2nd PACMAN Workshop

Debrecen, Hungary, June 2016

Advances on magnetic measurements by stretched wires at the ESRF

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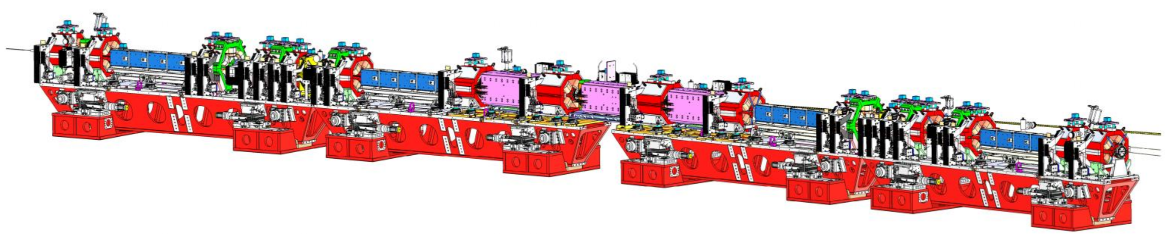

ESRF | The European Synchrotron

OUTLINE

I. Context

- ESRF-EBS: an upgrade of the ESRF storage ring

II. Stretched wire measurement method

- Basics
- Advanced measurements

•II. Measurements: instrumentation and results

- ESRF measurement benches
- Calibration and uncertainties
- Measurement results
- Measurement benches for the ESRF-EBS

IV. Summary

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INTRODUCTION

ESRF – The European Synchrotron

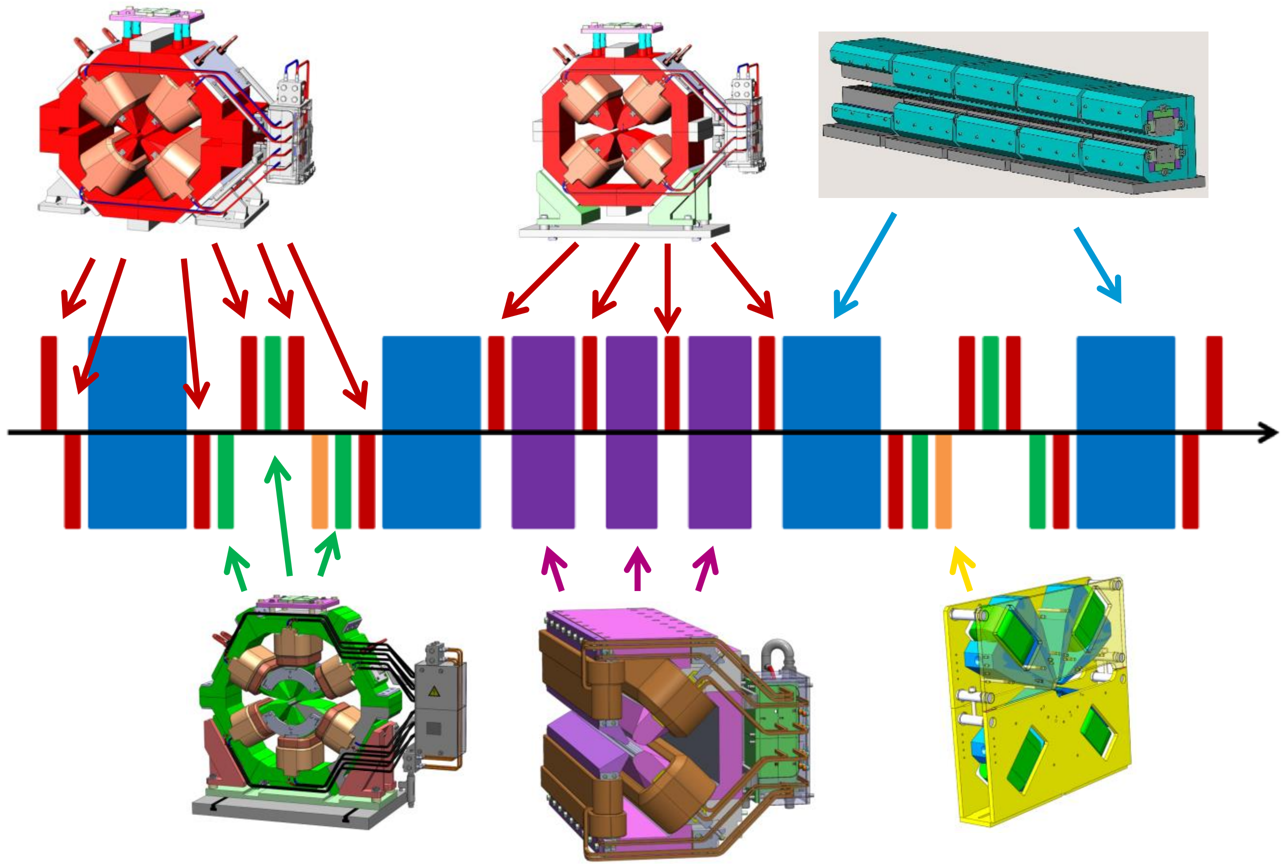
- Light source built in the 1990's
- Located in Grenoble, France
- 6 GeV machine
- 200 mA current
- 840 m long storage ring

INTRODUCTION

ESRF–EBS project

- Increased brightness
- Horizontal emittance: 4 nm·rad→ 135 pm·rad
- New storage ring
- Increased number of bending magnets
- Strong focusing
- Installation in 2019

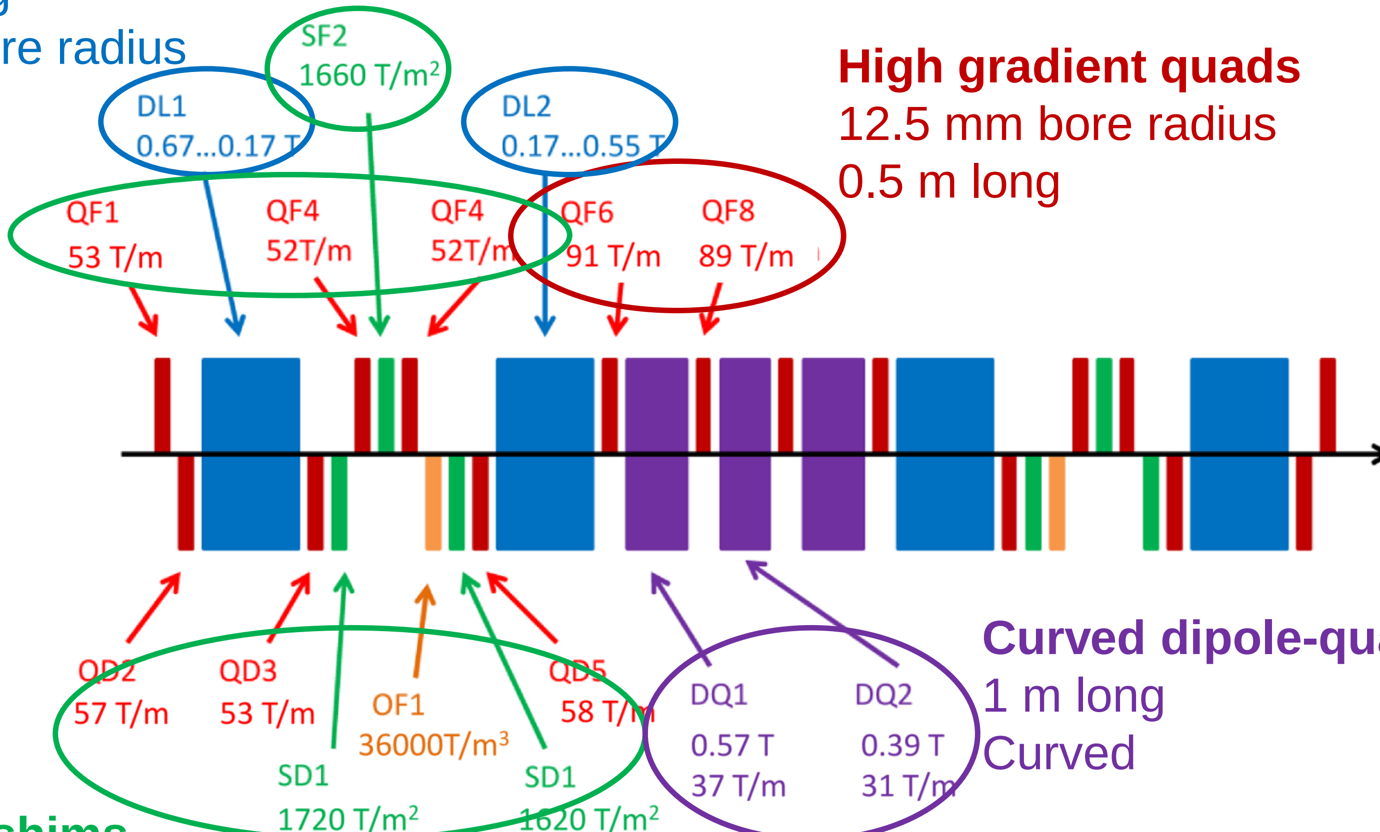
ESRF-EBS storage ring magnets: one cell (1/32 of the ring)



INTRODUCTION

Dipoles with long. grad.
1.8 m long
13 mm bore radius
Curved

High gradient quads
12.5 mm bore radius
0.5 m long



Curved dipole-quadrupoles
1 m long
Curved

Position shims

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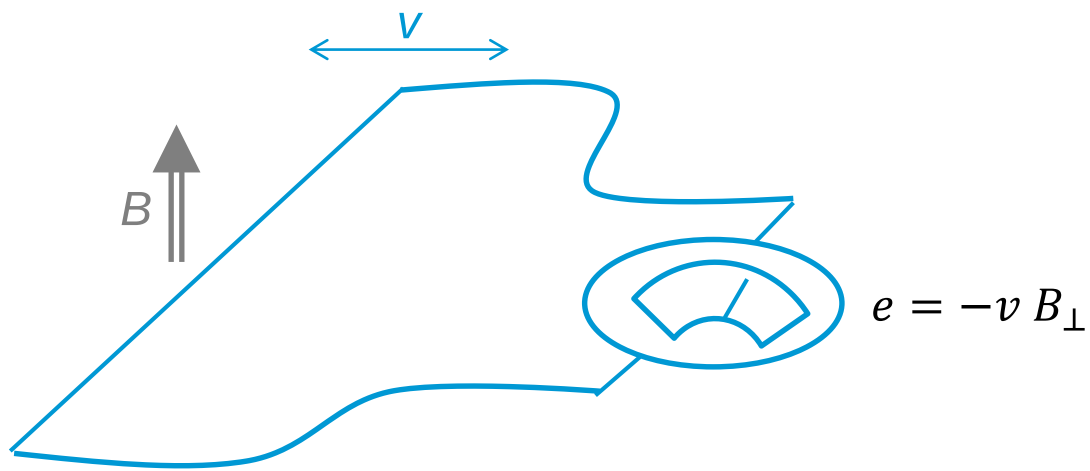
STRETCHED WIRE MEASUREMENT METHODS

Linear wire motion

- Moving stretched wire
- Voltage measurements



Applications

- Alignment
- Field strength and gradient measurements
- Homogeneity

Main challenges

- High sensitivity to wire motion errors
- Low voltage measurements

STRETCHED WIRE MEASUREMENT METHODS

Advanced measurements

- Based on field multipole analysis
- Can be used for alignment, strength measurements, higher order multipoles

Method

$$B = \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{z}{\rho_0} \right)^{n-1}$$

Multipole expansion

$$\mathbf{B}_\perp = (B_{\perp 1}, \dots, B_{\perp M}) \approx \mathbf{M}(a_1, \dots, a_N, b_1, \dots, b_N)^T$$

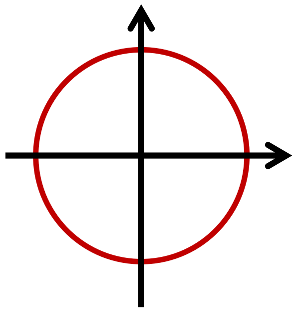
N first multipoles
Field perp. to wire motion

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

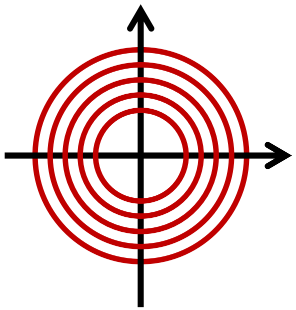
$$\hat{\mathbf{C}} = \left(\widehat{a_1}, \dots, \widehat{a_N}, \widehat{b_1}, \dots, \widehat{b_N} \right)^T = \mathbf{M}^+ \mathbf{B}_\perp$$

where **M**$^+$ is a pseudoinverse of **M**

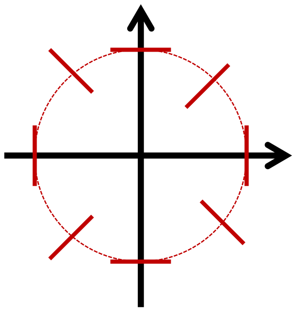
Advanced measurements (cont.)



Single radius
Good repeatability
Fast



Multi-radii
Improved accuracy
Relatively fast



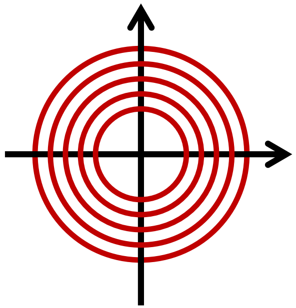
Compensated
Insensitive to 4-pole
Slow

$$B = \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{z}{\rho_0}\right)^{n-1}$$

$$\hat{\mathbf{C}} = \left(\widehat{a_1}, \dots, \widehat{a_N}, \widehat{b_1}, \dots, \widehat{b_N}\right)^T = \mathbf{M}^+ \mathbf{B}_\perp$$

Advanced measurements (cont.)

Example: multi-radii method



$$\hat{\mathbf{C}} = \mathbf{M}^{+}\mathbf{B}_{\perp}$$

M may be difficult to invert. It can be rewritten as

$$\mathbf{M}^{+} = \mathbf{R}\begin{pmatrix} \mathbf{M}_1^{+} & & 0 \\ & \ddots & \\ 0 & & \mathbf{M}_P^{+} \end{pmatrix}$$

where $\mathbf{M_i}^{+}$ is for the radius ρ_i and **R** depends only on the measurement and normalization radii

M for 10 multipoles and ρ = 12 … 2 mm

STRETCHED WIRE MEASUREMENT METHODS

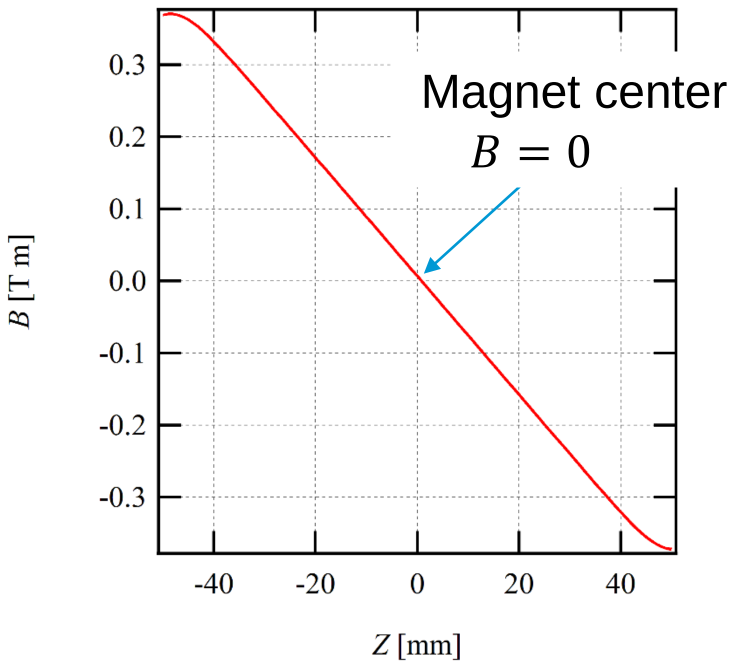
Alignment

Linear measurements

- Zero field at magnet centre
- Large higher order multipoles may lead to alignment errors
- Axis obtained by moving the wire extremities in opposite directions
- Suitable for quadrupole alignment

Multipole measurements

- Similar to rotating coil methods
- Better results for 6- and 8-poles



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•Basics

•Advanced measurements

•II. Measurements: instrumentation and results

•ESRF measurement benches

•Calibration and uncertainties

•Measurement results

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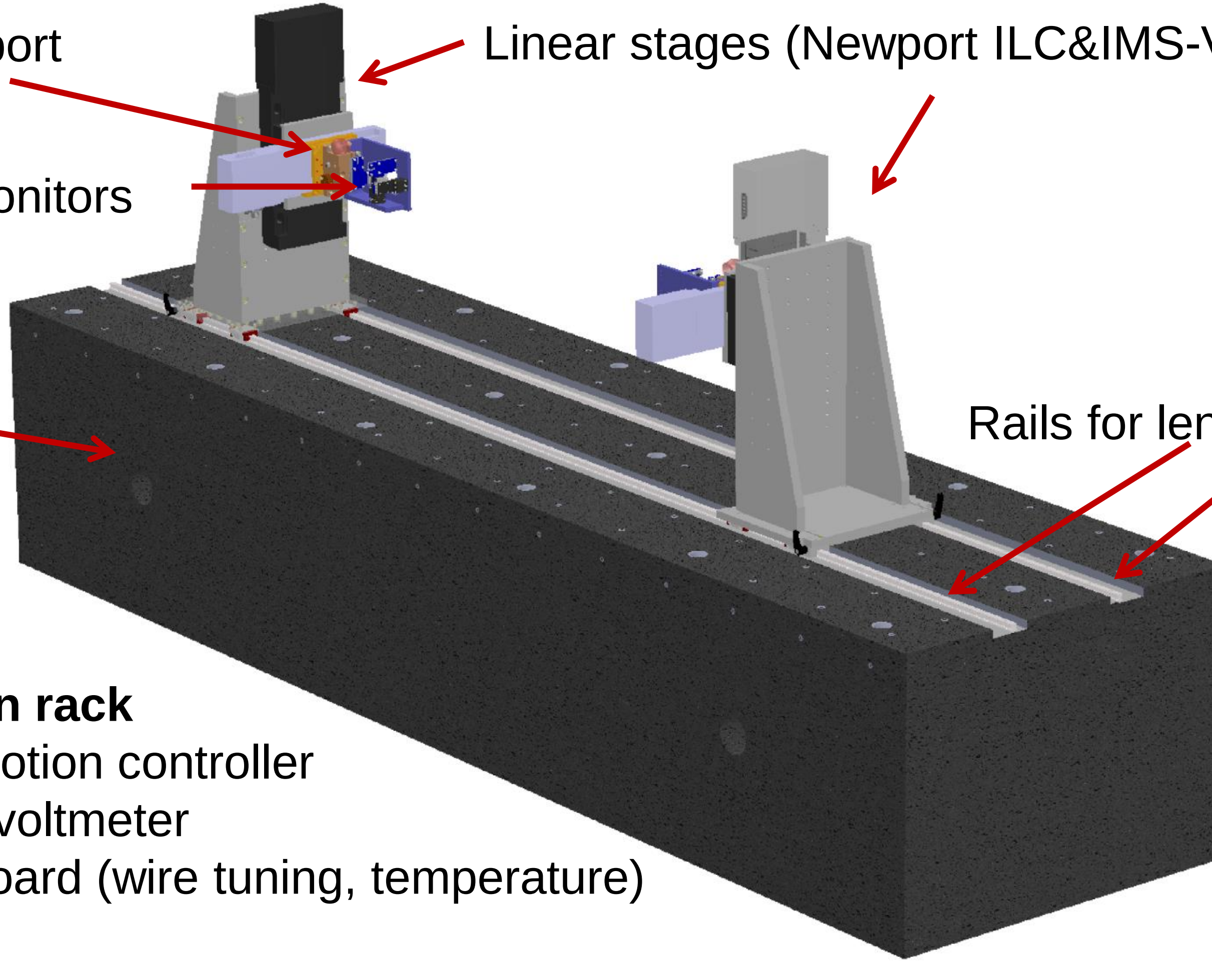
ESRF MEASUREMENT BENCHES



New wire support

Linear stages (Newport ILC&IMS-V)

Wire position monitors (optional)

3 m long granite table

Rails for length adjustment

Instrumentation rack

Newport XPS motion controller

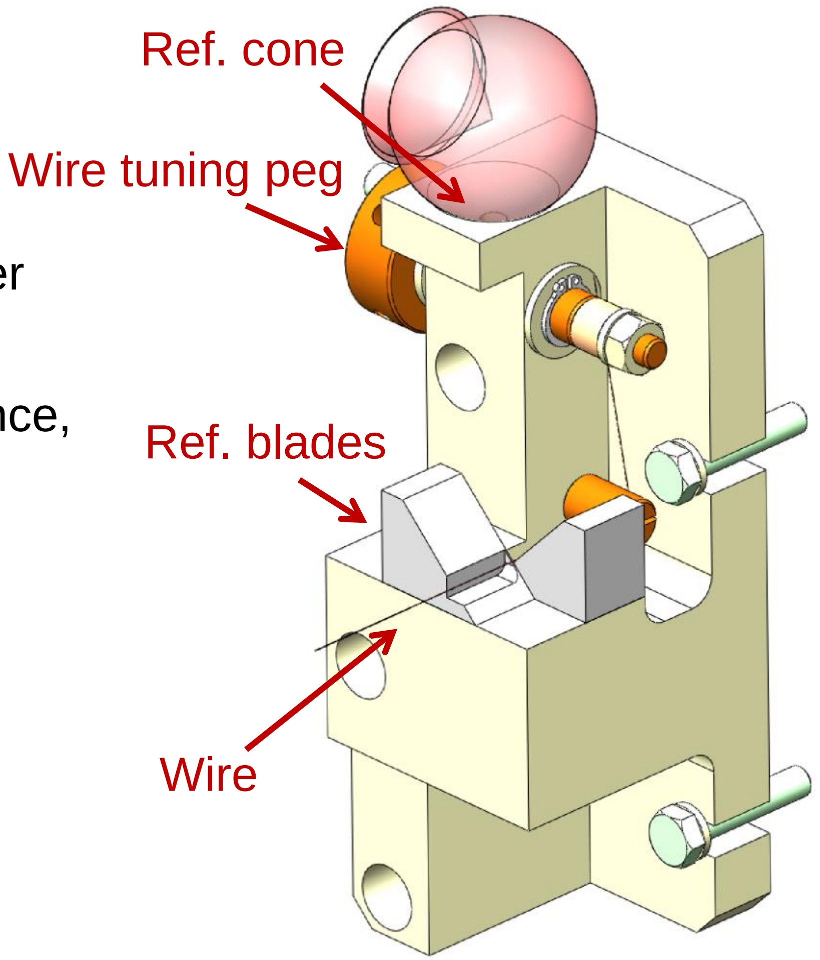
Keithley 2182A voltmeter

NI acquisition board (wire tuning, temperature)

Industrial PC

Wire supports

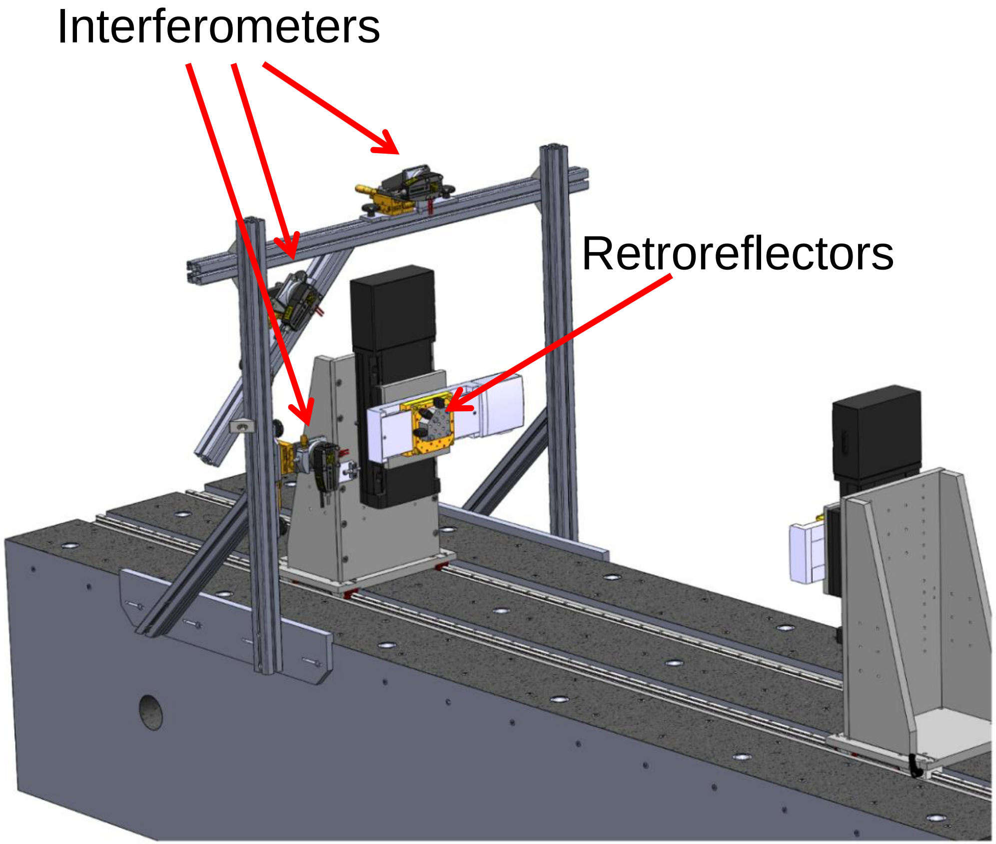
- Two rectified blades (±0.004 mm error measured)
- Wire position can be measured with a laser tracker or a FaroArm
- A reference cone is installed for convenience, but its use is not mandatory



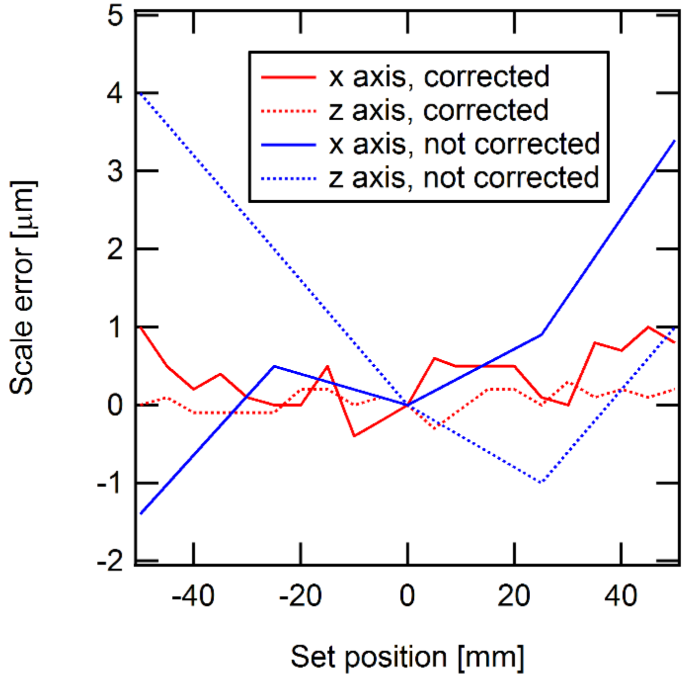
ESRF MEASUREMENT BENCH

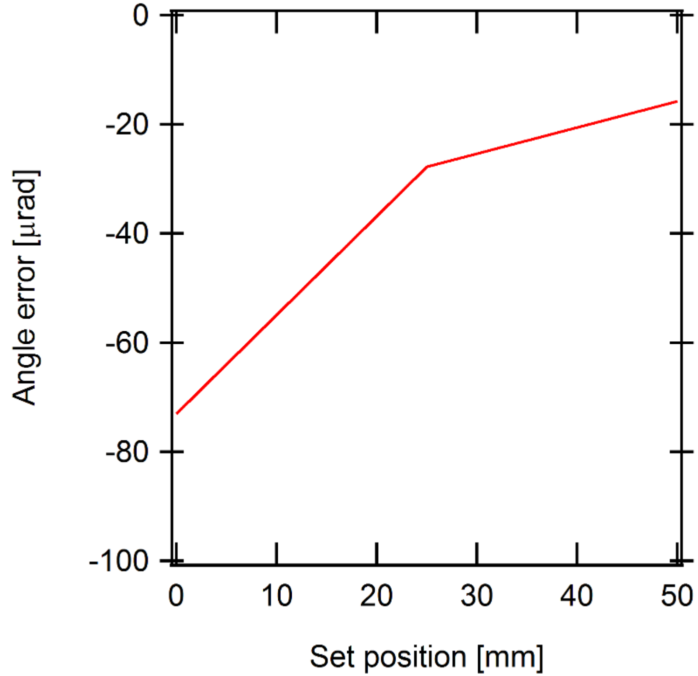
Stage calibration bench

- Fast calibration
- Based on 3 interferometers
- Measurements of scale errors
- Measurement of stage angles
- Implementation of correction tables
- Easy to install and to transport



Stage calibration results





Standard deviation < 0.5 µm
(measured in the one direction to avoid backlash)

Perpendicularity error

Portable Coordinate Measurement Machine

Laser tracker measurement: $\sigma = 20\,\mu\text{m}$

Magnetic measurements

Error	St Dev [µm]	Type[1]
Mag. Meas. Repeat.	1	A
Wire Pos. Repeat.	5	A
Wire Radius. Acc.	3	B
Total	**7**	

[1]According to the Guide to the expression of Uncertainties in Measurements (GUM), type A uncertainties are obtained from observed distribution while type B are not obtained from repeated observations.

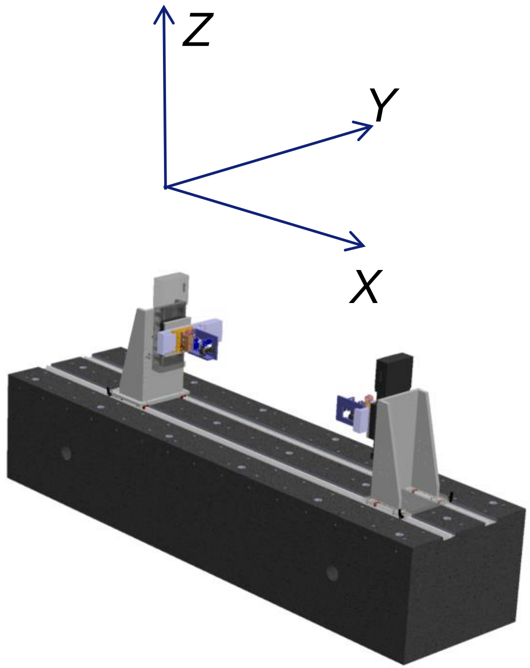
UNCERTAINTIES OF STRETCHED-WIRE ALIGNMENT

Summary of alignment uncertainties

$$\sigma_x = \sigma\sqrt{2+\frac{1}{2}\left(\frac{H}{L}\right)^2} = 29\ \mu\text{m}$$

$$\sigma_Y = \sqrt{\left(\frac{3}{2}+2\left(\frac{x_0}{L}\right)^2+\frac{1}{2}\left(\frac{H}{W}\right)^2\right)\sigma^2+\sigma_{MM}{}^2} = 28\ \mu\text{m}$$

$$\sigma_Z = \sqrt{\left(\frac{3}{2}+2\left(\frac{x_0}{L}\right)^2\right)\sigma^2+\sigma_{MM}{}^2} = 26\ \mu\text{m},$$



with σ = 20 mm (laser tracker uncertainty), H = 0.6 m (magnet length), L = 1.2 m (wire length), x_0 = 0.2 m (long. position of fiducial), σ_{MM} = 7 mm (magnetic measurement uncertainty)

MEASUREMENT RESULTS – ONE MAGNET

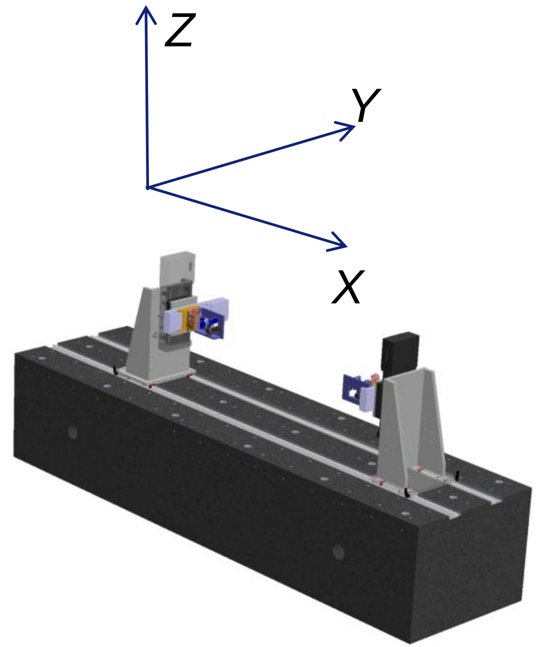
Magnetic measurement repeatability (before transfer to fiducials)

$\sigma_{Y,Z} < 1\ \mu m$ without removing the wire

$\sigma_{Y,Z} < 5\ \mu m$ wire removed, reinstalled and tuned

$\sigma_{\theta Y,\theta Z} < 100\ \mu rad$

$\sigma_{\theta X} < 10\ \mu rad$



(measured on a 22 T/m, 66 mm aperture, 530 mm long quadrupole, see [Le Bec, IMMW2009] for details)

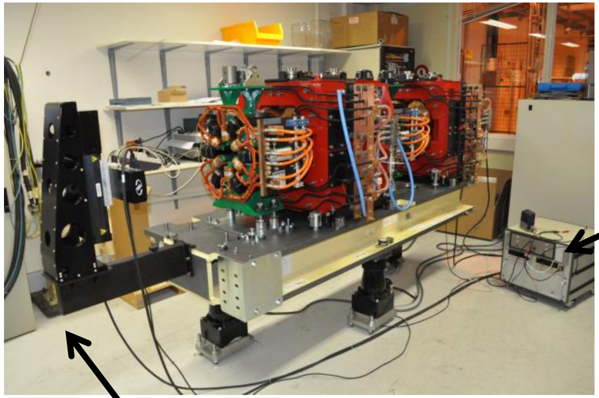
Suitable for multipole analysis

Measurement duration

Alignment: $T \approx 5$ min (without transfer to fiducials)

Multipoles: $T \approx 2$ min

MEASUREMENT RESULTS – MAGNET GIRDER

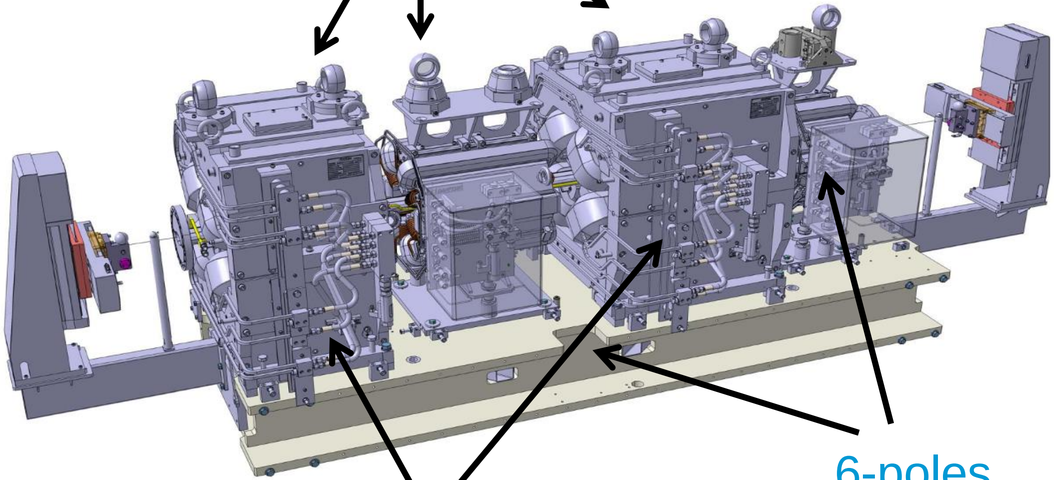


Control rack
Motion controller
Voltmeters

Titanium wire
100 µm diameter
2.8 m length

Survey monuments

Linear stages



6-poles

4-poles

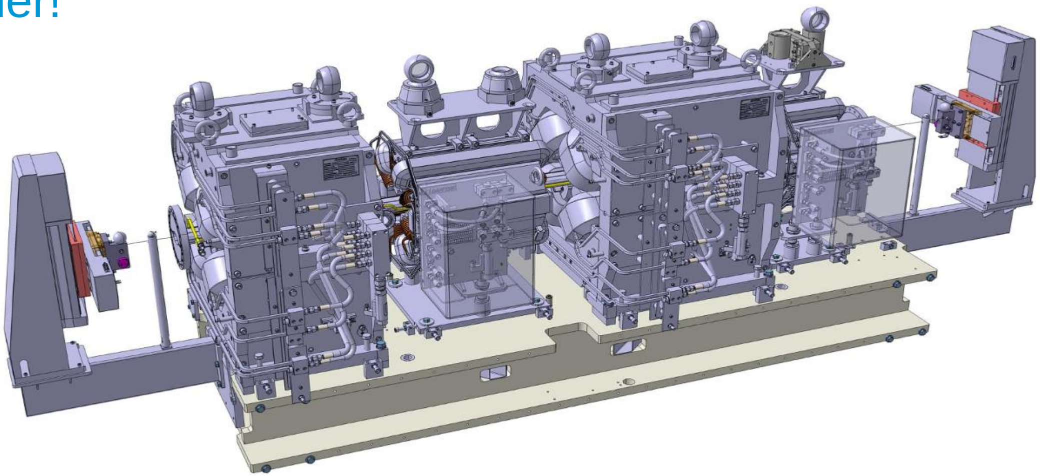
MEASUREMENT RESULTS – MAGNET GIRDER

Alignment of 4 magnets on a girder

- Magnets aligned on the wire within 20 µm
- Alignment errors dominated by magnet adjustment precision
- Stage supports not rigid enough
- Magnet cycling needed (remanent field cause offsets)

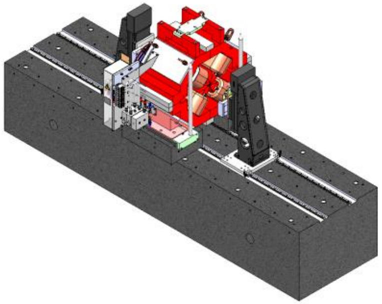
Not suitable if dipoles on the girder!

→Not used for the ESRF-EBS

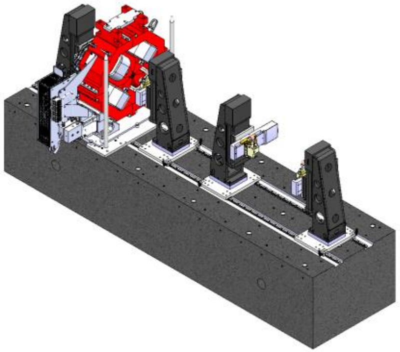


[Le Bec, IMMW2013]

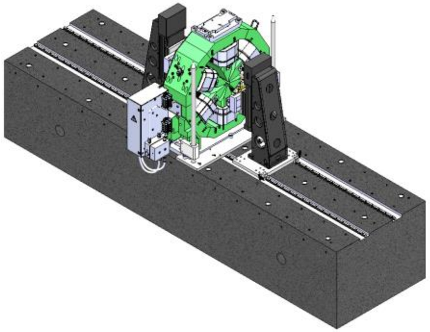
MEASUREMENT BENCHES FOR THE ESRF-EBS



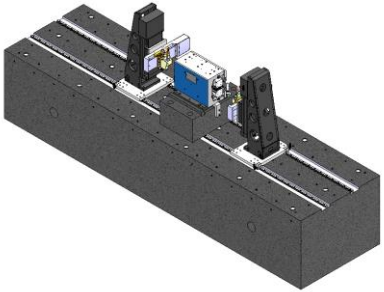
High gradient quads



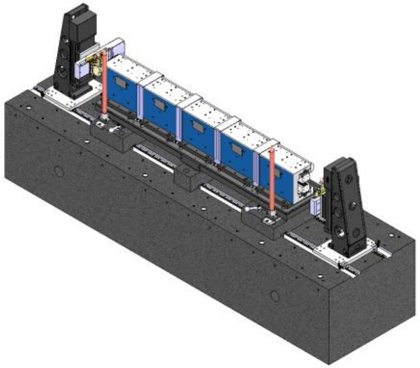
High gradient quads, 2 stands



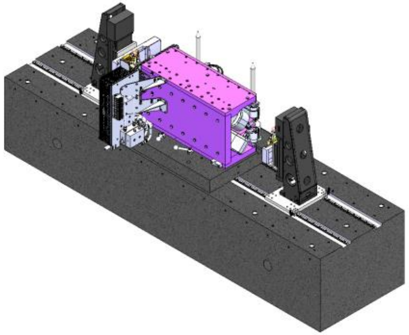
Sextupoles



Dipole modules



Dipoles



Dipole-quadrupoles

MEASUREMENT BENCHES FOR THE ESRF-EBS

Stretched wire measurement benches at the ESRF

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SUMMARY

ESRF-EBS magnetic measurements

- Approximately 1000 magnet to be measured
- PM dipole to be measured at the ESRF
- Other magnets to be measured by magnet suppliers, with ESRF benches
- Stretched wire alignment of magnet girders not foreseen (dipoles on all girders)

Results

- Repeatability of magnetic centre measurement < 5 µm (incl. wire installation)
- Fiducialization uncertainties ≈ 25 to 30 µm, dominated by laser tracker errors
- Suitable for multipole analysis (quality control & beam dynamics)
- Fast measurements

MANY THANKS FOR YOUR ATTENTION

REFERENCES

Cited in the slides

[Le Bec, IMMW2009] G. Le Bec, J. Chavanne, Ch. Penel, *Stretched wire measurement bench at the ESRF,* IMMW16, 2009, Bad-Zurzach, Switzerland.

[Le Bec, IMMW2013] G. Le Bec, J. Chavanne, Ch. Penel, *Stretched wire measurement of multipole magnets at the ESRF,* IMMW17, 2013, Brookhaven, USA.

Other references

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