Sigmaphi magnetic measurements on FAIR HESR dipole and quadrupole magnets

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Samuel Tailhardat, Anthony Le Baquer (SIGMAPHI)
- SIGMAPHI presentation
- Introduction to FAIR project
- Harmonic bench configuration, rotating coil and Flux coil manufacturing
- Measurement qualification
- Measurement results
- Conclusion
Sigmaphi is focused on Accelerator Technologies and Superconducting Magnets

2014: sales budget 22 M€
143 highly qualified people (of which 80 engineers and managers)

- Magnets facility in Vannes (France)
- Electronics facility in Haguenau (France)
- 100% Sigmaphi owned magnets facility in Beijing
- Sales branch in Tokyo (Japan)
Particle beamlines and components
   From optics to installation and alignment

Magnets: from small to very large (resistive, SC, PM, AC)

High stability power supplies

Vacuum

HV Decks

Diagnostics

Installation
The High-Energy Storage Ring (HESR) is dedicated to Strong Interaction studies with antiprotons in the momentum range from 1.5 to 15 GeV/c.

FZJ: German contribution to the international facility FAIR at Darmstadt (HESR)
84 quadrupole magnets
60 cm long, 5.2 t

44 dipole magnets
4.2 m long, 35 t
0.17T < B < 1.7 T

FAIR HESR dipole and quadrupole magnets - SIGMA PHI measurement results
IMMW19, Hsinchu - Taiwan, October 25-30, 2015
FAIR QUADRUPOLE measurements
- Designing and manufacturing of a new harmonic bench
- 1 new rotating coil
- 1 new quadrupole reference magnet

FAIR DIPOLE measurements
- 1 new search (flux) coil
  - long flux coil, 3 planes, 9 trajectories
- Measurement Qualification
- serial Measurement setup

Measurement main issues

Same concept as our « Medaustatron bench »
But for 6 tons

FAIR HESR dipole and quadrupole magnets - SIGMAPHI measurement results
IMMW19, Hsinchu - Taiwan, October 25-30, 2015
Setup of measurement bench thanks to the help of 2 PhD students – Pacman / CERN (Industrial secondment – 2 months)
FAIR HESR dipole and quadrupole magnets - SIGMAPHI measurement results
IMMW19, Hsinchu - Taiwan, October 25-30, 2015
Bench alignment process (with the quadrupole permanent magnet)

1- Marble horizontality

2- Girder fixation and levelling

3- Rotating coil support fixation and alignment (Encoder and motor bearings alignment, with the Faro Arm)
Rotating coil, Design and manufacture

**Dimension**
- External $\varnothing = 98$ mm
- Max reference radius = 46 mm
- Overall length is 2000 mm, Active length = 1500 mm

**Mechanical design**
- sag : 44 $\mu$m
- weight : 10 kg
- material : carbon (115000 N/mm$^2$)

**Litz wire**
- Multi-filament wire = 66 filaments
- External $\varnothing$ 1.15mm, 1 turn

**TOSCA**
By=f(s) (X=40, Y=0) @ 24T/m

@ s=750 mm $\Rightarrow$ B = 4 Gauss
5+/-750mm $\Rightarrow$ B=10$^{-5}$ with 5+/-850mm

FAIR HESR dipole and quadrupole magnets - SIGMAPHI measurement results
IMMW19, Hsinchu - Taiwan, October 25-30, 2015
Rotating coil calibration with our quadrupole permanent magnet

New design

Rotation coil (5 sub coils)

Quadrupole permanent magnet – central position

New analysis
Rotating coil calibration results

D98 Rotating coil CALIBRATION with quadrupole permanent magnet
Rotating coil D98 & Rref=46mm

Final rotating coil offset

<table>
<thead>
<tr>
<th>Offset Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DxBob</td>
<td>2.7 μm</td>
</tr>
<tr>
<td>DyBob</td>
<td>247.6 μm</td>
</tr>
<tr>
<td>Angle Bob</td>
<td>1.67 mrad</td>
</tr>
</tbody>
</table>
D98R46 Rotating coil measurement qualification: axis shift

Parameters

<table>
<thead>
<tr>
<th></th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil sensitivity Dx</td>
<td>22 μm (on 200 μm)</td>
</tr>
<tr>
<td>Coil sensitivity Dy</td>
<td>10 μm (on 85 μm)</td>
</tr>
<tr>
<td>Horizontality</td>
<td>0.026 mrad</td>
</tr>
<tr>
<td>10 level measurements</td>
<td></td>
</tr>
</tbody>
</table>
| 10 successives measurements | Δdx < 1 μm  
|                          | Δdy < 1 μm  
|                          | Δdθ < 0.03 mrad                      |

V shape 60 μm thickness (Kapton) ⇒ 85 μm in dy
FAIR specification @ Inom, R21mm
- b6 < 1
- b10 < 0.05

c10 (b10) @ R21 = 0.01
453.4A, Rref40mm variation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔDx (mm)</td>
<td>0.003</td>
</tr>
<tr>
<td>ΔDy (mm)</td>
<td>0.006</td>
</tr>
<tr>
<td>Δ Angle (mrad)</td>
<td>0.57</td>
</tr>
<tr>
<td>Δ Sum Cn 3to14</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Opening Test
Quad Prototype measurement results
<table>
<thead>
<tr>
<th>Rref21mm</th>
<th>MEASURE</th>
<th>MEASURE</th>
<th>TOSCA</th>
<th>TOSCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I(A)</td>
<td>453.5</td>
<td>758.61</td>
<td>453.9</td>
<td>758.61</td>
</tr>
<tr>
<td>Main field module (T.m)</td>
<td>0.257957</td>
<td>0.300640</td>
<td>0.259801</td>
<td>0.30578</td>
</tr>
<tr>
<td>Gd1 (T.m/m)</td>
<td>12.284</td>
<td>14.316</td>
<td>12.371</td>
<td>14.561</td>
</tr>
<tr>
<td>Gl/I ((T.m/m))/A</td>
<td>0.024602</td>
<td>0.018872</td>
<td>0.024778</td>
<td>0.019194</td>
</tr>
<tr>
<td>Field quality (unit)</td>
<td>+0.48/-0.81</td>
<td>/</td>
<td>+0.56/-0.28</td>
<td>/</td>
</tr>
<tr>
<td>Sum Cn 3to15 (unit)</td>
<td>0.83</td>
<td>0.83</td>
<td>0.56</td>
<td>0.50</td>
</tr>
<tr>
<td>C3</td>
<td>0.30</td>
<td>0.37</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C4</td>
<td>0.44</td>
<td>0.33</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>C6</td>
<td>0.07</td>
<td>0.12</td>
<td>0.26</td>
<td>0.20</td>
</tr>
<tr>
<td>C10</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>C14</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**FAIR specification @ R21mm**
- $|b6| < 1$ unit
- $|b10| < 0.05$ unit
c6 and c10 for series magnets @Inom and Rref21mm

- FAIR specification @ R21mm:
  - |b6| < 1 unit
  - |b10| < 0.05 unit
HESR FAIR dipole
4.2 m long, 35 t
0.17 T < B < 1.7 T

**Search coil Parameter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>29432 mm</td>
</tr>
<tr>
<td>Conductor</td>
<td>litz wire (66 wires)</td>
</tr>
<tr>
<td>Number of turns</td>
<td>5</td>
</tr>
<tr>
<td>Width of the coil + support</td>
<td><strong>11.15 mm</strong></td>
</tr>
<tr>
<td>Height of the coil</td>
<td>6 mm</td>
</tr>
<tr>
<td>Insulated wire diameter</td>
<td>1 mm</td>
</tr>
<tr>
<td>Coil length</td>
<td>6200 mm</td>
</tr>
<tr>
<td>Fringe field coils length</td>
<td>2*1000 mm</td>
</tr>
<tr>
<td>Substrate material</td>
<td>GP03</td>
</tr>
<tr>
<td>Process</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>HALL</td>
<td>beam exit side @1743A, plane 0mm &amp; main trajectory with the specific tool for the fringe field. Fiducial position measurement with the Faro arm.</td>
</tr>
<tr>
<td>SHIM</td>
<td>adjustment (opposite electric side) to be within Leff proto +/-0.5mm.</td>
</tr>
<tr>
<td>FLUX</td>
<td>BL meas @ Ip.s=1743A with current ramp (200A to 1743), Main trajectory, plane 0mm.</td>
</tr>
<tr>
<td>SHIM</td>
<td>adjustment (Electric side = Beam entrance) to be within BL proto +/-3.00E-4.</td>
</tr>
<tr>
<td>FLUX</td>
<td>BL @ 16 I with current ramp (main trajectory &amp; plane 0mm). BL @ 3 I with current ramp (search coil). 9 trajectories (X+/-35mm, step 8.75mm), 3 planes (Y 0/+20/-20mm), 3 current.</td>
</tr>
<tr>
<td>HALL</td>
<td>Local homogeneity (Hall probe fixed on the search coil) @ 3 I ⇒ transverse dB/B.</td>
</tr>
<tr>
<td>FLUX</td>
<td>BL from 0A to 200A (R200A-S-1) (main trajectory &amp; plane 0mm) for the entire BL calculation.</td>
</tr>
<tr>
<td>HALL</td>
<td>Electric side @1743A, plane 0mm &amp; main trajectory with the specific tool for the fringe field. Fiducial position measurement with the Faro arm.</td>
</tr>
</tbody>
</table>
Offset trajectory x+/−35mm step 8.75mm

Search coil

Search coil base plate

Plan adjustment
(y=0, y=+20, y=-20mm)

Search coil external support
specific tool for the fringe field measurement

Repeatability
$\Delta L_{eff} = 0.25 \text{mm}$
HESR-002: Main trajectory and plane 0mm – repeatability one set of measurement (9+1 traj)

<table>
<thead>
<tr>
<th>Time</th>
<th>T° H4 (°C)</th>
<th>T° yoke (°C)</th>
<th>Flux (V.s)</th>
<th>BL(T.mm)</th>
<th>B THM(T)</th>
<th>Leff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13h59</td>
<td>24.6</td>
<td>19.7</td>
<td>14.304</td>
<td>3887.44382</td>
<td>1.043778</td>
<td>3724.397</td>
</tr>
<tr>
<td>14h52</td>
<td>25.7</td>
<td>20.1</td>
<td>14.304</td>
<td>3887.36422</td>
<td>1.043945</td>
<td>3723.725</td>
</tr>
</tbody>
</table>

Repeatability Δ 2.05E-5
Integrated field @1.046T, middle plane before and after opening / closing test

- Magnet opening test

- FAIR HESR dipole and quadrupole magnets - SIGMAPHI measurement results

- IMMW19, Hsinchu - Taiwan, October 25-30, 2015
dBL/BL @ 1.046T
comparison Tosca and Search coil measurements

offset trajectory
Shim, 0.35mm thickness
On each side
dBL/BLproto - main trajectory @ Inom=1743A - after shimming
Conclusion

• Both test benches (harmonic + search coil) have been successfully qualified

• The performances of the prototype magnets have been confirmed to be in line with the calculated predictions

• 8 dipole magnets have been measured and shimmed to be identical to the prototype dipole

• 12 quadrupole magnets have been measured and are within the specification

Thank you for your attention