Magnetic measurement of ESS quadrupole and corrector electro-magnets at Elettra

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Elettra
Sincrotrone
Trieste

Outline

Introduction to Elettra's contribution to ESS

Rotating-coil system for ESS magnets at Elettra

- Design
- Realization
- Calibration
- First measurement results

Elettra

No profit shareholder company, recognized of national interest, estabished in 1987

Elettra (1994):

- third generation light source, 2.4 GeV
- 28 beam lines

FERMI (2010):

- single-pass, externally seeded Free Electron Laser 1.5 GeV
- 2 FEL lines, 5 beam lines for users

European Spallation Source (ESS)

- Currently in construction in Lund (Sweden)
- Largest neutron facility ever built
- Most powerful proton linear accelerator (2 GeV, 5 MW)

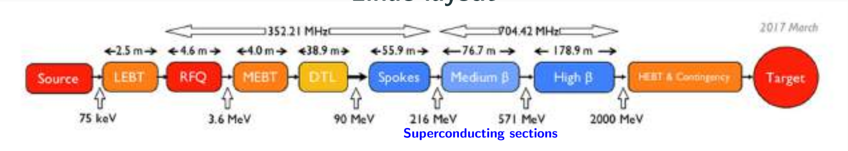
Credits:ESS

- 50 % of construction cost covered by Sweden, Norway and Denmark
- In-Kind Contribution from other countries cover the rest
- Italian In-Kind Contribution:
  - Elettra, INFN and CNR
  - Elettra: magnets, power converters, RF power stations, beam diagnostics instrumentation (wire scanner)
  - Design, prototyping, production follow-up and magnetic measurement of 213 magnets out of 353

ESS proton linac magnets

Linac layout

Energy 2.0 GeV
H^+ ion source
from gas heating



Rotating tungsten target
Neutron generation by **spallation**

Normal-conducting magnets for different sections
DC power
Dedicated power converters

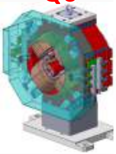
Interested sections

- Q5, C5: spoke linac
- Q6: Medium-β, High-β, HEBT
- C6: Medium-β, High-β, HEBT and Accelerator-To-Target
- Q7: Accelerator-To-Target ramp

Quadrupoles

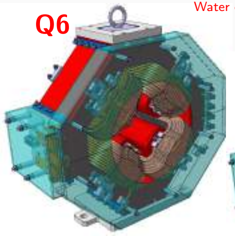
Water cooled

Q5



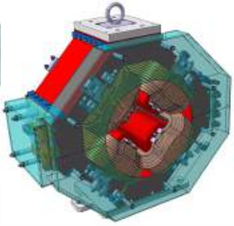
Bore Ø67 mm
Length 250 mm
GdL 1.8 T
GFR(*) 22 mm

Q6



Bore Ø112 mm
Length 350 mm
GdL 2.2 T
GFR 35 mm

Q7



Bore Ø112 mm
Length 400 mm
GdL 2.7 T
GFR 35 mm

(*) Good Field Region radius

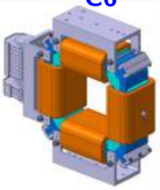
Correctors

Dual plane, Air cooled

C5

Bore Ø67 mm
Length 70 mm
BdL 12 G m
GFR 22 mm

C6



Bore Ø112 mm
Length 100 mm
BdL 24 G m
GFR 35 mm

Requirements

Quadrupoles Q5, Q6, Q7

Field quality: $|\mathbf{c}_n| < 10 \times 10^{-4} \quad \forall n$

Magnetic center vs Mechanical center $\leq 250\,\mu\text{m}$

Magnetic field direction (roll angle) $< 1\,\text{mrad}$

Transfer function determination

Measurement of fringe field ($\Rightarrow$ hall probe mapper)

Correctors C5, C6

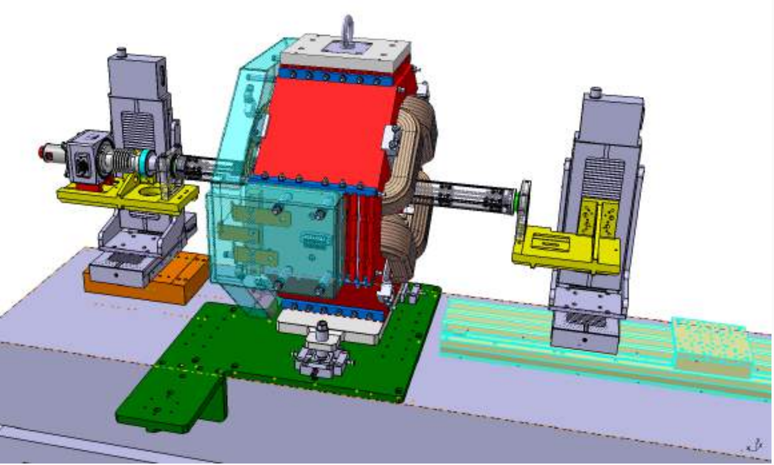
Field homogeneity: $|\delta(Bdl)/Bdl| < 4\,\%$

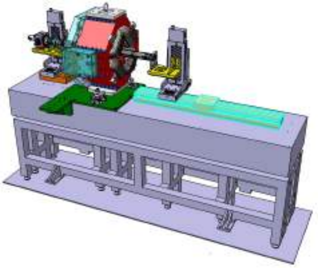
Mechanical center used for alignment

Solution

Rotating-coil system for magnet characterization and fiducialization

Versatility: easy integration of other systems (e.g. hall sensors, stretched wires)





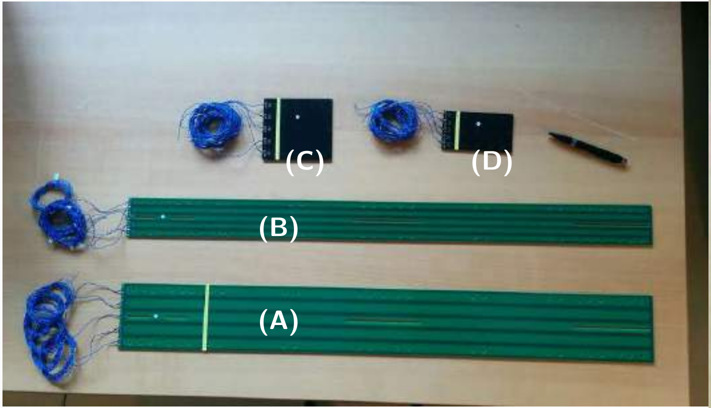
Marble bench

XY linear stages for horizontal and vertical motion

Rotary motor stage + Encoder

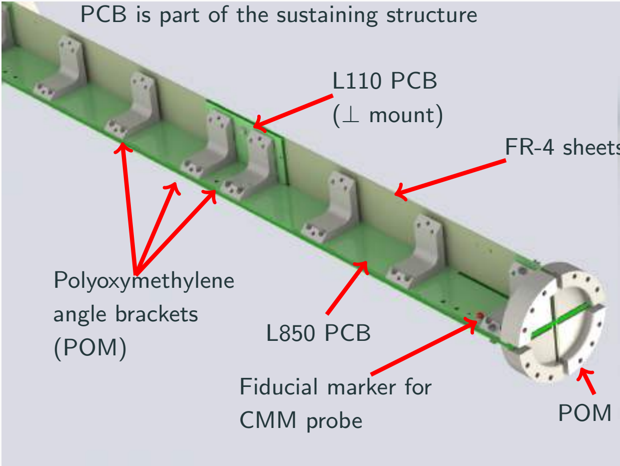
Long travel (1 m) linear stage for axial displacement (for upcoming hall probe mapper)

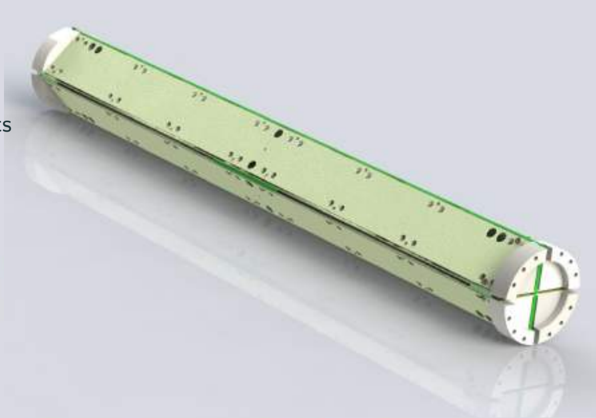
PCB design

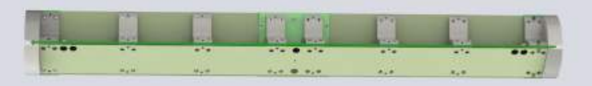


Standard array of 5 radial coils for dipole and quadrupole bucking (digital)
10 turns x 16 layers (3 mm thickness)
A, B coil length 850 mm
C, D coil length 110 mm
Holes for shaft assembly and fiducial markers

Rotating shaft design





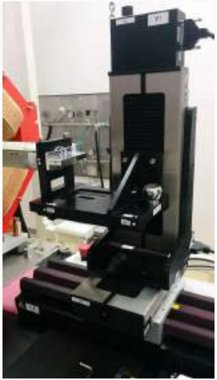


POM components designed in house and produced by outsourcing

FR-4 (fiberglass + epoxy resin) material bought and machined in house

Shaft assembly and installation

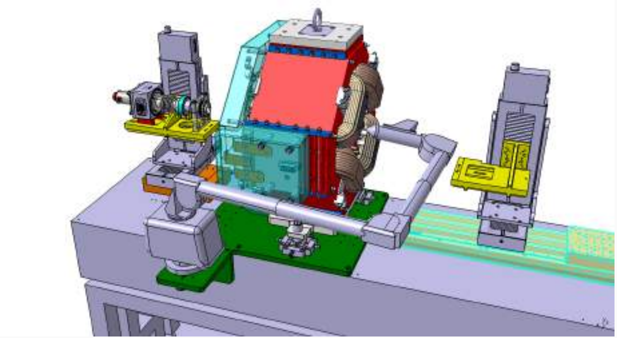

Plastic screws (PIC) for tightening

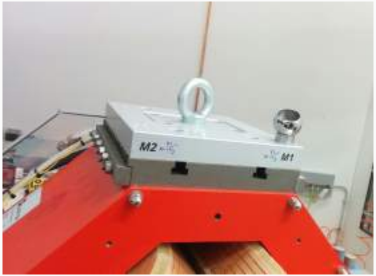



Stage A (left), Stage B (right)
Bellow to transmit rotary motion
Slip rings
Cylindrical bearings

Clinometer support for calibration of coil angle at acquisition start

Fiducialization tools





4 fiducial markers on magnet top plate (3 for correctors)

Coordinate measuring machine: FARO® arm, 0.029 mm precision, ±0.041 mm accuracy

Magnet frame constructed by probing reference surfaces on polar expansions, on both magnet sides

Magnet is aligned w.r.t. bench frame

Shaft rotation axis determined by probing PCB fiducial markers at different angular positions

Shaft angle at acquisition start determined by probing the shaft reference plate (determined with ±180 μrad uncertainty)

Coil calibration (1/2)

Step 1: coil surface calibration in **CERN reference dipole**

PCBs shipped to CERN before assembling the shafts

Standard calibration flipping upside down the coils in a known dipole field

$$-\int_0^t V_c \, \mathrm{d}t = \Phi - (-\Phi) = 2A_c \bar{B}$$

D105 coil array param.	M.U.	Int.1	Central	Int.2	Main
Design surface	m^2		2.402 51		
Calibrated surface	m^2	2.40226	2.40262	2.40252	2.40251
Rel. Difference	-	-1.0×10^{-4}	0.5×10^{-4}	0.0×10^{-4}	0.0×10^{-4}

(**M. Buzio**, "Fabrication and calibration of search coils", *Cern Accelerator School*, 2009.)

Coil calibration (2/2)

Step 2: coil array parallelism, rotation radius

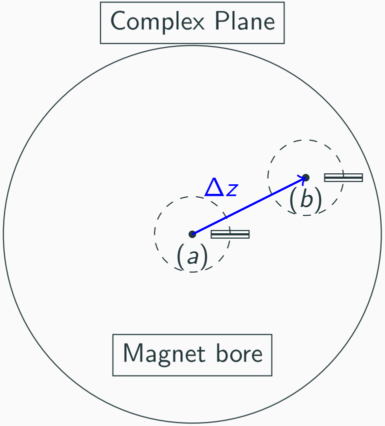
Performed **in-situ** with **unknown** quadrupole thanks to linear stages and known coil surfaces

Pure quadrupole case

- Taking rotating-coil measurements in two different shaft locations: (a) and (b)
- Coil array parallelism from phase differences in the measured *feed-down* dipole
- Then, K_2 and $\mathbf{C}_2$

$$K_2 = K_1 \frac{\Delta z}{2} \frac{\Psi_3^{(a)} + \Psi_3^{(b)}}{\Psi_2^{(b)} - \Psi_2^{(a)}}$$

$$\mathbf{C}_2 = r_0 \frac{\Psi_3^{(a)}}{K_2} = r_0 \frac{\Psi_3^{(b)}}{K_2}$$



Generalization to non-pure quadrupole (1/2)

Starting from relation between $\mathbf{C}_n^{(a)}$ and $\mathbf{C}_n^{(b)}$ ...

$$\mathbf{C}_n^{(b)} = \sum_{k=n}^{\infty} \mathbf{C}_k^{(a)} \binom{k-1}{k-n} \left(\frac{\Delta z}{r_0}\right)^{k-n}$$

... writing for N harmonics ...

$$\begin{aligned}
\mathbf{C}_1^{(b)} &= \mathbf{C}_1^{(a)} \binom{0}{0} + \mathbf{C}_2^{(a)} \binom{1}{1} \frac{\Delta z}{r_0} + \cdots + \mathbf{C}_N^{(a)} \binom{N-1}{N-1} \left(\frac{\Delta z}{r_0}\right)^{N-1} \\
\mathbf{C}_2^{(b)} &= \mathbf{C}_2^{(a)} \binom{1}{0} + \mathbf{C}_3^{(a)} \binom{2}{1} \frac{\Delta z}{r_0} + \cdots + \mathbf{C}_N^{(a)} \binom{N-1}{N-2} \left(\frac{\Delta z}{r_0}\right)^{N-2} \\
&\vdots \\
\mathbf{C}_{N-1}^{(b)} &= \mathbf{C}_{N-1}^{(a)} \binom{N-2}{0} + \mathbf{C}_N^{(a)} \binom{N-1}{1} \left(\frac{\Delta z}{r_0}\right) \\
\mathbf{C}_N^{(b)} &= \mathbf{C}_N^{(a)} \binom{N-1}{0}
\end{aligned}$$

(**P. Arpaia, M. Buzio, O. Koster, G. Severino, S. Russenschuck**, "Rotating-coil calibration in a reference quadrupole, considering roll angle misalignment and high-order harmonics", *Measurement*, 2016.)

Generalization to non-pure quadrupole (2/2)

... substituting ...

$$\mathbf{C}_n^{(a)} = r_0^{n-1} \frac{\Psi_{n+1}^{(a)}}{K_n}, \qquad \mathbf{C}_n^{(b)} = r_0^{n-1} \frac{\Psi_{n+1}^{(b)}}{K_n}, \qquad n = 1, \ldots, N$$

a system of equations is obtained with the unknowns $\frac{1}{K_i}$, coefficient matrix Γ and known term β

$$[\Gamma]_{i,j} = \begin{cases} \Psi_{j+2}^{(a)} \binom{j}{-i+j+1} (\Delta z)^{-i+j+1} & j \geq i \\ -\Psi_{i+1}^{(b)} + \Psi_{i+1}^{(a)} & j = i-1 \\ 0 & j < i-1 \end{cases} .$$

$$\beta = \begin{bmatrix} \frac{\Psi_2^{(b)} - \Psi_2^{(a)}}{K_1} & 0 & \cdots & 0 \end{bmatrix}^T ,$$

$$\upsilon = \Gamma^{-1} \beta ,$$

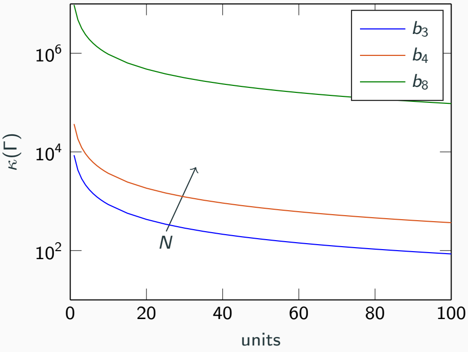
$$K_i = \frac{1}{\upsilon_i} \qquad i = 2, \ldots, N-1$$

Some observations

To exploit bucking, the equation system is written with DFT coefficients of bucked fluxes (i.e. dipole-bucked for quadrupole terms, dipole-quadrupole bucked for higher order ones)

… and the unknowns are the equivalent sensitivity factors K_n^{eq}

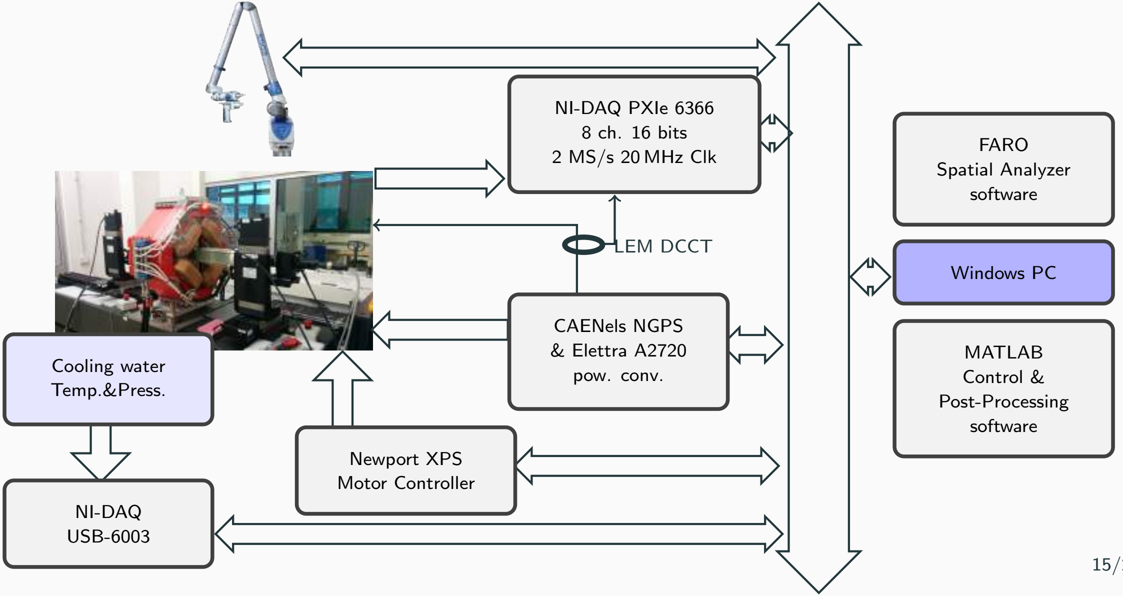
How to choose N? Look at the **condition number** κ of Γ matrix …



← Condition number of Γ for different multipole error components ($\Delta z/r_0 = 0.33$)

Large values of κ points out an **ill-conditioned** system, which may result in amplification in error propagation with inaccurate results

Control, Acquisition and Post-Processing Architecture



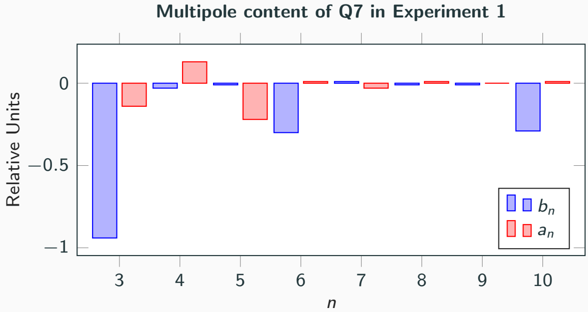
Calibration results

Experiment 1: Calibration in Q7 first-of-series

Shaft displacement $\Delta z = 4\,\text{mm}$
Integrated gradient 3.2852 T (@ 200 A)

Agreement at micrometric level between design and calibrated interaxis distances between the coils of the array

D105 coil array param.	M.U.	Int.1	Central	Int.2	Main
Design surface	m^2		2.402 51		
Calibrated surface	m^2	2.40226	2.40262	2.40252	2.40251
Parallelism	mrad	0.10	−1.20	−0.38	0.00
Design interaxis dist.	mm	20.500	0.000	20.500	41.000
Calibrated interaxis dist.	mm	20.508	0.000	20.508	41.016
Offset from rotation axis	mm		0.053	$\angle -147.11^\circ$	

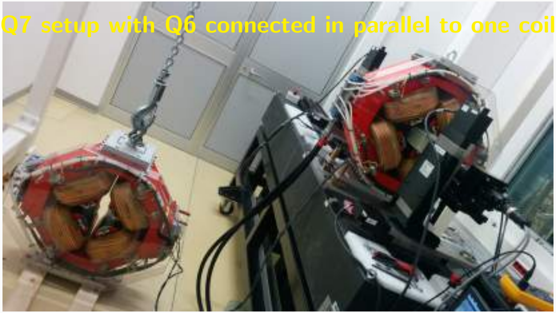


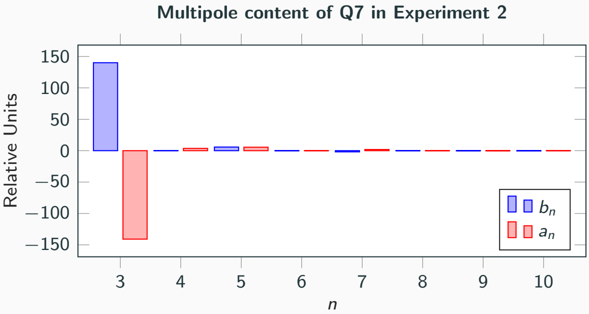
Calibration results in presence of multipole errors (1/2)

The multipole content of the Q7 is poor to test the calibration technique effectiveness in presence of multipole errors

⇒ **Experiment 2:** introducing an artificial sextupole component, a current absorber was put in parallel to one of the coil windings of the magnet poles

The adsorbing circuit was another magnet, a Q6 (about the same resistance and inductance per coil), such as to adsorb about the 20 % of the current





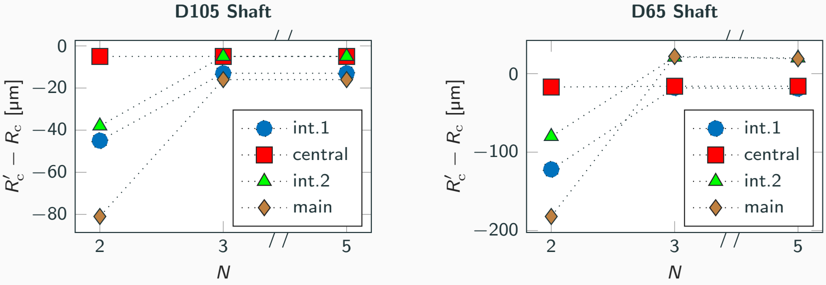
Calibration results in presence of multipole errors (2/2)

Difference between calibrated rotation radii R'_c in **Exp.2** and R_c in **Exp.1** (with and without multipoles)

Increasing N means taking into account for multipole errors (that is (b_6, a_6) in Exp.2

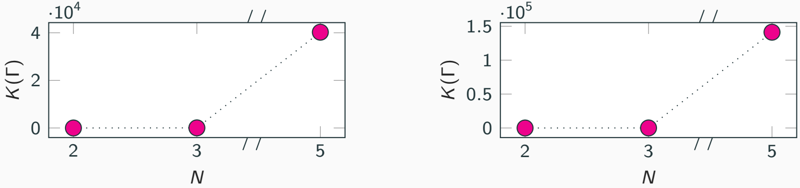
D105: 16 units of difference for gradient due to b_6 ($\Delta z = 4\,\text{mm}$)

D65: 82 units of difference for gradient due to b_6 ($\Delta z = 20\,\text{mm}$)



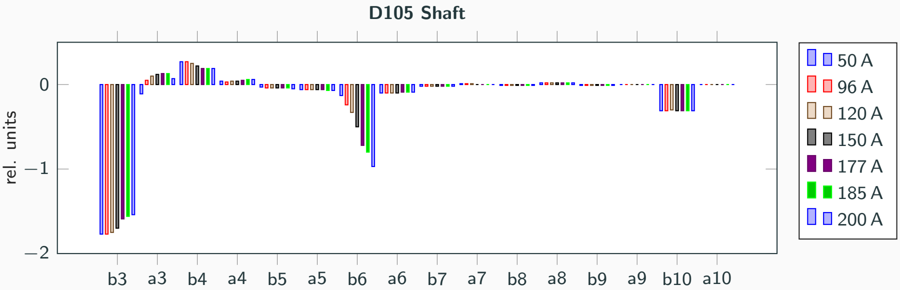
Condition number

Increasing N more than 3 provides no more advantage

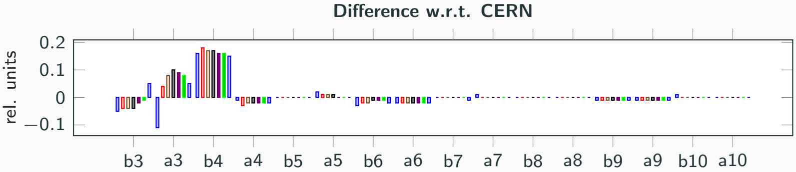


Validation against Q6 prototype magnet measured at CERN

Prototype of Q6 magnet, built and measured at CERN



Measurement Std. Deviation on 5 turns ≤ 0.03 units max $\forall n$



Integrated field gradient agreement 25 units rms, with measurement Std. Dev. ≤ 5 p.p.m. on 5 turns

Summary of results of ESS magnets measured so far

Status report

Measured magnets: 12 Q7, 72 Q6, 55 C6 $\Rightarrow$ 139 out of 201

To measure: 23 Q6, 26 Q5, 13 C5

All the quadrupole magnets are largely within the tolerance specification

Sextupole and octupole components ≤ 2 units, remaining components ≤ 1 unit (specification: 10 units max $\forall n$)

Offset of magnetic center w.r.t. mechanical axis 60 µm for both coordinates (comparable with the fiducialization uncertainty) (specification 250 µm)

Main field direction such as fiducialized within $\pm$200 µrad (specification 1 mrad)

Outlook

Coming soon ... 3D hall-probe mapper as complementary measurements on the first-of-series of each ESS magnet type

Near future: Elettra 2.0: 26 mm aperture, combined function magnets ...

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Near future: Elettra 2.0: 26 mm aperture, combined function magnets ...

THANKS FOR YOUR ATTENTION!

The authors wish to tank ...

Carlo Petrone, *Ricardo B. Mercadillo*, *Marie Elsa Cervera*, CERN

Alessandro Fabris and *Rodolfo Laghi*, Elettra