Stretched-wire measurements of magnet girders

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Outline

Introduction

Alignment issues

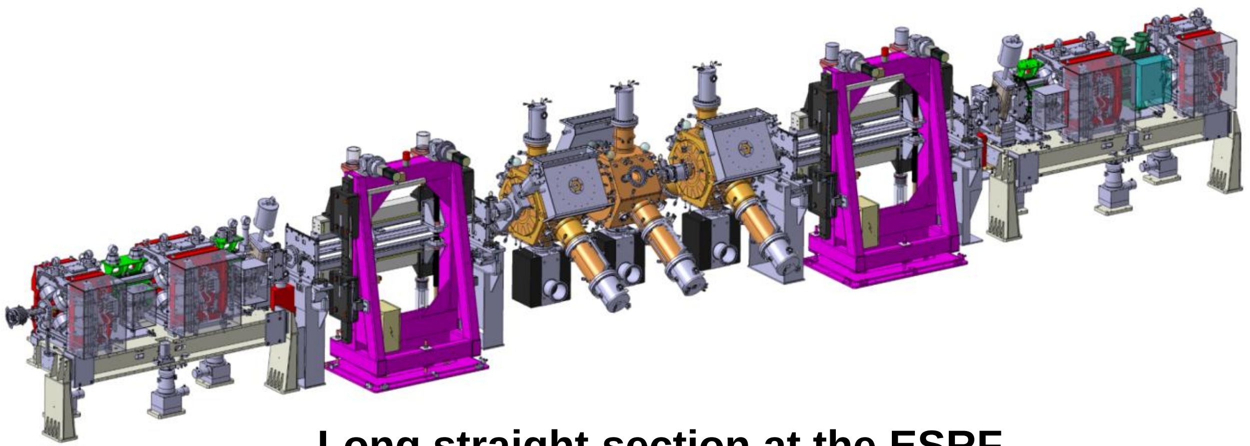
Harmonic analysis

Conclusion and perspectives

Context

ESRF Upgrade Phase I

- Long straight section : 5 m → 7m
- Two girders replaced, equipped with stronger magnets



Long straight section at the ESRF

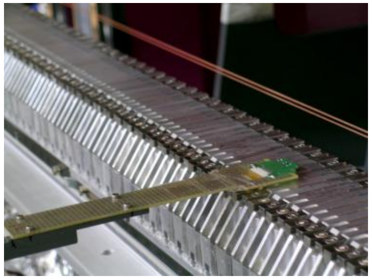
ESRF Upgrade Phase II

- New lattice, more than 1000 magnets
- Strong magnets, small apertures, tight tolerances

Context

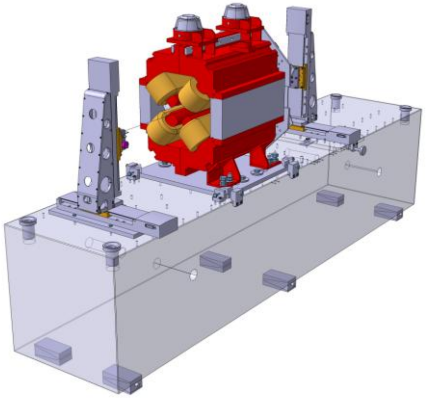
Flipping coil benches

- Insertion devices
- First and second field integrals
- Non-circular apertures
- No need for accuracy



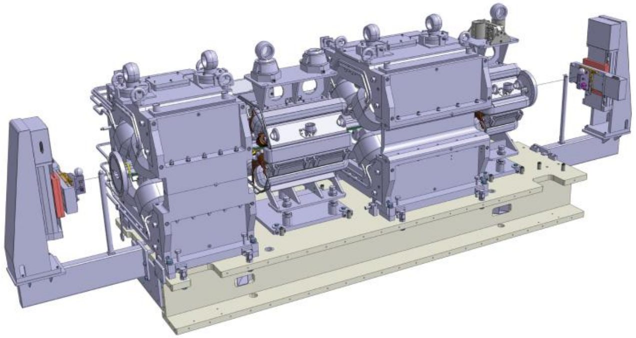
Single Streched Wire (SSW)

- Multipole magnets
- Alignment
- Harmonic analysis

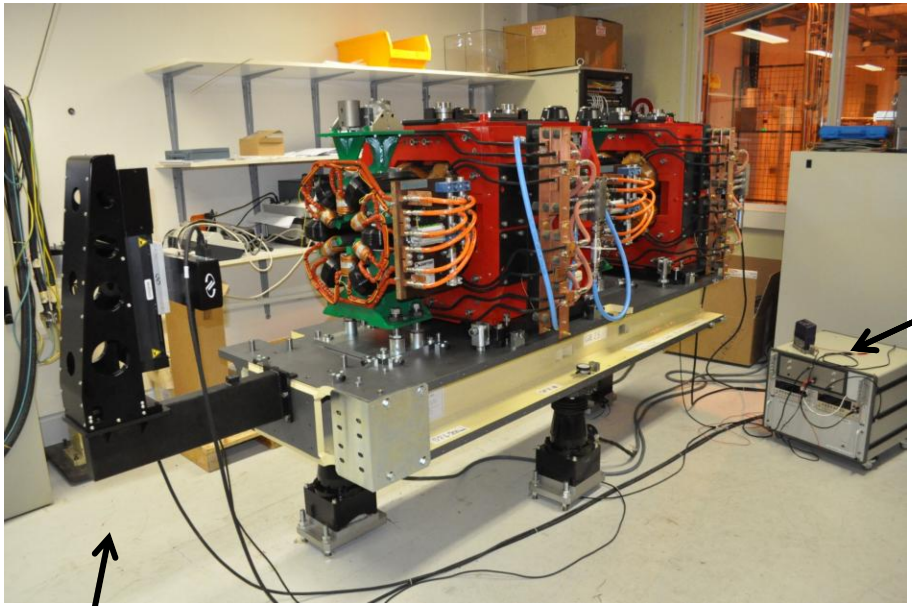


SSW girder measurements

- Magnet alignment on the wire axis
- Interaction between the magnets



SSW Girder measurement bench



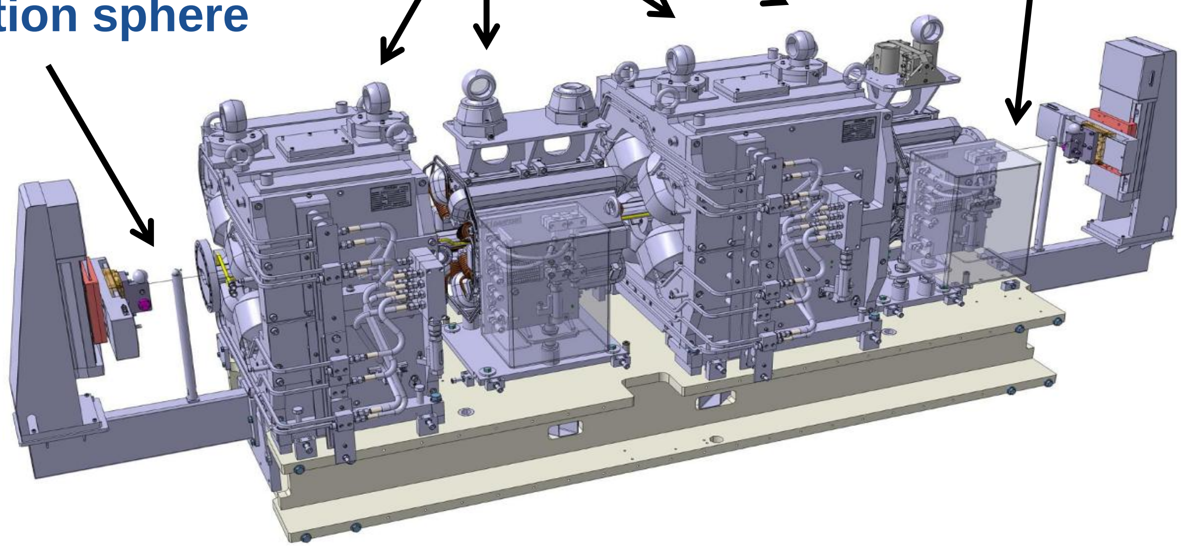
Motion controller
Newport XPS
Voltmeters
Keithley 2182 (main)
Keithley 2701

Titanium wire
100 µm diameter
2.8 m length

Survey monuments

Wire calibration sphere

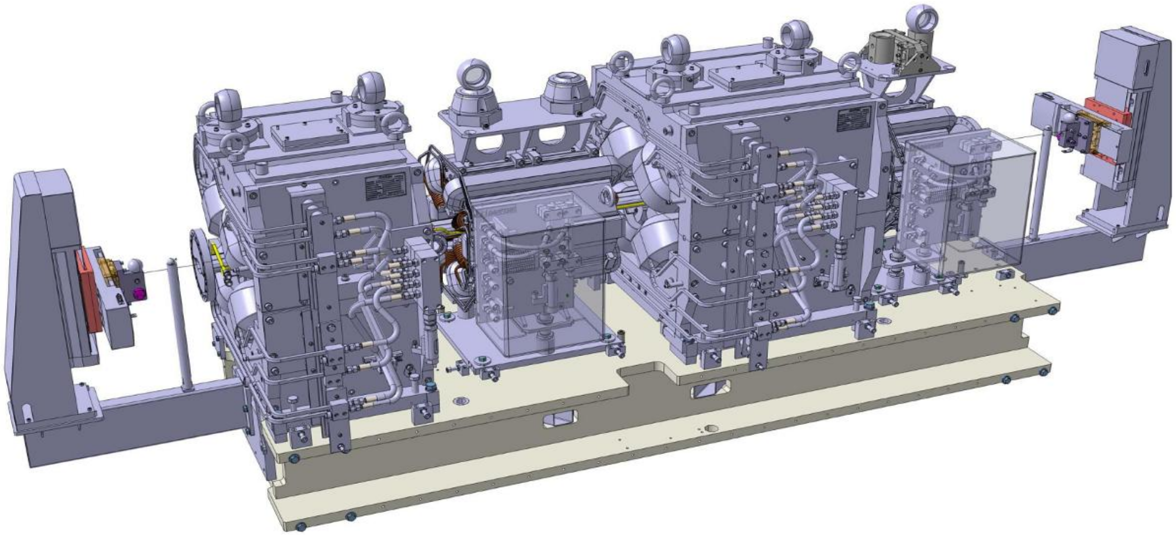
Linear stages
Newport IMS100V
Newport ILS100CC



Alignment

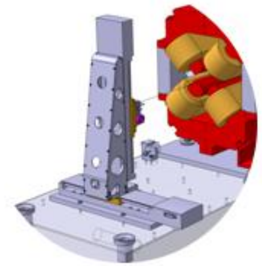
Main issues

- Alignment of linear stages
- Magnet alignment and error budget



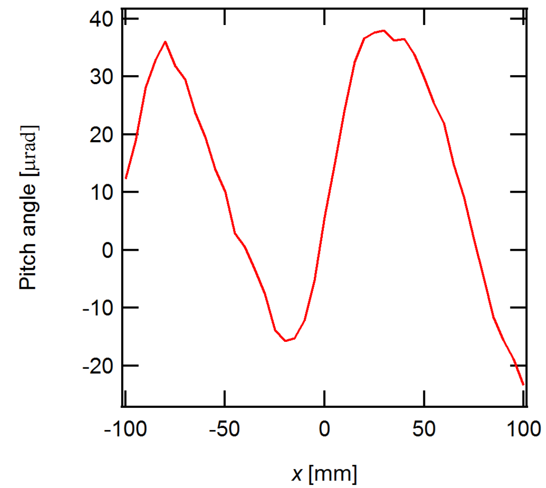
Version 1

Multipole measurement bench



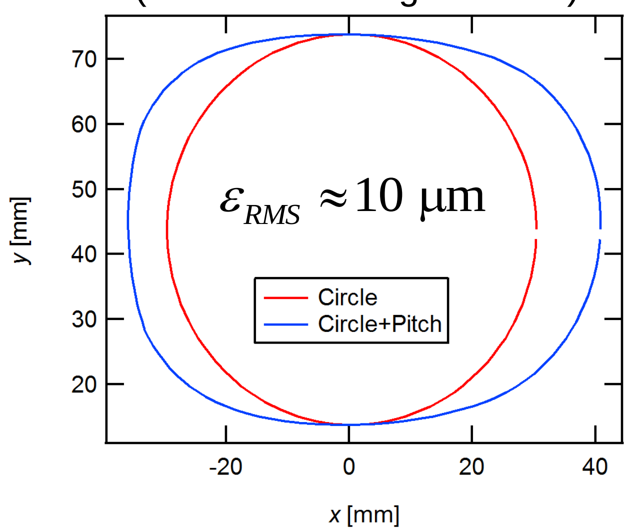
Horizontal stage pitch

Laser Interferometer
Pitch measurement



Trajectory errors

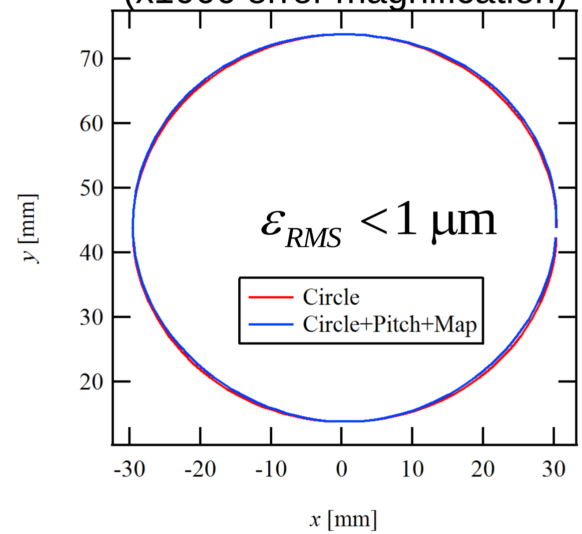
(x1000 error magnification)



Error map

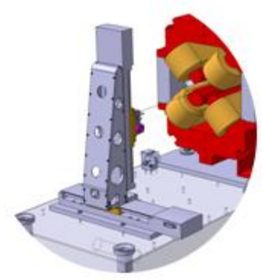
Laser Interferometer
Distance measurement

(x1000 error magnification)



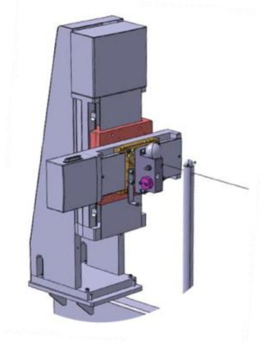
Linear stages alignment

Version 1
Multipole measurement bench



Reverse T assembly
- Simple and cheap
- Needs laser interferometer calibration

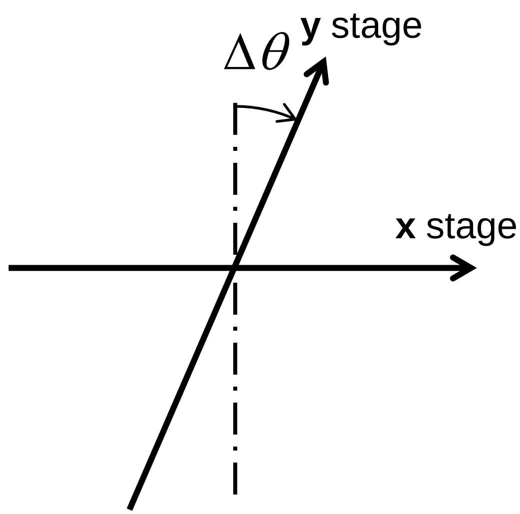
Version 2
Girder measurement bench



Cross assembly
- Easier calibration
- Lower trajectory errors
- Needs stronger stages

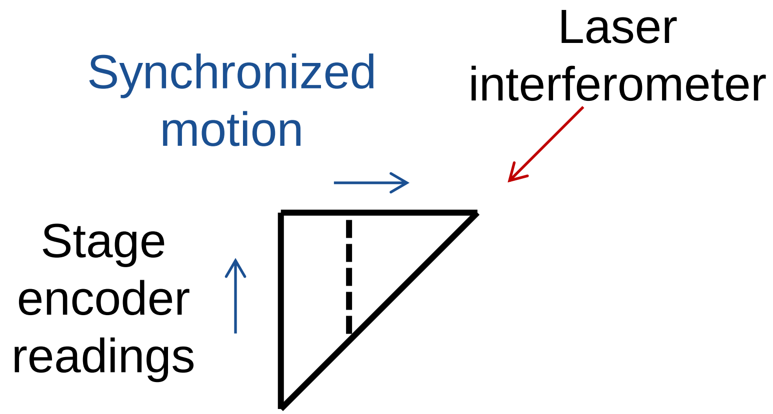
Linear stages alignment

Stage perpendicularity errors



Skew components

$$\Delta a_2 = b_2 \Delta\theta$$



Interferometer set-up for perpendicularity calibration

Calibration methods

- Magnet rotated by 180 º
- Laser interferometer
- CMM (Laser tracker, FARO Arm)
- …

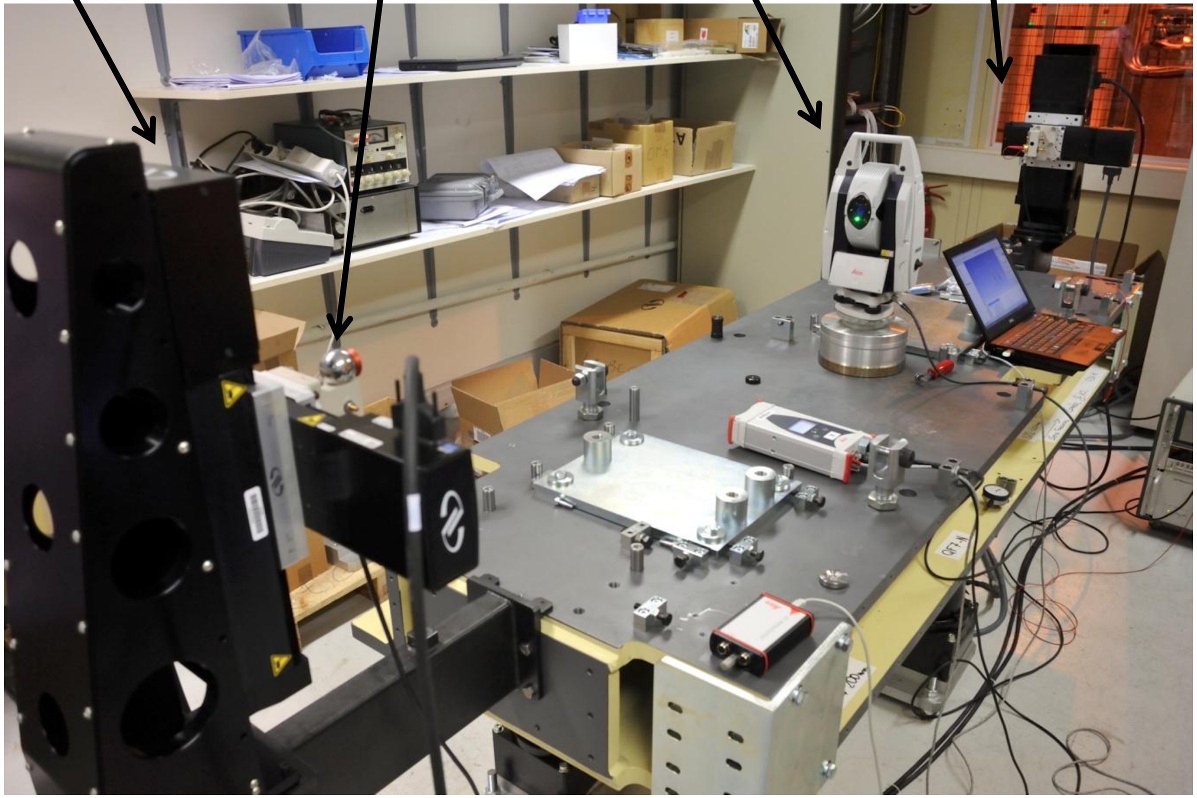
Linear stages alignment

Laser tracker
Leica AT401

Linear stage group 1

Retroreflector

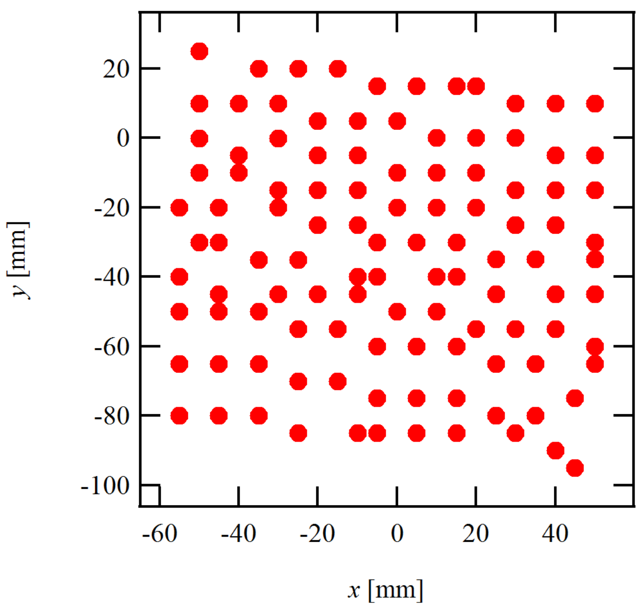
Linear stage group 2



Linear stages alignment

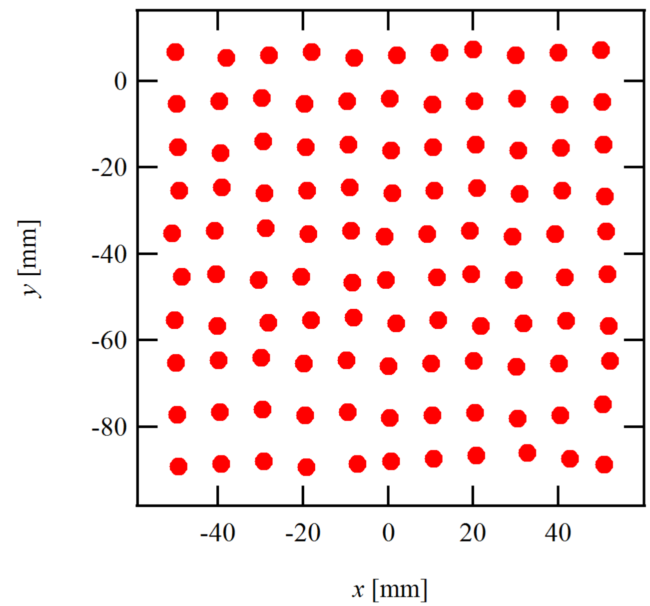
Laser tracker measurements

- Perpendicularity
- Roll angle
- Alignment of the two groups of stages



Points before correction (errors x500)

Least square correction

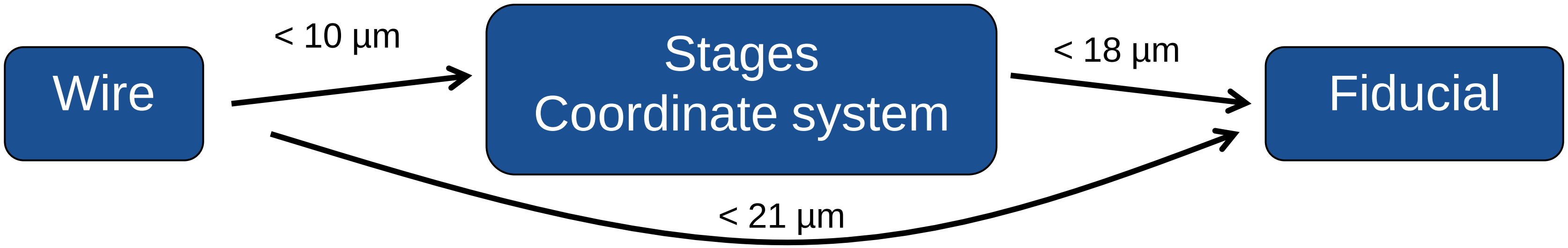


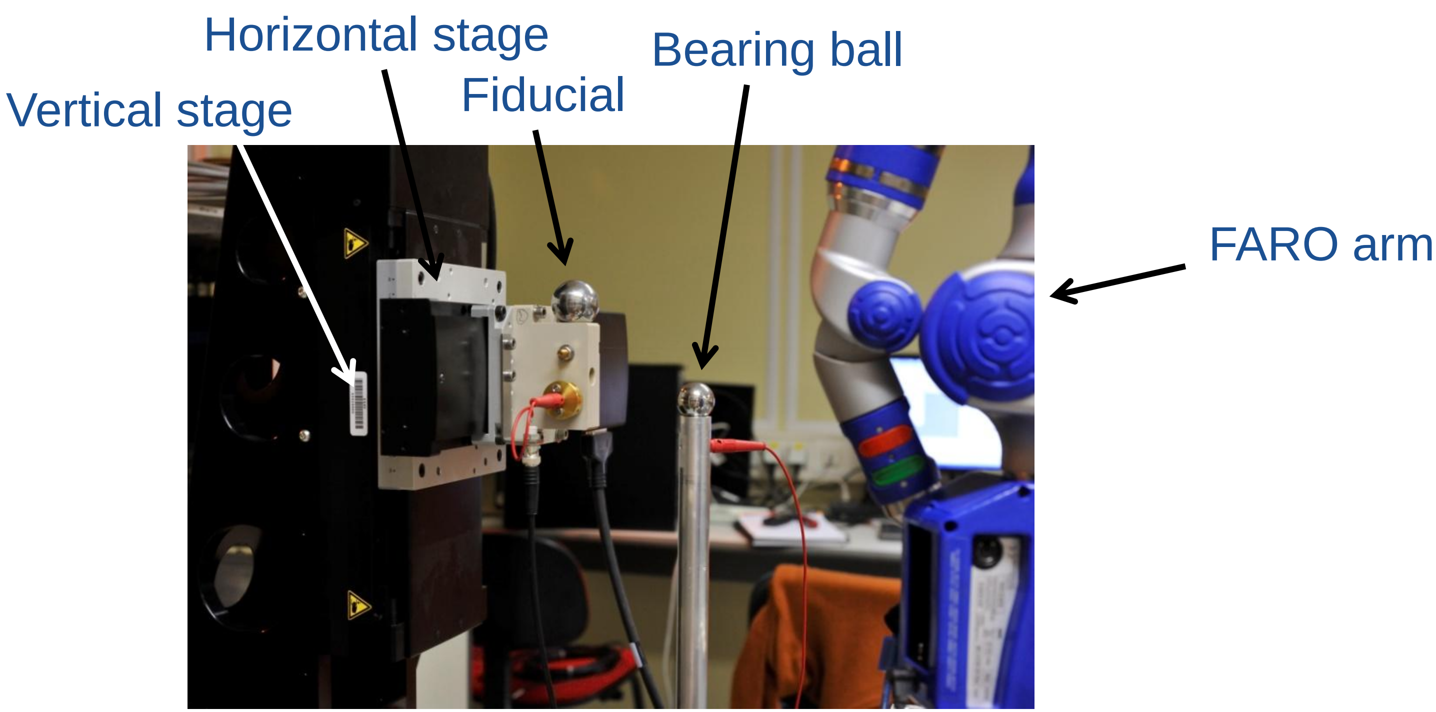
Points after correction (errors x500)

Linear stages alignment

Calibration of the wire position

Electrical contact between the wire and a bearing ball





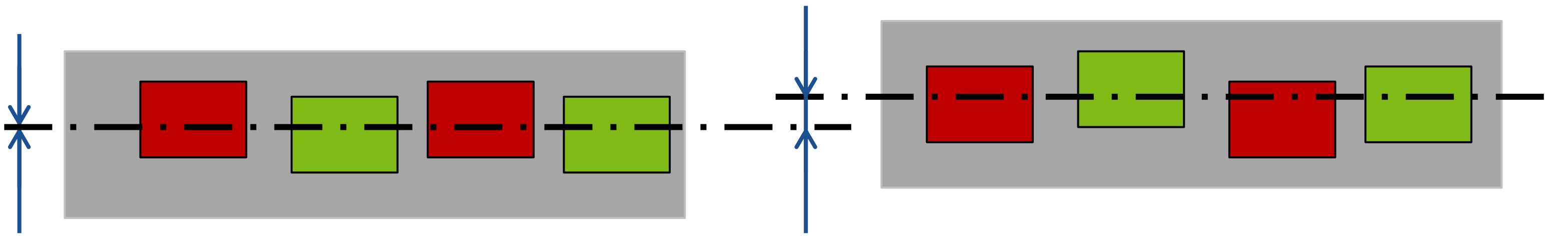
Magnet alignment

Alignment on the wire			
SSW measurement precision	1	µm	← Magnetic measurement
Wire diameter precision	10	µm	
Magnet adjustment precision	15	µm	← Adjusment
RMS error	**20**	**µm**	

"Classical" alignment			
Wire position calibration (for each stage)	2 x 21	µm	← Wire position calibration
Wire installation	2 x 10	µm	
SSW measurement precision	1	µm	← Magnetic measurement
Wire diameter precision	10	µm	
Bench coordinate system measurement	20	µm	← Coordinate measurement
Fiducial measurement	20	µm	← On the magnetic bench
Fiducial measurement	20	µm	← On the girder
Magnet adjustment precision	15	µm	← Adjusment
RMS error	**50**	**µm**	

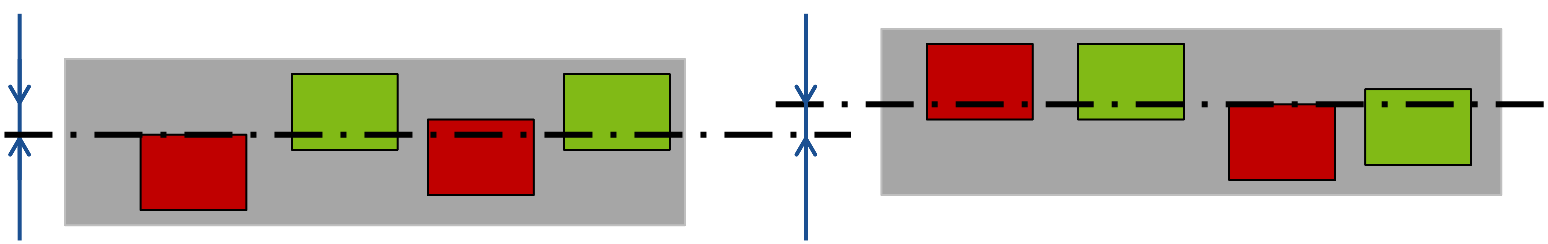
Alignment strategies

SSW measurement on the girder



$\sigma \approx 20\ \mu\mathrm{m}$ on the same girder $\sigma \approx 50\ \mu\mathrm{m}$ between girders

In lab magnetic measurements + fiducials

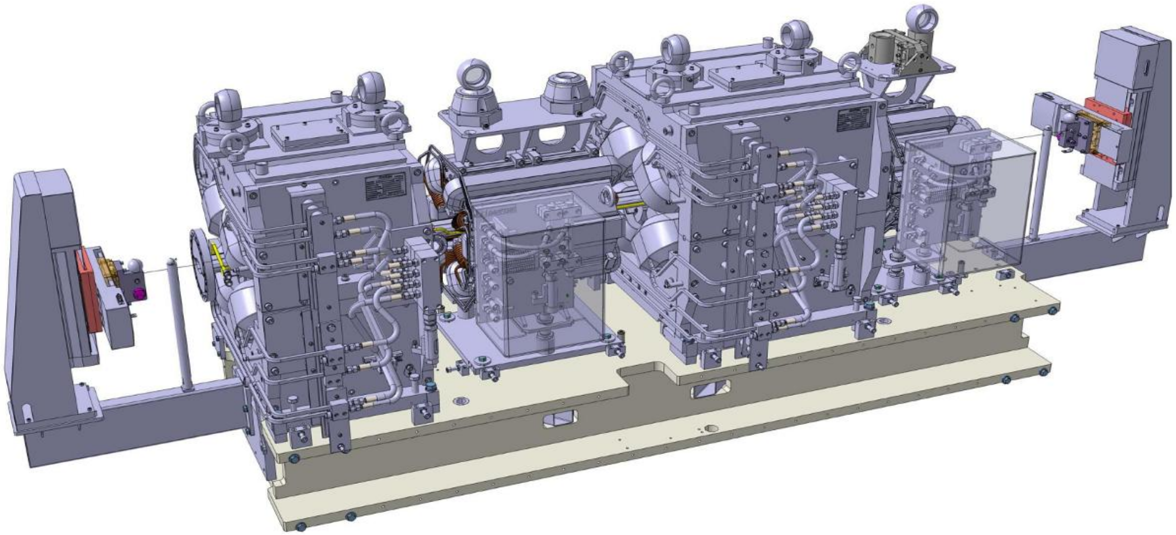


$\sigma \approx 50\ \mu\mathrm{m}$ on the same girder $\sigma \approx 50\ \mu\mathrm{m}$ between girders

Harmonic analysis

Purpose

- SSW harmonic analysis on the complete girder
- One magnet is powered, the others are OFF
- Study of interaction between magnets



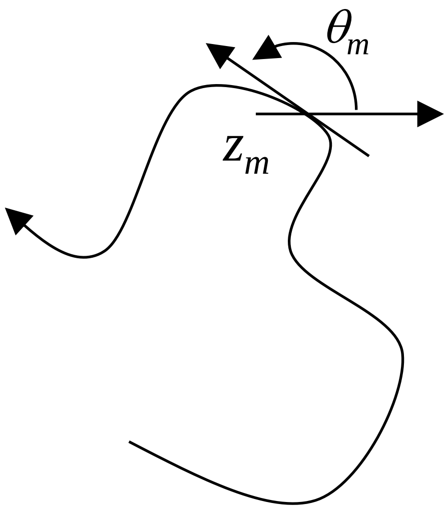
Least square multipole estimation

Matrix Formalism[1]

$$\mathbf{B}_{\mathbf{MEAS}} = \mathbf{M}\,\mathbf{C}$$

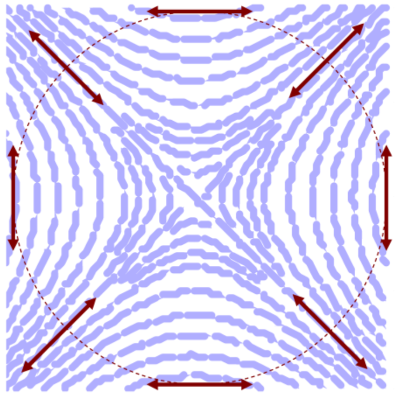
were $\mathbf{C}$ contains the multipole coefficients and

$$M_{mn} = f(z_m, \theta_m, n)$$



Arbitrary wire trajectory

➔ **Matrix inversion (least square)**



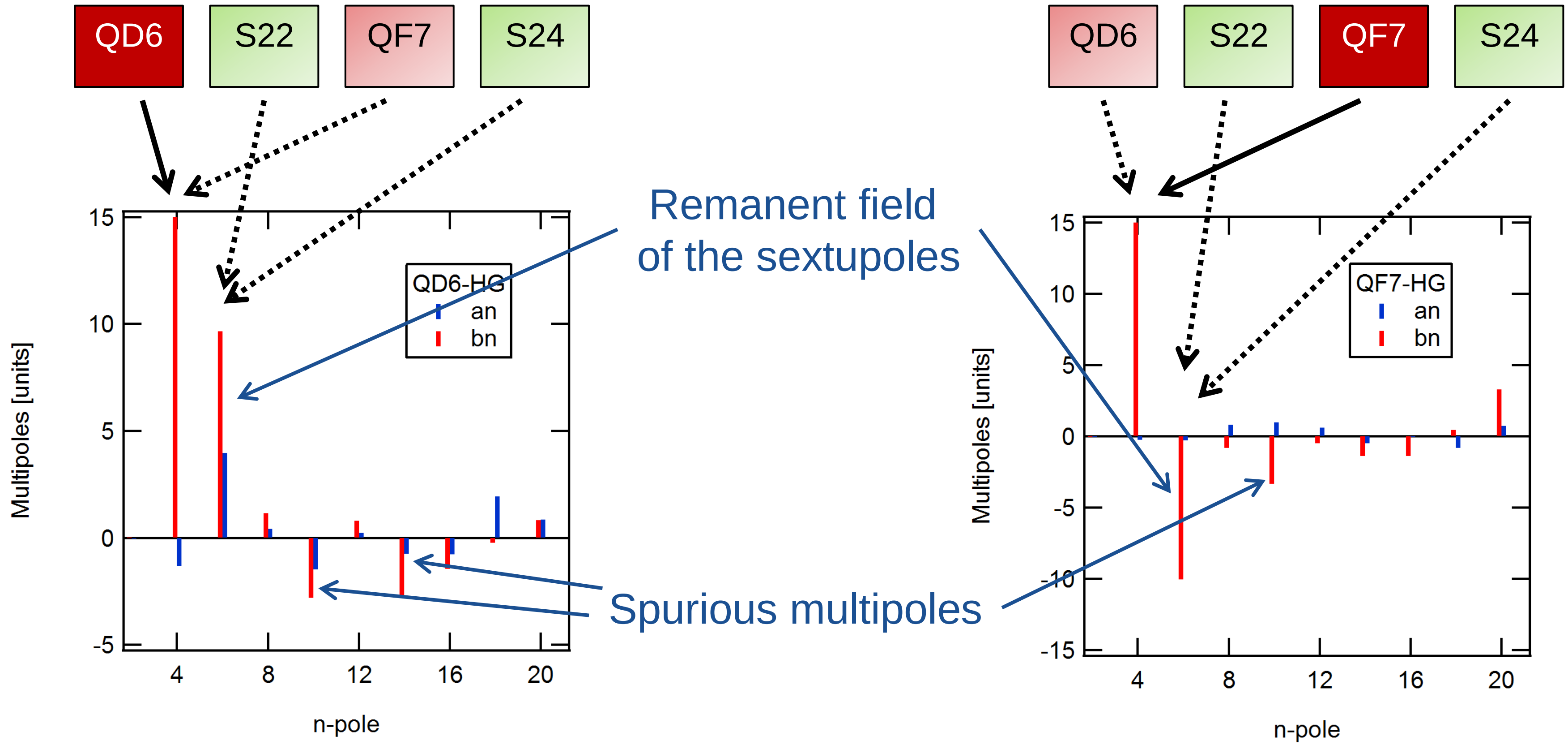
Compensation of the quadrupole component

Advantages

- Compensation of the main multipoles
- Measurements in non-circular gaps

[1] Le Bec *et al.*, PRSTAB 15 (2012) 022401

Harmonic analysis



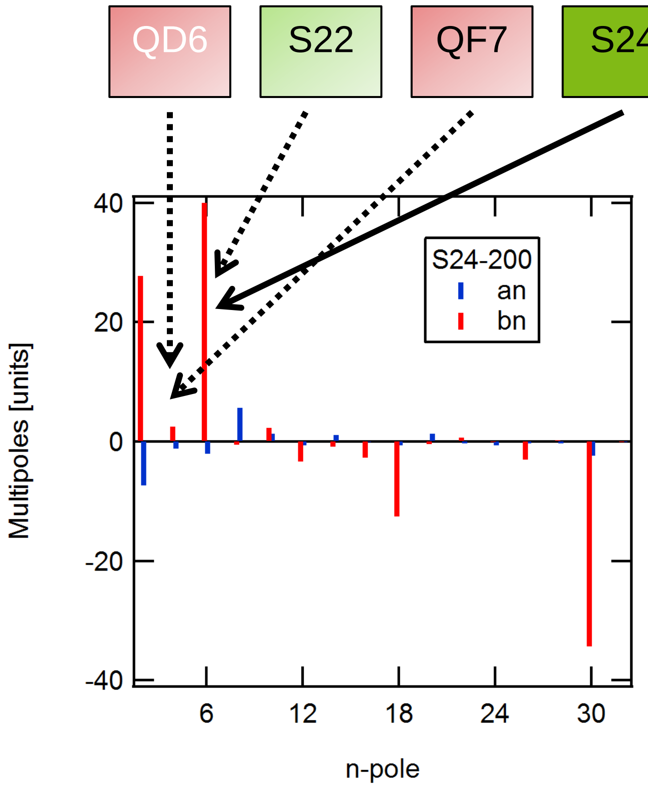
QD6-HG magnet. The 4-pole was normalized to 10^4.

QF7-HG magnet. The 4-pole was normalized to 10^4.

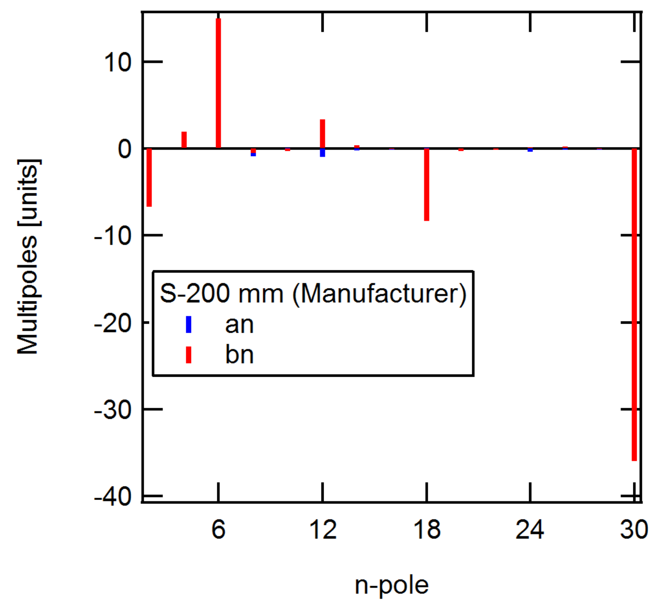
Quadrupole *in situ* harmonic measurements

- Limited accuracy due to the 2.8 m wire length (sag and vibrations)
- No magnetic interaction observed (dominated by remanent field)

Harmonic analysis



S24-200 *in situ* measurements. The 6-pole was normalized to 10^4.



S24-200 rotating coil measurements (done by manufacturer)

Sextupole *in situ* harmonic measurements

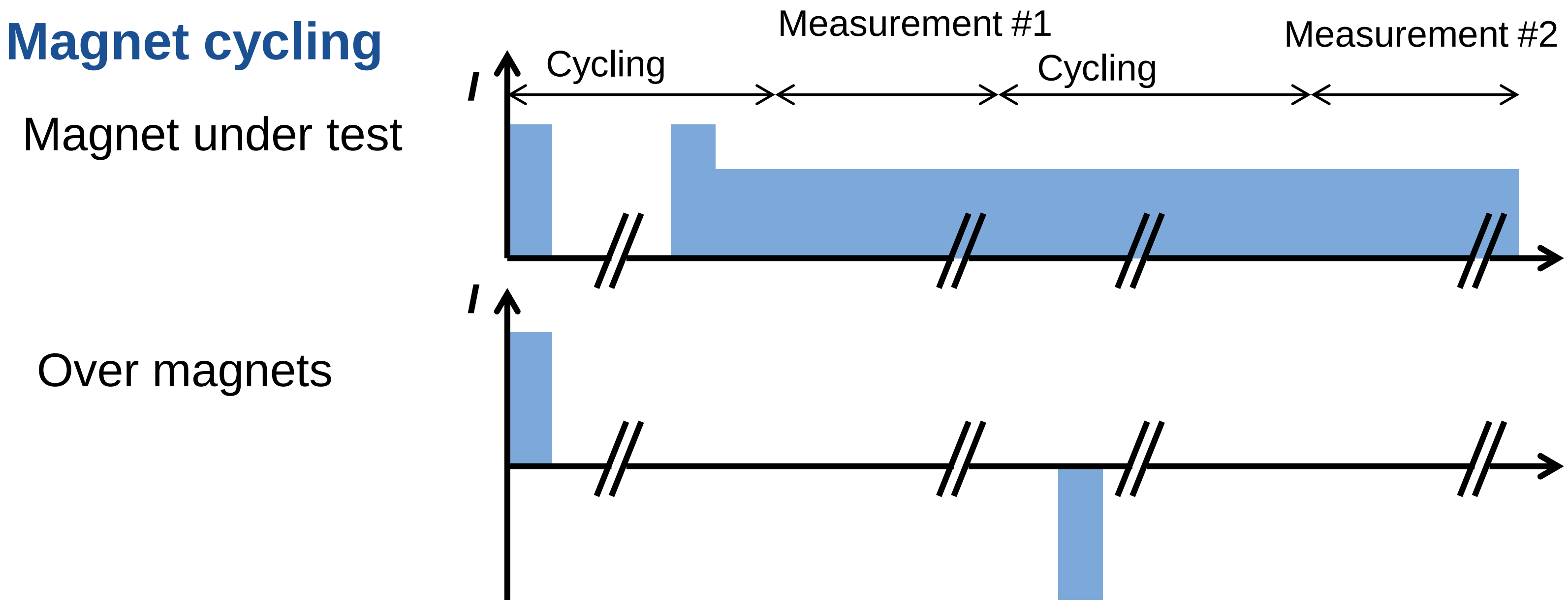
- Good agreement with rotating coil measurements
- Remanent quadrupole components ➔ **biased estimation of sextupole centre**

Remanent field of lower order terms

Biased centre position

- Measurement radius $r_0 = 30 \text{ mm}$
- Quadrupoles remanent field $g \approx 0.09 \text{ T/m x } 0.9 \text{ m},\ b_2 \approx 0.25 \text{ T cm}$ ⇒ $\Delta x \approx 1.25 \text{ mm!}$
- Main sextupole field $d^2B/dx^2 \approx 330 \text{ T/m}^2 \text{ x } 0.2 \text{ m},\ b_3 \approx 3 \text{ T cm}$

Magnet cycling



Conclusion

Alignment

- Alignment of linear stages is not trivial
- Reduced alignment errors between magnets installed on the same girder
- During the alignment of one magnet, all the other magnets must be cycled

Harmonic analysis

- Remanent fields of non powered magnets are not negligible
- Limited accuracy due to the increased wire length
- Interaction between neighboring magnets was not observed
- Longitudinal resolution would be useful for studying the interactions

Perspectives

Bench developments

- Mechanical supports with enhanced rigidity
- Vibrating wire system

Measurements

- Deeper investigation of girder measurements