21st International Magnetic Measurement workshop

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Measurement and fiducialization of the ESRF-EBS magnets

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ESRF | The European Synchrotron

OUTLINE

I. Introduction

- Magnets for the EBS

II. Measurement and fiducialization of the magnet series

- Initial plans, tolerances, difficulties encountered
- Measurements and fiducialization at the ESRF
- Main results

III. Magnet calibration and measurement of combined function magnets

- Calibration, cycling and thermal effects
- Curved dipole-quadrupoles
- Combined function sextupole-correctors

IV. Conclusion

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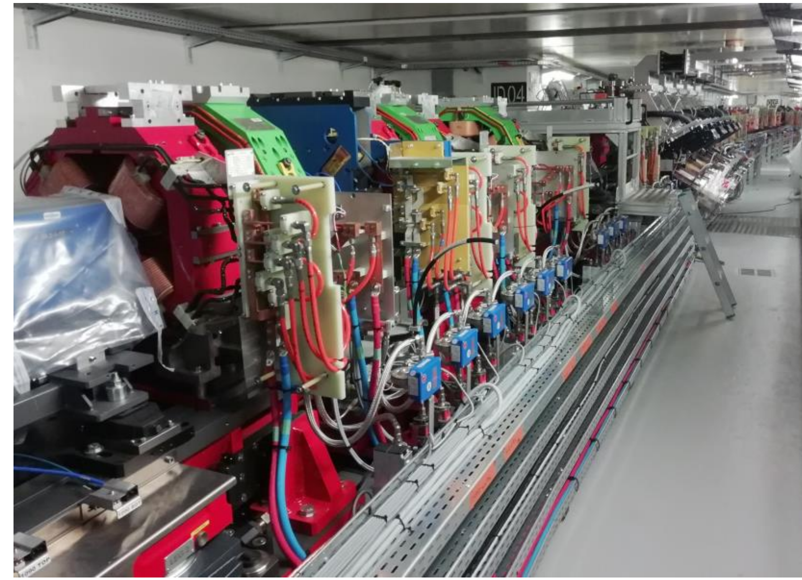
INTRODUCTION

Magnets for the EBS

- About 1000 magnets
- Small aperture magnets
- PM dipoles (see Joël's talk)
- Quadrupoles with gradient ~ 90 T/m
- Dipole-quadrupoles
- Sextupoles
- Octupoles



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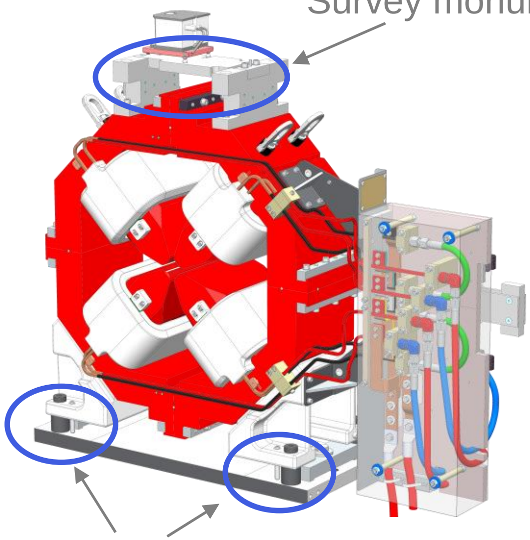
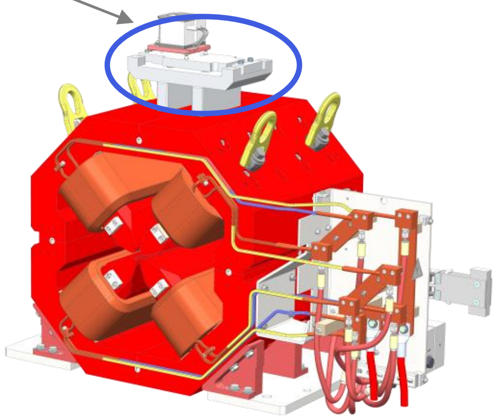
Alignment tolerances

- Fiducialization errors within ± 50 μm
- Magnet centre positioned within ± 50 μm by mechanical shims (depends on magnet families)
- Roll angle tolerance within ± 50 μrad initially, relaxed to ± 130 μrad

Survey monuments and inclinometer plate



Mechanical shims to be adjusted



Magnet without position shim

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Field quality

- The ESRF was responsible for the magnetic design
- Magnets with shape and assembly errors were simulated

Simulated standard deviation of multipoles for the high gradient quads, at 7 mm radius, for a ± 0.04 mm tolerance

n	σ_n	$3\sigma_n$	
1	16.3	49.0	Fiducialization
2	10.0	30.0	Current
3	4.8	14.4	
4	1.9	5.7	Magnetic design
5	1.0	3.1	
6	0.5	1.7	Magnetic design
7	0.3	0.9	
8	0.2	0.5	Magnetic design
9	0.1	0.3	
10	0.06	0.2	Magnetic design

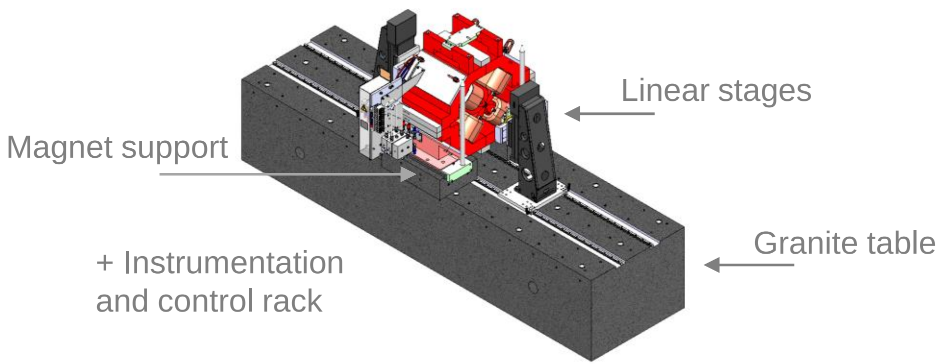
Large values of a_3, b_3, a_5 or b_3 indicate a quality issue and trigs further investigations

- Mechanical tolerances
- Material
- Coil windings

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Initial plans

- Measurements and fiducialization to be done by the magnet suppliers
- Five ESRF stretched wire measurement benches installed at supplier premises
- One (far from Grenoble) supplier encouraged to use its own bench
- Shims to be installed by suppliers for positioning the magnet centres
- Site Acceptance Tests at the ESRF on randomly selected magnets



Design view of a stretched wire bench installed at magnet factory

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Difficulties encoutered

- Our benchs are prototypes rather than commercial products
  - → Maintenance and software updates needs “expert” users
  - → Press-button measurement macros developed… with a few bugs

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- Calibration of the benches
  - → Weekly measurement of a reference magnet

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- Calibration of the benches
  → Weekly measurement of a reference magnet

- Fiducialisation
  → The
  → Meas
  magnet
  → Meas ne with
  usual to
  → The pliers
  were ou

The fiducialization was the main difficulty

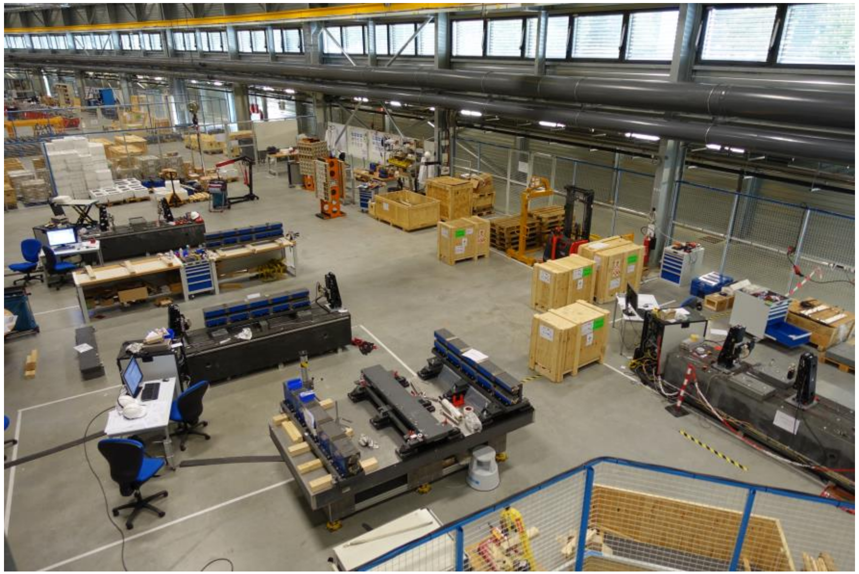
Solutions envisaged

1. To send laser trackers and staff to the factories
2. **To fiducialize all magnets in house (adopted)**

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Measurement zone at the ESRF

- 132 PM dipoles assembled and measured
  →Two stretched wire measurement benches
- About 800 magnets to characterize in ~ 1 year
  → Two additional benches dedicated to the SAT and fiducialization



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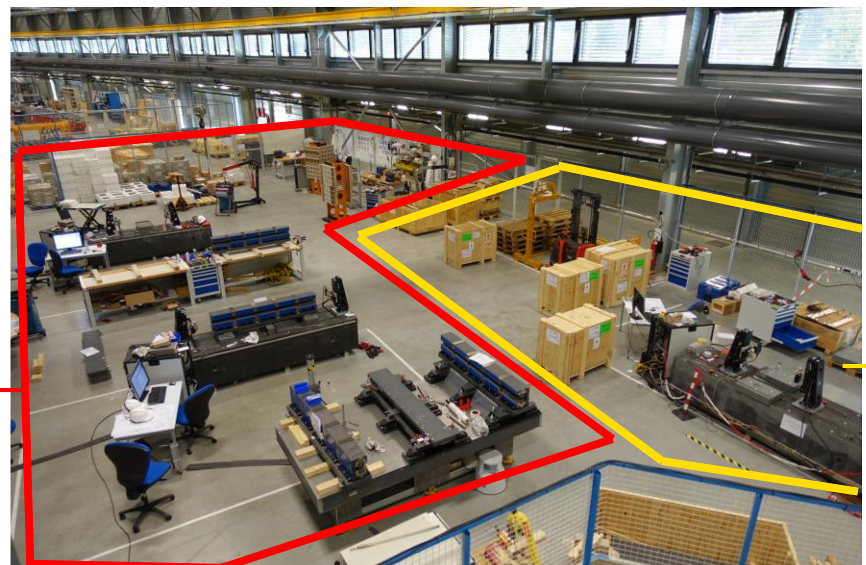

PM dipole assembly and measurements

Pre-series tests and ficucialization zone

Measurement zone at the ESRF

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  → Two stretched wire measurement benches
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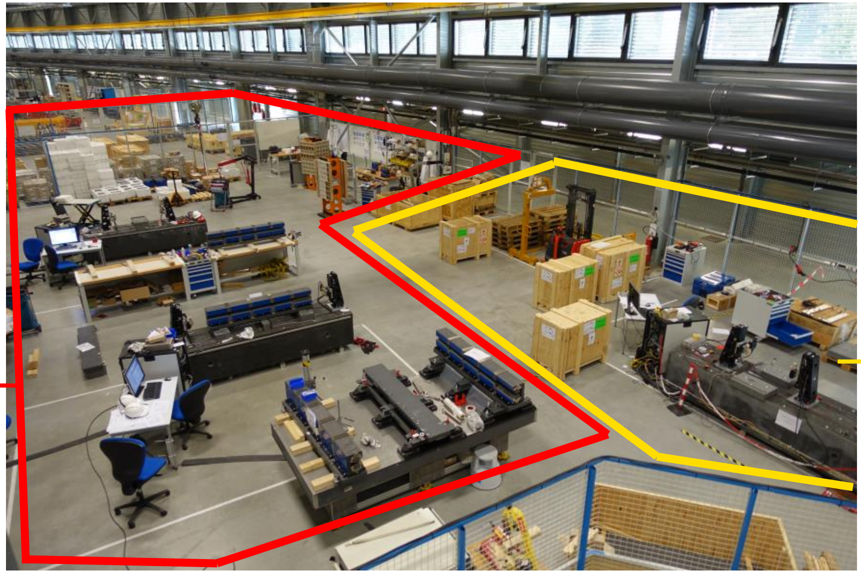
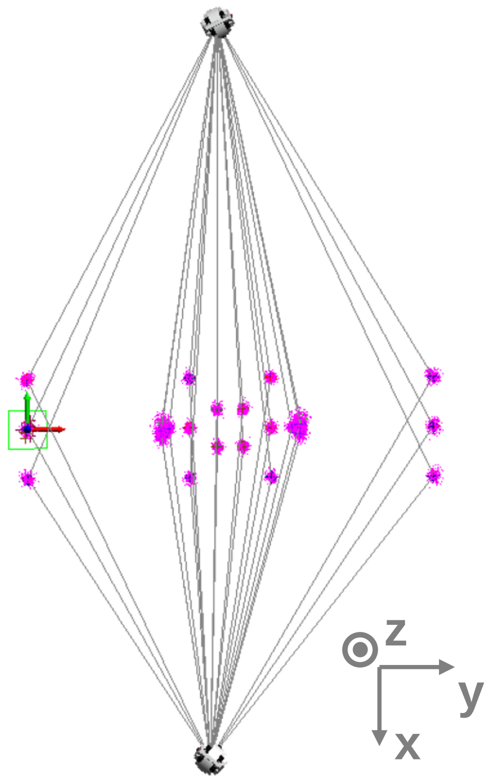
Magnet handling and short term storage



Fiducialization and measurements

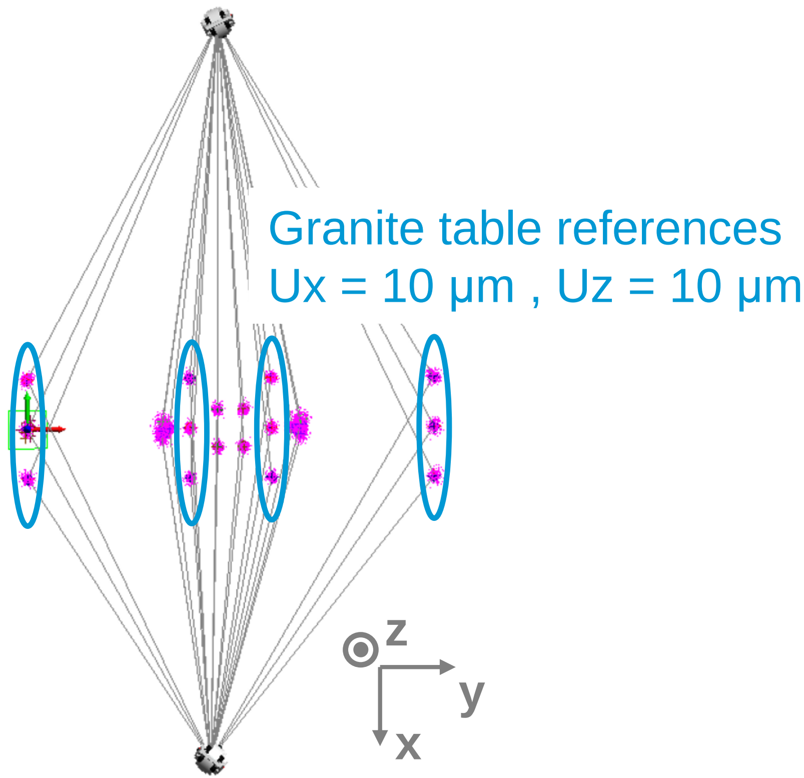
MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Coordinate measurements with two laser tracker stations



[Courtesy D. Martin, ESRF, IWAA2018]

Coordinate measurements with two laser tracker stations



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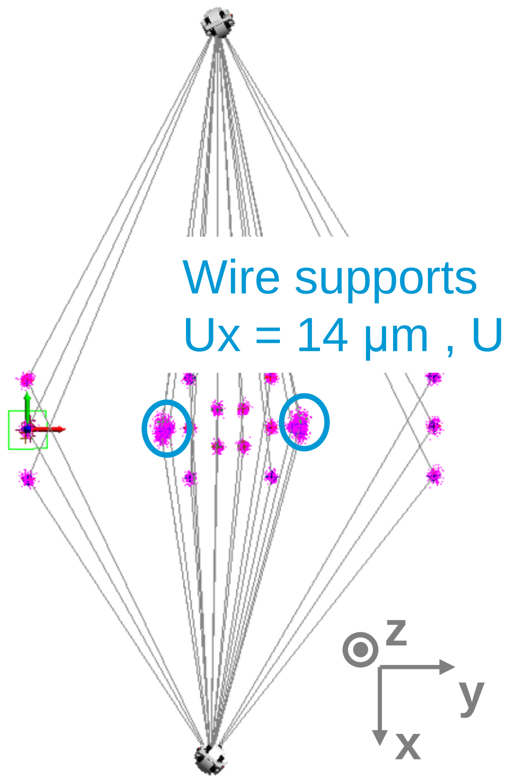

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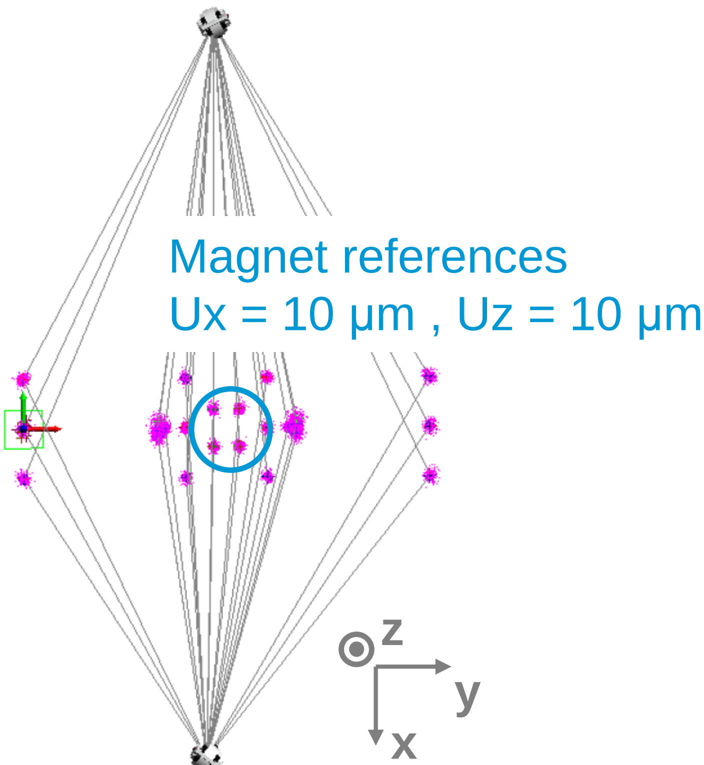

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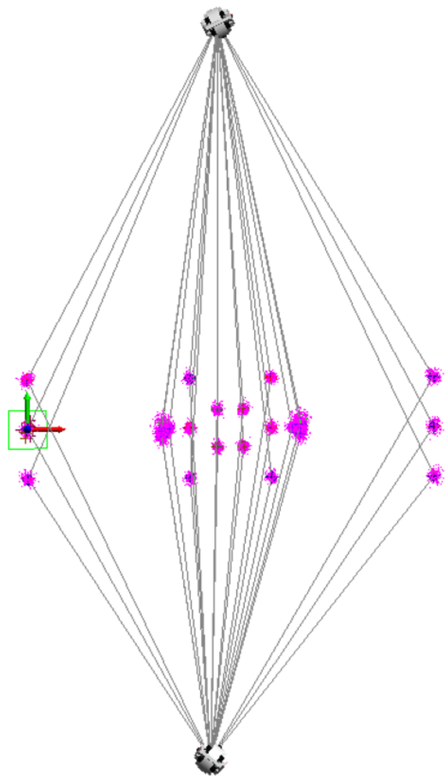
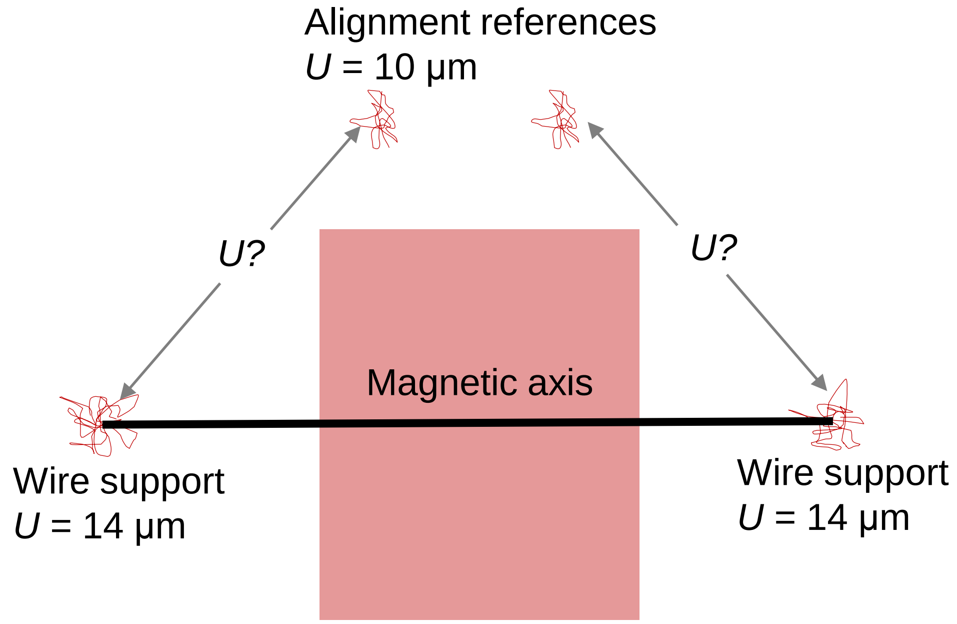
Uncertainty analysis



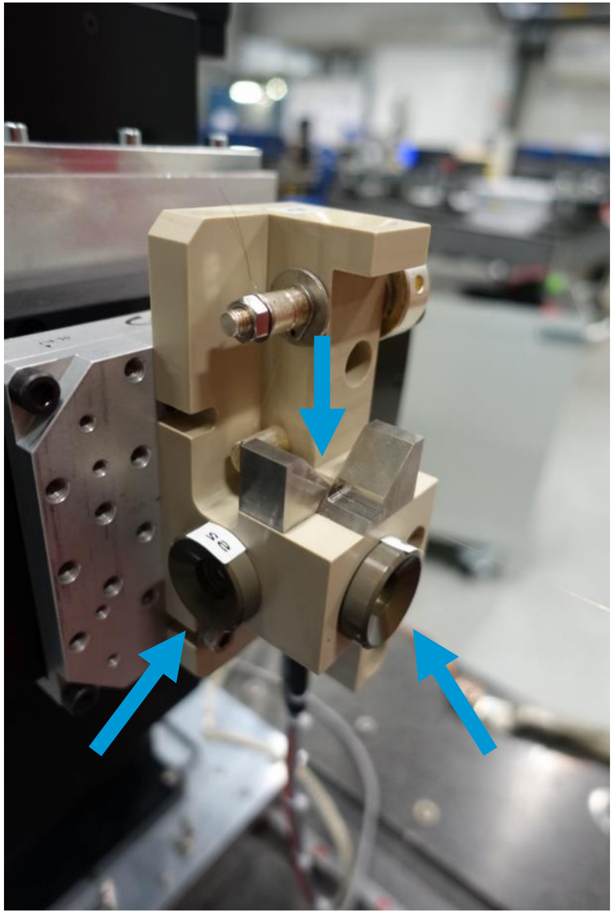


MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Uncertainty analysis

1. Calibration of the wire support references

$U_X = 15$ µm, $U_Z = 18$ µm



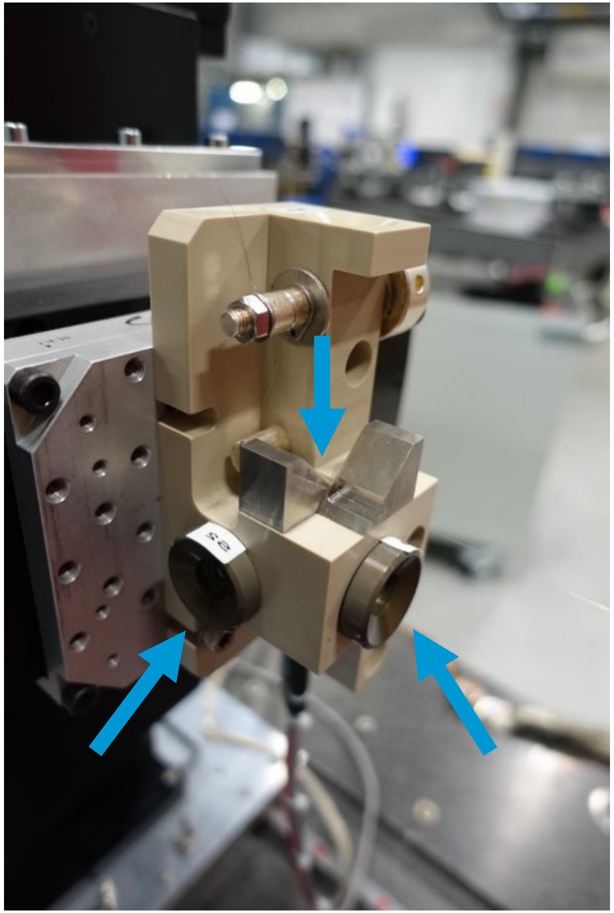
Uncertainty analysis

1. Calibration of the wire support references

$U_X = 15$ μm, $U_Z = 18$ μm

2. Magnetic measurement

$U_{MM} = 4$ μm (including wire diameter)



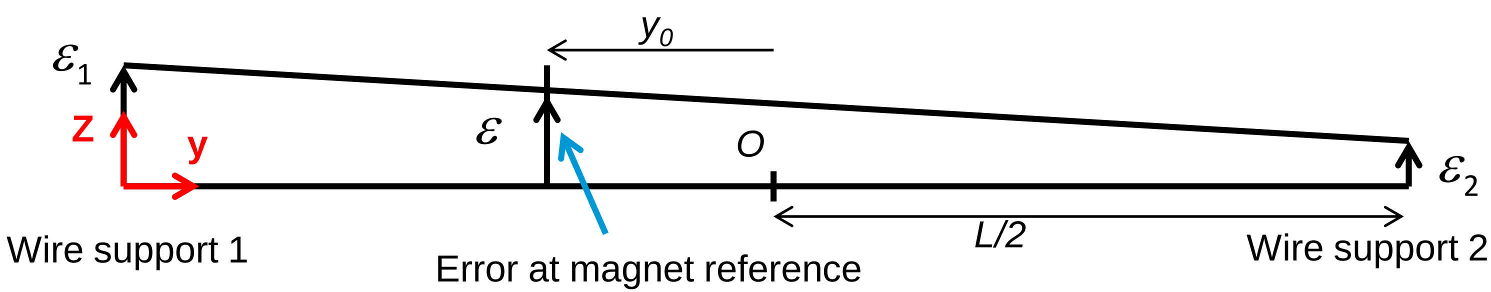
Uncertainty analysis: one reference

3. Measurements of the wire supports

$$\varepsilon = \frac{\varepsilon_1 + \varepsilon_2}{2} + \frac{\varepsilon_2 - \varepsilon_1}{L} y_0$$

$$U_{WS}{}^2 = \mathrm{Var}\left(\frac{\varepsilon_1 + \varepsilon_2}{2}\right) + \mathrm{Var}\left(\frac{\varepsilon_2 - \varepsilon_1}{L} x_0\right) + \mathrm{Cov}\left(\frac{\varepsilon_1 + \varepsilon_2}{2}, \frac{\varepsilon_2 - \varepsilon_1}{L} y_0\right)$$

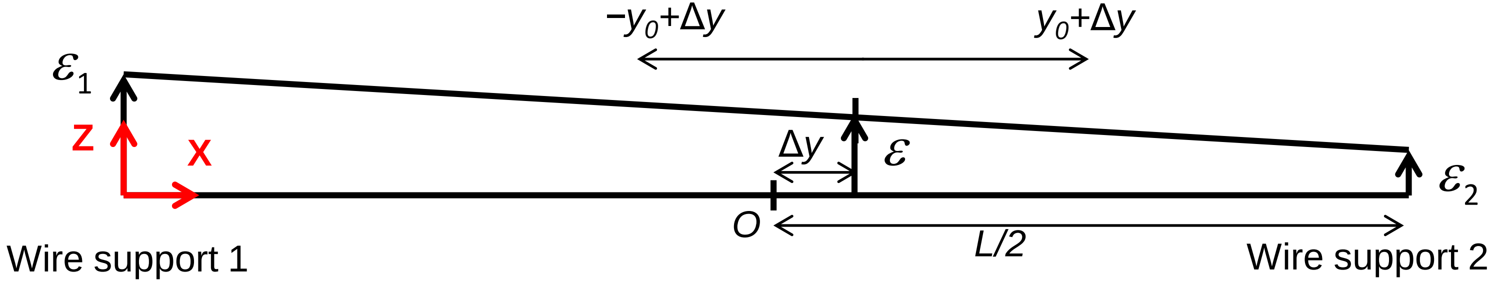
$$= \frac{\sigma_{WS}{}^2}{2L^2}\left(L^2 + 4y_0{}^2\right)$$



Uncertainty analysis: four references

3. Measurements of the wire supports

$$U_{ws}^2 = \frac{\sigma_{ws}^2}{4L^2}\left(L^2 + 4\Delta y^2\right)$$



Uncertainty analysis

4. Measurement of the magnet reference $U_{REF}{}^{2} = \sigma_{REF}{}^{2}$

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Uncertainty analysis

Calibration of the wire supports

Magnetic measurements

Measurements of the wire support references

Measurements of the magnet references

$$U^2 = U_{X,Z}^{\ 2} + U_{MM}^{\ 2} + U_{WS}^{\ 2} + U_{REF}^{\ 2}$$

$$= U_{X,Z}^{\ 2} + U_{MM}^{\ 2} + \frac{\sigma_{WS}^{\ 2}}{4L^2}\left(L^2 + 4\Delta y^2\right) + \sigma_{REF}^{\ 2}$$

Fiducialization uncertainties

$U_{Horiz} = 20$ µm, $U_{Vert} = 22$ µm

with $U_X = 15$ µm, $U_Z = 18$ µm, $U_{MM} = 4$ µm, $\sigma_{WS} = 14$ µm, $\sigma_{REF} = 10$ µm, $L = 1.2$ m and $\Delta y = 1$ cm

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Uncertainty analysis − How much can fiducialization be improved?

$$U^2 = U_{X,Z}{}^2 + U_{MM}{}^2 + U_{WS}{}^2 + U_{REF}{}^2$$

- Using a more accurate CMM may allow to decrease these numbers
- Measure the wire supports instead of its references

With a laser tracker

$U_{X,Z} = 10$ µm, $U_{MM} = 4$ µm, $\sigma_{WS} = 10$ µm, $\sigma_{REF} = 10$ µm,
$L = 1.2$ m and $\Delta x = 1$ cm ➔ $U = 15.5$ µm

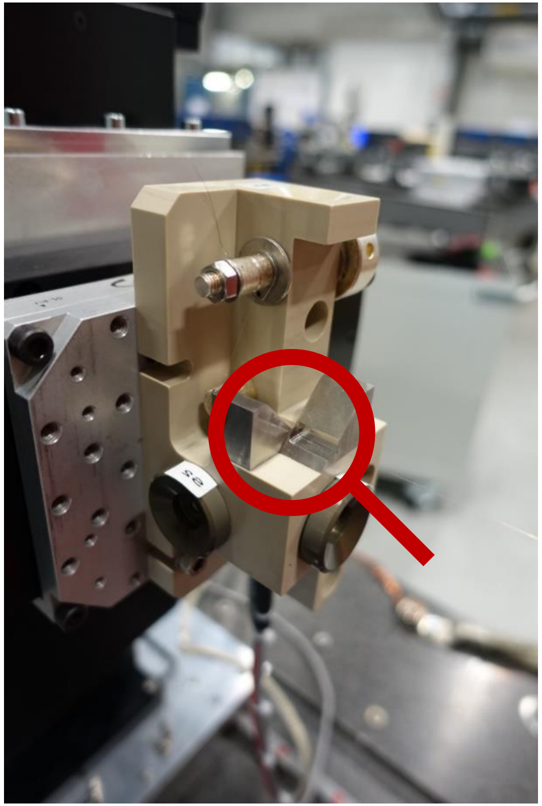
With a CMM

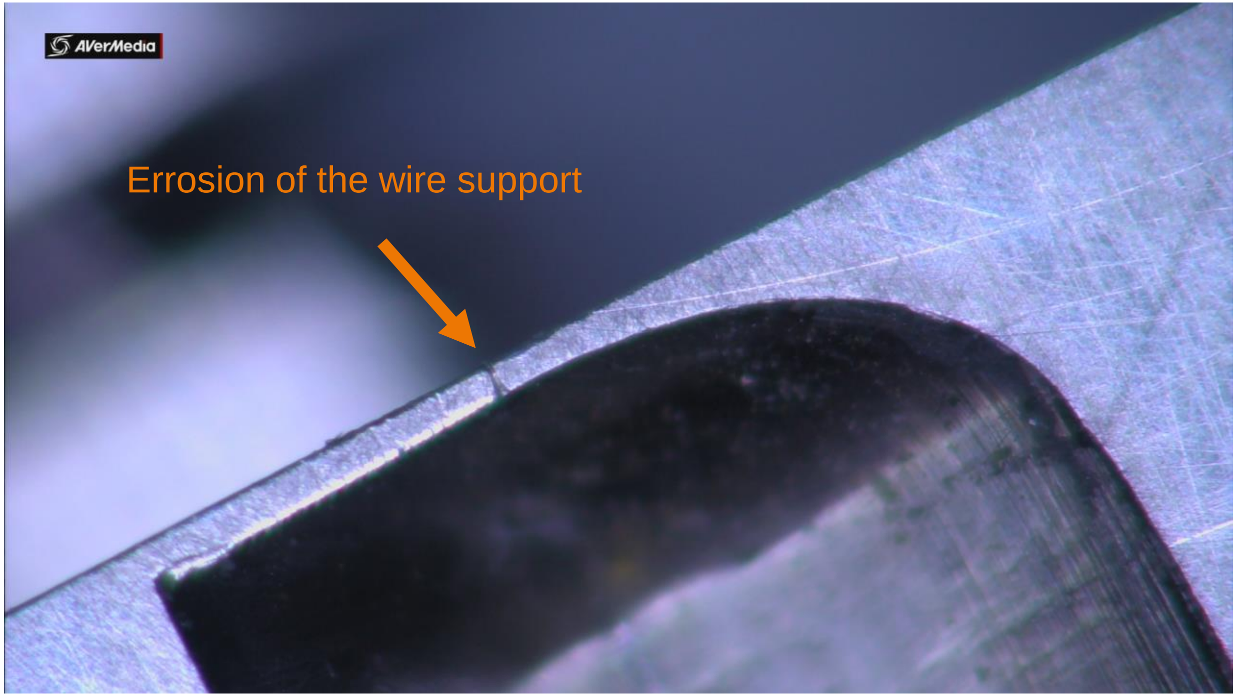
$U_{X,Z} = 0$ µm, $U_{MM} = 4$ µm, $\sigma_{WS} = 5$ µm, $\sigma_{REF} = 5$ µm,
$L = 1.2$ m and $\Delta x = 1$ cm ➔ $U = 7.5$ µm

This would imply a lot of engineering…

… and would not solve all possible issues!

Uncertainty analysis − How much can fiducialization be improved?





MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Uncertainty analysis − How much can fiducialization be improved?

- Using a more accurate CMM
- Measure the wire supports instead of its references
- Use finer wire
- Frequent measurements of a reference magnets are necessary (recalibration once per week during the EBS magnet measurements)

Fiducialization uncertainties are NOT alignment uncertainties

- Magnet alignment on girders
  → Position shims may help as it avoid a 2nd measurement of the references
- Alignment between girders
- Transportation(s)
- Thermal effects (time constants ~ 5 h)
- …

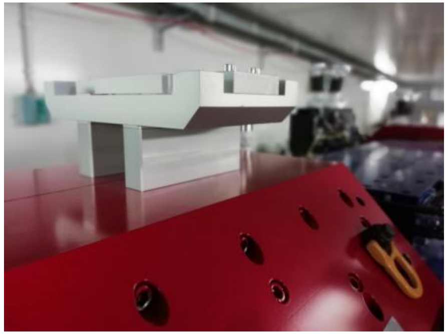
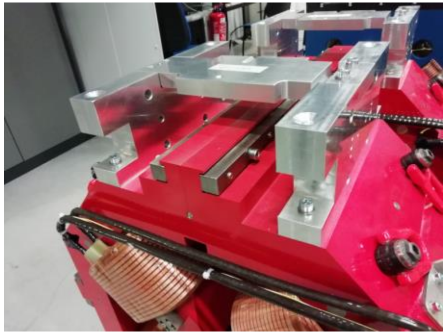
MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

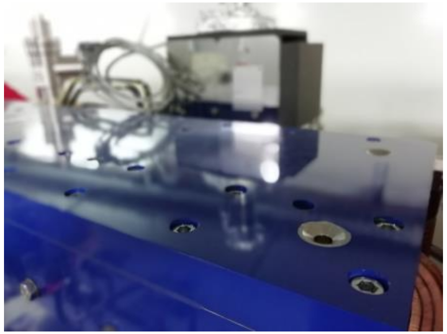
References before fiducialization vs magnetic center

- Loose tolerances specified (the position errors were measured)
- Show how the references are improved by the fiducialization
- Depends on the design

Magnet familly	Horiz. σ_X [mm]	Vert. σ_Z [mm]	Long. σ_Y [mm]
Q-MG	0.14	0.14	0.26
Q-HG	0.28	0.18	0.38
S	0.11	0.14	0.22
DQ	0.12	0.14	0.22

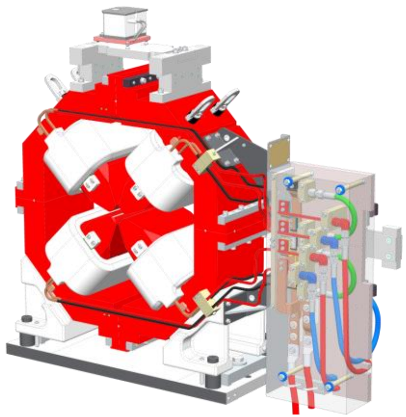
One order of magnitude improvement by fiducialization

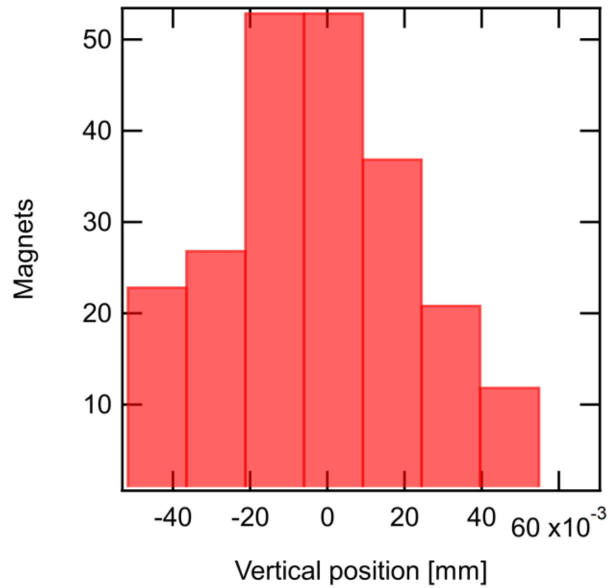



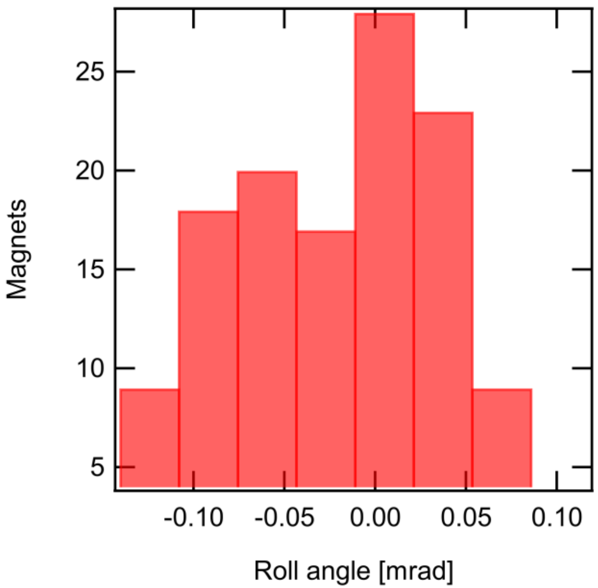


MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Alignment shims





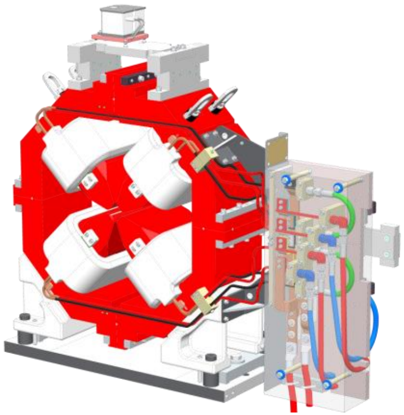


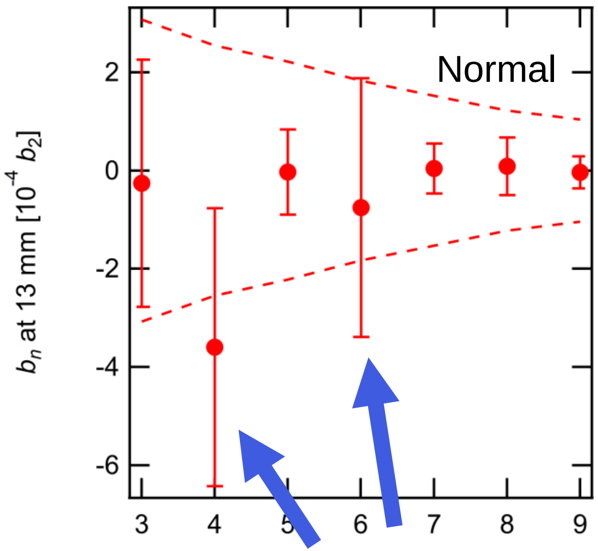
QD2 moderate grad. quads
220 magnets
Gradient ~ 50 T/m
Bore radius: 16.4 mm
GFR radius: 13 mm
Iron length: 212 mm
Laminated FeSi, machined poles
Chamfers at pole extremities
Alignment shims

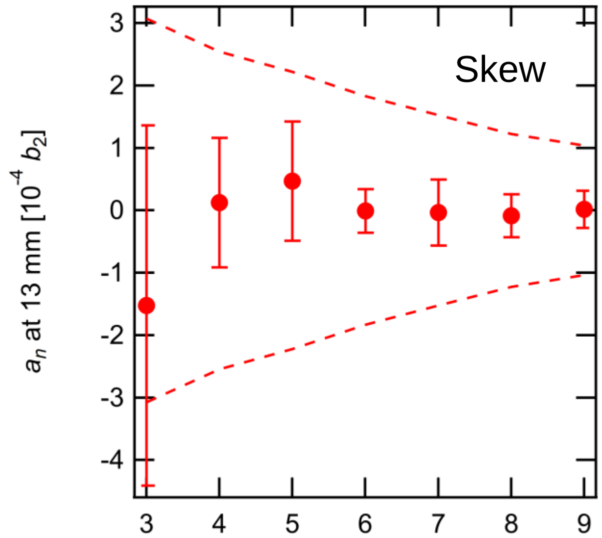
Vertical position and roll angle of shimmed QD2 quadrupoles (tolerance: ± 50 µm, ± 130 µrad)
Vertical position: − 3 ± 24 µm, roll angle: −19 ± 60 µrad
Vertical position: − 3 ± 33 µm if the bench uncertainty is ± 22 µm

MEASUREMENT AND FIDUCIALIZATION OF THE MAGNET SERIES

Higher order multipoles







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Chamfers at pole extremities

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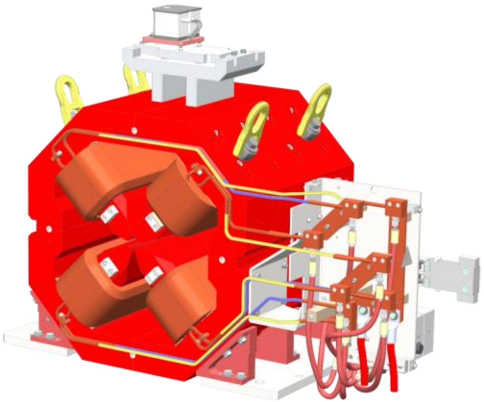
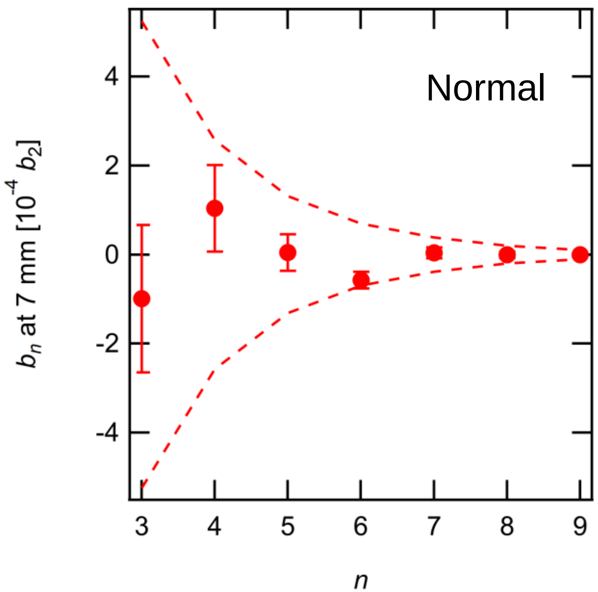
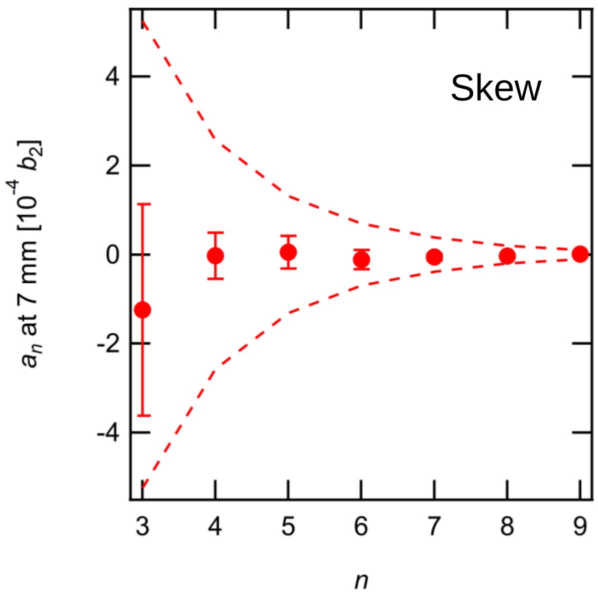
Significantly higher st. dev. for b_4 and b_6
Accuracy of the extremity chamfer machining?

Higher order multipoles



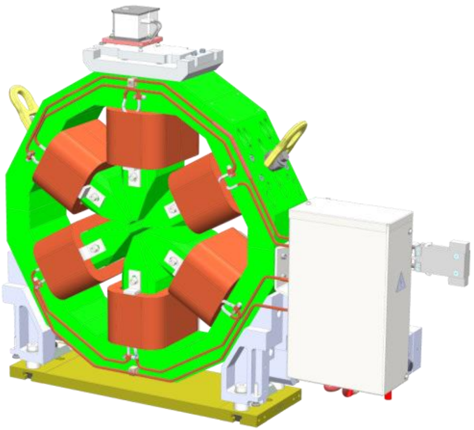




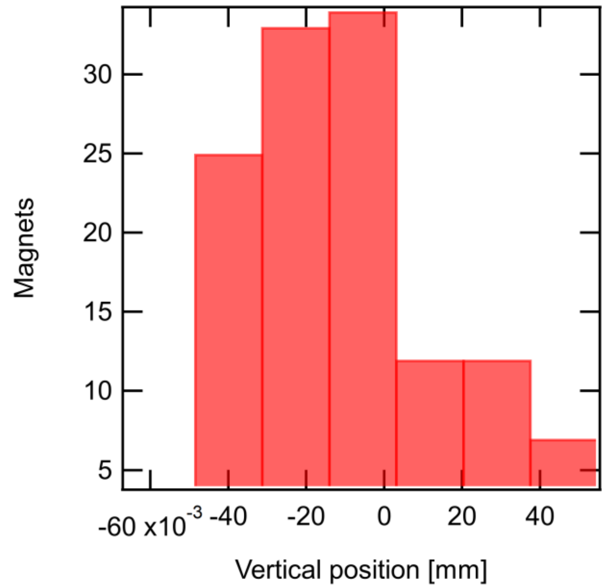
QF8 high grad. quads
66 magnets
Gradient: 88 T/m
Bore radius: 12.5 mm
GFR radius: 7 mm
Iron length: 484 mm
Solid iron (AISI 1010) poles, wire cut
No chamfer at extremity

Dashed lines: mechanical errors with 23 µm st. dev., corresponding to a ± 40 µm uniform distribution of errors

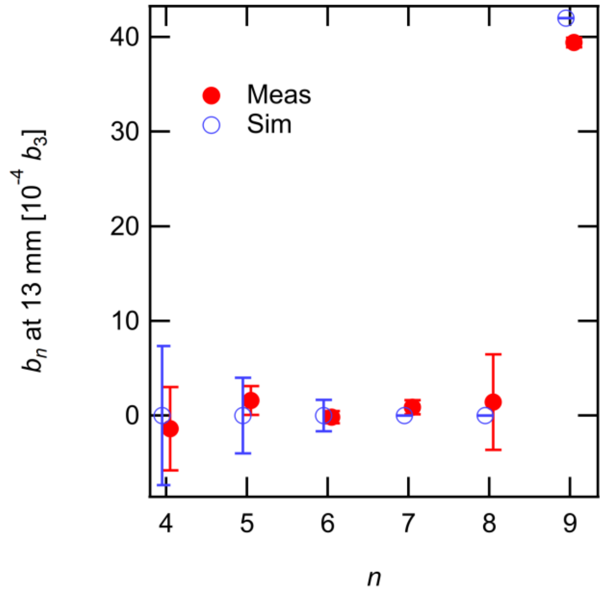
Higher order multipoles



SD1 sextupoles
128 magnets
Gradient: 1700 T/m^2
Bore radius: 19.2 mm
GFR radius: 13 mm
Iron length: 166 mm
Solid iron (AISI 1010) poles wire cut



Vertical position: − 10 ± 34 µm
if the bench uncertainty is ± 22 µm



Simulations: mechanical errors with 23 µm st. dev., corresponding to a ± 40 µm uniform distribution of errors

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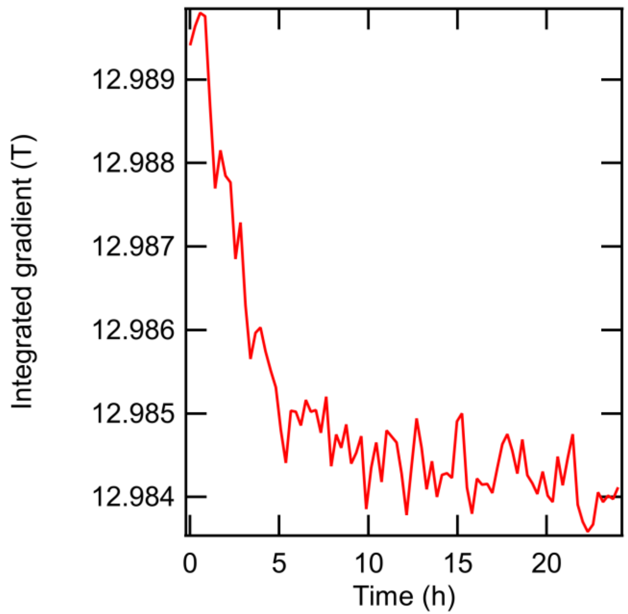
Thermal effects

Moderate gradient quads

Thermal time constant: 5.6 h

$\Delta G/G = 4 \times 10^{-4}$



CALIBRATION, CYCLING AND THERMAL EFFECTS

Thermal effects

Moderate gradient quads

Thermal time constant: 5.6 hours

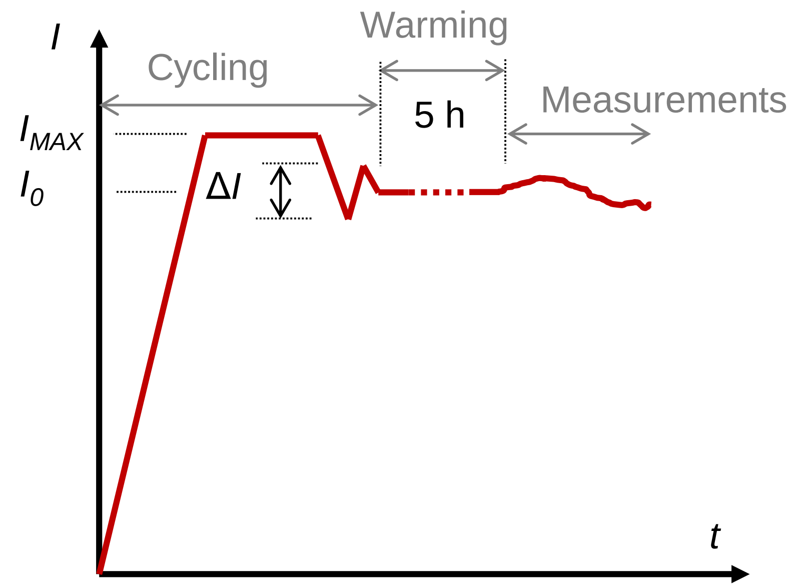
$\Delta G/G = 4 \times 10^{-4}$

Current cycling

- Various cycling schemes studied
- Cycling at restarts, but not during operations: accuracy of current settings?

    → Depends on ΔI

    → Limits the current range



CALIBRATION, CYCLING AND THERMAL EFFECTS

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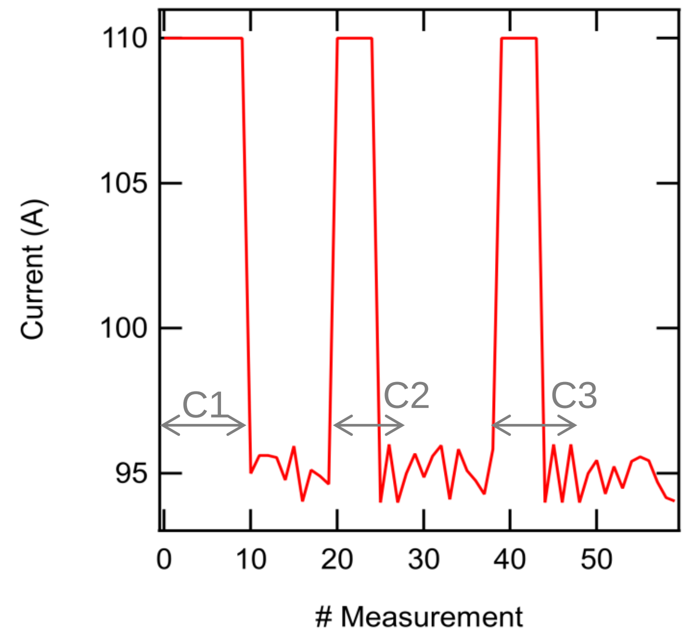
- Cycling at restarts, but not during operations: accuracy of current settings?
  - → Depends on ΔI
  - → Limits the current range

Excitation curves

- Being remeasured using cycle C2 and 5 hours warming time



$\Delta G/G$ for different cycling parameters

	$\Delta I = 2\ A$	$\Delta I = 6\ A$
C1	2.4×10^{-4}	
C2	0.5×10^{-4}	
C3	0.5×10^{-4}	3.4×10^{-4}

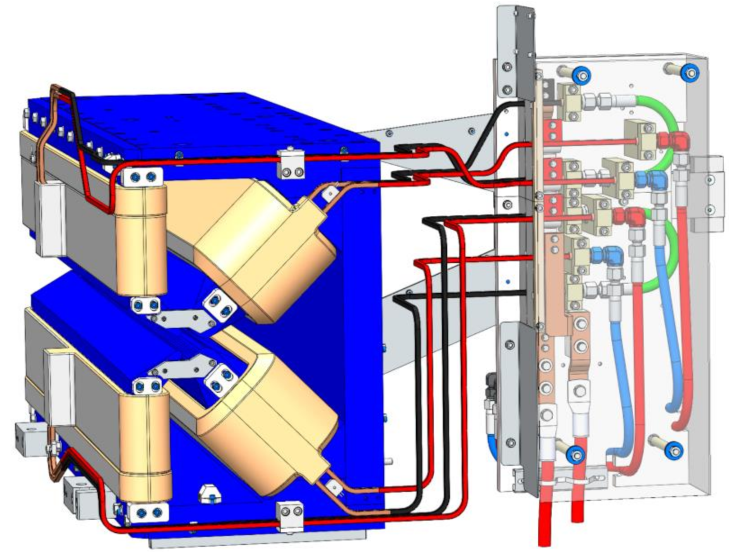
COMBINED DIPOLE-QUADRUPOLE MEASUREMENTS

Dipole-quadrupoles (DQs)

Main parameters (DQ1)
Integrated field: 584 Tmm
Integrated gradient: 38.4 T
Iron length: 1028 mm
Pole radius of curvature: 35.21 m
GFR: 14 x 10 mm x mm

Machined solif iron plates
Curved poles

64 DQ1 and 32 DQ2 installed



Design view of the DQ1 magnet

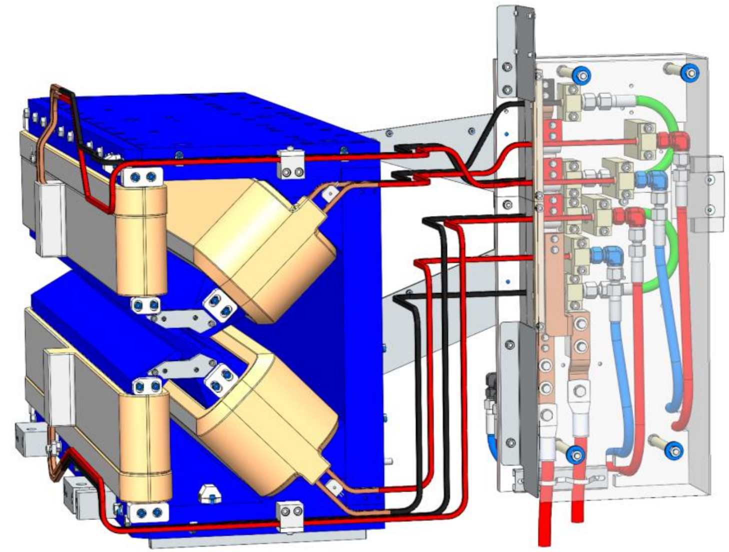
DQ measurement method

Hall probe mapping

- Done on pre-series magnets
- Time consuming
- Limited accuracy: homogeneity and multipoles are difficult to extract

Stretched wire measurements

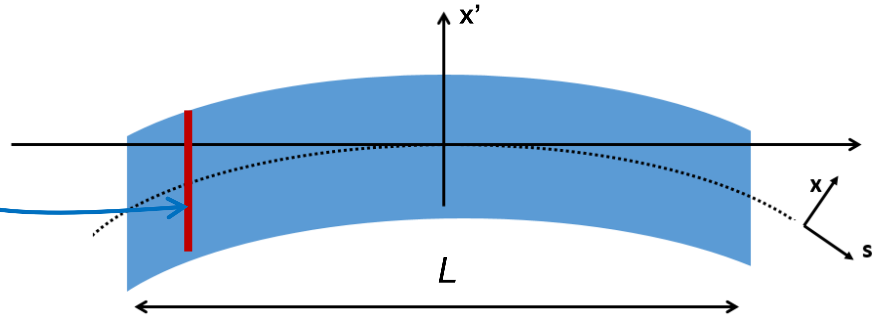
- Preliminary method presented at the previous IMMW
- Some improvements done



Design view of the DQ1 magnet

DQ measurement method

$$B \approx \sum_{n=1}^{N} (\beta_n + i\alpha_n) \left(\frac{u}{\rho_0}\right)^{n-1}$$



$$I = \int B\, dy = \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x' + iz}{\rho_0}\right)^{n-1}$$

$$\approx \sum_{n=1}^{N} \frac{\beta_n + i\alpha_n}{\rho_0{}^{n-1}} \frac{1}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} \left(x' + \frac{l^2}{2R} + iz\right)^{n-1} dl$$

$$\begin{pmatrix} b_1 + i a_1 \\ \vdots \\ b_N + i a_N \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1N} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & A_{NN} \end{pmatrix} \begin{pmatrix} \beta_1 + i\alpha_1 \\ \vdots \\ \beta_N + i\alpha_N \end{pmatrix} \Rightarrow \begin{pmatrix} \beta_1 + i\alpha_1 \\ \vdots \\ \beta_N + i\alpha_N \end{pmatrix}$$

DQ measurement method

Magnet alignment sequence

Field integrals and 2nd field integrals on straight lines

→Magnet centre (including longitudinal position)

→Yaw and pitch angles

→Magnetic length

→Radius of curvature of the poles

Integrated field multipoles

Measured on a straight line

→ Conversion to “pseudo multipoles” integrated along a parabola

(Paper submitted to PRAB)

DQ measurement method

Simulation results

3D model implemented with the Radia code

Normal pseudo multipole coefficients at 7 mm, computed with different methods

	Trajectory	Parabola	Straight to parabola
1	10000	10000	10000
2	−4550.8	−4548.0	−4548.5
3	2.5	2.1	4.1
4	3.7	3.8	3.7
5	−2.7	−2.6	−2.9
6	−9.0	−9.3	−9.6
7	2.9	2.8	1.9
8	9.5	10.1	11.0

Can be obtained from SW measurements

DQ stretched wire measurement results

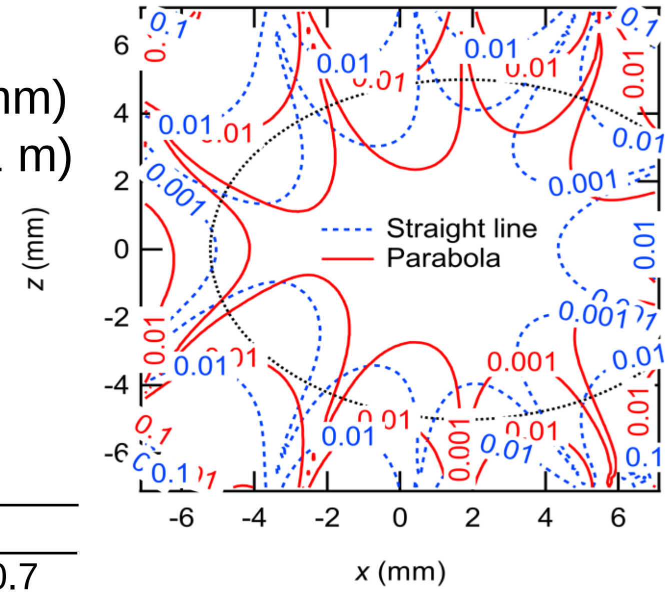
Gradient mag. length: 1047±1.4 mm (sim: 1044 mm)
Pole radius of curvature: 32.12±0.8 m (sim: 32.21 m)

Alignment

Repeatability of the mag. measurement: 4 µm
(without removing the wire)

Multipoles

	b_1	β_1	a_1	α_1
1	10000	10000	7.0 ± 0.7	6.4 ± 0.7
2	5020.8 ± 1.0	4590.9 ± 0.9	0.4 ± 0.3	−0.1 ± 0.3
3	−3.0 ± 0.2	−5.0 ± 0.2	1.3 ± 0.2	1.8 ± 0.2
4	−4.1 ± 0.3	−5.6 ± 0.4	−1.1 ± 0.1	−1.3 ± 0.2
5	−0.7 ± 0.3	5.0 ± 0.2	0.4 ± 0.2	0.4 ± 0.2
6	4.7 ± 0.1	19.1 ± 0.4	−0.1 ± 0.1	0.4 ± 0.1
7	13.95 ± 0.3	8.3 ± 0.5	−0.5 ± 0.1	−0.6 ± 0.1
8	−3.1 ± 0.1	−9.1 ± 0.2	0.2 ± 0.1	0.3 ± 0.2

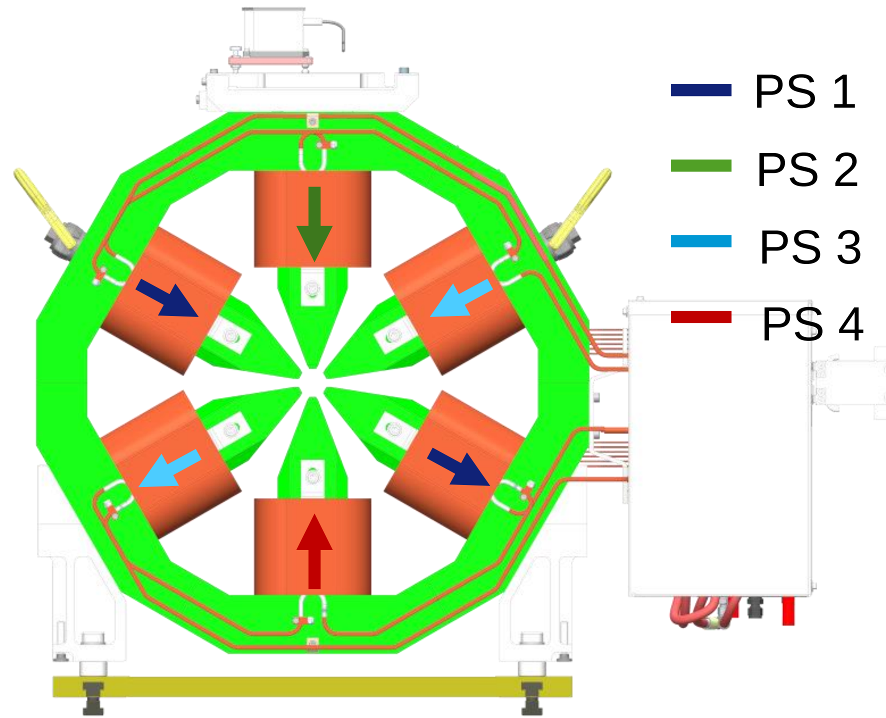


Gradient homogeneity computed from stretched wire measurements
Specification: ±1% within the 14x10 mm ellipse

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

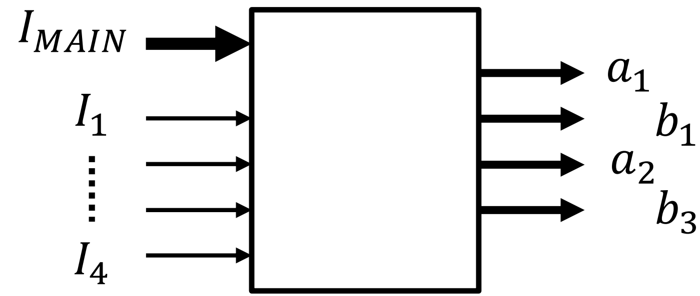
- 1 main PS, 6 main coils
  → b_3
- 4 corrector PS, 6 correction coils
  → a_1, b_1, a_2, b_3
- Correctors and skew quad settings must not affect the sextupole, and *vice versa*
- $b_3(I_{Main}, I_1 \ldots I_4)$ is non-linear
- and $a_1, b_1, a_2(I_{Main}, I_1 \ldots I_4)$ are not linear in $I_1 \ldots I_4$!



COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

- A 5 inputs and 4 outputs NL numerical model was developed
- Linear and quadratic terms in $I_1 \ldots I_4$
- Cubic spline interpolation in I_{MAIN}



Numerical sextupole model

Forward computations

$I_{MAIN}, I_1 \ldots I_4 \rightarrow a_1 \ldots b_3$

Inverse computations

$a_1 \ldots b_3 \rightarrow I_{MAIN}, I_1 \ldots I_4$

Difficulties

A lot of parameter
(81 parameters a … s must be used
symmetry taken in

In simulations, the errors between a 3D model (Radia) and the NL model are ~ 10^{-4}

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

- All coefficients can be obtained from measurements at 8 corrector currents

$$\begin{pmatrix}0\\0\\0\\0\end{pmatrix}$$

Sextupole at I_{MAIN}

$$\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \begin{pmatrix}-1\\0\\0\\0\end{pmatrix}$$

Linear and quadratic terms PS 1 and PS 3

$$\begin{pmatrix}0\\1\\0\\0\end{pmatrix} \begin{pmatrix}0\\-1\\0\\0\end{pmatrix}$$

Linear and quadratic terms PS 2 and PS 4

$$\begin{pmatrix}0\\1\\1\\0\end{pmatrix} \begin{pmatrix}1\\0\\-1\\0\end{pmatrix} \begin{pmatrix}0\\1\\0\\-1\end{pmatrix}$$

Crossed terms

- Each single multipole measurement (SW, rotating coil) give $a_1 \dots b_3$

8 corrector current settings at each main current
➔ Measurement feasible in a reasonable time

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

- Cycling and "degaussing" sequence defined
- Symmetries used to clean the data
- 15 current settings at each main current

Raw multipoles measured at a given I_{MAIN}

I_{MAIN} (A)	I_1 (A)	I_2 (A)	I_3 (A)	I_4 (A)	a_1 (T mm)	b_1 (T mm)	a_2/r_0 (T)	$b_3/{r_0}^2$ (T / mm)
90	0	0	0	0	0.081586	-0.25307	-0.02438	0.457691
90	-2	0	0	0	4.080059	-2.5587	-0.02304	0.449297
90	0	0	-2	0	-3.94271	-2.58475	-0.02333	0.44921
90	2	0	0	0	-3.24079	1.659555	-0.02389	0.464308
90	0	0	2	0	3.406766	1.64995	-0.02331	0.464314
90	0	-2	0	0	0.095563	-2.15319	0.055295	0.461032
90	0	0	0	2	0.075286	-2.18184	-0.10247	0.461091
90	0	2	0	0	0.065564	1.976168	-0.11822	0.453468
90	0	0	0	-2	0.083707	2.010712	0.074977	0.453385
90	-2	-2	0	0	4.021977	-4.52737	0.06373	0.452847
90	0	0	-2	2	-3.87582	-4.57373	-0.10912	0.452872
90	-2	0	-2	0	0.065562	-5.27636	-0.02135	0.439055
90	2	0	2	0	0.083672	3.567156	-0.02289	0.470726
90	0	-2	0	2	0.085843	-4.12948	-0.02378	0.464452
90	0	2	0	-2	0.068178	4.422182	-0.02006	0.449141

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

- Cycling and "degaussing" sequence defined
- Symmetries used to clean the data
- 15 current settings at each main current

Processed multipoles at a given I_{MAIN} (model parameters)

I_{MAIN} (A)	I_1 (A)	I_2 (A)	I_3 (A)	I_4 (A)	a_1 (T mm)	b_1 (T mm)	a_2/r_0 (T)	$b_3/{r_0}^2$ (T / mm)
90	0	0	0	0	0	0	0	0.457691
90	-2	0	0	0	4.011387	-2.31865	0	0.449297
90	2	0	0	0	-3.32378	1.907827	0	0.464308
90	0	-2	0	0	0	-1.91444	0.078882	0.461032
90	0	2	0	0	0	2.246515	-0.0966	0.453468
90	-2	-2	0	0	3.948899	-4.29747	0.086426	0.452847
90	-2	0	-2	0	0	-5.02329	0	0.439055
90	0	-2	0	2	0	-4.27583	0	0.464452

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

- Cycling and “degaussing” sequence defined
- Symmetries used to clean the data
- 15 current settings at each main current

Processed multipoles at a given I_{MAIN} (model parameters)

I_{MAIN} (A)	I_1 (A)	I_2 (A)	I_3 (A)	I_4 (A)	a_1 (T mm)	b_1 (T mm)	a_2/r_0 (T)	$b_3/{r_0}^2$ (T / mm)
90	0	0	0	0	0	0	0	0.457691
90	-2	0	0	0	4.011387	-2.31865	0	0.449297
90	2	0	0	0	-3.32378	1.907827	0	0.464308
90	0	-2	0	0	0	-1.91444	0.078882	0.461032
90	0	2	0	0	0	2.246515	-0.0966	0.453468
90	-2	-2	0	0	3.948899	-4.29747	0.086426	0.452847
90	-2	0	-2	0	0	-5.02329	0	0.439055
90	0	-2	0	2	0	-4.27583	0	0.464452

COMBINED SEXTUPOLE-CORRECTORS

Sextupole correctors

Random multipole strength specifications

↓ Inverse model

Currents

↓ Measurement

Measured multipole strengths specifications

Sample test results at 90 A (i.e. saturated)

		Test #1		Test #2	
		Spec.	Meas	Spec.	Meas
a_1	(T mm)	0	0.034	0	0.003
b_1	(T mm)	6	5.96	0	0.097
a_2/r_0	(T)	0	-0.003	0.13	0.1287
$b_3/{r_0}^2$	(T / mm)	0.46984	0.46916	0.46984	0.46956

Work in progress…

OUTLINE

I. Introduction

- Magnets for the EBS

II. Measurement and fiducialization of the magnet series

- Initial plans, tolerances, difficulties encountered
- Measurements and fiducialization at the ESRF
- Main results

III. Magnet calibration and measurement of combined function magnets

- Calibration, cycling and thermal effects
- Curved dipole-quadrupoles
- Combined function sextupole-correctors

IV. Conclusion

CONCLUSIONS

Measurement of magnet series

- Late decision to characterize all magnets in house
- About 800 electromagnets measured and fiducialized in about 1 year
- Strethed-wire benches used successfully for calibration, field mapping and fiducialization

Fiducialization

- Two laser tracker stations for each magnet
- Benches recalibrated every week vs a reference magnet
- Fiducialization uncertainties estimated to $U_X = 20$ µm and $U_Z = 23$ µm (These are not magnet to magnet alignment uncertainties!)

Higher order multipoles

- Depends on the technology (laminated, solid iron, machined, wired cut, chamfer)

CONCLUSIONS

Calibration

- Thermal effects stronger than cycling effects
- Cycling scheme defined

Curved dipole-quadrupoles

- Stretched wire measurement sequence developed and demonstrated
- Alignment, pole radius of curvature and pseudo multipole measured with SW

Combined Sextupole-correctors

- NL model developed
- Tests in progress

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