Design status of a high field superconducting septum magnet

Kei Sugita, Egbert Fischer, Peter Spiller
Superconducting Magnets & Testing, SIS100/18
GSI
Contents

- Background: FAIR Project
- Overview of the concept (Analytical calculations)
- Engineering design study
- Next steps and possible applications
- Summary
Background

Superconducting magnets & testing at FAIR

Heavy ion synchrotron SIS100
(Beam rigidity 100 Tm)

108 Dipoles
- Manufacturing: Series production started, BNG, Germany
- Testing: GSI Series Test Facility commissioned

166 Quadrupoles + more than 140 correctors.
- Manufacturing and testing Q-units: First of Series production started JINR, Russia
- Doublet module integration: Preparation for tender
- Doublet testing: Preparation for collaboration/tender

Super Fragment Separator (Super-FRS)

24 Dipoles
- Manufacturing: Tender ongoing

76 Quadrupoles + more than 90 correctors.
- Multiplet manufacturing: Pre-series multiplet production soon, ASG, Italy
- Testing: CERN-GSI collaboration
  - Test facility commissioning at CERN B.180.

Contribution from partners
- APPA large aperture quadrupole
- CBM dipole magnet
- PANDA solenoid magnet
**Background**

- **Future SIS“x”00 (x ≥ 3)**
  - (Beam rigidity x00 Tm)

  **Heavy ion synchrotron SISx00**
  - **Main magnets:** Fast ramp cosine-theta type 4.5 T (x=3), 6 T (x=4), 1T/s
  - **SPS upgrade:** Fast-cycling SC magnets, 6-7T, ~1T/s

  **Superconducting septum magnets:** 3.6 T (x=3), 4.8 T (x=4)
  - **Superconducting septum magnet:** 4T

**Figure 2.3.1.5:** Ion optics layout of the beam lines from SIS100/300 to the Super-FRS.

- Top: side view.
- Middle: ion optics functions SIS100 beam (Emittance: 25/10 mm*mrad)
- Bottom: Beam size for a SIS300 beam with emittances 10/4 mm*mrad.

- Colour code of squares are identical to Figure 2.3.1.3. Purple squares denote open apertures of switched off divider dipoles.

**Magnetic dipole field**

- **Zero magnetic field**

- **Injection/extraction beam**

- **Circulating beam**

**Septum magnet**

- SIS300-Level, @-12.1m
- SIS100-Level, @-13.5m
- SIS100 beam dump, @-7.4m
- SIS300 beam dump + CBM cave, @-6m
- Super-FRS and other experiments, @0m
- Crossing of SIS18 injection beam, @approx. -10.5m, vertical slope 15deg.

**Injection beam pathlength [mm]**

- **Magnetic dipole field**

**Superconducting septum magnet:** 4T
Overview of the concept

- Concept

**Septum magnet**
- Iron yoke
- Circulating beam
- Injected/Extracted Beam
- \( B = 0 \)

**Dipole magnet**
- Iron yoke
- Iron-dominated (Window-frame) Magnet

**Iron-dominated (Window-frame) Magnet**
- More than ~2 Tesla

**Current dominated, cosine-theta Magnet**
Overview of the concept

- **Concept**

  **Septum magnet**
  - Iron yoke
  - \( B = 0 \)
  - Circulating beam
  - Injected/Extracted Beam
  - More than \( \sim 2 \text{ Tesla} \)

  **Dipole magnet**
  - Iron yoke
  - Iron-dominated (Window-frame) Magnet
  - More than \( \sim 2 \text{ Tesla} \)

**New Patent granted**

**Iron yoke**

**Truncated cosine-theta with iron yoke**

**Pure cosine-theta**

**Current dominated, cosine-theta Magnet**

**Zero field**

- Presented at
  - FCC Week 2015
    - [https://indico.cern.ch/event/340703/contributions/802239/](https://indico.cern.ch/event/340703/contributions/802239/)
  - FCC Week 2016
    - [https://indico.cern.ch/event/438866/contributions/108009/](https://indico.cern.ch/event/438866/contributions/108009/)
Overview of the concept

- Analytical calculation with line currents

**Remark 1**
If the iron yoke is saturated by a magnetic field more than 2 T, magnetic flux leaks at the circulating beam area. This is essential problem for operation at more than 2 T.

**Answer 1**
Yes.
Peak field in the yoke must be < 2 T, then, no leakage to via saturated yoke area.
Let's us put a distance between the coil and yoke. How much?

→Optimization
- Magnetic field quality,
- Leakage of magnetic field

cf.
- High field cosine-theta magnet (LHC main dipole)
Overview of the concept

**Remark 2**
The coil at septum wall has to cover with constant current density over the height of the opening. Otherwise field leaks at the circulating beam area.

**Answer 2**
For conventional one, yes.
But, for the truncated cosine-theta type, No.

---

**Pure cosine-theta magnet with yoke:**
Pure analytical form (with image current)

- **Parameters**
  - Coil radius $R_c$: 0.044 m
  - Iron yoke radius $R_y$: 0.10 m
  - Ampere-turn/pole ($J_0$): 474 kA
  - Field in Aperture $B_i$: 8.079 T

---

**Magnetic field $B_y$ on y-axis**

$$B_y = \frac{j_0}{2} \left( \frac{1}{R_c} + \frac{R_c}{R_y^2} \right)$$

**Current density must be proportional to the magnetic field strength**

$$\kappa = \frac{1}{\mu_0}$$

**Current density**

$$j_y = \frac{j_0}{2} \left( \frac{1}{R_c} + \frac{R_c}{R_y^2} \right)$$
Overview of the concept

- Analytical calculation

<table>
<thead>
<tr>
<th>Cosine-theta part</th>
<th>r</th>
<th>theta</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real current</td>
<td>$R_c$</td>
<td>$-\pi/2 \to \pi/2$</td>
<td>$j = -j_0 \cos \theta$</td>
</tr>
<tr>
<td>Image current</td>
<td>$\frac{R_c^2}{R_y}$</td>
<td>$-\pi/2 \to \pi/2$</td>
<td>$j = -j_0 \cos \theta$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Block-coil part</th>
<th>r</th>
<th>theta</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within coil radius</td>
<td>$-R_c \to R_c$</td>
<td>$\pi/2$</td>
<td>$j_h = \frac{j_0}{2} \left( \frac{1}{R_c} + \frac{R_c}{R_y^2} \right)$</td>
</tr>
<tr>
<td>Between coil and image coil</td>
<td>$R_c \to \frac{R_c^2}{R_y}$</td>
<td>$\pi/2$</td>
<td>$j_b = \frac{j_0}{2} \left( \frac{R_c}{R_y^2} + \frac{R_c}{R_y} \right)$</td>
</tr>
<tr>
<td>Out of image current coil</td>
<td>$\frac{R_c^2}{R_y} \to \infty$</td>
<td>$\pi/2$</td>
<td>$j_e = \frac{j_0}{2} \left( \frac{1}{R_c} + \frac{R_c}{R_y^2} \right) \left( \frac{R_c}{y} \right)^2$</td>
</tr>
</tbody>
</table>

$B = \mu_0 j(r, \theta)$

with Mathematica
Overview of the concept

- Analytical calculation

<table>
<thead>
<tr>
<th>Cosine-theta part</th>
<th>r</th>
<th>theta</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real current</td>
<td>$R_c$</td>
<td>$-\pi/2 \rightarrow \pi/2$</td>
<td>$j = j_0 \cos \theta$</td>
</tr>
<tr>
<td>Image current</td>
<td>$\frac{R_c^2}{\pi}$</td>
<td>$-\pi/2 \rightarrow \pi/2$</td>
<td>$j = j_0 \cos \theta$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Block-coil part</th>
<th>r</th>
<th>theta</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within coil radius</td>
<td>$-R_c \rightarrow R_c$</td>
<td>$\pi/2$</td>
<td>$j_0 = \frac{3}{2} \left( \frac{1}{R_c} + \frac{R_c}{\pi^2} \right)$</td>
</tr>
<tr>
<td>Between coil and image current coil</td>
<td>$R_c \rightarrow \frac{R_c^2}{\pi}$</td>
<td>$\pi/2$</td>
<td>$j_0 = \frac{3}{2} \left( \frac{R_c}{\pi^2} - \frac{R_c}{\pi^2} \right)$</td>
</tr>
<tr>
<td>Out of image current coil</td>
<td>$\frac{R_c^2}{\pi} \rightarrow \infty$</td>
<td>$\pi/2$</td>
<td>$j_0' = \frac{3}{2} \left( \frac{1}{R_c} + \frac{R_c}{\pi^2} \right) \left( \frac{R_c}{\pi^2} \right)^2$</td>
</tr>
</tbody>
</table>

- Line currents (n=20, 23.7 kA)

$B = \mu_0 j(r, \theta)$

with Mathematica

cf. Equally arranged line current case

Leak field $\sim 10^{-3}$
Main field $\sim 10^{-1}$
Overview of the concept

- Use of simulation softwares: for “theory to real magnets”

Identical parameters as analytical calculation. No iron is necessary at circulating beam area.

**How to design?**
1. Design a dipole magnet
2. Truncate at desired position
3. Design block coil
4. Optimisation

**ROXIE2D**: Optimization

**Objective**
- Good field quality at the reference radius
- Reduce magnetic field leakage at circulating beam

**Variable**
- Iron yoke radius
- Cable position (insulation thickness, wedges)

Electromagnetic design softwares can be applicable for the design/optimization!
Remark 3
Even if cross section design is perfectly done, how can we manufacture such a coil/magnet?
How is the coil end design?

Answer 3
For realisation, engineering design/R&D is absolutely necessary.
We have got support from Helmholtz Association’s program:
“Matter and Technology, Accelerator Research and Development (ARD)”

https://www.helmholtz.de/en/research/matter/matter_and_technologies
https://www.helmholtz-ard.de

Engineering design studies in 2016
GSI
Remark 4
At circulating beam side, a massive support structure would be needed against Lorentz forces. This would increase the septum wall thickness.

Answer 4
The Lorentz forces on the block coil are equivalently distributed. Less pressure than the cosine-theta coil. Therefore, a mechanical support system would not be so massive, at least circulating beam area.

cf. Typical cosine-theta coil: ~ a few 10 MPa.
Engineering design study

Engineering design studies in 2016: Cryostat, Interfaces

Interfaces
- Current leads
- Helium supply/return
- Mechanical support in the tunnel are still missing.

As usual, iteration of electromagnetic optimisation mechanical design optimisation (incl. cooling etc.) is necessary.
Engineering design studies in 2016: Discussion points

**Rutherford cable or Nuclotron cable**

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Nuclotron cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Established technology for cosine-theta &quot;symmetric&quot; high field magnet</td>
<td>No liquid helium vessel needed</td>
</tr>
<tr>
<td>Magnetic field adjustment by shimming is possible</td>
<td>Lower requirements regarding the pressure equipment directive</td>
</tr>
<tr>
<td>Established technology for a ramped magnet</td>
<td></td>
</tr>
<tr>
<td>Insulated strands in the cable</td>
<td>low current operation is possible.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantage</th>
<th>Nuclotron cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special tooling for curing and colloring</td>
<td>Complex and space consuming coil ends.</td>
</tr>
<tr>
<td>Two layer design, cooling for the outer layer in helium bath. (introduction of “fishbone” between layers.)</td>
<td>Insulated strands in the cable</td>
</tr>
<tr>
<td>High voltage during quench.</td>
<td></td>
</tr>
<tr>
<td>Number of strand connections (Terminal box for the SIS100 corrector magnets have been developed.)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantage</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller aperture radius of the cosine-theta coil.</td>
<td>No need of iron at circulating beam area</td>
</tr>
</tbody>
</table>

Iron between coil and circulating beam is used for mechanical support for the Lorentz force

Geometrical requirements are updated. Detailed analysis on the design option is still needed.
Next steps

Update of design geometry, parameters (300 Tm)

- **B** = 3.6 T
- **L** = 4.0 m
- Integral **B**x**L** = 14.4 Tm

<table>
<thead>
<tr>
<th>Magnet</th>
<th>SC septum magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_p, min</td>
<td>1.2 T</td>
</tr>
<tr>
<td>B_p, max</td>
<td>3.6 T</td>
</tr>
<tr>
<td>dB/dt</td>
<td>0.8 T/s</td>
</tr>
</tbody>
</table>

**FCC Septum Geometry**

*Courtesy of J. Borburgh, CERN, Feb. 2017*

**Straight magnet**

- **R** = 45 mm
- **R** = 47 mm (cf. 60 mm, design in 2016)

**Injection**

- Red: 1.3 TeV
- Black: 3.3 TeV

**FCC beam rigidity:**

- Injection: 11000 Tm (3.3 TeV)
- Extraction: 166800 Tm (50 TeV)

*cf.*

**LHC**: 23400 Tm

**SIS300**: 300 Tm

**SISx00** septum should be designed as a curved magnet.
Next steps and Possible applications

- **Optimisation**: electromagnetic design - engineering design
- **R&D**: with available normal-/super-conducting wire/cable
  - Verification of concept
  - Demonstration of coil end winding
- **Cost estimation**

**Possible applications**

**Medical machine**

- Suitable for single strand surface/direct winding technology.

**Quadrupole or combined function septum**

- **Quadrupole**
- **Combined function: Dipole + Quadrupole**

Presented at FCC Week 2016
Summary

- GSI continues the development of superconducting septum magnet based on the truncated cosine-theta with iron yoke concept.

- Analytical calculation indicates possibility of superconducting high field septum magnets (> 2T).

- Engineering studies for SISx00 are started in collaboration with industry, supported by Helmholtz Association MT-ARD program.

- Applications for other machines, such as FCC, medical machines are promising and very exciting!
• Linearity of the main/leak field strength

![Graph showing linearity of main/leak field strength](image)

- Dipole field [T]
- Leak field at circulating beam [T]
- Current factor

- Dipole field
- Leak field

<table>
<thead>
<tr>
<th>Current factor</th>
<th>Dipole field [T]</th>
<th>Leak field at circulating beam [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.0</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.2</td>
<td>0.6</td>
<td>1.7E-03</td>
</tr>
<tr>
<td>0.3</td>
<td>1.2</td>
<td>3.3E-03</td>
</tr>
<tr>
<td>0.4</td>
<td>1.8</td>
<td>5.0E-03</td>
</tr>
<tr>
<td>0.5</td>
<td>2.4</td>
<td>6.7E-03</td>
</tr>
<tr>
<td>0.6</td>
<td>3.0</td>
<td>8.3E-03</td>
</tr>
<tr>
<td>0.7</td>
<td>3.6</td>
<td>1.0E-02</td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>