Safety aspects of superconducting magnets for Super-FRS

Hans Mueller, Yu Xiang, Eun Jung Cho, Piotr Szwangruber, Martin Winkler, Felix Wamers, Pierre Schnizer;
GSI, Darmstadt, Germany
Stefano Cuneo, Giovanni Drago, Matteo Tassito,
ASG, Genova, Italy
- What is Super-FRS
- SC- Magnets of Super-FRS
  - Dipoles
  - Multiplets
- Safety aspects
  - Pressure
  - Electrical
  - Other
What is Super-FRS

- Facility for Antiproton and Ion Research (FAIR)
- to be built at GSI Darmstadt
- Experimental pillars
  - CBM
  - PANDA
  - APPA
  - NUSTAR
What is Super-FRS

Design Parameters:
- $\sigma_x = \sigma_y = 40 \pi \text{ mm mrad}$
- $\varphi_x = \pm 40 \text{ mrad}$
- $\varphi_y = \pm 20 \text{ mrad}$
- $\Delta P/P = 2.5\%$
- $B_p = 2 - 20 \text{Tm}$
- $R_{\text{in}} = 750 / 1500$
  (first / secon stage)
- Spot size on target
  - $\sigma_x = 1.0 \text{ mm}$
  - $\sigma_y = 2.0 \text{ mm}$

Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to $10^{12} \text{ /s}$
  (depending on element)
- DC or pulsed operation

In-Flight Separation:
- Universal (all elements)
- Fast (submicroseconds)
- Efficient (kinematic focusing)
- Mono-isotopic or cocktail beams

GSI Helmholtzzentrum für Schwerionenforschung GmbH
SC-Magnets: Design principles

- Large acceptance → large aperture
- Superferric (magnetic field shaped by iron yoke)
- Cooling by LHe bath (dipoles 45 l; Multiplets 1200 l)
- Individually powered magnets → max.operation current < 300 A → high inductivity
- Different setting should be adjustable in reasonable time → ability for 3 consecutive triangular cycles with $t_r=120$ sec.
- Common cryo-system with SIS100 and avoiding loss of Helium → 20 bar design pressure
- Quench Protection Scheme: main dipoles and quads: energy extraction resistor steering dipoles, sextupoles & octupoles: self-protecting
- Warm beam pipe
# Super-FRS Dipoles

<table>
<thead>
<tr>
<th></th>
<th>Arranged in groups of 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dipole Type 2</td>
<td>Dipole Type 3</td>
</tr>
<tr>
<td>Number of Magnets</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Effective length</td>
<td>2.40 m</td>
<td>2.13 m</td>
</tr>
<tr>
<td>Gradient/ Field Range</td>
<td>0.15-1.6 T</td>
<td>0.15-1.6 T</td>
</tr>
<tr>
<td>Field Quality</td>
<td>$\pm 3 \times 10^{-4}$</td>
<td>$\pm 3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Usable aperture</td>
<td>380x140 mm</td>
<td>380x140 mm</td>
</tr>
</tbody>
</table>

Remark: 3 of the dipoles of type 3 are branching dipoles with an additional straight exit. No design exists up to now for these 3 magnets.
Super-FRS Dipole (conceptual design by CEA)

Dipole (9.75°)
E=450 kJ
L=15.4 H
I = 245 A
m= 50 t
warm iron
## Super-FRS Multiplets

<table>
<thead>
<tr>
<th></th>
<th>Quadrupole Type 3</th>
<th>Quadrupole Type 4</th>
<th>Sextupole</th>
<th>Steerer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Magnets</td>
<td>46</td>
<td>34</td>
<td>41</td>
<td>14 (13v/1h)</td>
</tr>
<tr>
<td>Effective length</td>
<td>0.8 m</td>
<td>1.2 m</td>
<td>0.5 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Gradient/ Field Range</td>
<td>1.0-10 T/m</td>
<td>1.0-10 T/m</td>
<td>4-40 T/m²</td>
<td>0-0.2 T</td>
</tr>
<tr>
<td>Field Quality</td>
<td>±1·10⁻³</td>
<td>±1·10⁻³</td>
<td>±5·10⁻³</td>
<td></td>
</tr>
<tr>
<td>Usable aperture</td>
<td>Ø 380 mm</td>
<td>Ø 380 mm</td>
<td>Ø 380 mm</td>
<td>Ø 380 mm</td>
</tr>
<tr>
<td>Inductance</td>
<td>30 H</td>
<td>43 H</td>
<td>1.04 H</td>
<td>0.067 H</td>
</tr>
<tr>
<td>Nominal max, current</td>
<td>300 A</td>
<td>300 A</td>
<td>291 A</td>
<td>280 A</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>670 kJ</td>
<td>950 kJ</td>
<td>37 kJ</td>
<td>2.6 kJ</td>
</tr>
</tbody>
</table>

In quadrupoles type 3 an octupole magnet with gradient 105 T/m³ is embedded.
Super-FRS long multiplet (ASG)

- Total height: 4.5 m
- Weight: 70 t
- Other lengths:
  - 6.2 m
  - 5.5 m
  - 2.7 m
  - 2.0 m
Super-FRS long multiplet

Design and manufacturing of multiplet according to AD2000
<table>
<thead>
<tr>
<th>RISK ID</th>
<th>DESCRIPTION</th>
<th>MITIGATION</th>
<th>PROBABILITY</th>
<th>IMPACT</th>
<th>RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Injury of Personnel</td>
<td>Electric short</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>insulation, design by code, quality control, operating and safety</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>instructions, personal safety equipment (insulating gloves and shoes),</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>warning panels, access restrictions,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>LHe vessel overpressure</td>
<td>none</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>redundant safety valves, design by code, operating instructions</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>1.2</td>
<td>Vacuum vessel overpressure</td>
<td>none</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>safety valves, design by code</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>1.3</td>
<td>Cryogen release</td>
<td>none</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cryogen release Safety instructions, warning panels, protections</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>shields, personal safety equipment (life support systems), personnel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>training, access restrictions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>Static stability</td>
<td>none</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>structural design with safety factors, seismic stability analysis,</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>alignment limits, installation instructions, access restrictions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>Fall while lifting</td>
<td>none</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>design by code, CE labelling, operation manual, safety rules, personal</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>protection devices, warning panels, access restrictions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>Fall</td>
<td>none</td>
<td>3</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>access ladders with protections balustrades, operation manual, personal</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>protection devices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>Heavy item fall</td>
<td>none</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lifting points, operation manual, personnel training, personal protection</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>devices, appropriate tooling recommendation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vessel and pipings for liquid and its vapor whose pressure is 0.5 bar more than atmosphere (1.013 bar) at its maximum allowed temperature.
Dipole will be treated in any case as category III vessel (notified body involvement)
Safety device calculations multiplet

L-He vessel: 20 bar

- Most catastrophic event for sizing:
  - loss of insulation vacuum
  - magnet(s) quench
  - dump resistor(s) fails

- Safety devices:
  - Safety valve (opening pressure 20 bar; min. orifice diameter 25 mm)
  - Rupture disc (additional device at 23.5 bar)
Safety device calculations multiplet

Vacuum vessel: 1.3 bar
• Most catastrophic event for sizing:
  after quench pressure rise in LHe circuit to 20 bar
  → rupture of He line and leakage of He-gas into the vacuum vessel
  → further rise of He temperature (and pressure)

• Safety device:
  • Drop-off plate (212 mm diameter)
Safety device calculations dipole

- Similar to multiplet
- Additionally:
  - Possibility of arc formation due to opening of a joint
    - (Not an issue for multiplets because joints are far away from He-vessel wall)
  - About 1.47 cm$^3$ stainless steel could be melted
  - Mitigation actions necessary (increasing tube thicknesses re-inforce wire insulation; G10 supporting parts)
## Voltages and temperatures during quench

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$R_d$</th>
<th>$R_{q_{\text{max}}}$</th>
<th>$V_{q_{\text{max}}}$</th>
<th>$T_{\text{max}}$</th>
<th>$V_{\text{max-coil to ground (ground in the middle)}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0</td>
<td>5.2</td>
<td>441</td>
<td>105</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>1.1</td>
<td>90</td>
<td>53</td>
<td>$\pm$ 360</td>
</tr>
<tr>
<td>Long quadrupole</td>
<td>0</td>
<td>17.8</td>
<td>2130</td>
<td>180</td>
<td>1600</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>11.3</td>
<td>1110</td>
<td>137</td>
<td>$\pm$ 950</td>
</tr>
</tbody>
</table>

Diagram showing the relationship between current ($i(t)$) and time, with parameters $V_{\text{max-coil to ground}}$, $R_q(t)$, and $T(t)$. Diagram of a simple circuit with components $L(i)$, $R_q(t)$, $R_d$, $S_1$, $S_2$, and $PS$.
current leads

- Vapour cooled
- Instrumentation:
  - Temperature sensors on 90% of length (for valve regulation)
  - Temperature sensors on warm terminal
  - Heaters on warm terminal (to prevent icing)
  - Voltage taps
    - Middle of magnet
    - End of the magnets
    - Top of current leads

- All instrumentation has to survive voltages during quench
  - Proper insulation of temperature sensors and heaters required
  - Voltage tap spacing has to consider Paschen effect
  - HV-tests at 2.5 kV are required.
Electrical safety: Paschen curve

Spacing between pins for adjacent voltage taps > 20 mm
Other electrical tests

- Electrical continuity test
  - For large inductance magnets check the presence and order of V-taps at max 100 mA and protect the current source with a resistor equivalent to the dc resistance of the coil at warm
  - Control the current source via software at 0.1 A/s
  
  \[ \textbf{very dangerous due to the high inductance (up to 40 H)} \]

- Inductance measurement with V-I method
  - A standard RLC might be damaged and therefore is not recommended

- Capacitor discharge to investigate the turn-to-turn insulation
  - Is the meter used at CERN suitable for 40 H magnet?
Other safety issues

- Weight of magnets (up to 70 t) → support frame and lifting devices have to be CE-certified
- Cryogenic connection instrumentation flange at >3 m height → instructions/measures for workers protection necessary
Conclusions

- Magnet design driven by requirements of machine
- Risk analysis of magnets
- Find mitigation actions
  - Designing/manufacturing according to standards
  - Instructions for operating testing

- Risk analysis for test station / machine operation
  .. but that’s another topic

Thank you