International Magnetic Measurement Workshop

DLS, Didcot, UK, June 2017

Overview of magnetic measurement activities at the ESRF

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ESRF | The European Synchrotron

OUTLINE

I. Introduction

- The ESRF light source and the EBS project

II. Stretched-wire measurements

- Standard measurements: quality control and alignment
- Stretched wire R&D

III. Hall probe measurements

- Measurement of the EBS dipoles and dipole-quads
- Cryogenic undulator measurements

IV. Conclusions and perspectives

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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

•32 straight sections, about 80 undulators installed

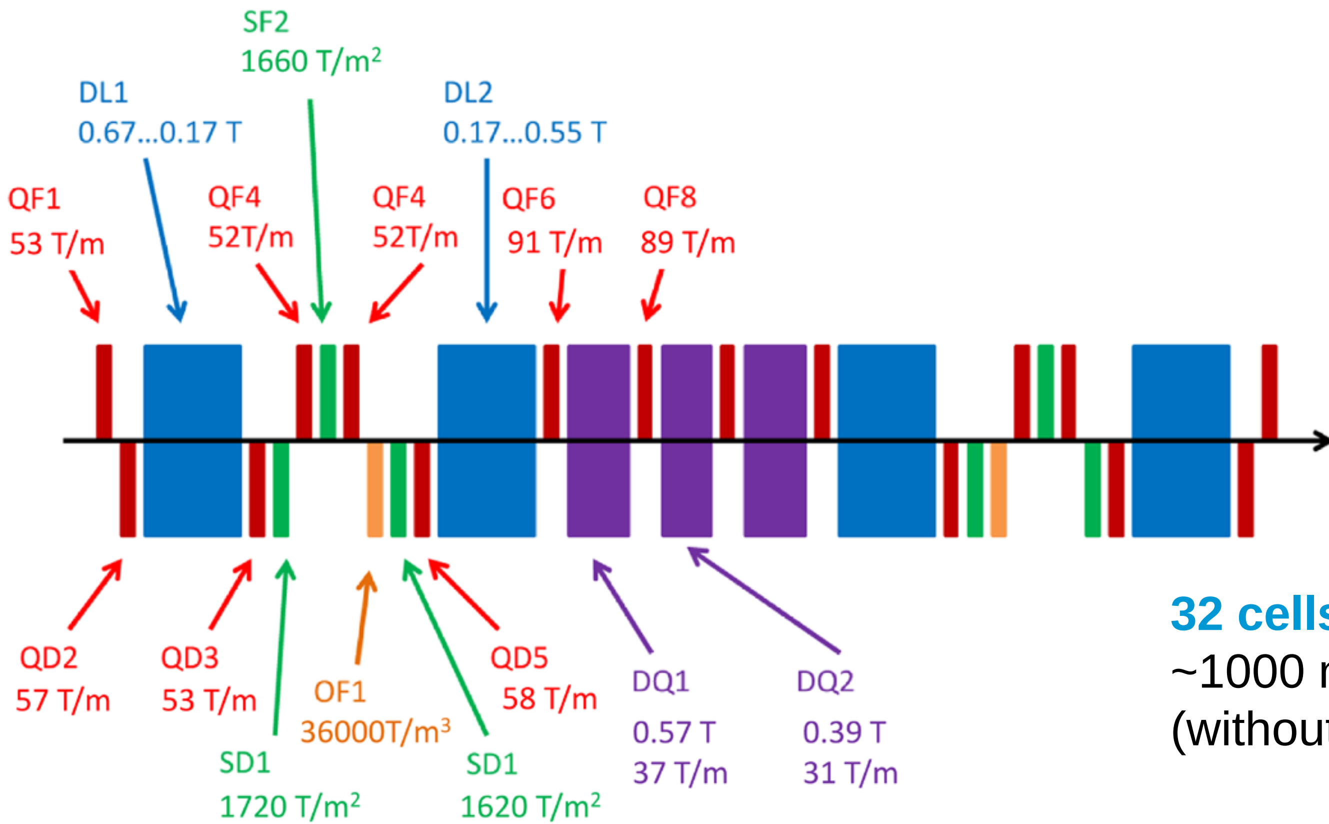
INTRODUCTION

ESRF–EBS project

- Extremely Brilliant Source (EBS)
- Increased brightness
- Horizontal emittance: 4 nm·rad→ 135 pm·rad
- New storage ring
- Increased number of bending magnets
- Strong focusing
- Production phase started
- Installation in 2019

More details about ESRF upgrade in [Farvacque , IPAC 2013]

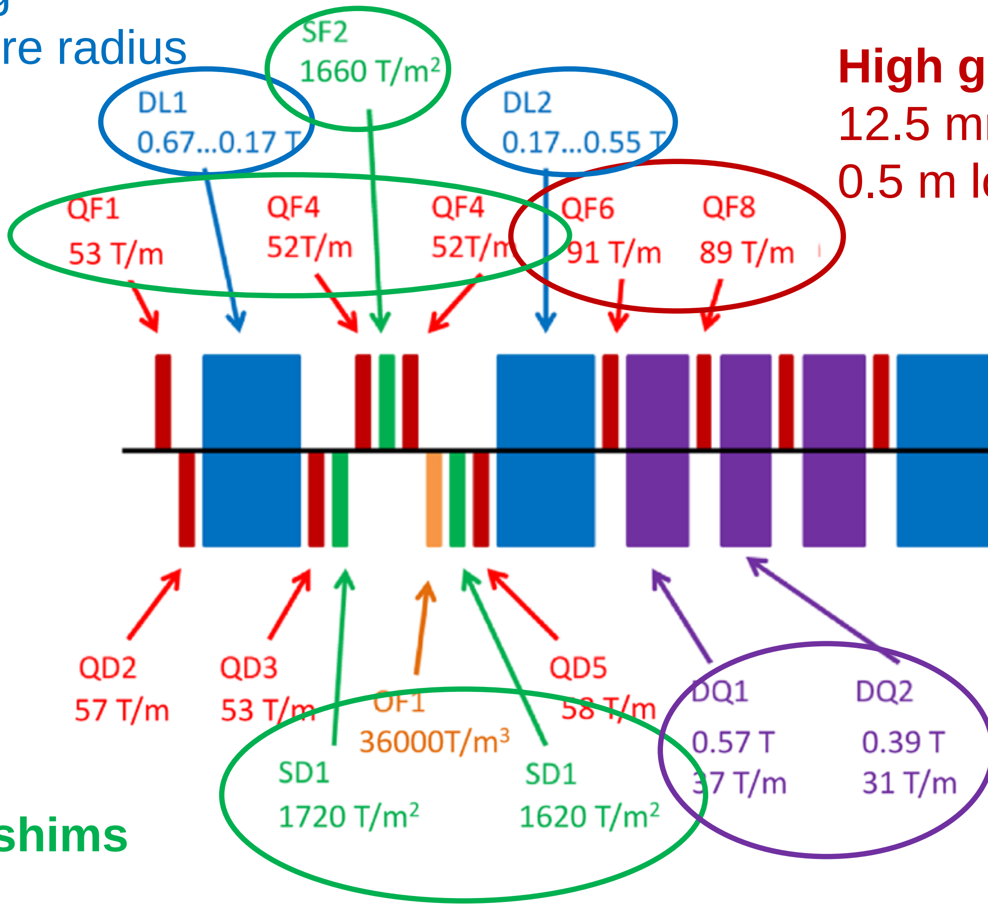
ESRF upgraded storage ring magnets: one cell



32 cells
~1000 magnets
(without correctors)

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
Small aperture

Position shims

INTRODUCTION

Moderate gradient quads
50 T/m

Sextupoles
1700 T/m2

High gradient quads
90 T/m

Dipole with longitudinal gradient
(DL)
0.17 … 0.67 T

Pre-series magnets installed on a mock-up cell

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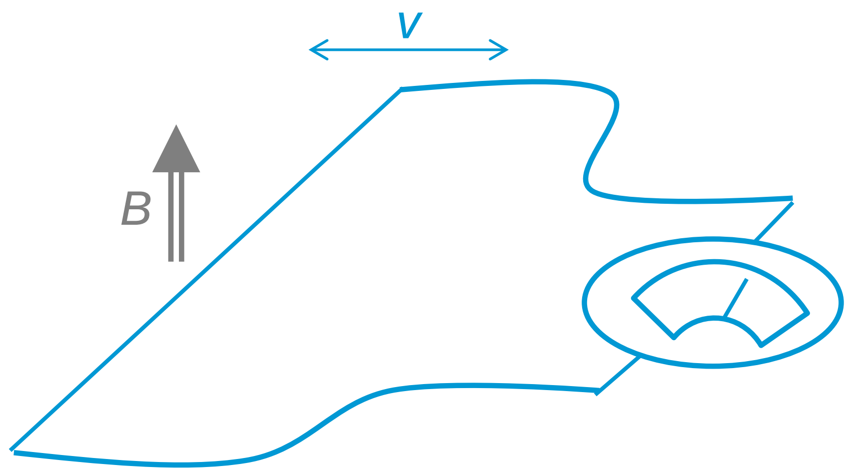
STRETCHED WIRE MEASUREMENTS: METHODS

Linear wire motion

•Moving stretched wire

•Voltage measurements



$$e = -v\,B_{\perp}$$

Applications

•Alignment

•Field strength and gradient measurements

•Homogeneity and field quality

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

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

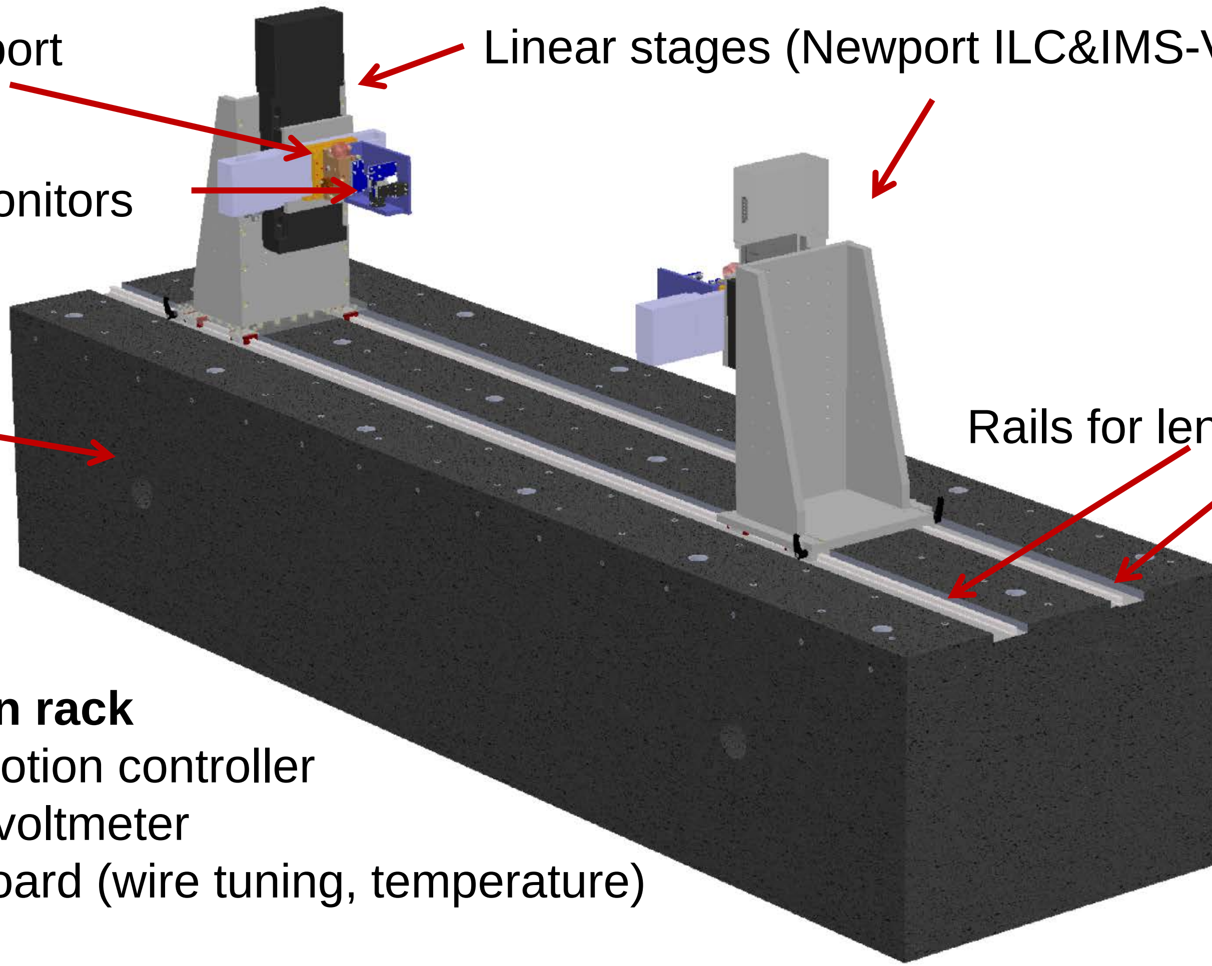
N first multipoles
Field perp. to wire motion

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**

STRETCHED WIRE MEASUREMENTS: BENCHES



Instrumentation rack

Newport XPS motion controller

Keithley 2182A voltmeter

NI acquisition board (wire tuning, temperature)

Industrial PC

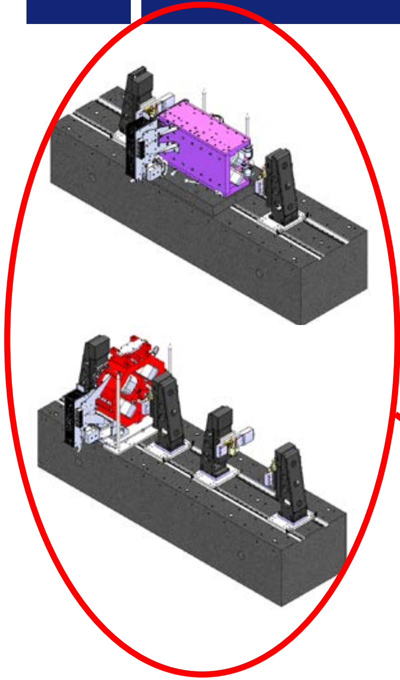
STRETCHED WIRE MEASUREMENTS: PRODUCTION OF EBS MAGNETS

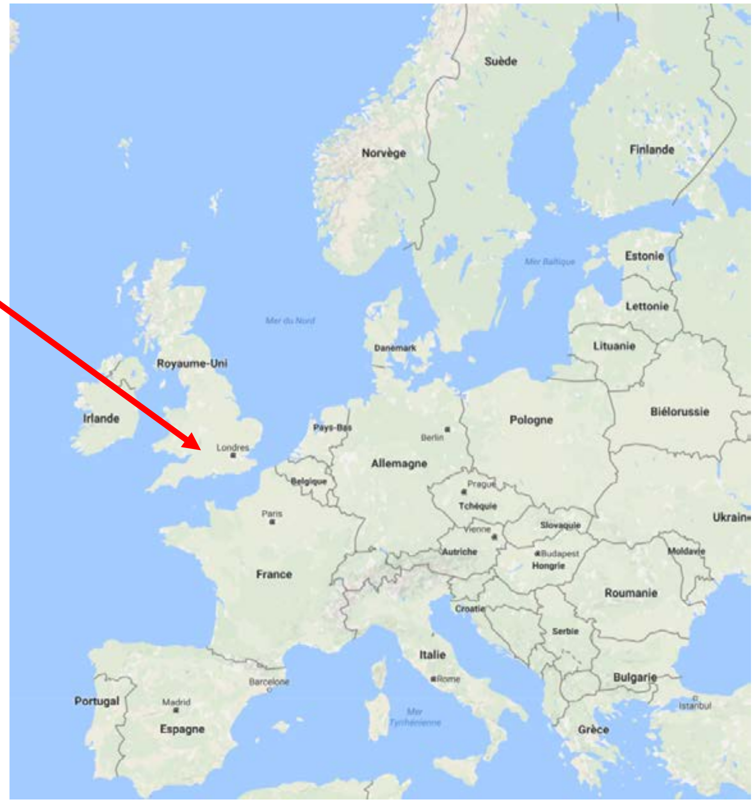
Measurement of the EBS series magnets

- Quality control
- Fiducialization and alignment
- Measurements and fiducialization done by the magnet suppliers
- ESRF stretched-wire benches used in most cases except octupoles
- 5 benches installed abroad + 3 in house, dedicated to the EBS measurements

Dedicated talk by Loïc Lefebvre on Tuesday

STRETCHED WIRE MEASUREMENTS: PRODUCTION OF EBS MAGNETS



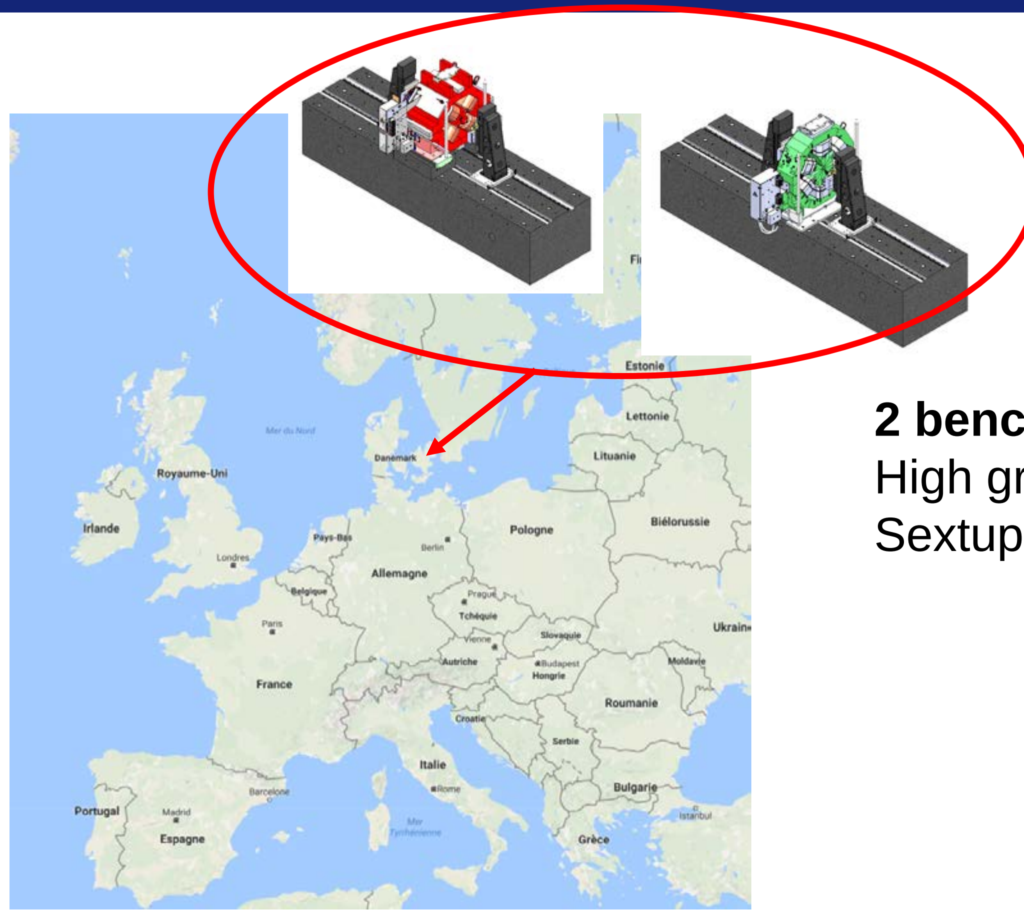


3 benches in UK

Quads,

Dipole-quads

STRETCHED WIRE MEASUREMENTS: PRODUCTION OF EBS MAGNETS

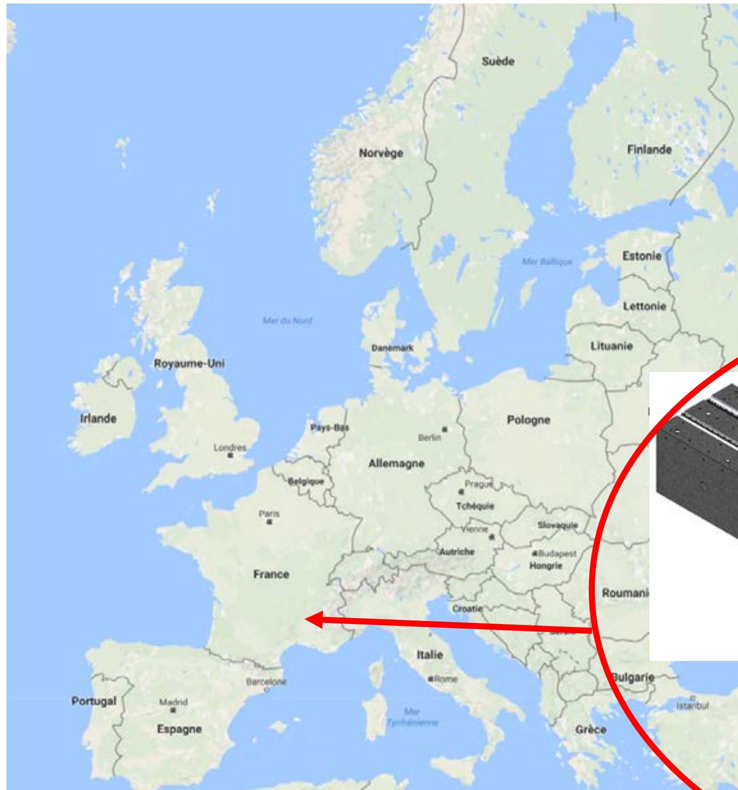


2 benches in Denmark

High gradient quads,

Sextupoles

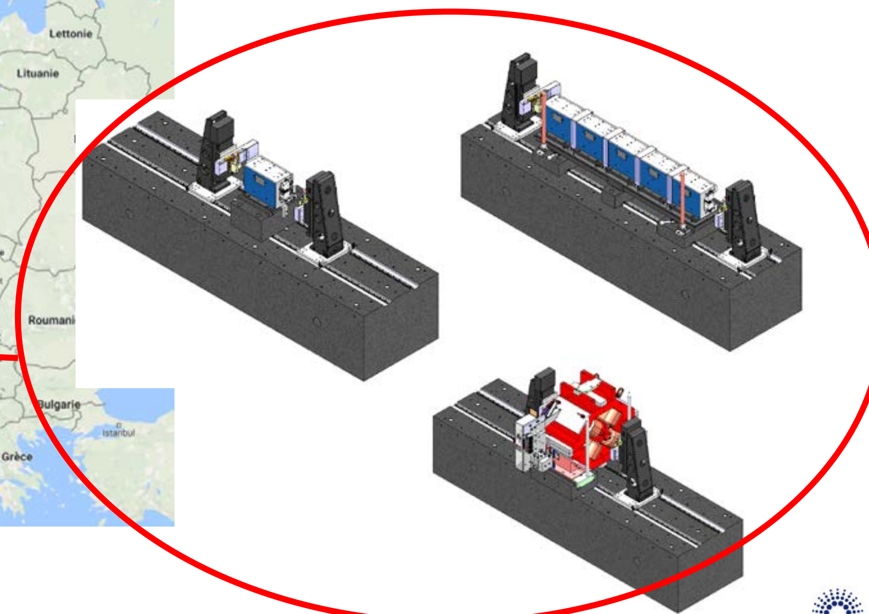
STRETCHED WIRE MEASUREMENTS: PRODUCTION OF EBS MAGNETS



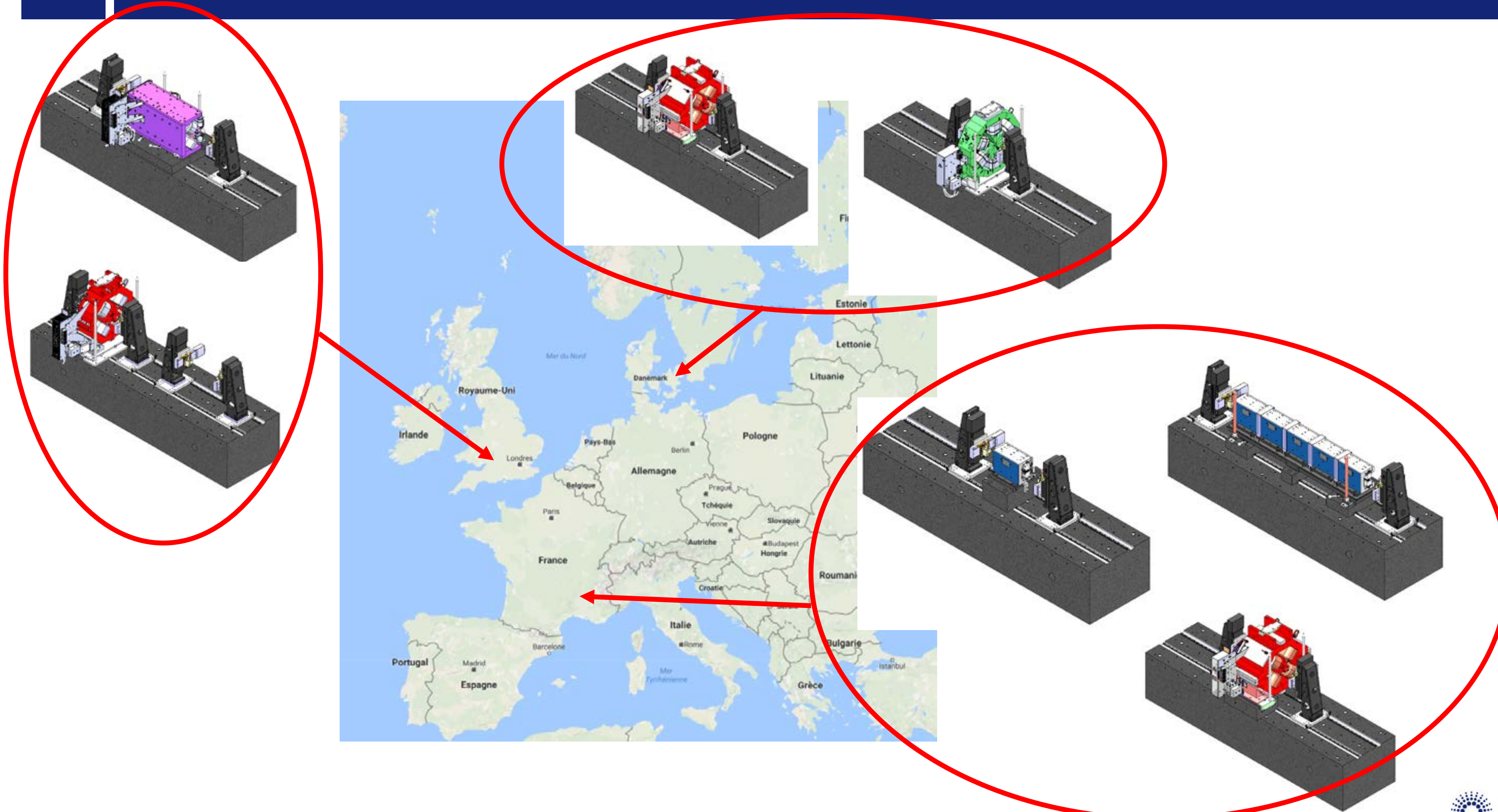
3 benches at the ESRF

2 for DL dipoles

1 for all magnets quality control



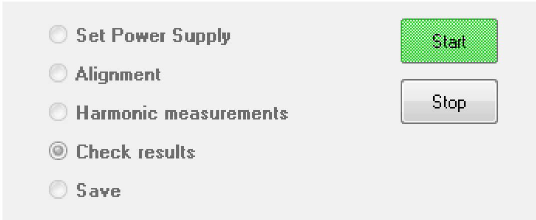
STRETCHED WIRE MEASUREMENTS: PRODUCTION OF EBS MAGNETS



STRETCHED WIRE MEASUREMENTS: BENCHES INSTALLED ABROAD

Benches installed at supplier premises

- Press-button macros developed as much as possible
- Integrated measurement sequence

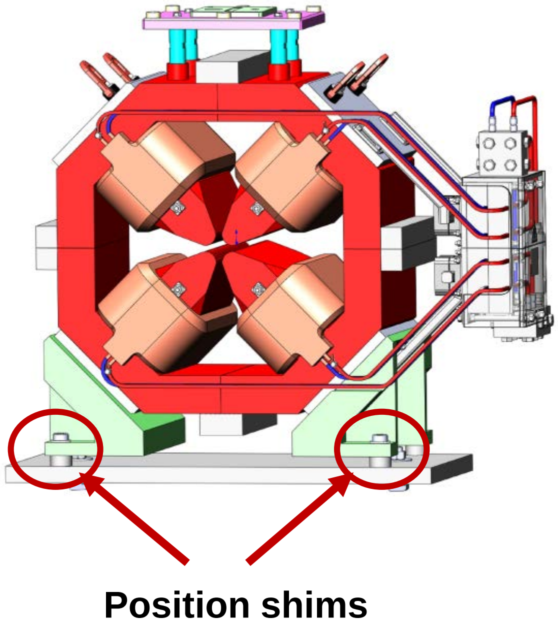


Press-button measurement sequences

STRETCHED WIRE MEASUREMENTS: BENCHES INSTALLED ABROAD

Benches installed at supplier premises

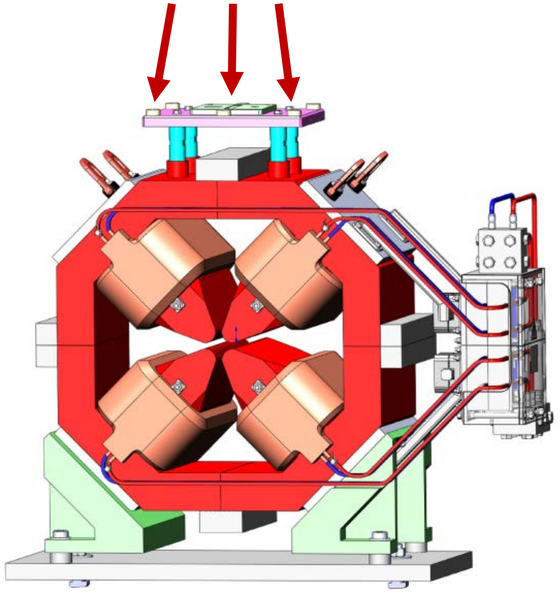
- Press-button macros developed as much as possible
- Integrated measurement sequence
- Position shim computations integrated



STRETCHED WIRE MEASUREMENTS: BENCHES INSTALLED ABROAD

Benches installed at supplier premises

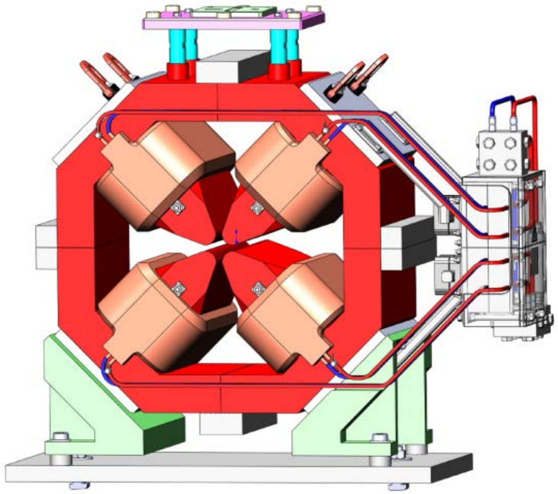
- Press-button macros developed as much as possible
- Integrated measurement sequence
- Position shim computations integrated
- Fiducialization not completely integrated
- Wire moved at the centre and roll angle measured
- Portable CMM arm and inclinometers used by suppliers



STRETCHED WIRE MEASUREMENTS: BENCHES INSTALLED ABROAD

Benches installed at supplier premises

- Press-button macros developed as much as possible
- Integrated measurement sequence
- Position shim computations integrated
- Fiducialization not completely integrated
- Multipole measurements integrated



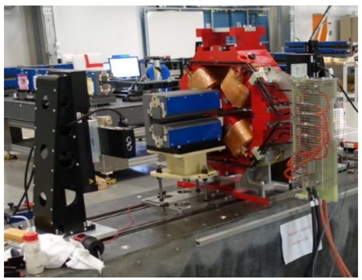
STRETCHED WIRE MEASUREMENTS: BENCHES INSTALLED ABROAD

Benches installed at supplier premises

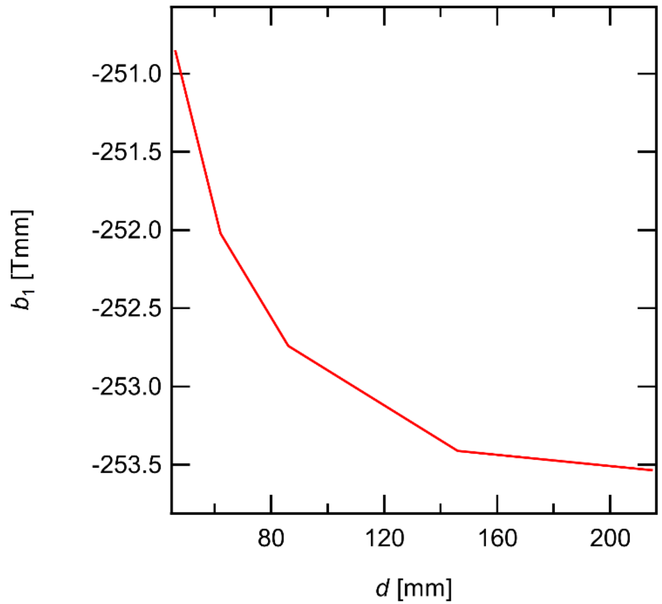
- Press-button macros developed as much as possible ✓
- Integrated measurement sequence ✓
- Position shim computations integrated ✓
- Fiducialization not completely integrated ✗
- Multipole measurements integrated ✓

More details in by Loïc's talk

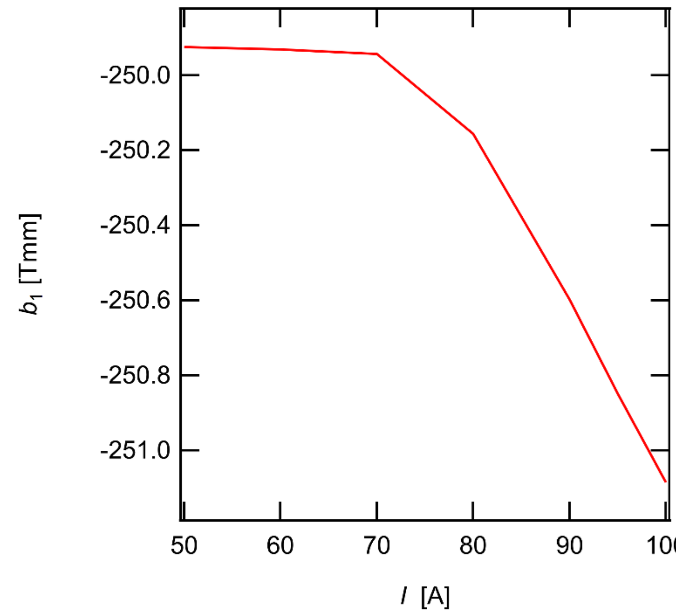
Dipole to quadrupole crosstalk



Measurement of the crosstalk between a PM dipole module and a quadrupole



Dipole component vs pole-to-pole distance at nominal quad current. Nominal distance: 47 mm.



Dipole component vs quad current at nominal distance. Nominal current: 95 A.

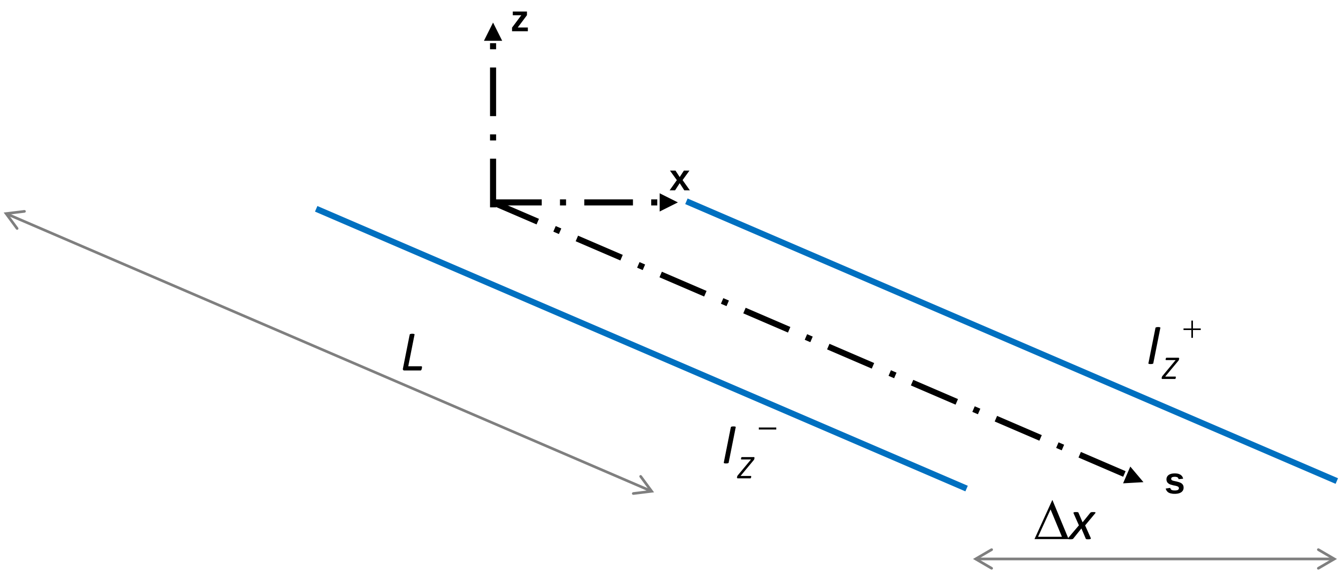
New quadrupole alignment sequence

1. Integrated gradient measurement

$$G = \int G ds = \frac{I_z^+ - I_z^-}{\Delta x}$$

with

$$I_z = \int B_z ds$$



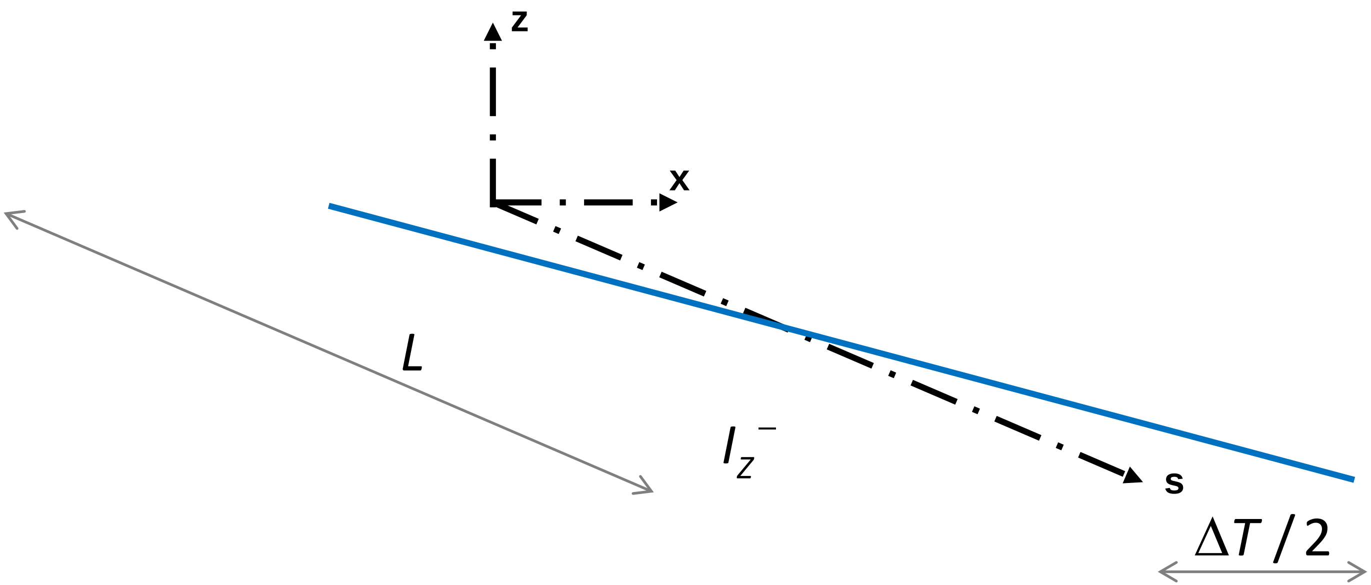
STRETCHED WIRE MEASUREMENTS: R&D

New quadrupole alignment sequence

2. Field integral measurements with an angular offset

$$I_z^1 = \int B_z ds$$

$$J_z^1 = \iint B_z ds$$



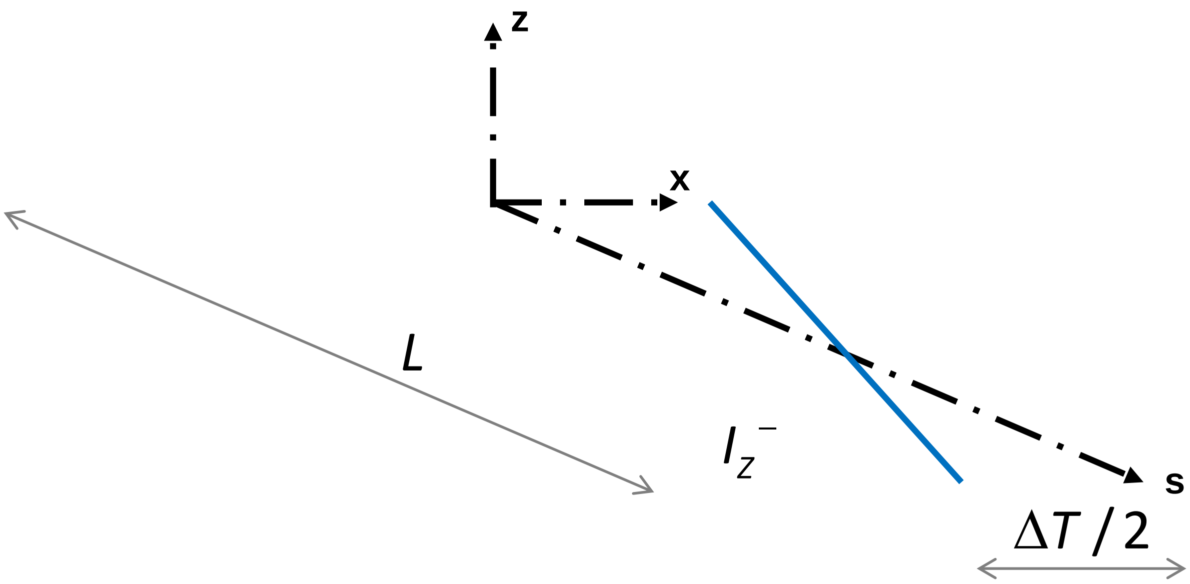
The European Synchrotron | ESRF

New quadrupole alignment sequence

3. Field integral measurements with the opposite angular offset

$$I_z^{\,2} = \int B_z ds$$

$$J_z^{\,2} = \iint B_z ds$$



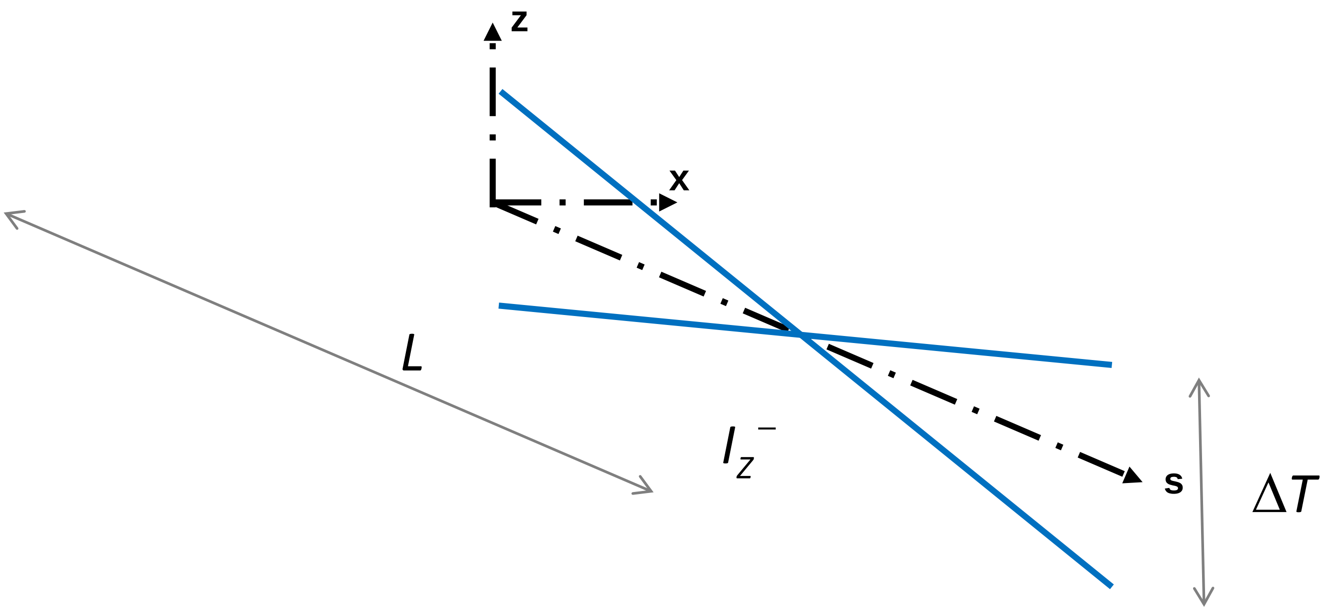
STRETCHED WIRE MEASUREMENTS: R&D

New quadrupole alignment sequence

4. Same measurements in the vertical plane

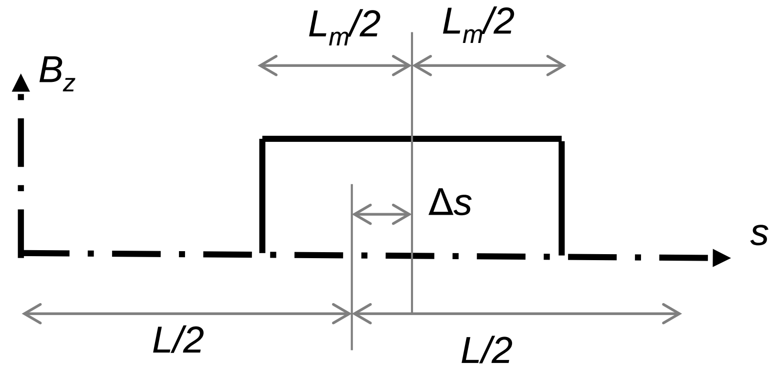
$$I_x^{\,i} = \int B_x ds$$

$$J_z^{\,i} = \iint B_z ds$$



New quadrupole alignment sequence

Hard edge quadrupole assumed



New quadrupole alignment sequence

Longitudinal position of the magnet:

$$\Delta s = \frac{L}{2G\Delta T}\left(I_z^{\ 1} - I_z^{\ 2}\right) = \frac{L}{2G\Delta T}\left(I_x^{\ 1} - I_x^{\ 2}\right)$$

Magnetic length:

$$L_m = \sqrt{6\left(\frac{L}{G\Delta T}\left(J_z^{\ 2} - J_z^{\ 1}\right) + \Delta s\left(L - 2\Delta s\right)\right)} = \sqrt{6\left(\frac{L}{G\Delta T}\left(J_x^{\ 2} - J_x^{\ 1}\right) + \Delta s\left(L - 2\Delta s\right)\right)}$$

New quadrupole alignment sequence

Centre position, yaw and pitch angles

$$G\begin{pmatrix} 2 & 2\Delta s/L \\ L-2\Delta s & (L-2\Delta s)\dfrac{\Delta s}{L} - \dfrac{L_m{}^2}{6L} \end{pmatrix}\begin{pmatrix} X \\ T_X \end{pmatrix} = \begin{pmatrix} I_Z{}^1 + I_Z{}^2 \\ J_Z{}^1 + J_Z{}^2 \end{pmatrix}$$

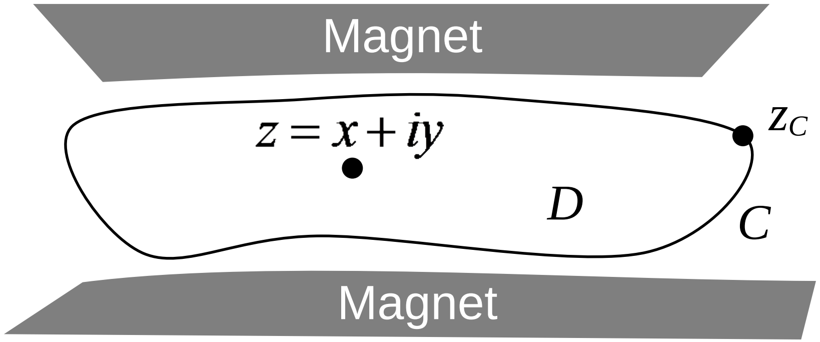
$$G\begin{pmatrix} 2 & 2\Delta s/L \\ L-2\Delta s & (L-2\Delta s)\dfrac{\Delta s}{L} - \dfrac{L_m{}^2}{6L} \end{pmatrix}\begin{pmatrix} Z \\ T_Z \end{pmatrix} = \begin{pmatrix} I_X{}^1 + I_X{}^2 \\ J_X{}^1 + J_X{}^2 \end{pmatrix}$$

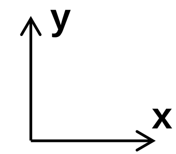
STRETCHED WIRE MEASUREMENTS: R&D

New quadrupole alignment sequence

- Used for series quadrupole measurements
- Similar results can be obtained for dipoles
- Seems more complicated for sextupoles due to their non linearity

A Cauchy's integral based method for non circular apertures



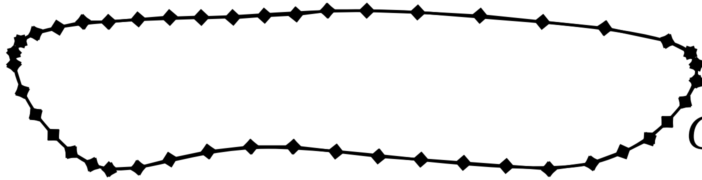


- 2D field: $B = B_Y + iB_Z$ is an analytic function of z
- Cauchy's integral theorem: $B(z) = \frac{1}{2\pi i} \oint_C \frac{B(z_C)}{z_C - z} dz_c$
- Valid within the simply connected domain D delimited by the boundary C.

(Measurement method developed by J Chavanne)

STRETCHED WIRE MEASUREMENTS: R&D

A Cauchy's integral based method for non circular apertures



$$C = \sum C_i$$

- C is segmented in N segments (straight segments, arcs, etc.)
- The field inside the domain D is obtained from the values on C

Measurement method

- Measure the $B_\perp$ normal to the boundary C with a stretched wire
- Determine equivalent boundary sources on each segment
  - Surface current and/or charge density depending on the formulation
  - Source distribution can be polynomial along each segment
- Analytical expressions used for the contribution from each segment

STRETCHED WIRE MEASUREMENTS: R&D

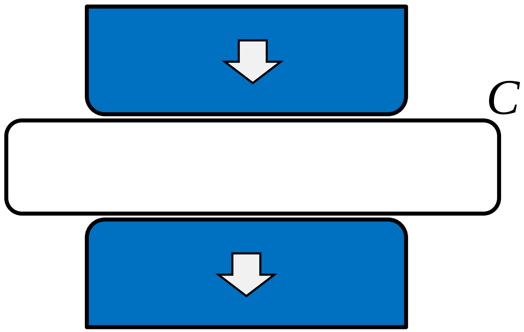
A Cauchy's integral based method for non circular apertures

Benefits of the method

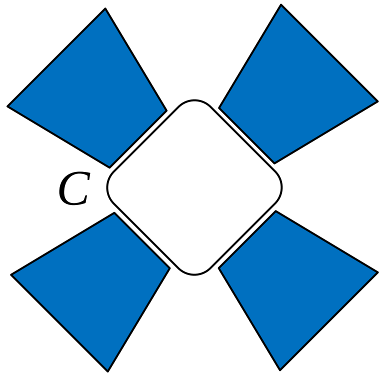
•The domain can be adapted to the magnet aperture

•No divergence of field or potential *on and outside* boundary C
(however magnetic field outside boundary does nor represent actual magnet)

•Accessible to modern motion controllers used for stretched wire



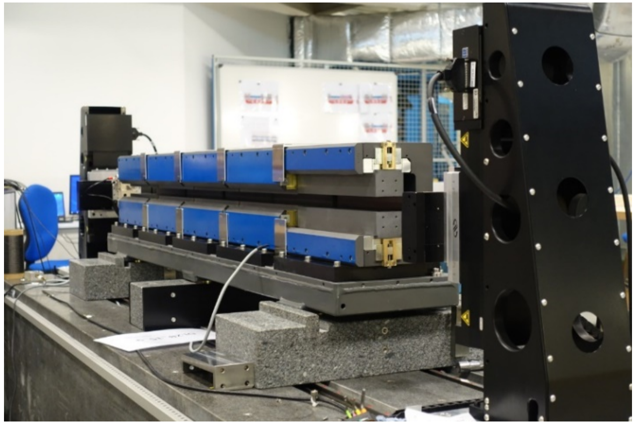
Example of racetrack type boundary for insertion devices or dipoles



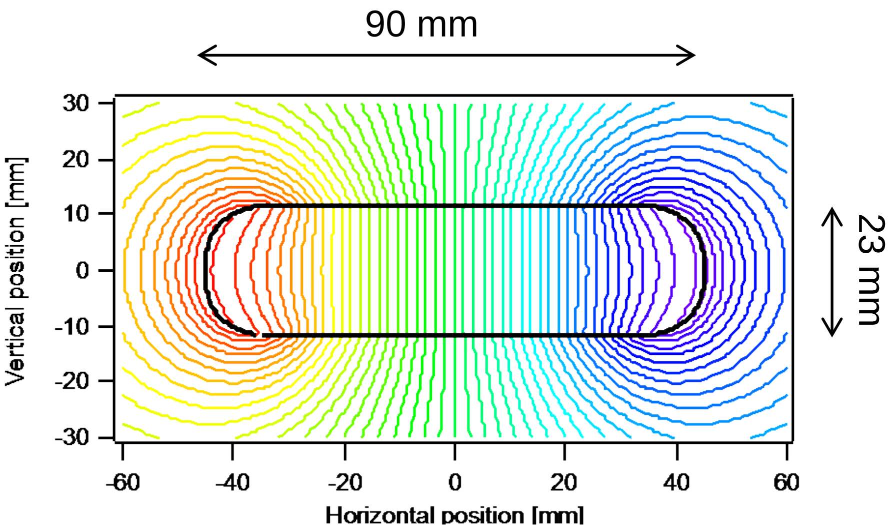
Example of racetrack type boundary for quadrupoles

STRETCHED WIRE MEASUREMENTS: R&D

A Cauchy's integral based method for non circular aperture

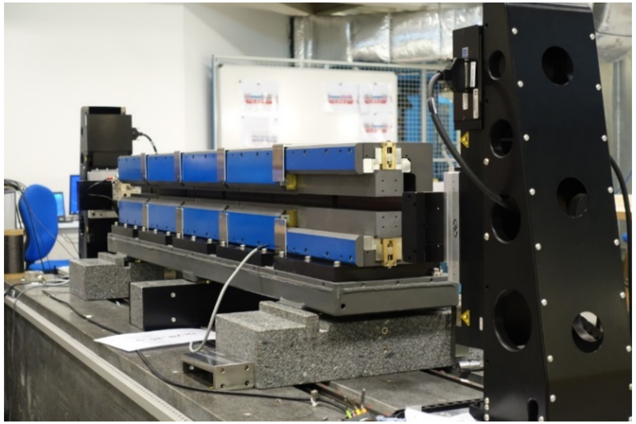


DL dipole installed on SW bench (gap: 25 mm; length 1.8 m).



Reconstructed potential (real part). The contour was subdivided in 332 segments. The GFR is a 26 x 18 mm ellipse

A Cauchy's integral based method for non circular aperture



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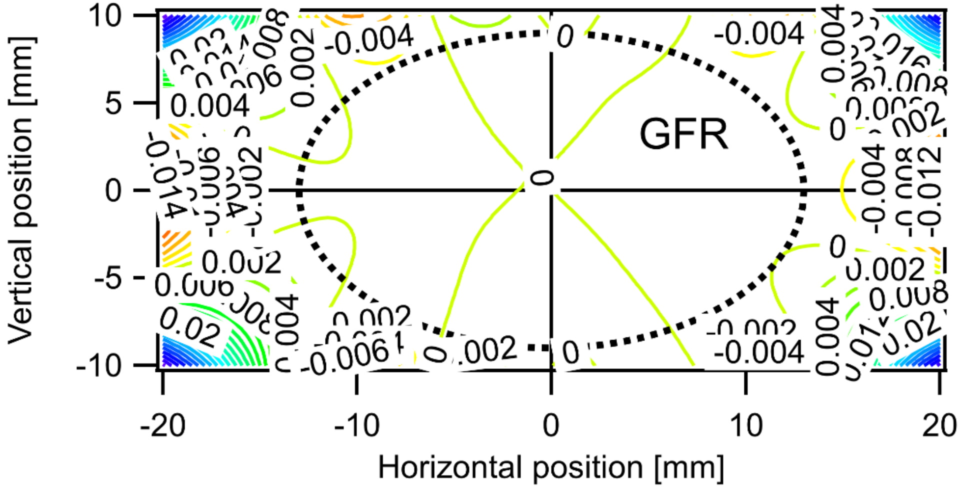


Homogeneity of the normal dipole field

A Cauchy's integral based method for non circular aperture

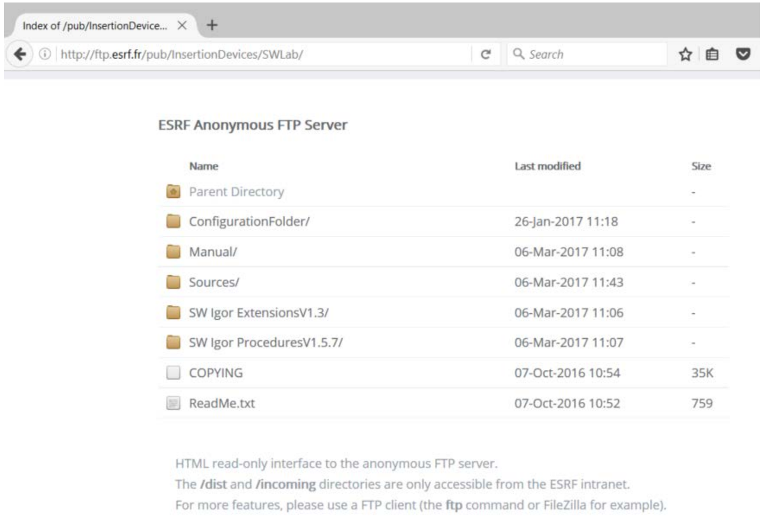
Implementation status

- Routinely used for insertion devices since two years
- Used for the production of the EBS PM dipoles
- Tests on quadrupoles in progress

STRETCHED WIRE MEASUREMENTS: AN OPEN SOURCE PROJECT

SW Lab: an open source project

- DLLs implemented in C++
- User interface with Igor Pro (Wavemetrics)
- Source code and executables on the ESRF FTP server: ftp.esrf.fr/pub/InsertionDevices/SWLab/



- Most of the multipole measurement sequences are available (except the Cauchy's integral based methods)

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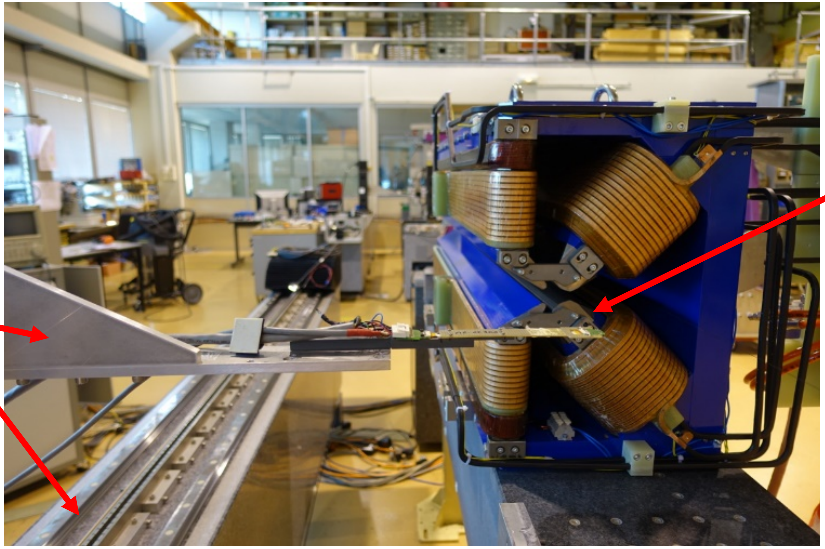
EBS Dipole-quadrupoles

Standard undulator bench
Linear motor
Optical encoder
“On-the-fly” measurements at 24 mm/s

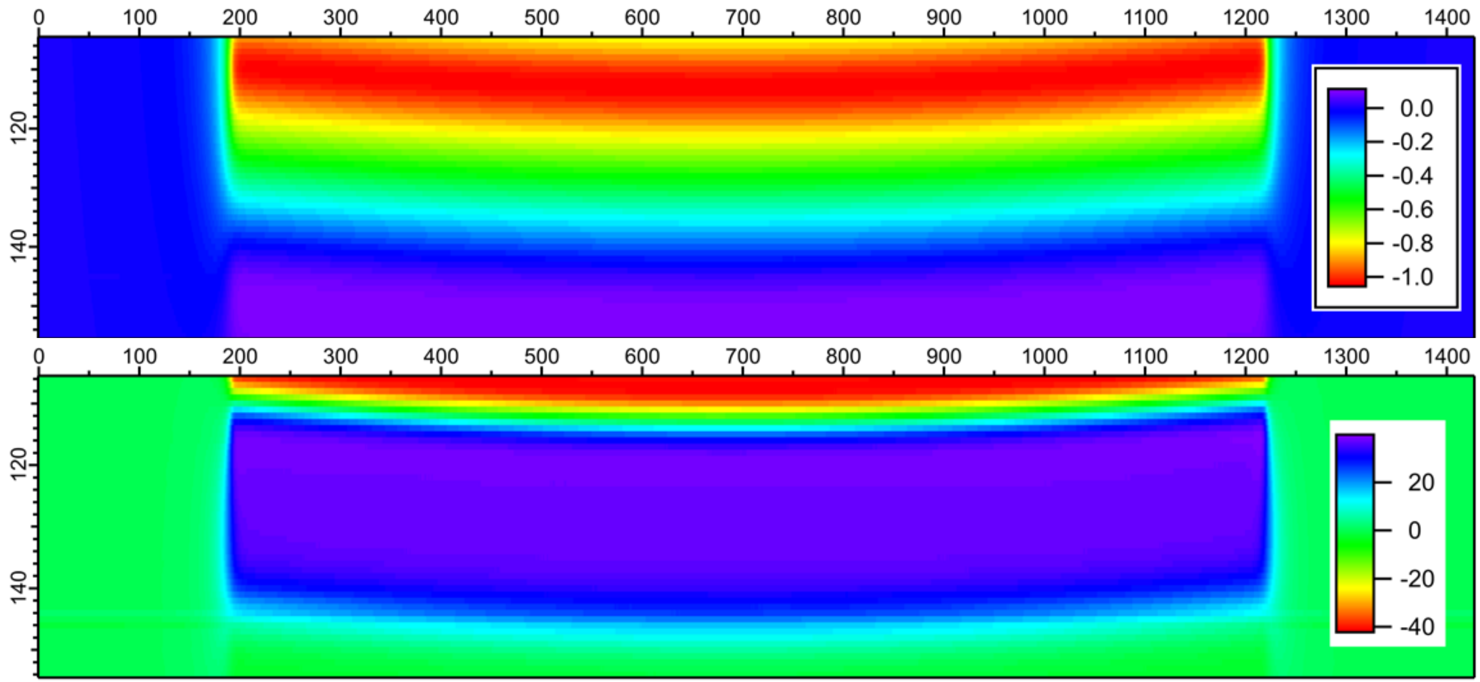


3 Hall sensors

DQ1 Pre-series installed on a Hall probe bench

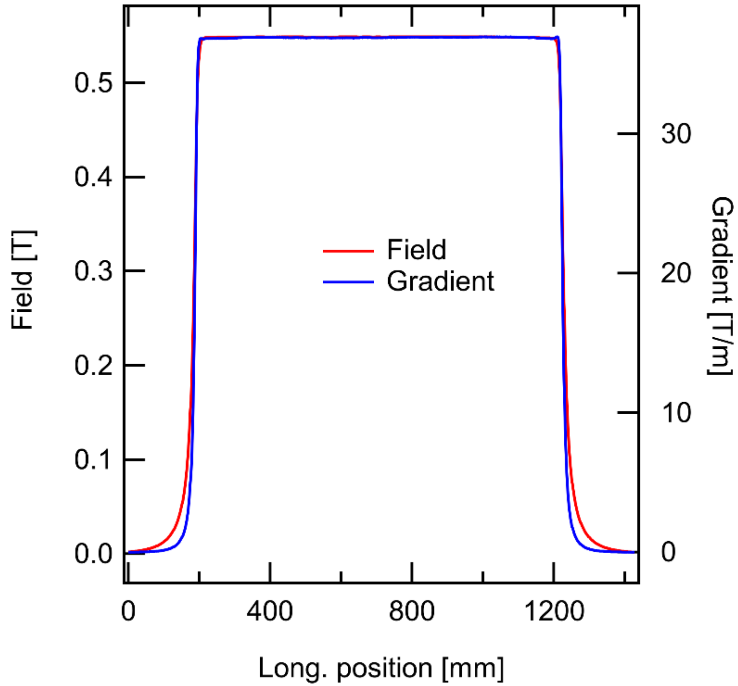
HALL PROBE MEASUREMENTS: EBS DIPOLES

EBS Dipole-quadrupoles



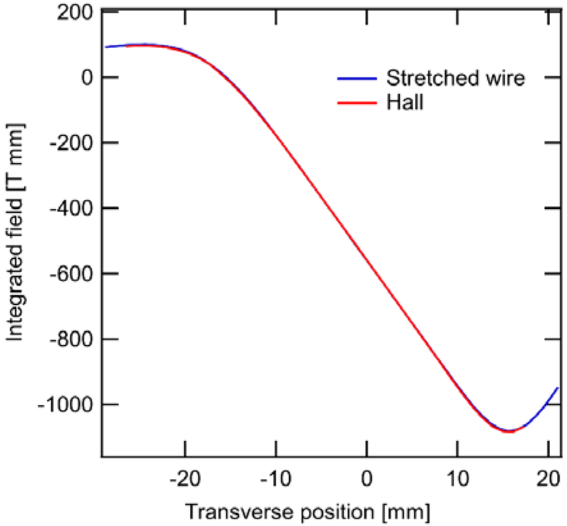
2D maps of DQ1 pre-series field (top, in [T]) and gradient (bottom, in [T/m]). Transverse and longitudinal steps: 1 mm; positions are expressed in [mm].

EBS Dipole-quadrupoles



Field and gradient vs longitudinal position, assuming a 35210 mm radius (nominal). Computations from 2D field maps.

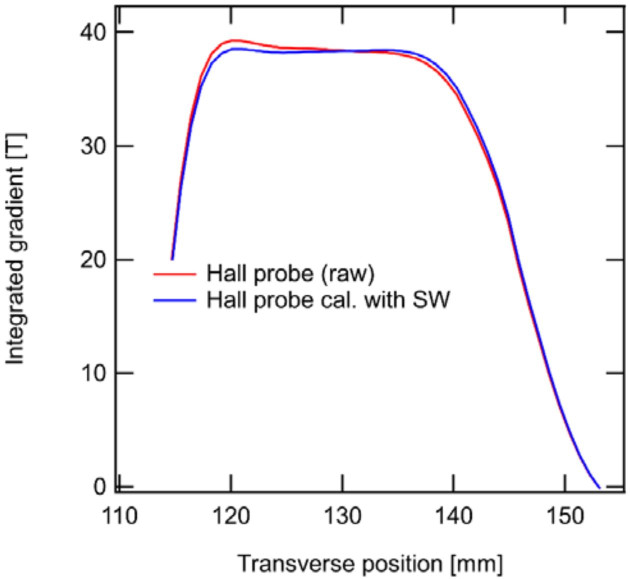
EBS Dipole-quadrupoles



Hall probe measurements integrated along a straight line vs stretched wire measurements.

Hall probe calibration

$$I_H = \alpha_0 + \alpha_1 I_{SW} + \alpha_2 I_{SW}{}^2$$



Gradient integrated along a curved trajectory (radius: 35210 mm).

HALL PROBE MEASUREMENTS: EBS DIPOLES AND DIPOLE-QUADS

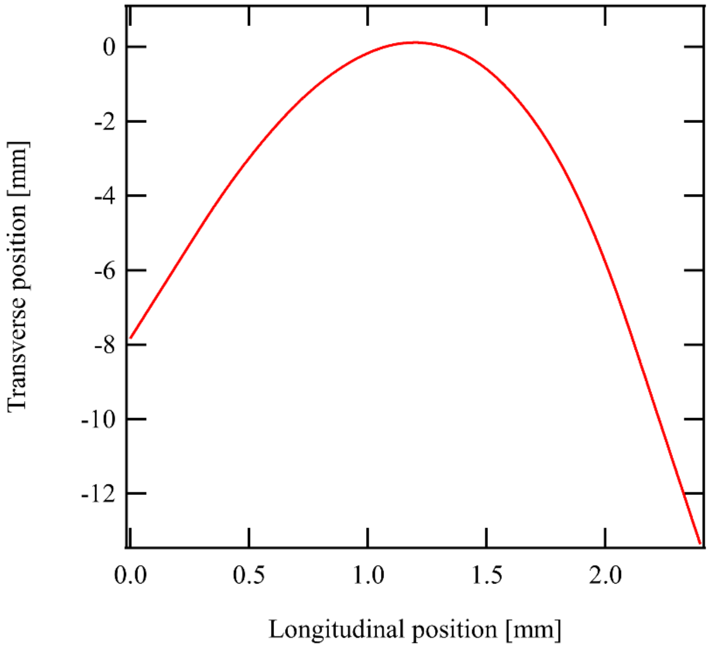
EBS Dipoles with longitudinal gradient (DLs)

Measurements along the electrons' trajectory

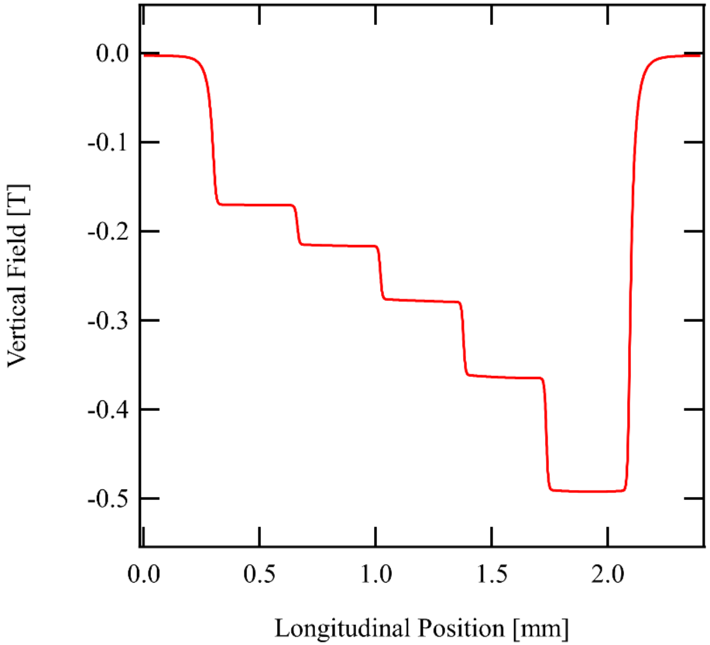
1. Set an initial trajectory
2. Measure the field along this trajectory
3. Compute a new trajectory from the measured field
4. Repeat until convergence

HALL PROBE MEASUREMENTS: EBS DIPOLES AND DIPOLE-QUADS

EBS Dipoles with longitudinal gradient (DLs)



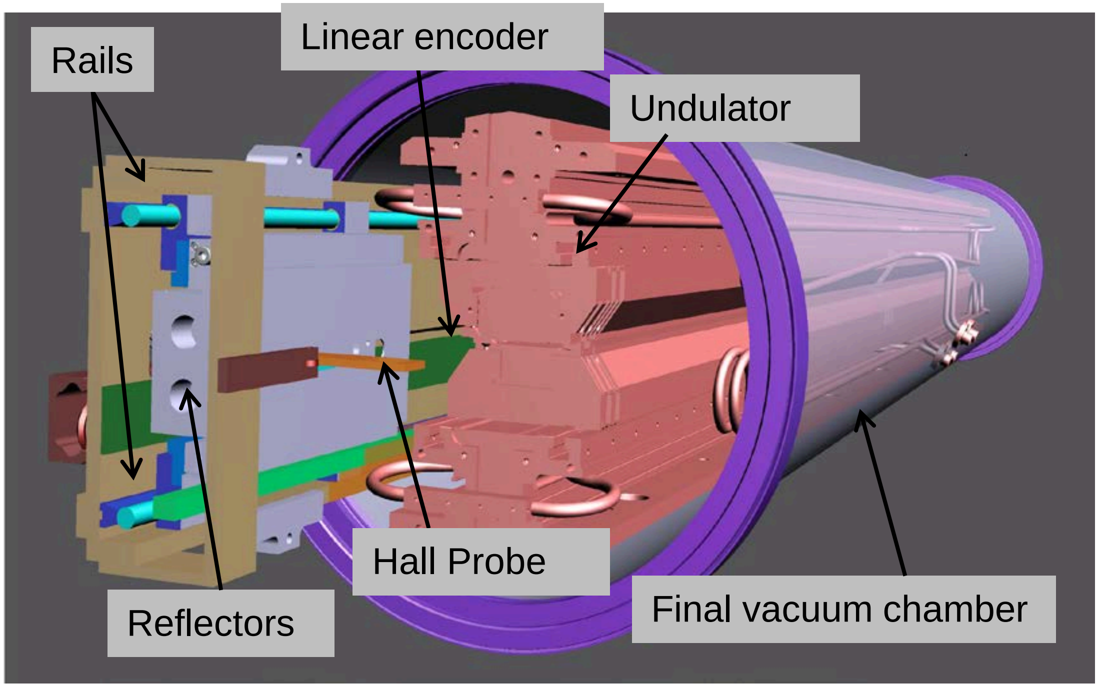
Transverse position of the Hall probe.



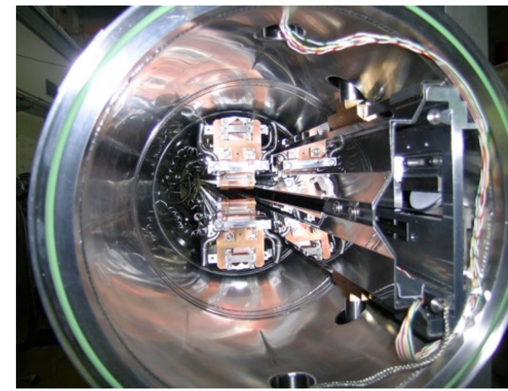
Vertical field on the electron trajectory.

HALL PROBE MEASUREMENTS: CRYOGENIC UNDULATORS

Cryogenic undulator measurement bench



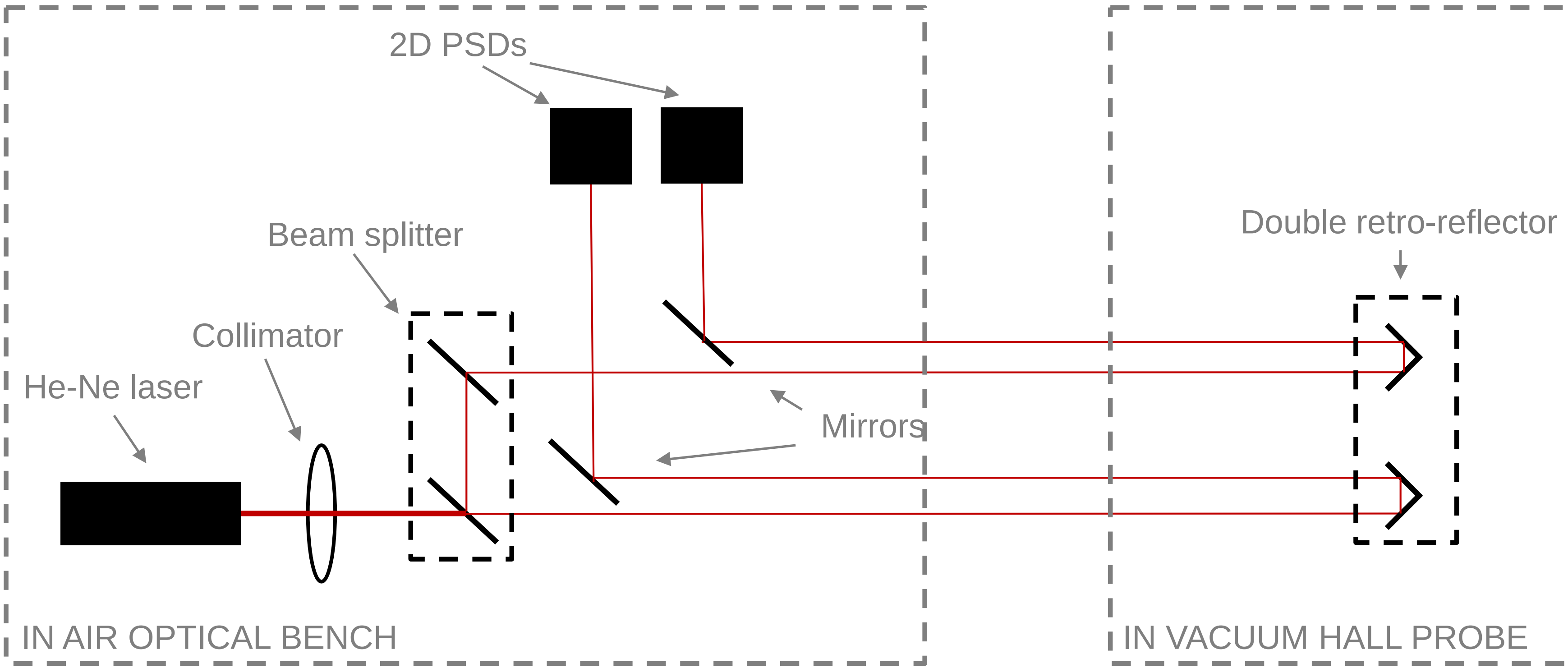
Design view of the *in situ* Hall probe bench (stretched wire system not shown)



Inside the bench

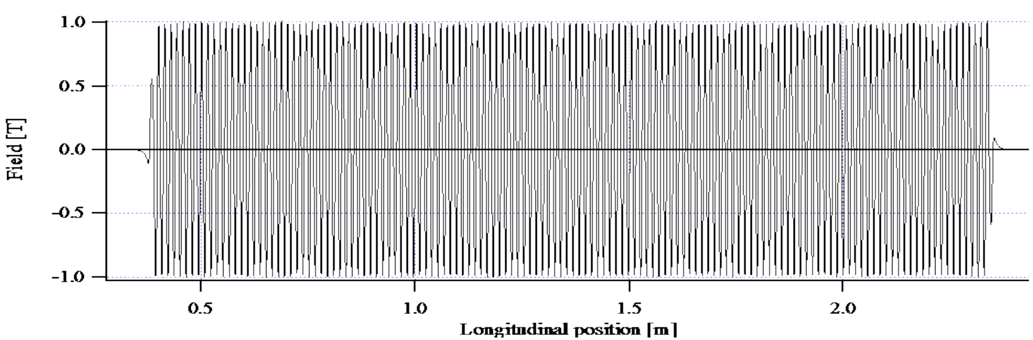
(Design in collaboration with ProActive Engineering, Spain)

Cryogenic undulator measurement bench

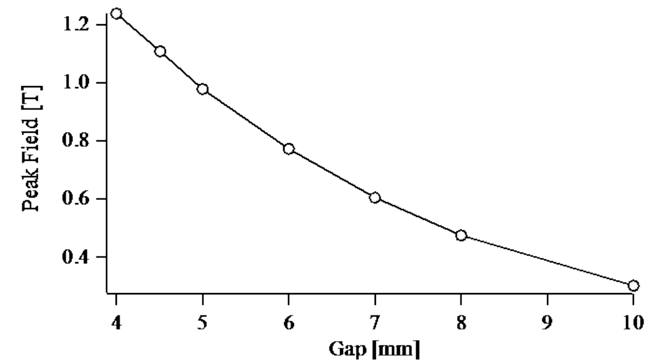


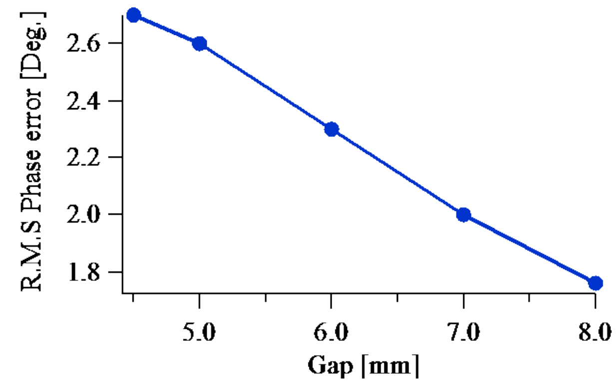
Laser setup for the measurement of the transverse positions and roll angle of the Hall probe.

Cryogenic undulator measurement bench



CPMU field measurement at 97 K.
Period: 14.5 mm, gap: 5 mm.





CPMU measurements at 95 K. Top: Peak field vs gap. Bottom: RMS phase error vs gap.

OUTLINE

CONCLUSIONS AND PERSPECTIVES

The Extremely Brilliant Source

- A new storage ring at the ESRF
- About 1000 magnets in production phase

Stretched wire measurements

ESRF SW benches installed at supplier premises

- Quality control OK
- Fiducialization not obvious

Development topics

- New measurement sequences for alignment
- Cauchy’s integral based method for non circular magnet apertures
- SW Lab: an open source code for SW measurements

CONCLUSIONS AND PERSPECTIVES

Hall probe measurements

- Measurement of some exotic EBS magnets (in progress)
- *In situ* bench for Cryogenic PM Undulators

Perspectives

- Various SW developments
- Get basic longitudinal data from stretched/vibrating wire
- Upgrade of the Hall probe benches

MANY THANKS FOR YOUR ATTENTION