MULTIPLE FUNCTION MAGNET SYSTEMS FOR MAX IV

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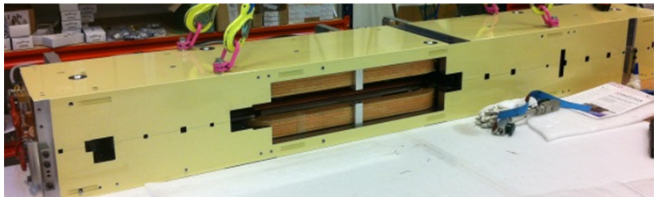
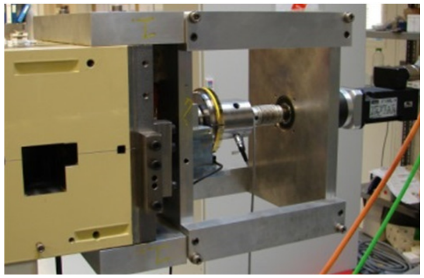
Outline

- 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

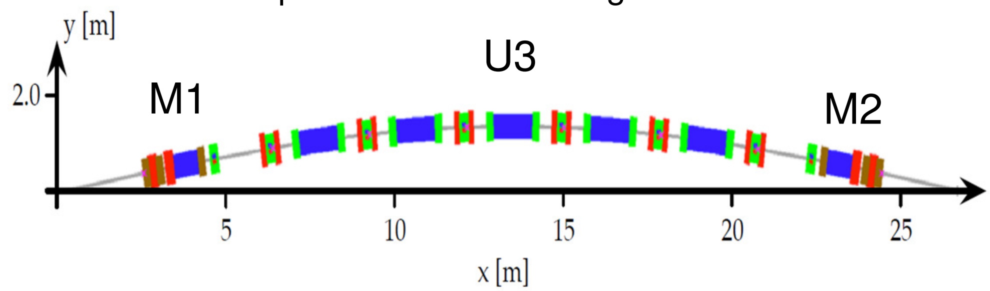
- Harmonic coil measurements
  - Description of concept
  - Stability of the measurements
  - Some measurement results



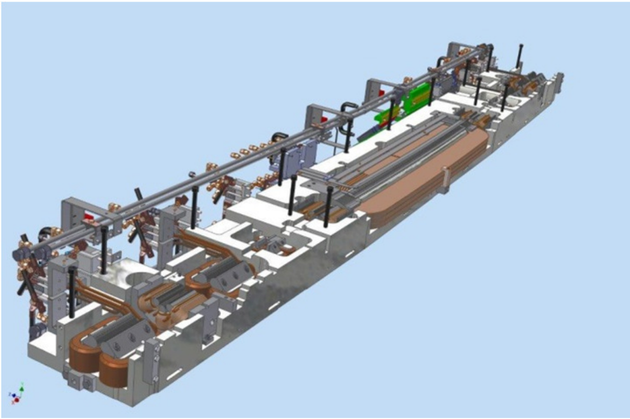
Production of MAX IV magnet girders

- 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

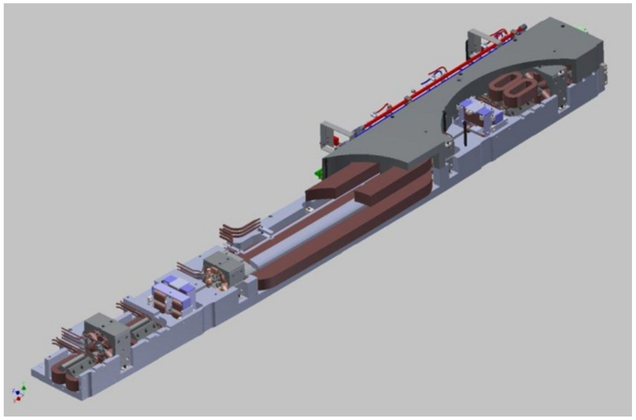
Girder positions in the 20 ring achromats



M1

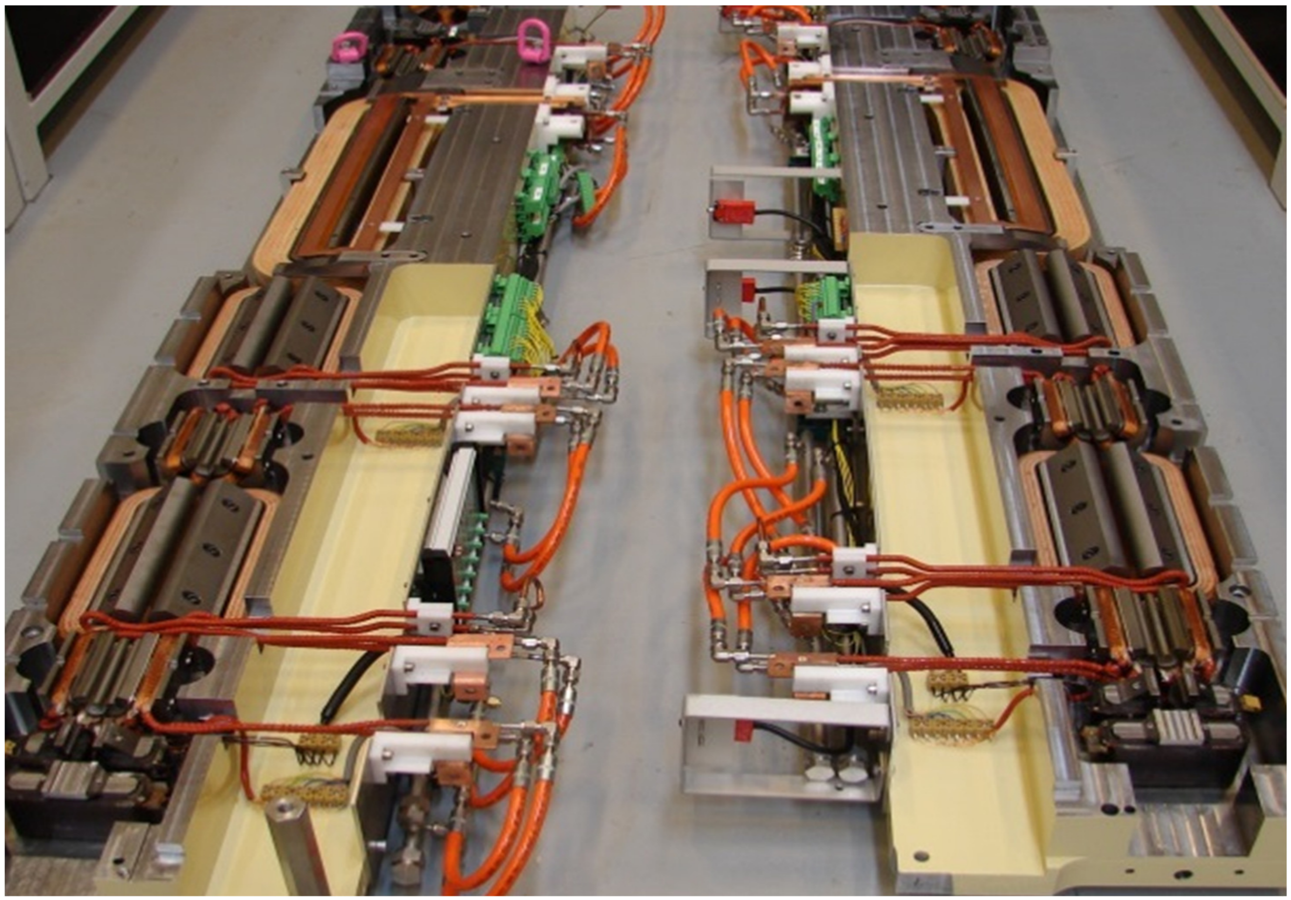


U3



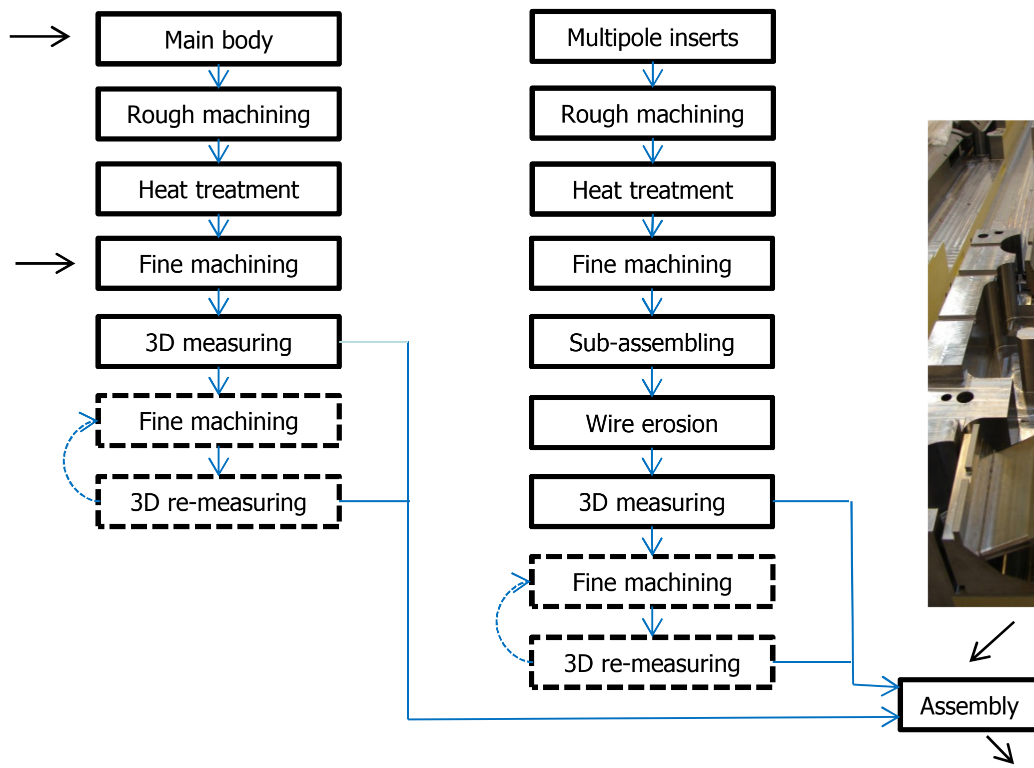
Top/bottom M1 girder as produced

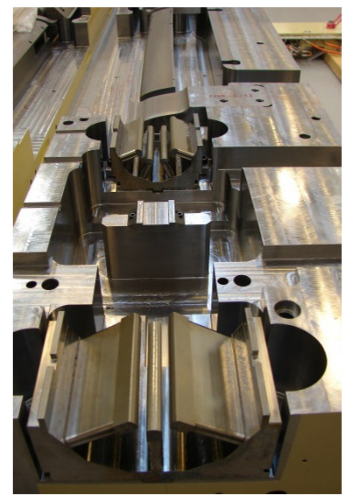
Yokes machined out of one solid piece of low carbon steel

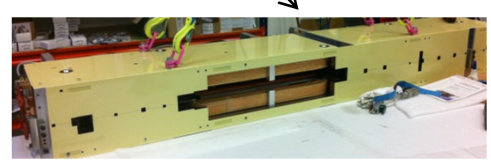


Machining and production

- 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







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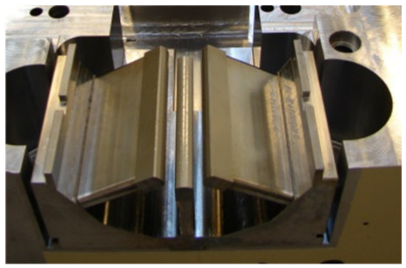
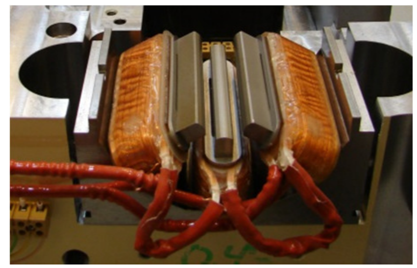
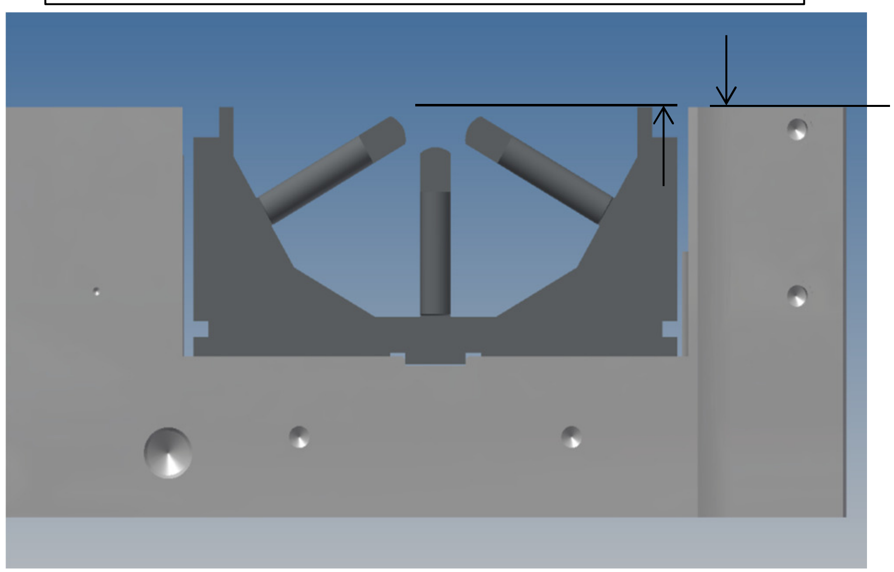
Positioning accuracy for multipoles

- 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



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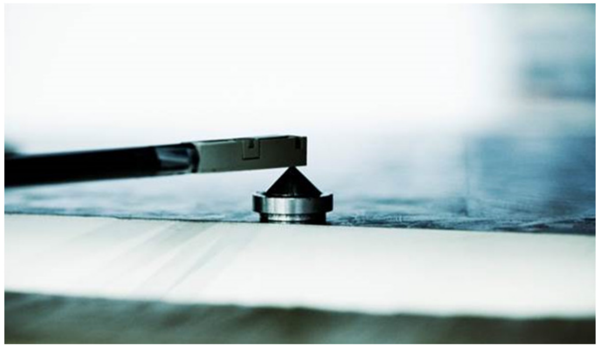
Hall probe mapper setup

- 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 know positions
- Short term position st.dev. < 2 μm, long term drift <10 μm

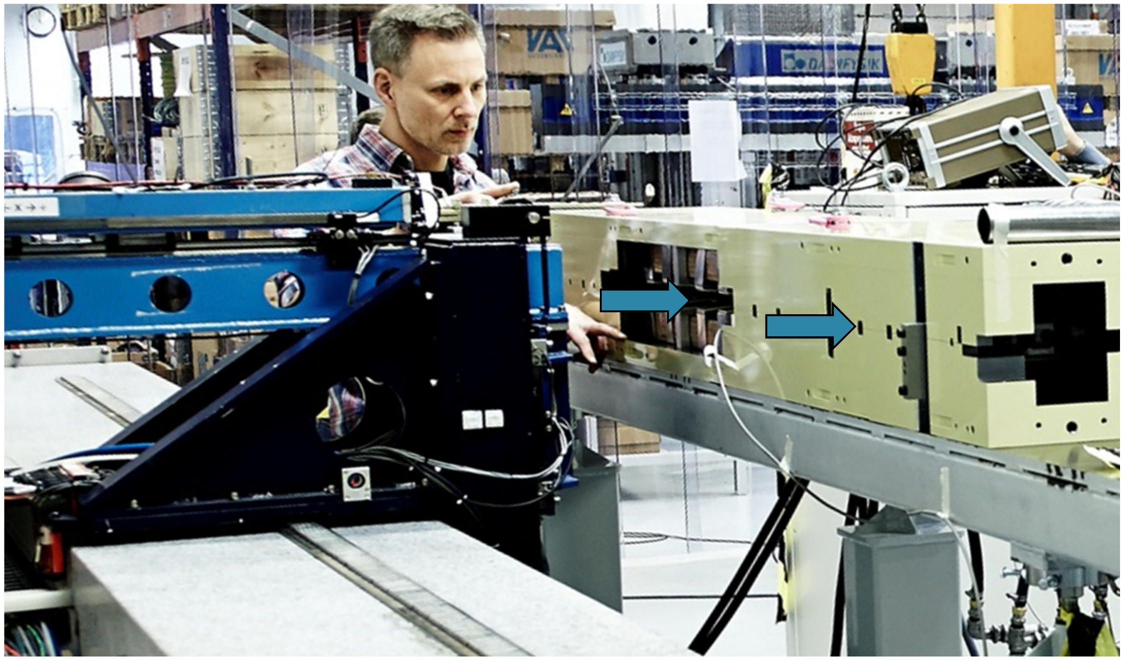
Alignment with magnet tip



Short term repeatability

	Z (mm)	X (mm)
Round 1	2888.7707	-61.7454
Round 2	2888.7697	-61.7483
Round 3	2888.7695	-61.7465
Round 4	2888.7698	-61.7491
Round 5	2888.7709	-61.7448
St. Dev.	**0.0006**	**0.0016**

Scanning dipole from side & quadrupoles through small holes in yoke

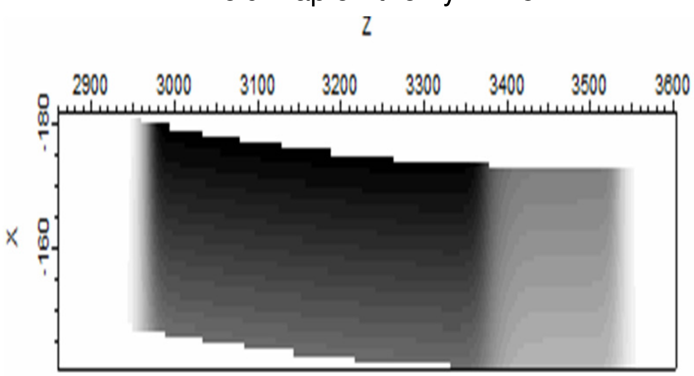


Hall probe field mapping

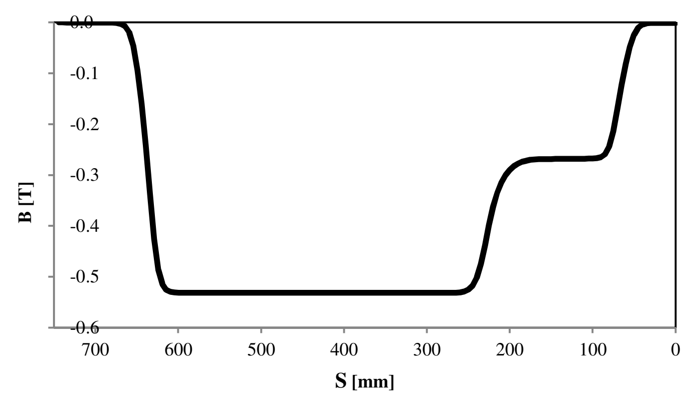
- High stability temperature calibrated Hall probe allows on-the-fly mapping
- Large field grid measured on-the-fly of the combined function dipoles
- Interpolated on-the-fly data agree with step-and-go data within $1.6 \cdot 10^{-4}$
- Repeated measurements of field integral stable within $7 \cdot 10^{-5}$

⇨ The alignment precision and stability more than adequate

Field map on-the-fly in 1.5 h

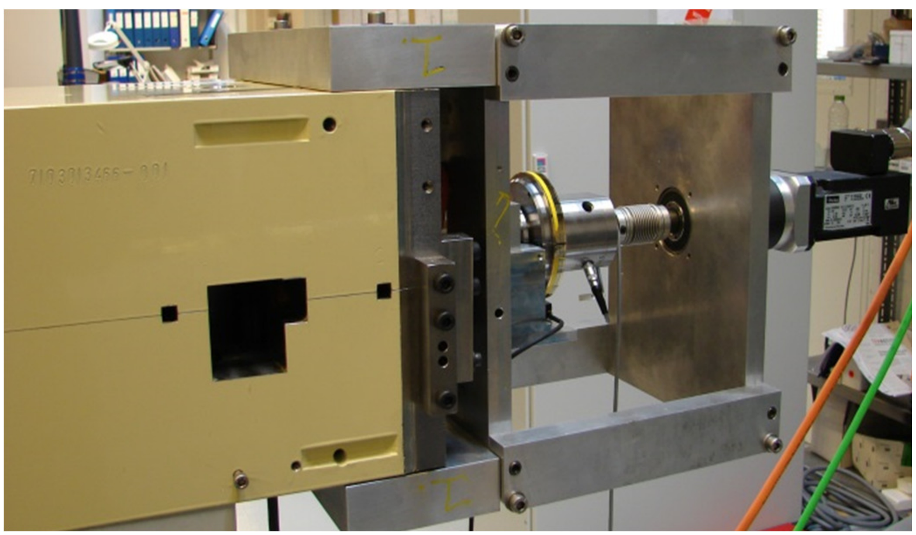


Interpolated field values along trajectory



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 → phase and gradient strength
- Full test automation with storage of calibration and setup values

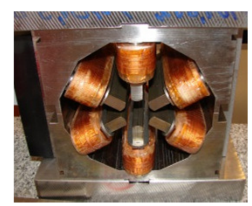


Coil segment positions for U3 (symmetrical ends)

Permanent magnet based calibration quad

160 mm

Calibration sextupole



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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 $2 \cdot 10^{-4}$

⇨ OK stability → supports tuning of strength

Short term repeatability test on a quad

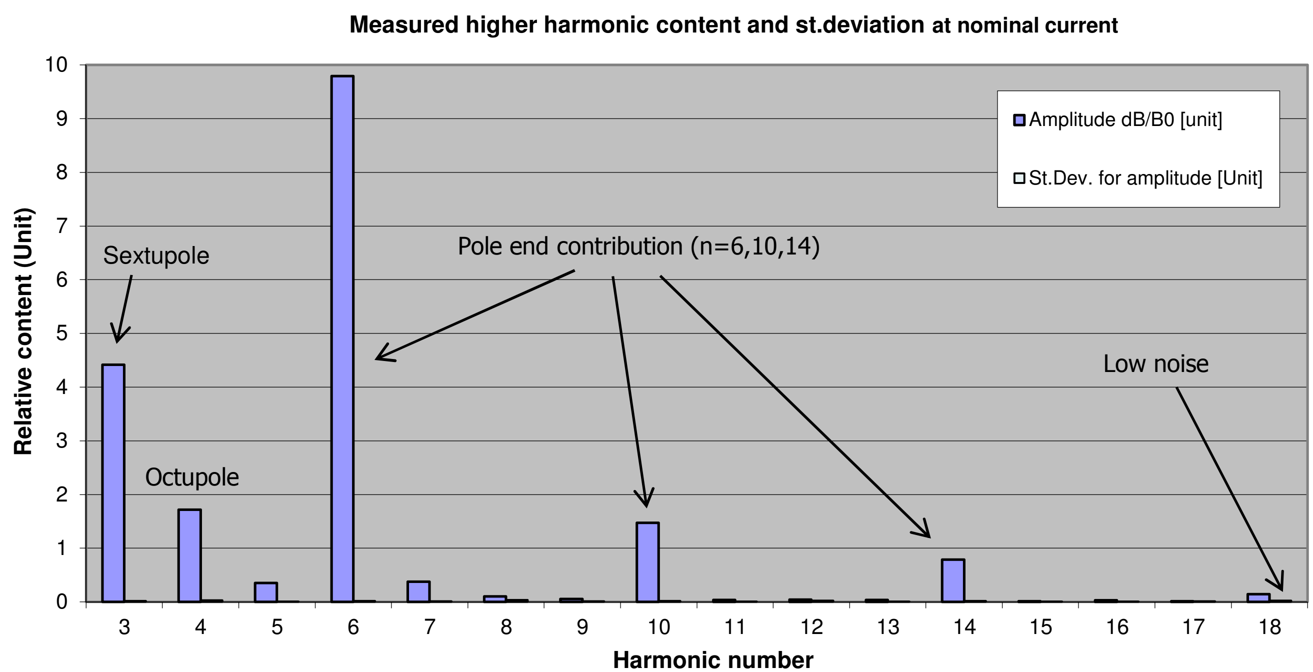
Test on M1 quad	Repeatability	Thermal change/°C	
Field gradient strength	0.4	0.2	Unit, 10^{-4}
Higher harmonics, n3-4	< 0.1	0.2	Unit, 10^{-4}
Higher harmonics, n≥5	< 0.03	0.2	Unit, 10^{-4}
Magnet center dX, dY	< 0.001	< 0.001	mm
Magnet rotation	0.01	-0.03	mrad

Long term stability with jig/yoke disassembly

Average result, 6 quads	Stability	
Field gradient strength	2	Unit, 10^{-4}
Higher harmonics, n3-6	< 0.4	Unit, 10^{-4}
Higher harmonics, n≥7	< 0.1	Unit, 10^{-4}
Magnet center dX,dY	0.004	mm
Magnet rotation	0.14	mrad

Higher harmonics of an M2 quadrupole

- Pole end contributions n=6,10,14 → 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% → pole profile is ok
- Measuring noise level is low
- Similar pattern for sextupole and octupole magnets



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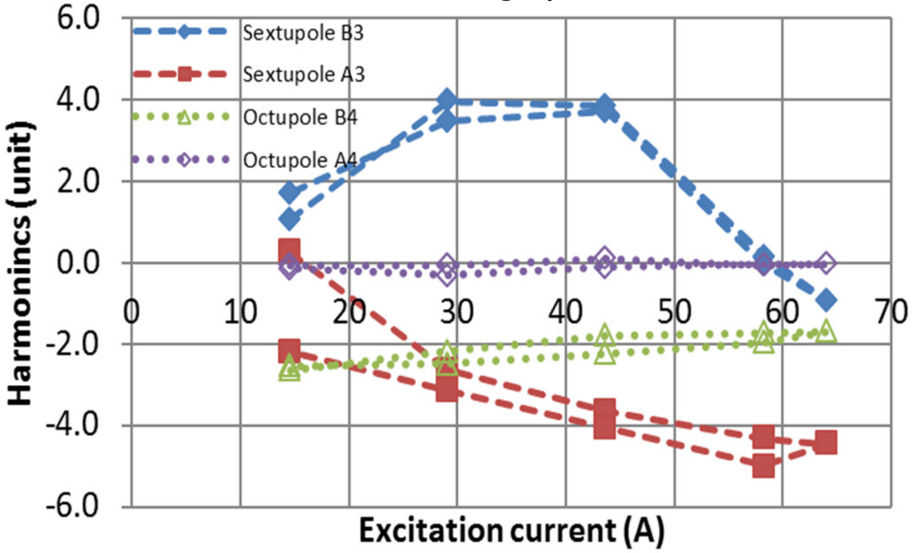
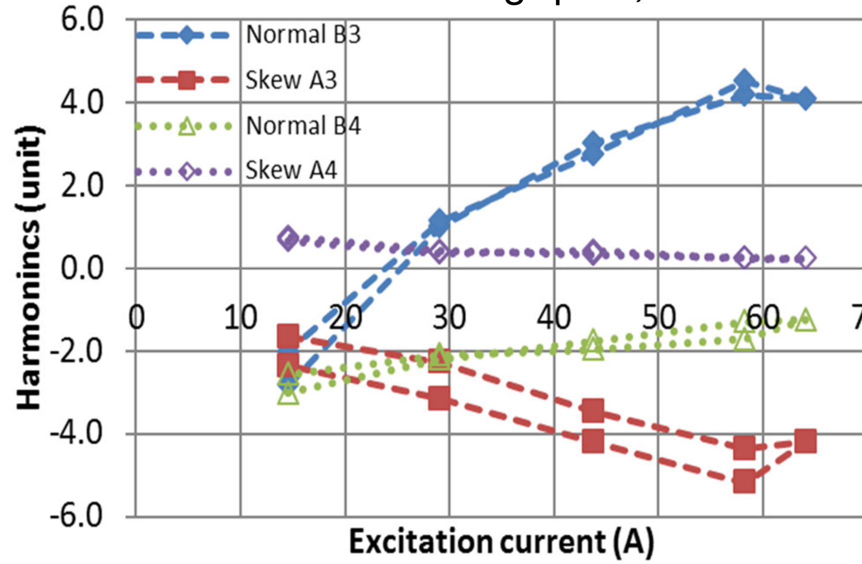
Higher harmonic variations with excitation

- 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

Focusing quad, M2



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 ☺