hours, @ 2.4 T (ok for FCC)
  - Cheap and simple
- HTS tape prototype (helical, multilayer wrap) ✗
  - Field penetrates already at very low fields (due to geometry?)
  - Full penetration above 0.25 T – much below expectations. Degraded J$_c$?
  - Relaxation...
- NbTi/Nb/Cu multilayer? (this year...)

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Outlook

- Candidate #1 so far is MgB$_2$
- With the best candidate:
  - Test fast & reliable detection of flux jumps/quench
  - Test massless configuration
  - Develop a dedicated SC coil & shield to produce a homogeneous field
Acknowledgements & Colleagues

- FCC Collaboration
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