MULTIPLE FUNCTION MAGNET SYSTEMS FOR MAX IV

Franz Bødker
Research & Technology
Danfysik A/S, Denmark

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Outline

• Production of MAX IV magnet girders
  – What is special
  – Production status and mechanical performance

• Hall probe field mapping
  – Description of concept
  – Stability of alignment & measurements

• Harmonic coil measurements
  – Description of concept
  – Stability of the measurements
  – Some measurement results
Production of MAX IV magnet girders

- MAX IV designed for 3 GeV with very low emittance
- Danfysik is producing 20 each of M1, M2 and U3 with up to 12 magnets
- In total 60 dipoles, 220 steerers, 160 quads, 120 sextupoles, 120 octupoles
- Small Ø25 mm aperture in the multipoles
Top/bottom M1 girder as produced

Yokes machined out of one solid piece of low carbon steel
Machining and production

- Challenging tolerances of ±0.02 mm over full length of up to 3.3 m
- Iterative machining refinement process
- First M1, M2 and U3 completed and machining finished for first 10 M1
- 3D measurement campaign results are within spec
Positioning accuracy for multipoles

- Tolerance built-up is an issue for multipoles
- Special functional machining of sextupoles and octupoles

Multipole midplane surface are placed flushed to girder midplane within +0.00 / -0.01 mm
Hall probe mapper setup

- Precision Hall mapper on long granite table
- Laser feedback on longitudinal z-axis and linear encoders on x,y-axes
- Usual probe positioning not possible without line-of-sight though magnet
- Alignment by scanning over magnetic pins at known positions
- Short term position st.dev. < 2 µm, long term drift <10 µm

Alignment with magnet tip

<table>
<thead>
<tr>
<th>Round</th>
<th>Z (mm)</th>
<th>X (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round 1</td>
<td>2888.777</td>
<td>-61.7454</td>
</tr>
<tr>
<td>Round 2</td>
<td>2888.7697</td>
<td>-61.7483</td>
</tr>
<tr>
<td>Round 3</td>
<td>2888.7695</td>
<td>-61.7465</td>
</tr>
<tr>
<td>Round 4</td>
<td>2888.7698</td>
<td>-61.7491</td>
</tr>
<tr>
<td>Round 5</td>
<td>2888.7709</td>
<td>-61.7448</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.0006</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

Scanning dipole from side & quadrupoles through small holes in yoke

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Hall probe field mapping

- High stability temperature calibrated Hall probe allows on-the-fly mapping
- Large field grid measured on-the-fly of the combined function dipoles
- Interpolated on-the-fly data agree with step-and-go data within $1.6 \cdot 10^{-4}$
- Repeated measurements of field integral stable within $7 \cdot 10^{-5}$

The alignment precision and stability more than adequate
Harmonic insertion coil concept

- For us a new harmonic insertion coil concept
- Coil inserted from girder end with external encoder and motor
- Mechanical coil positioning from girder reference surfaces
- Tangential coil with a 10.7 mm measurement radius
- One short harmonic coil segment for each magnet
- 3-5 coil segments per support rod, 13 segments in total
- Calibration of each segment \(\rightarrow\) phase and gradient strength
- Full test automation with storage of calibration and setup values
Stability of the harmonic measurements

- **Short term repeatability test, st.dev.**
  - Field gradient variation $0.4 \cdot 10^{-4}$
  - Higher harmonics below 0.1 unit
  - Magnet rotation variation 0.01 mrad
  - Very stable

- **Simple test of thermal stability**
  - Field gradient drift 0.2 unit/°C
  - Magnet rotation drift -0.03 mrad/°C
  - Quite modest thermal drift, no problem

- **Long term stability, average for 6 quads**
  - Disassembly of test jig and yoke
  - Three measurements over several days
  - Good stability after solving some test issues
  - Field gradient variation $2 \cdot 10^{-4}$

$\rightarrow$ OK stability $\rightarrow$ supports tuning of strength

**Short term repeatability test on a quad**

<table>
<thead>
<tr>
<th>Test on M1 quad</th>
<th>Repeatability</th>
<th>Thermal change/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field gradient strength</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Higher harmonics, n3-4</td>
<td>&lt; 0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Higher harmonics, n≥5</td>
<td>&lt; 0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>Magnet center dX, dY</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Magnet rotation</td>
<td>0.01</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

**Long term stability with jig/yoke disassembly**

<table>
<thead>
<tr>
<th>Average result, 6 quads</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field gradient strength</td>
<td>2</td>
</tr>
<tr>
<td>Higher harmonics, n3-6</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>Higher harmonics, n≥7</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Magnet center dX,dY</td>
<td>0.004</td>
</tr>
<tr>
<td>Magnet rotation</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Higher harmonics of an M2 quadrupole

- Pole end contributions $n=6,10,14 \rightarrow$ reduced for U1-5 quads by chamfering
- Remaining harmonic errors: mainly sextupole ($n=3$) and octupole ($n=4$)
- Remaining terms typically below 1 unit = 0.01% $\rightarrow$ pole profile is ok
- Measuring noise level is low
- Similar pattern for sextupole and octupole magnets
Higher harmonic variations with excitation

- Higher harmonics are relatively constant with excitation
- Exception is the skew and normal sextupole – tend to grow with current
- Might be due to asymmetries in flux return paths & permeability
- Variation is only a few units
- Similar trends for sextupole & octupole magnets
- Test finished for first M1, M2 and U3 girder magnets

\[ \text{Focusing quad, M2} \]

\[ \text{Defocusing quad, M2} \]
Summary

• MAX-lab magnet girders are machined to the required tolerances

• Hall probe field mapping with very good alignment and stability

• Harmonic coils inserted from girder end give high quality results

• The results are in general agreement with MAX-lab calculations

• No show stoppers so far 😊