Magnetic measurements on superconducting accelerator magnets

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CERN TE-MSC-TM

Lectures on Superconducting Magnet Test Stands, Magnet Protections and Diagnostics -SMTF & IDSM Workshops

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Outline

- **Introduction**
- **SC magnets and magnetic measurements**
- **When, what, how to measure**
- **Examples of real cases**

Introduction

Accelerators and magnets

- Particle accelerators have magnets as major components.
- The magnets are used for bending and focusing the beam, as well as for higher order corrections.
- A thorough characterization of the magnetic field in the magnets is crucial for proper operation of an accelerator.

Magnets: design vs reality

- Magnets are designed for **stringent field quality** using advanced computational tools.
- The as-built magnets almost never exhibit the perfect design field quality. This is partially due to limitations of computational tools, but largely due to systematic and random **construction errors.**
- It is necessary, therefore, to measure the field in the as-built magnets and **iterate the design** if any systematic errors are noticed.
- The measurements can also be used to monitor trends and random errors in a large **magnet production** run.

A. Jain, CERN Academic Training Program 2003

When to perform magnetic measurements

Development cycle of a new type of SC magnet

- The development of a superconducting magnets is a complex process encompassing different phases

STUDY OF TECHNOLOGIES	DESIGN	VALIDATION OF FULL SIZE UNIT	SERIES PRODUCTION	OPERATION IN THE ACCELERATOR
DEMONSTRATORS	**SHORT MODELS**	**PROTOTYPES**	**PRODUCTION UNITS**	**SPARE UNITS**
▪ Often without a true aperture ▪ Ex. racetrack coils	▪ Usually ~1-m long ▪ Extensive test campaign	▪ Same as series but with more instrumentation ▪ Extensive test campaign	▪ Usually test time is limited ▪ Optimization of the test campaign	▪ Special cycling conditions not tested before

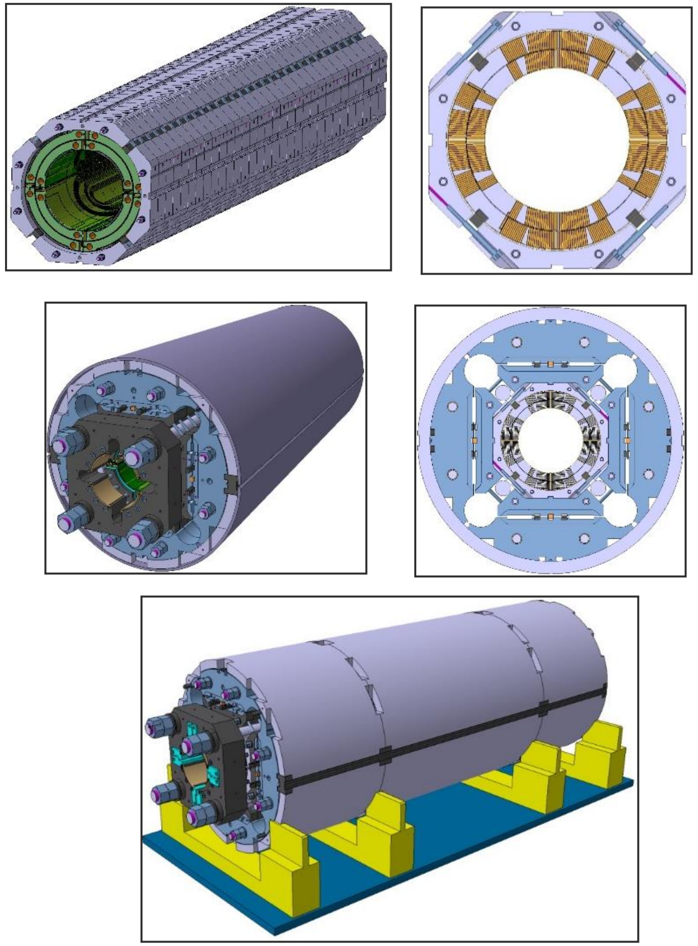
- Magnetic measurements are performed at all stages: i) for checking different aspects, and ii) by using different instruments

Production of a SC magnet

Magnetic measurements within the typical **construction steps** of a superconducting magnet:

- Production of coils ✗
- Assembly of coil pack ✓
- Assembly of iron yoke ✓
- Cold-mass preparation ✓
- Cryostating ✗
- Test at cryogenic temperature ✓

Short model of MQXF for HL-LHC

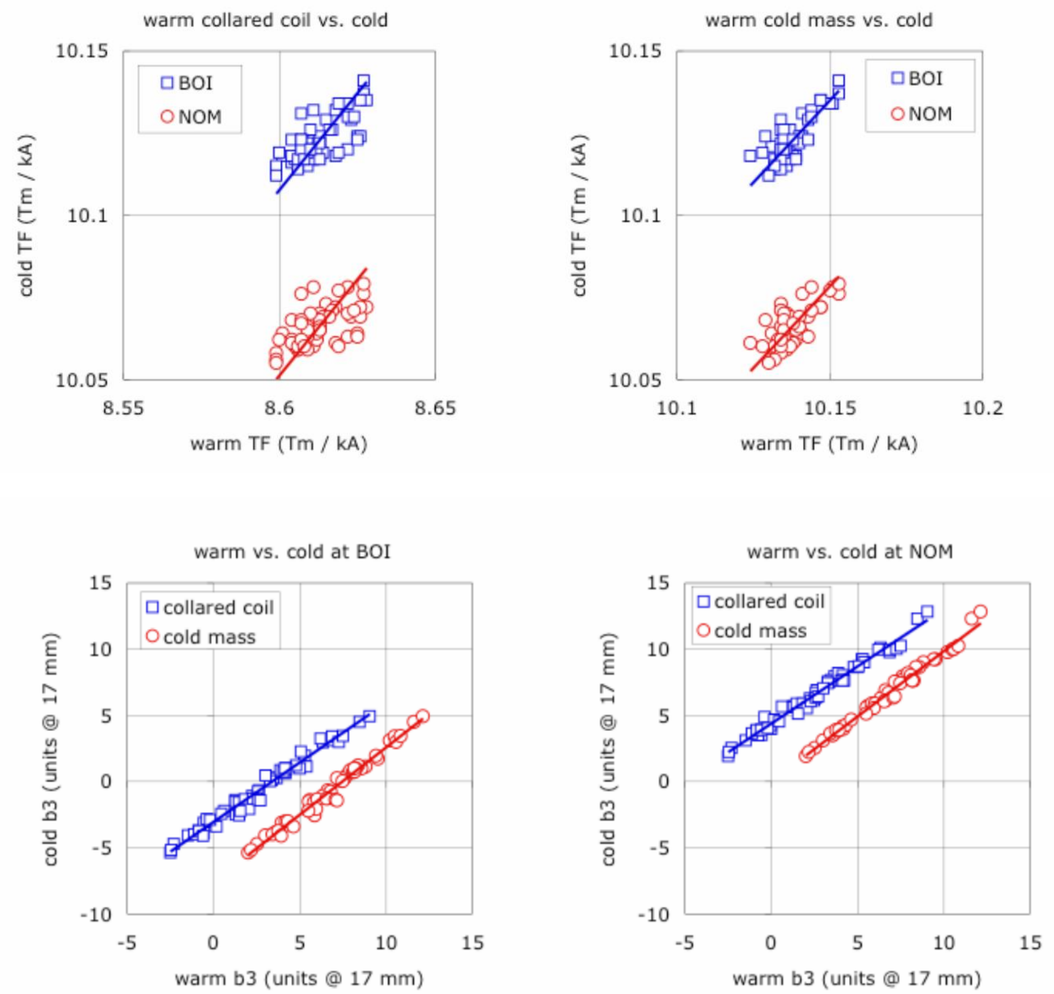


https://indico.cern.ch/event/355818/contributions/840361/

Ambient vs cryogenic temperature

Can we get meaningful information from measurements at ambient temperature?

- Current flowing in the copper
- No persistent currents
- Lower field level (~mT vs ~T)
- No saturation of iron
- But relative position of conductors is the same (geometric factor)



Warm-Cold Magnetic Field Correlation in the LHC Main Dipoles, LHC Project Note 326

What to measure

Quantities of interest

The harmonic description of the field is used, both for characterizing the field quality, as well as for particle tracking studies.

- For most accelerator magnets, the results are given in terms of:
  - Transfer function (ratio of main field and current)
  - Field direction with respect to a reference
  - Magnetic center / axis with respect to a reference
  - Field homogeneity in terms of harmonics with order higher than main field
- All the above quantities can be measured:
  - locally or integrated on the full magnet length
  - as function of the current (proper cycling is important)

How to measure

Rotating coils

The **multipoles** can be retrieved from the **flux** intercepted by a **coil**, with known **geometry**, **rotating** in the magnet aperture

N = No. of turns
L = Length
δ = angle at (t = 0)
ω = angular velocity
$\theta = \omega t + \delta$ (angle at t)

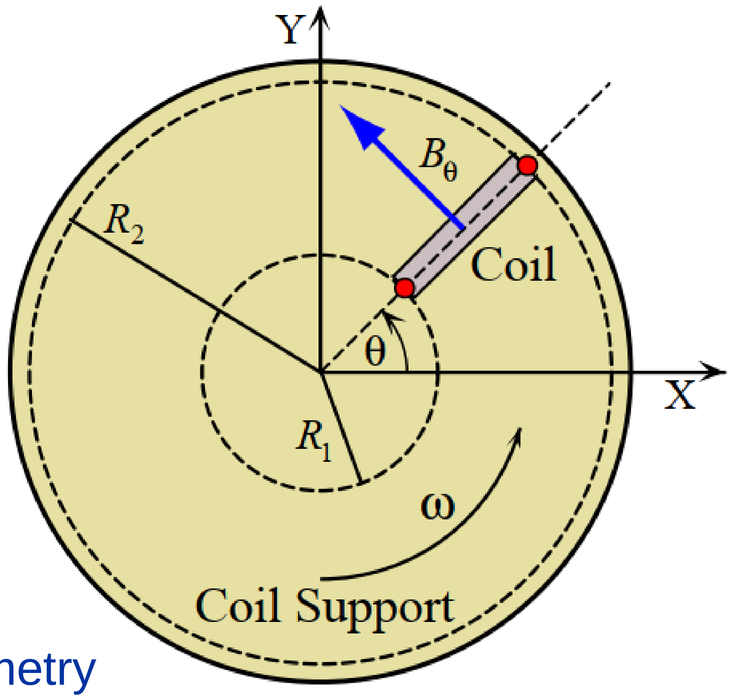
Flux through the coil at time t is:

$$\Phi(t) = NL\int_{R_1}^{R_2} B_\theta(r,\theta)dr$$

$$= \sum_{n=1}^{\infty} \frac{NLR_{ref}}{n}\left[\left(\frac{R_2}{R_{ref}}\right)^n - \left(\frac{R_1}{R_{ref}}\right)^n\right] \times$$

$$[B_n \cos(n\omega t + n\delta) - A_n \sin(n\omega t + n\delta)]$$

Flux
=
Coil geometry
x
Harmonics



Signal processing of rotating-coil signals:

- The induced voltage is integrated over time to get the flux $\mathbf{\Phi}$(t)
- The integration is triggered by an angular encoder to get $\mathbf{\Phi}(\theta)$
- Fourier transform of the flux $\mathbf{\Phi}(\theta)$ to the get $\mathbf{\Phi}_n$
- Coil sensitivity factors (coil geometry) are applied to get B_n and A_n

The radius dominates the sensitivity to high order harmonics!

A. Jain, CERN Academic Training Program 2003

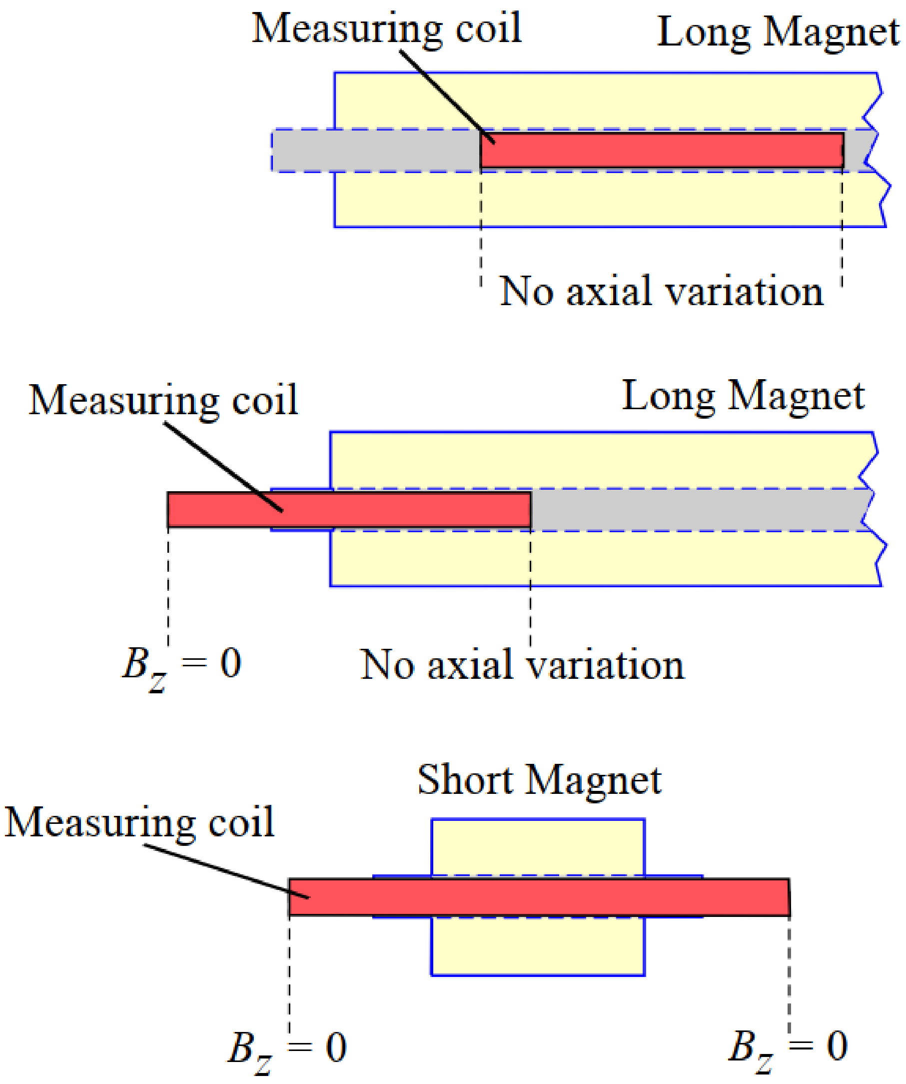
Validity of the 2-D field expansion

The magnetic field has all three components (it is **not 2-D**):

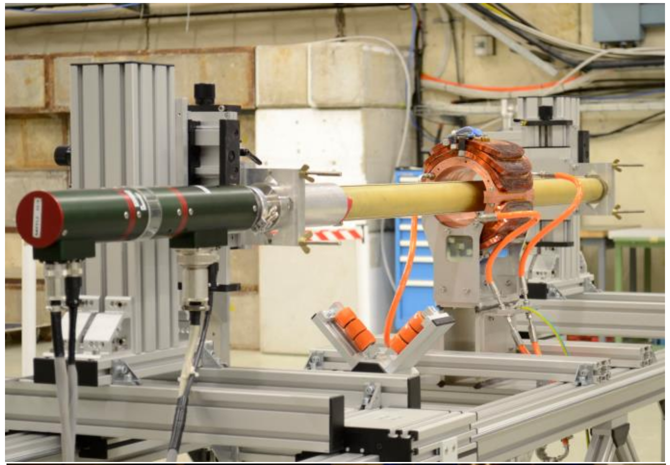
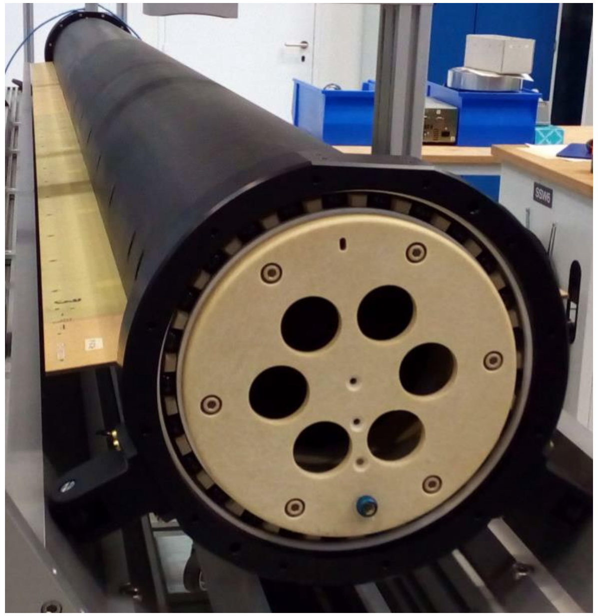
- near the ends of a long magnet
- everywhere in a short magnet

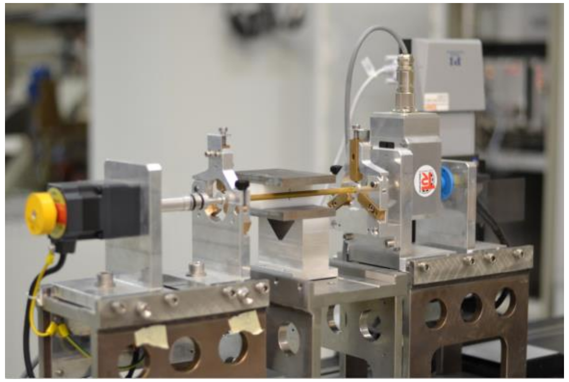
In these cases, the simple 2-D expansion is not valid locally!

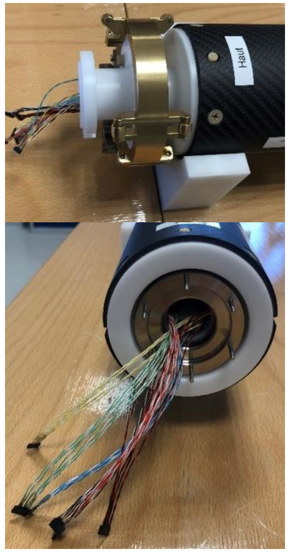
However, if we consider the integral of the field components from/to a region where B_z is constant, the 2-D expansion is valid.



Rotating coils in reality





The rotating probe must be adapted to the magnet geometry.

A procedure for combining rotating-coil measurements of large-aperture accelerator magnets, https://doi.org/10.1016/j.nima.2016.02.019

Single stretched wire

In a **quadrupole**, from the flux measured by moving the wire

$$\Phi_H^{\pm} = L_m \int_0^{\pm D} B_y \cdot dx = L_m G \left[b_2 \frac{D^2}{2} \quad (b_2 x_0 + a_2 y - a_2 y_0) D \right]$$

we can retrieve the **integral field**

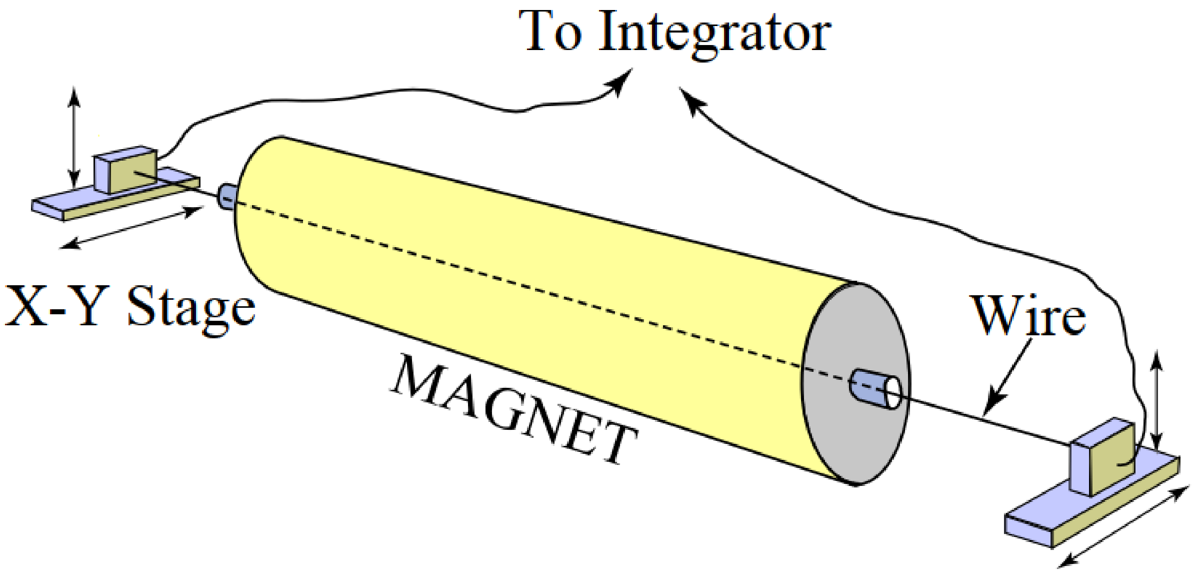
$$L_m G = \left(\frac{\Phi_H^+ + \Phi_H^-}{b_2 D^2} \right) = \left(\frac{\Phi_V^+ + \Phi_V^-}{b_2 D^2} \right)$$

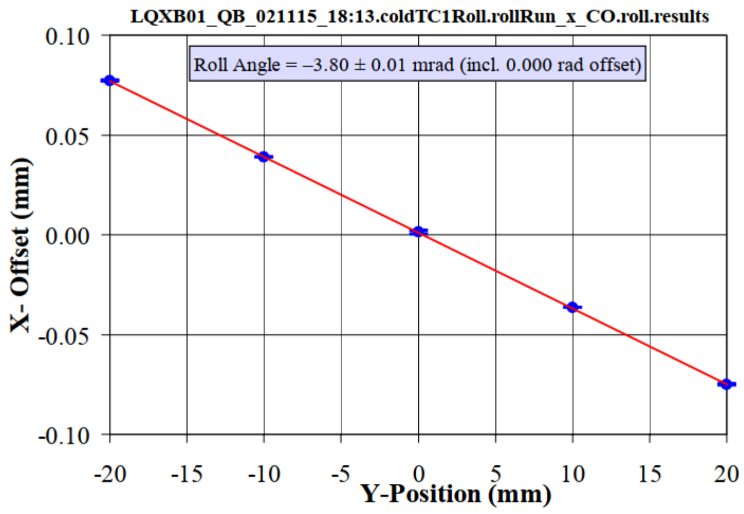
For roll angles, α, less than 7 mrad, $b_2 \approx 1$ may be used with < 0.01% error.

and the **magnetic center**

$$x_0' = -\left(\frac{D}{2} \right) \left(\frac{\Phi_H^+ - \Phi_H^-}{\Phi_H^+ + \Phi_H^-} \right); \quad y_0' = -\left(\frac{D}{2} \right) \left(\frac{\Phi_V^+ - \Phi_V^-}{\Phi_V^+ + \Phi_V^-} \right)$$

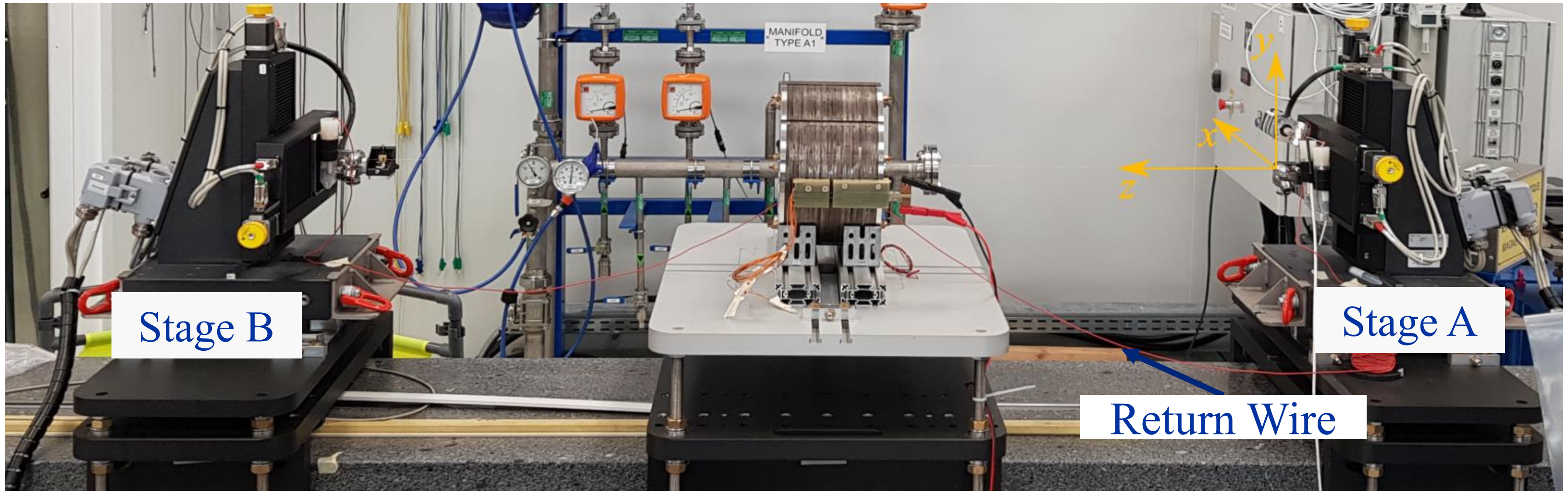
By measuring the magnetic center at different heights, we can get the **field direction**.

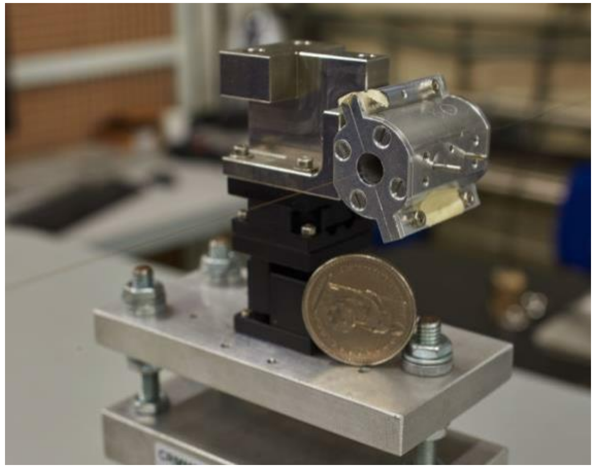




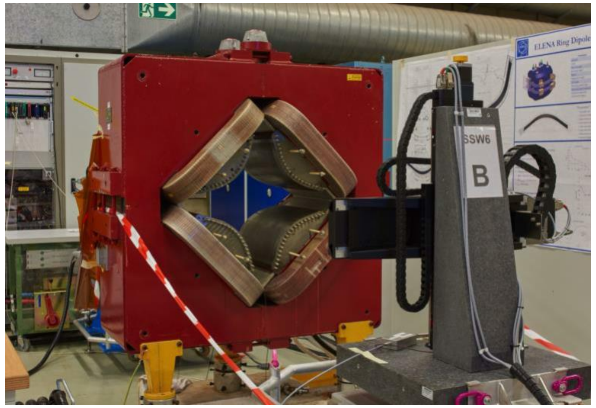
A. Jain, CERN Academic Training Program 2003

Single stretched wire in reality





- Positioning stages accuracy <1 μm
- Copper-Beryllium wire 0.125 mm
- Integrator with gain 0.1 to 100

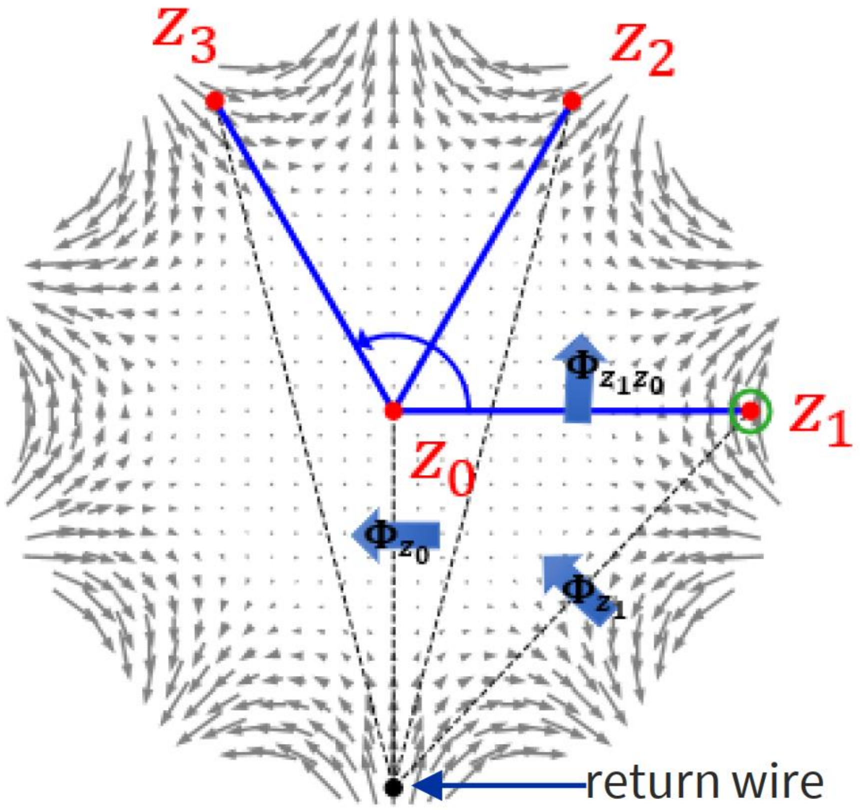


Same hardware for measuring magnets with much different geometry:

- aperture ~10 mm to ~300 mm
- length ~1 cm to ~10 m

Single stretched wire in AC mode

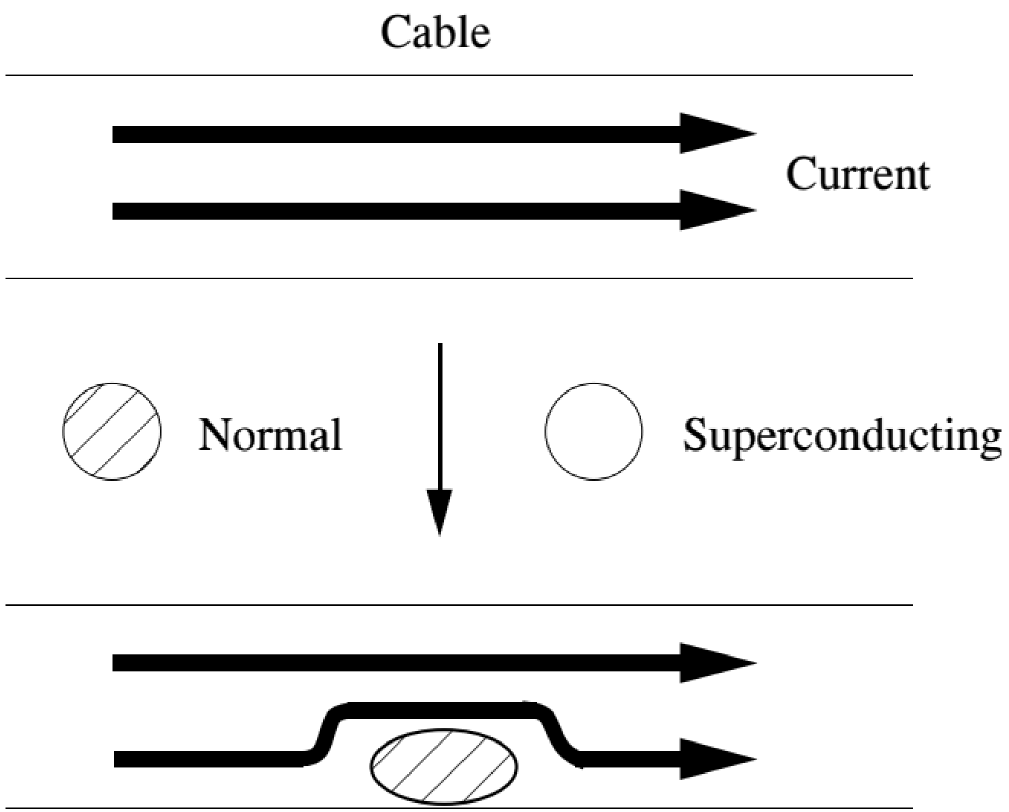
- Magnet powered with AC current (~10 Hz)
- A sinusoidal voltage is induced on the wire without any motion
- Significant SNR improvement with respect to DC mode
- Measuring in different positions to mimic a radial rotating-coil
- Suitable for alignment of SC magnets at ambient temperature



$$\Phi_{z_n z_0} = \Phi_{z_n} - \Phi_{z_0}$$

https://indico.cern.ch/event/1263286/

Quench localization



T. Ogitsu, Review of Magnetic Quench Antenna
for Accelerator Magnets, IDSM01 2019

At the quench onset, some current must bypass the forming resistive region.

Considering only the change, it is equivalent to a $-\Delta$ current flowing in the resistive region, and a $+\Delta$ current flowing at a certain distance.

- Magnetic moment

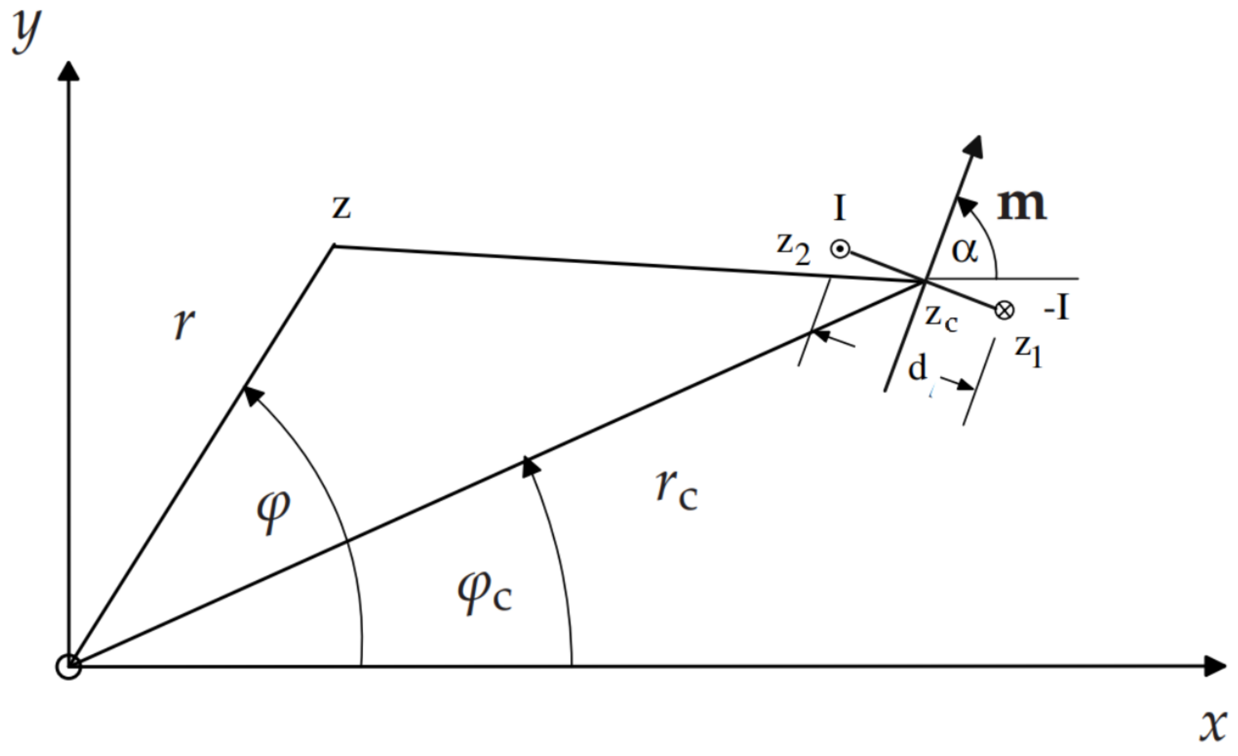
Quench localization

In 2D, the field generated by a magnetic moment can be written in terms of multipoles:

$$C_n = m\frac{i\mu_0 n}{2\pi}\frac{e^{i\alpha}}{z_c^2}\left(\frac{r}{z_c}\right)^{n-1}$$

We can retrieve z_c by knowing two (complex) multipoles of different order, for example C_3 and C_4

$$z_c = \frac{4}{3}\frac{C_3}{C_4}\,\mathrm{r} = \frac{4}{3}\frac{B_3 + i\,A_3}{B_4 + i\,A_4}\,\mathrm{r}$$

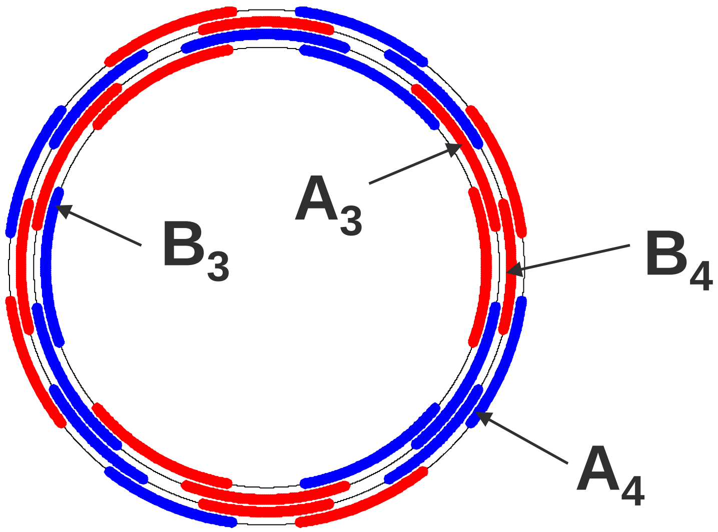


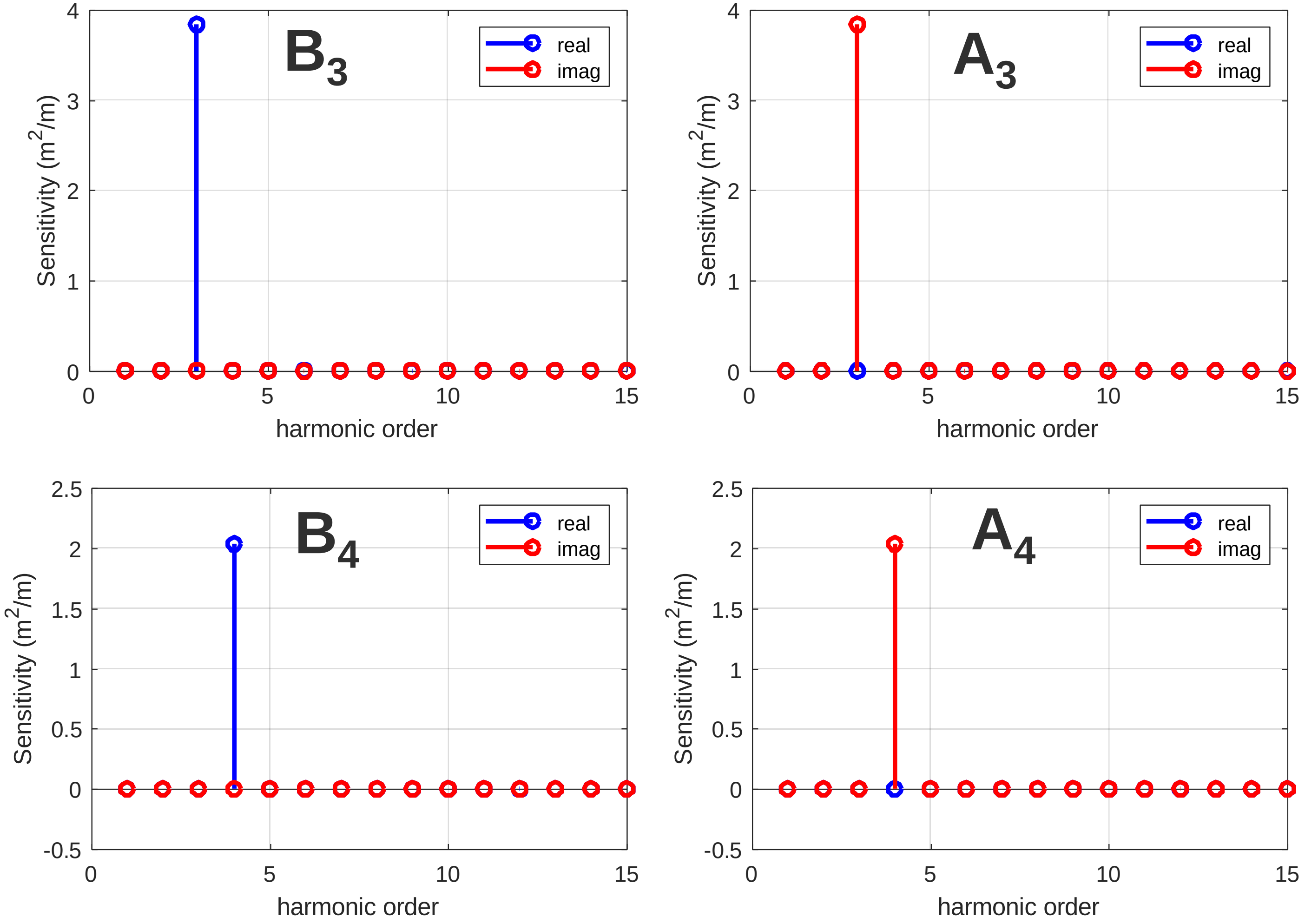
S. Russenschuck, Field Computation for Accelerator Magnets, WILEY 2010

Quench localization with static pickup coils

We can design a coil to be sensitive to one multipole (we design a magnet to produce one multipole)

Ex. Four layers each sensitive to one multipole





Quench localization with static pickup coils

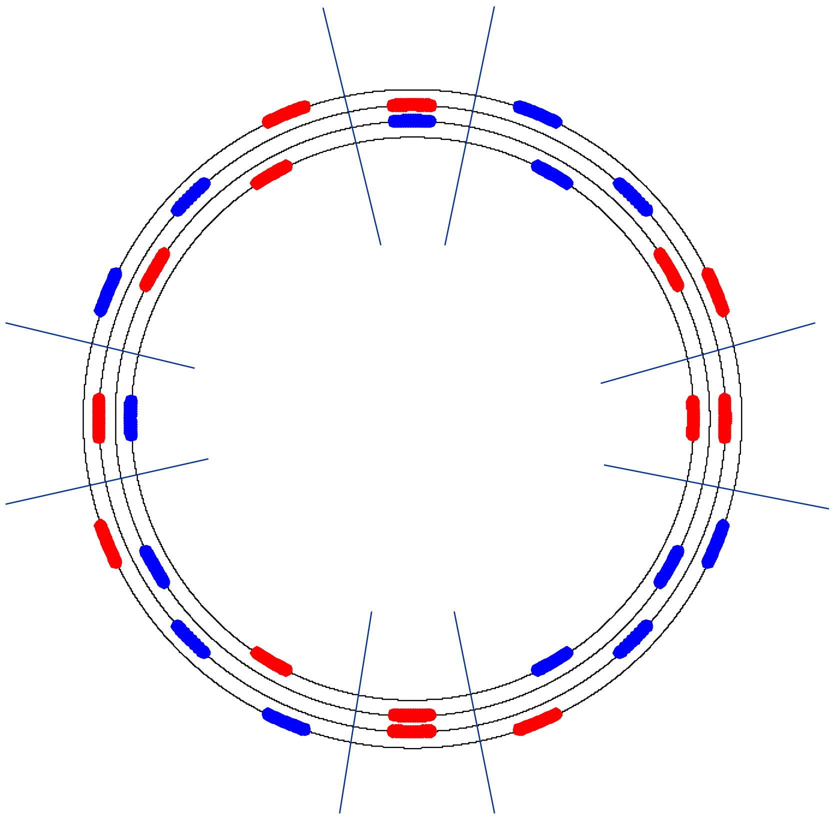
Practical constraints

The 4 sets of coils can be “easily” realized on separate layers of a flexible PCB, then wrapped around a support tube.

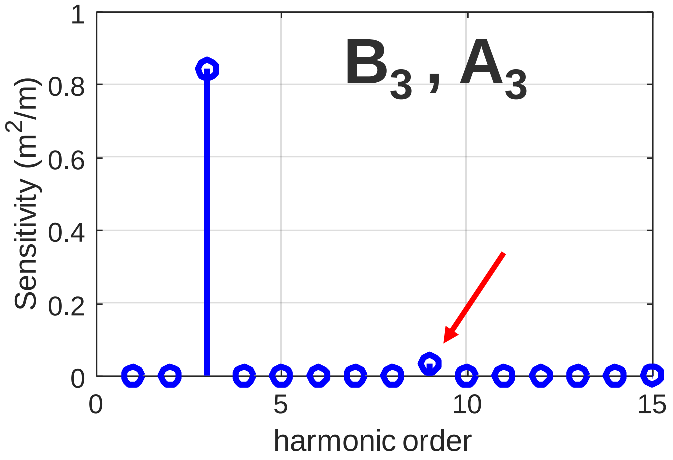
The multilayer PCB guarantees the alinement among coils.

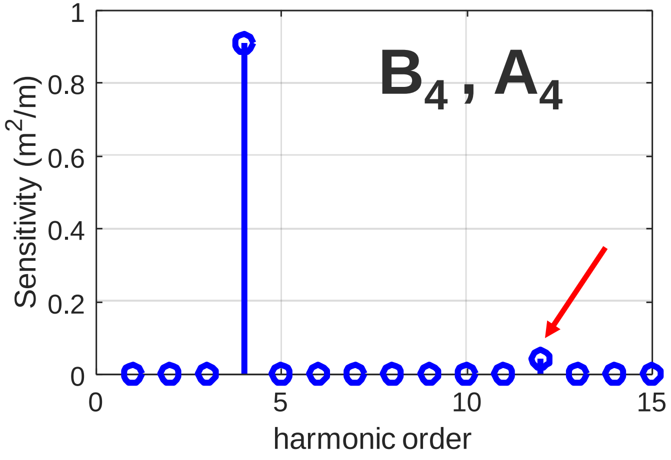
Need of areas free of traces for:

- making a cut along the PCB
- alignment holes



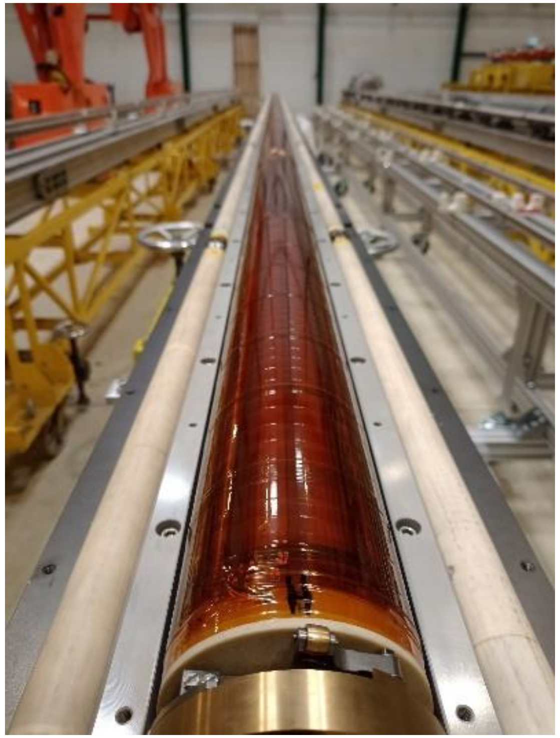
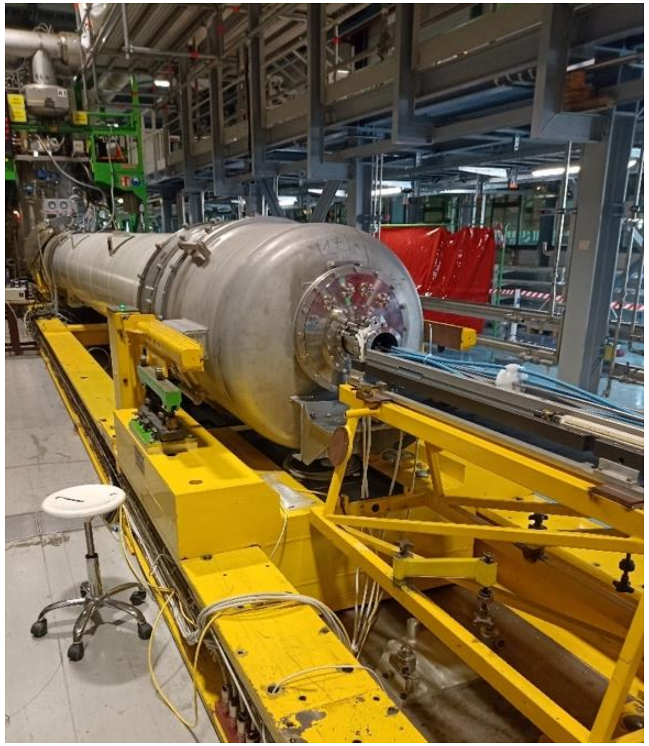
Narrower coils at the price of a not-perfect sensitivity (first allowed)





Quench localization with static pickup coils in reality



Examples of actual measurements

- Racetrack model magnet **RMM** for FCC studies
- **Corrector Package** at ambient temperature for HL-LHC
- **Q2** prototype for HL-LHC
  - at ambient temperature
  - at cryogenic temperature
  - quench and flux jumps localization
- MCBC and MCBY **orbit correctors** and the luminosity scans for LHC

Racetrack model magnet for FCC

Racetrack Model Magnet (RMM)

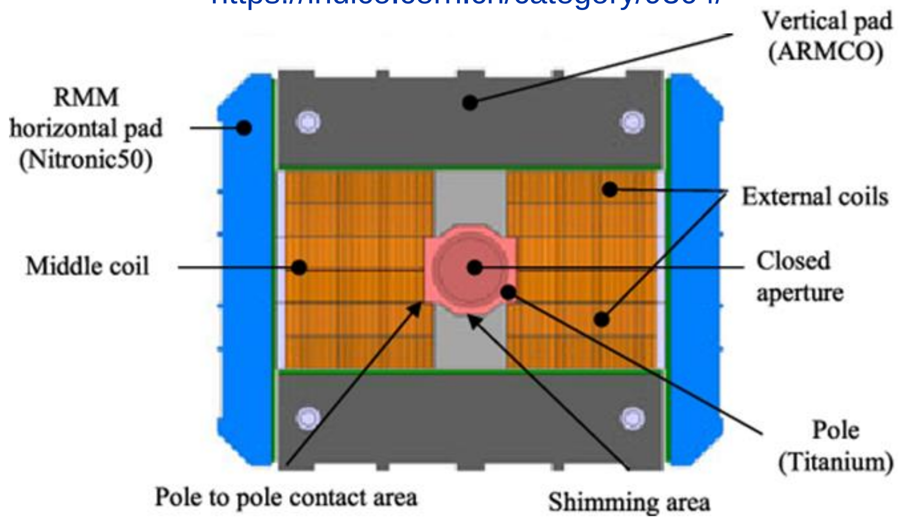
50-mm closed cavity

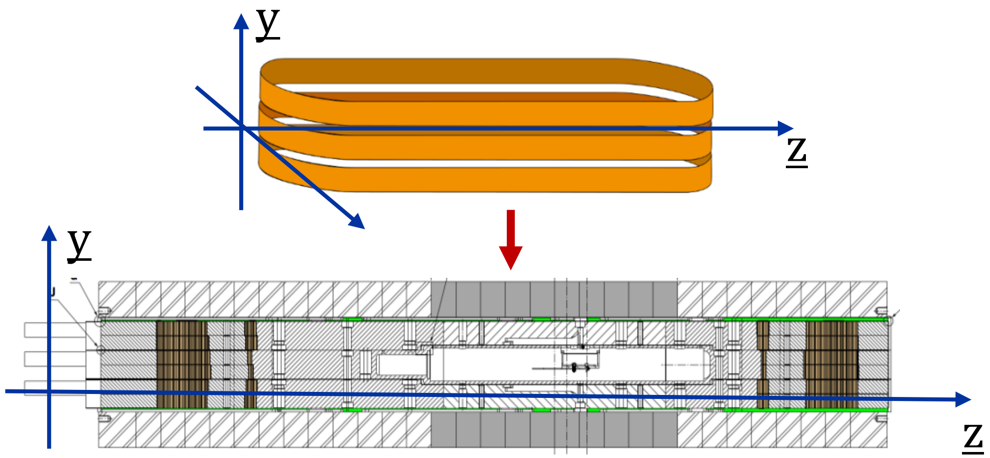
Nb_3Sn RRP Rutherford cable

Bladders and keys technology

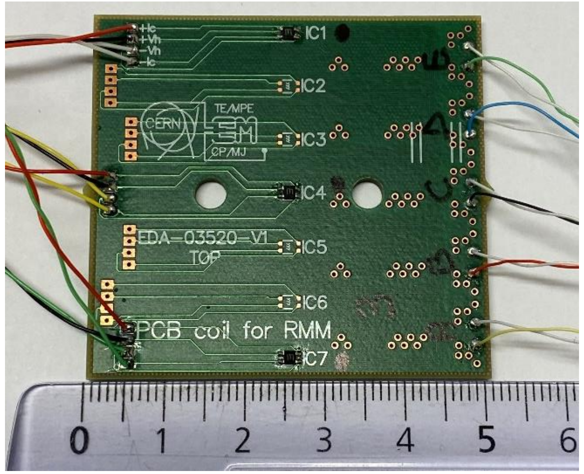
- to reproduce the mechanics of the straight section of a 16+ T dipole

https://indico.cern.ch/category/9304/





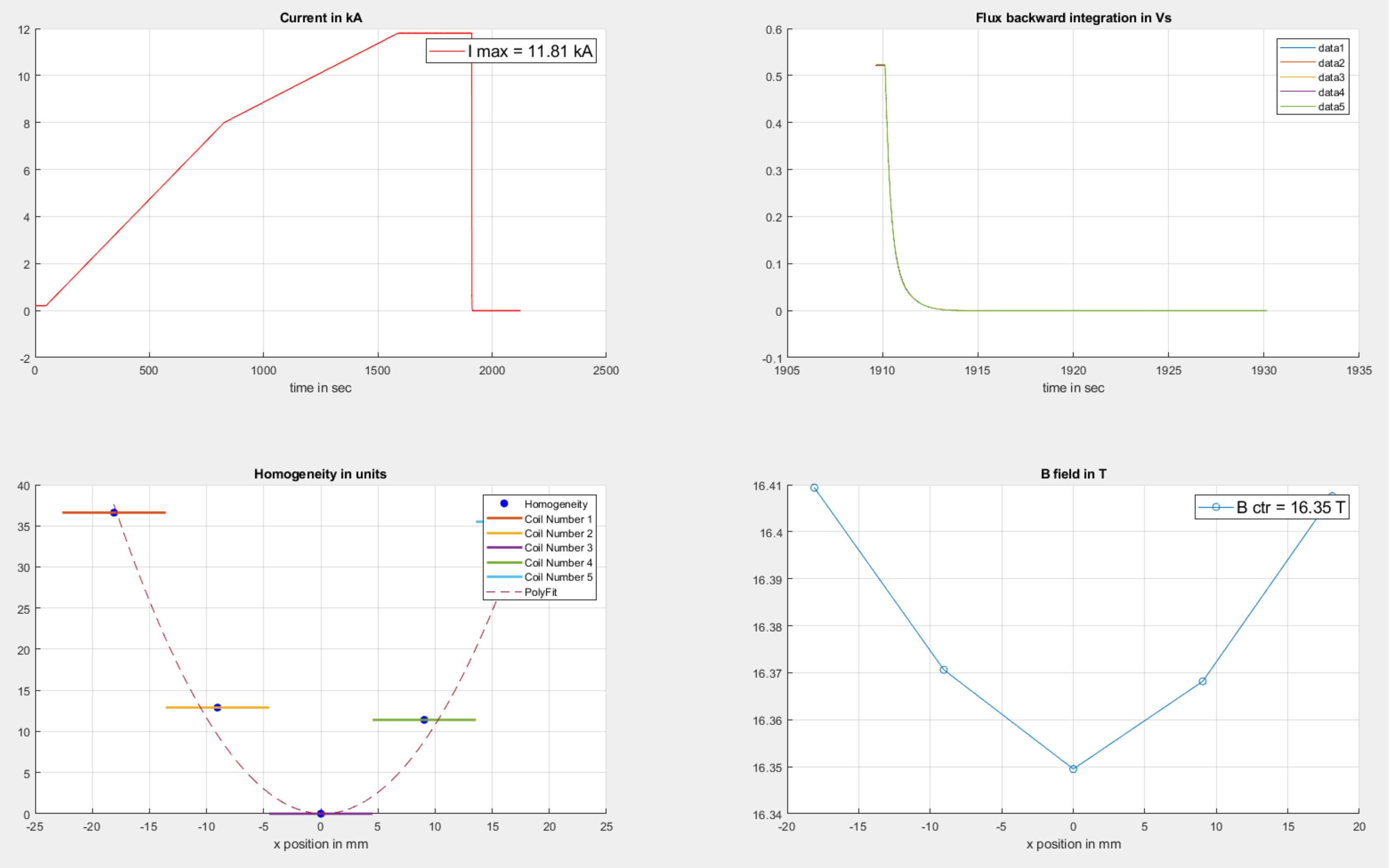
- A rotating coil could not be used
- An **array of 5 static coils** was placed in the cavity during magnet assembly
- Pickup coils implemented on **PCB** board



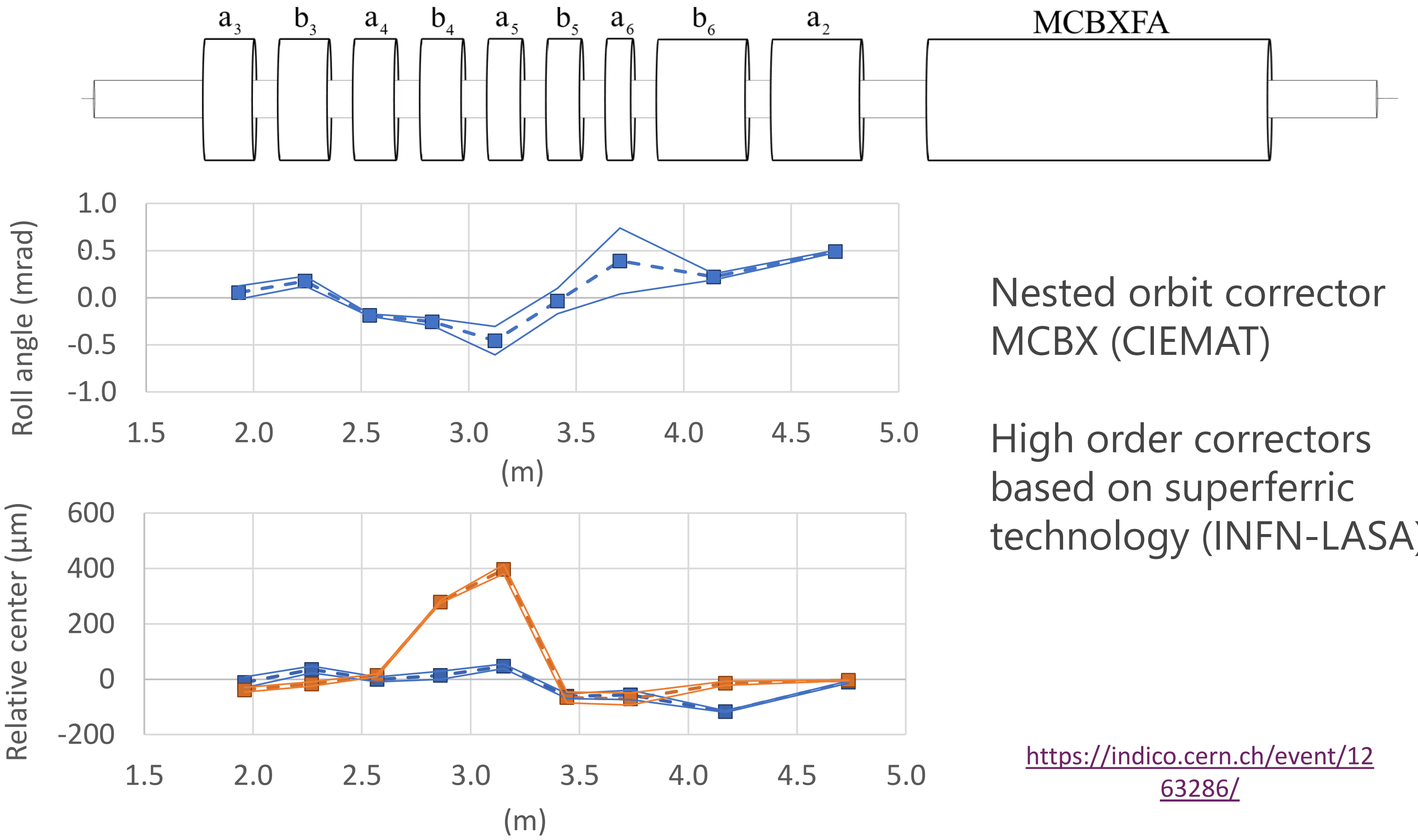
Racetrack model magnet for FCC

- The ramping-up of the magnet requires ~2000 seconds.
- Integration of the voltage from the pickup coils is affected by a large drift.
- Since the magnet can be discharged in a few seconds, the integration is performed on the fast ramping down.
- Field level and homogeneity could be measured.

I = 11.81 kA, B = 16.35 T

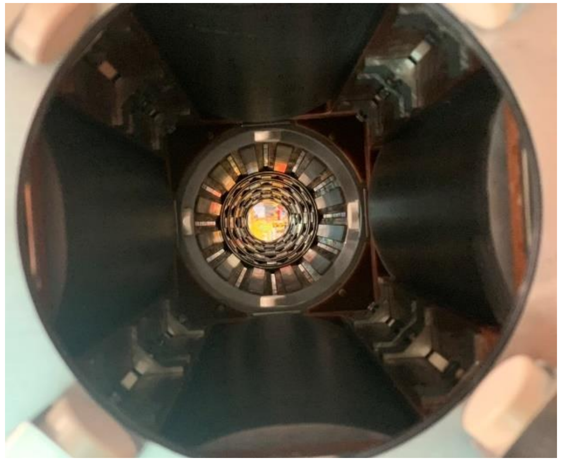


CP for HL-LHC at ambient temperature



Nested orbit corrector MCBX (CIEMAT)

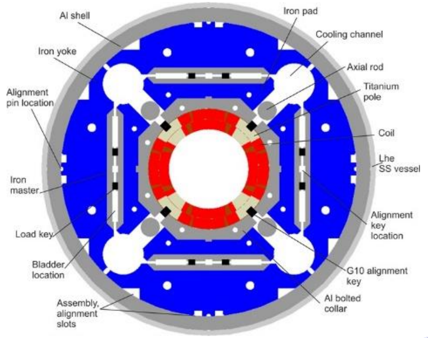
High order correctors based on superferric technology (INFN-LASA)



https://indico.cern.ch/event/1263286/

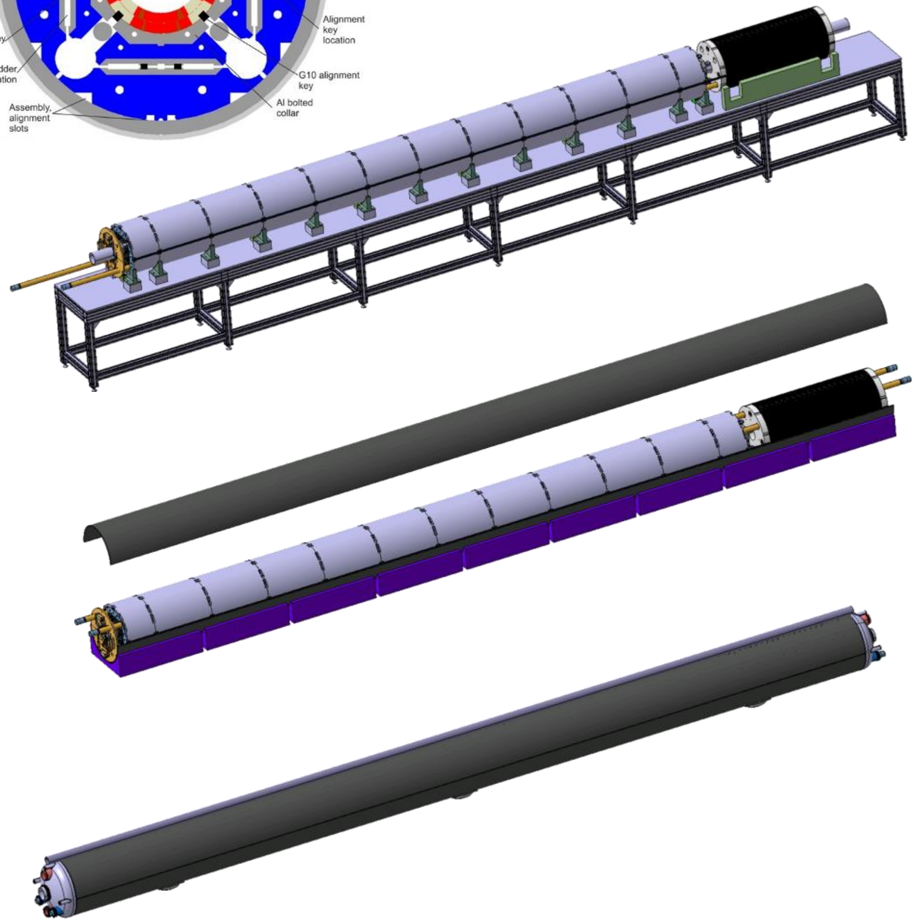
Q2 for HL-LHC at ambient temperature

The new low-beta quadrupole with 150-mm aperture for HL-LHC



Check during magnet assembly

- Coil-pack
- Centering
- Loading



Realignment during cold-mass assembly

- Angular alignment before welding

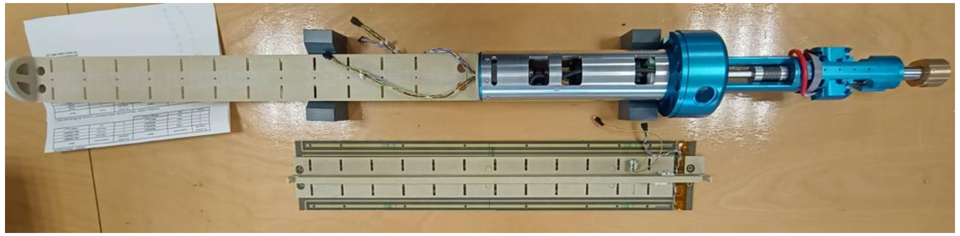
On the final cold-mass assembly

- Final measurement and alignment wrt reference points

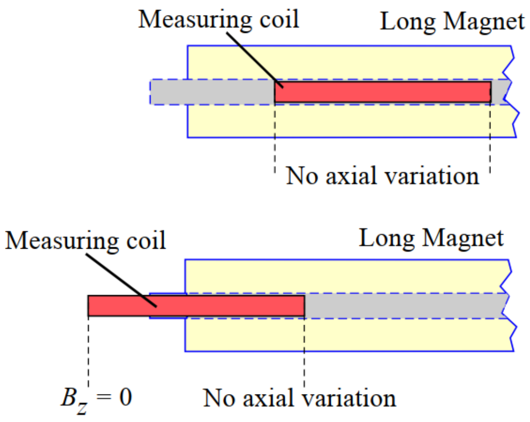
Q2 for HL-LHC at ambient temperature

Rotating coil scanner

- Measurement length 600 mm
- 13 positions to cover the MQXFB
- Measurement radius 50 mm
- PCB for the coils
- On-board tilt sensor and optical targets

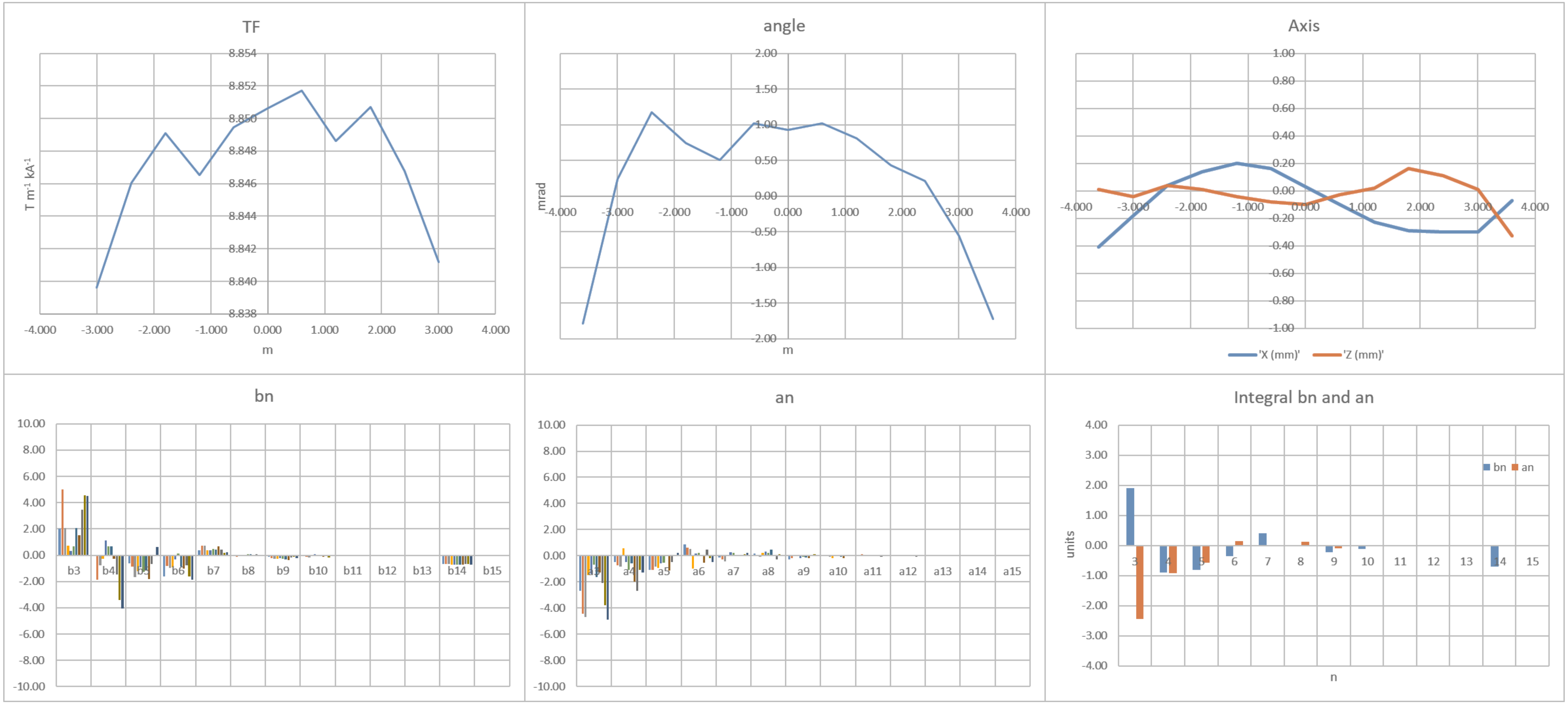


A full scan of the 8-m-long magnet takes 1.5 hours approximately



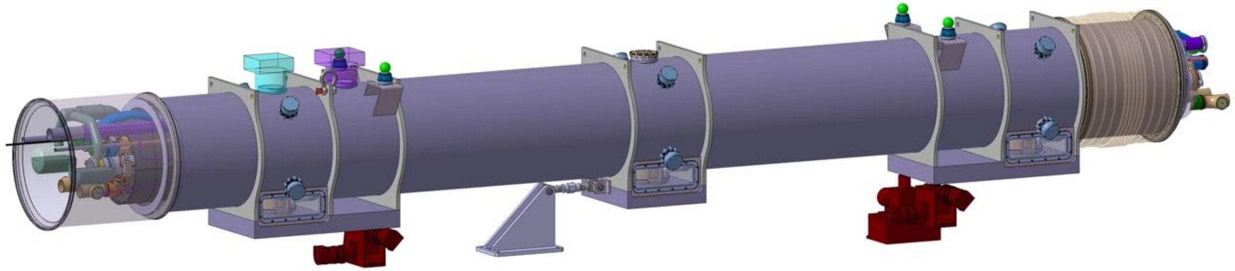
Development of a rotating-coil scanner for superconducting accelerator magnets, https://doi.org/10.5194/jsss-9-99-2020

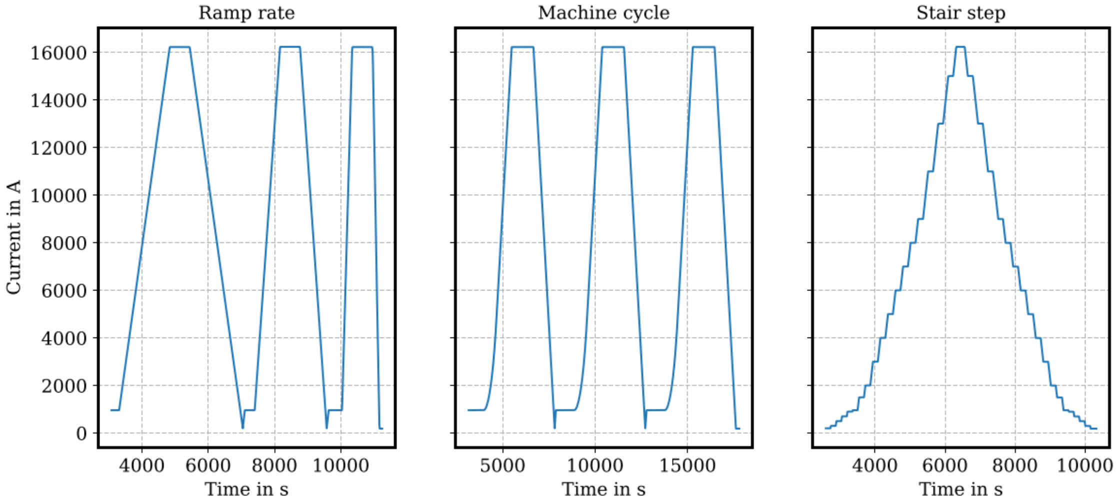
Q2 for HL-LHC at ambient temperature



Q2 for HL-LHC at cryogenic temperature

- Powering cycles by using rotating coils
  - Stair step
  - Machine cycles
  - Variable ramp-rate
- TF calibration and alignment at nominal by using the stretched wire

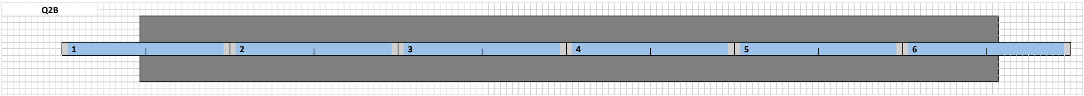




Q2 for HL-LHC at cryogenic temperature

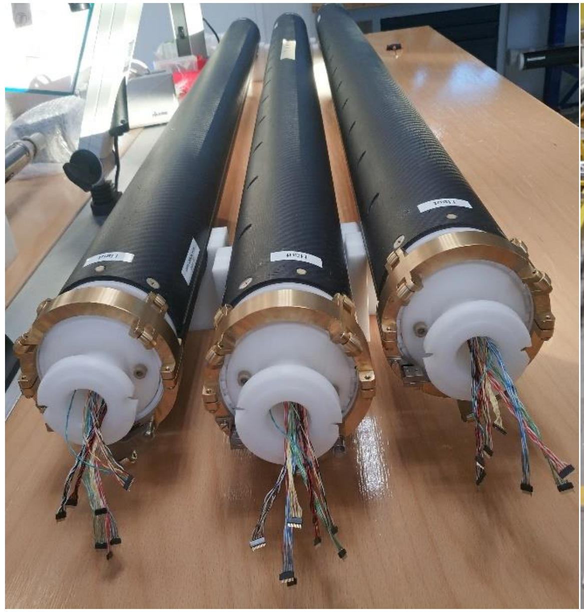
Rotating-coil chain

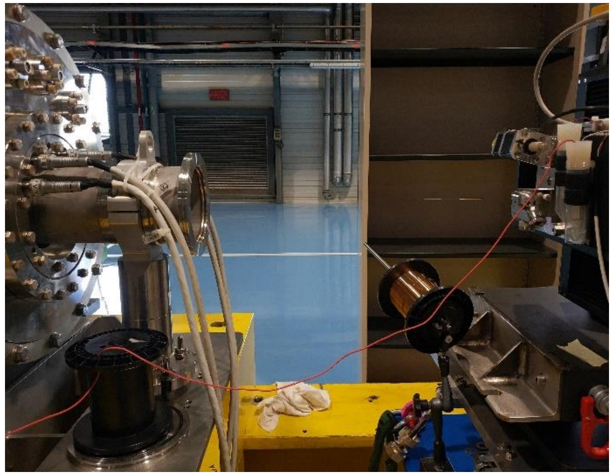
- 6 segments measuring in parallel
- Length 1.3 m each
- Radius 50 mm
- PCB for the coils
- Composite material for the structure



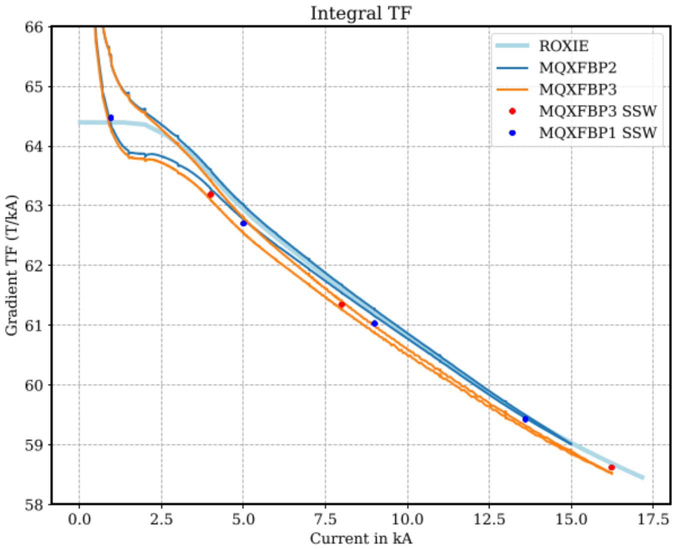
Single stretched wire

- X-Y tables
- Wire tension control
- Positioning accuracy 1 µm

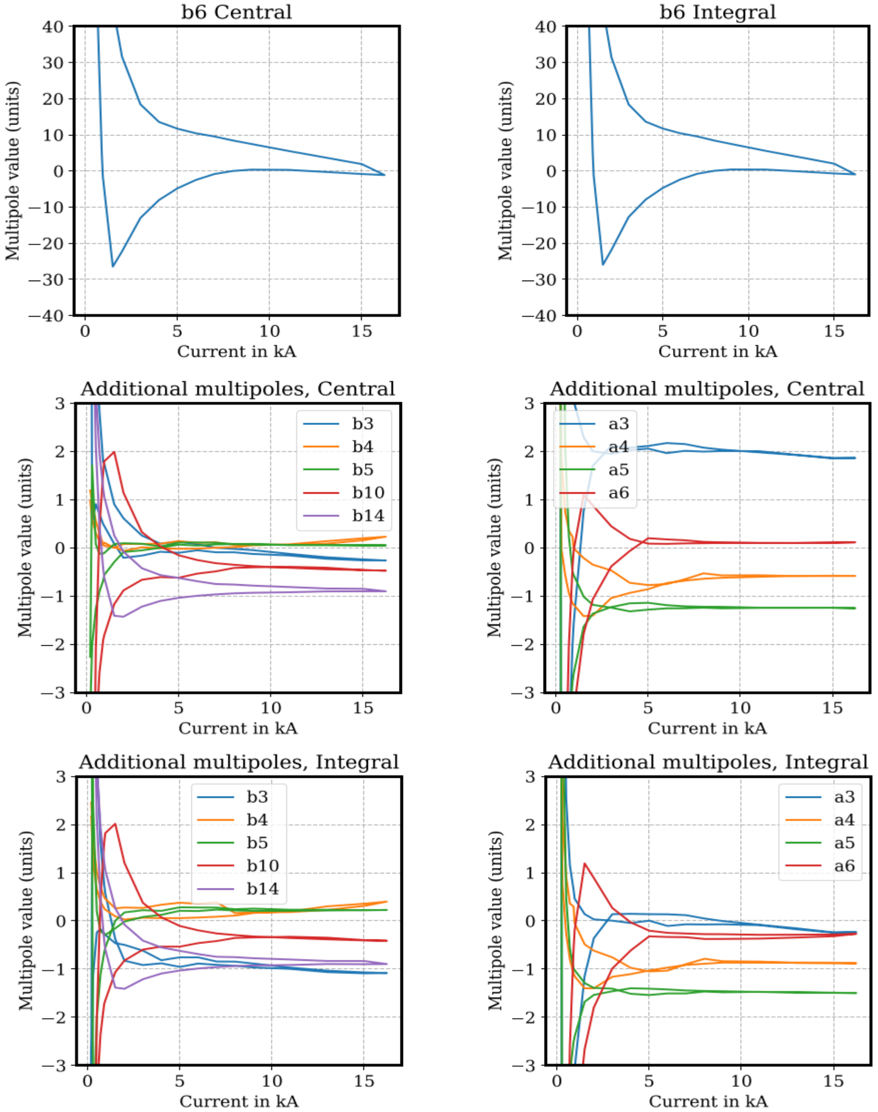




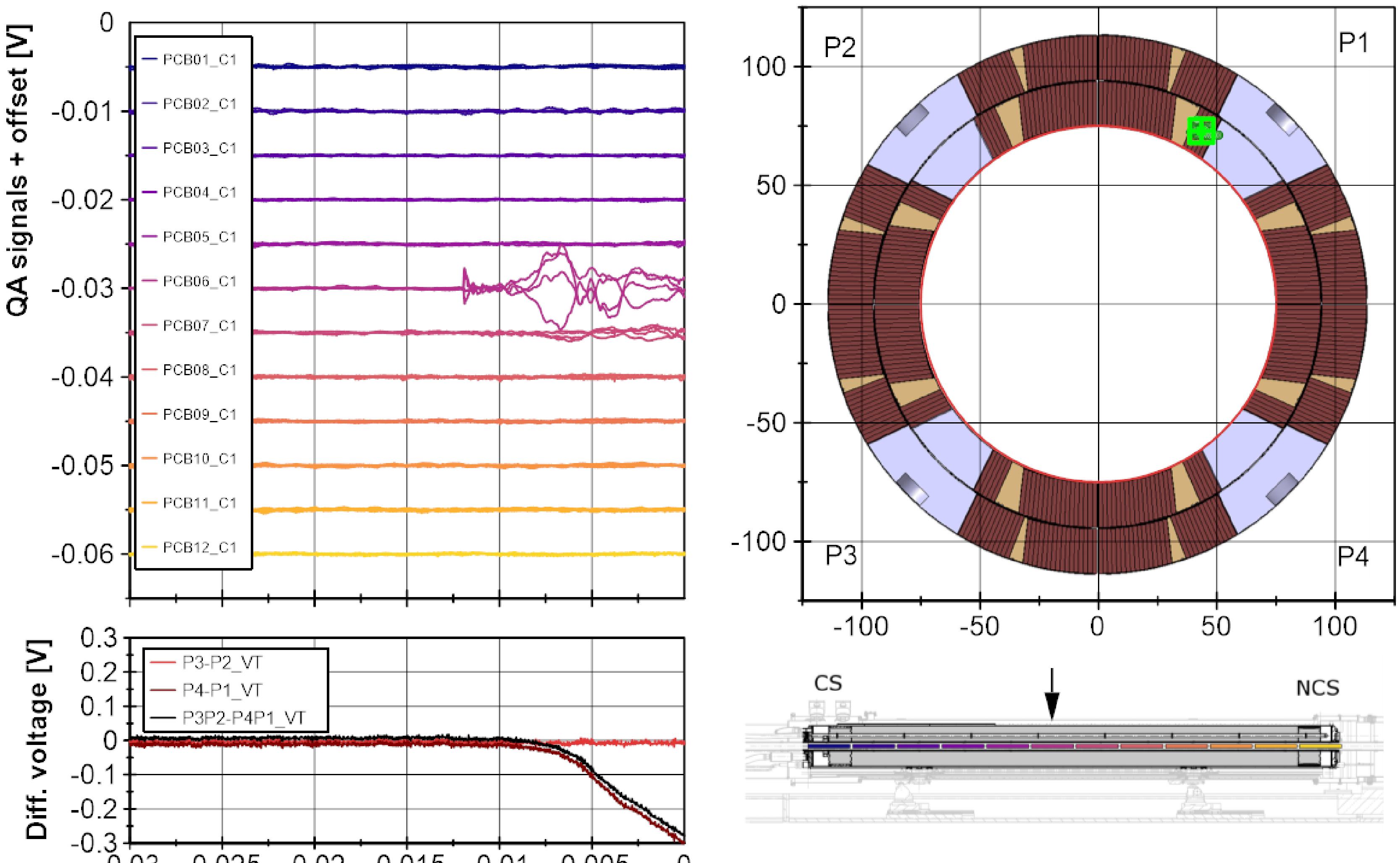
Q2 for HL-LHC at cryogenic temperature



Integral field (all segments)								
960 A			16230 A			Warm		
n	bn	an	n	bn	an	n	bn	an
3	0.14	-1.30	3	-1.08	-0.23	3	-0.29	0.03
4	0.35	-0.60	4	0.40	-0.88	4	-0.12	-0.65
5	-0.42	-1.71	5	0.23	-1.50	5	0.17	-1.29
6	38.65	-2.41	6	-0.95	-0.27	6	-0.81	-0.41
7	-0.56	0.34	7	-0.67	0.61	7	-0.58	0.42
8	0.02	0.19	8	0.17	0.25	8	-0.22	0.06
9	0.00	-0.15	9	0.08	-0.14	9	0.04	-0.01
10	0.09	0.01	10	-0.41	-0.03	10	-0.30	-0.10
11	-0.03	0.02	11	-0.09	0.06	11	-0.08	0.03
12	-0.02	0.01	12	-0.05	0.00	12	-0.04	0.00
13	-0.01	0.00	13	-0.02	0.00	13	0.00	0.00
14	0.23	-0.03	14	-0.90	0.01	14	-0.70	-0.18
15	-0.02	0.00	15	-0.01	0.00	15	-0.01	-0.01

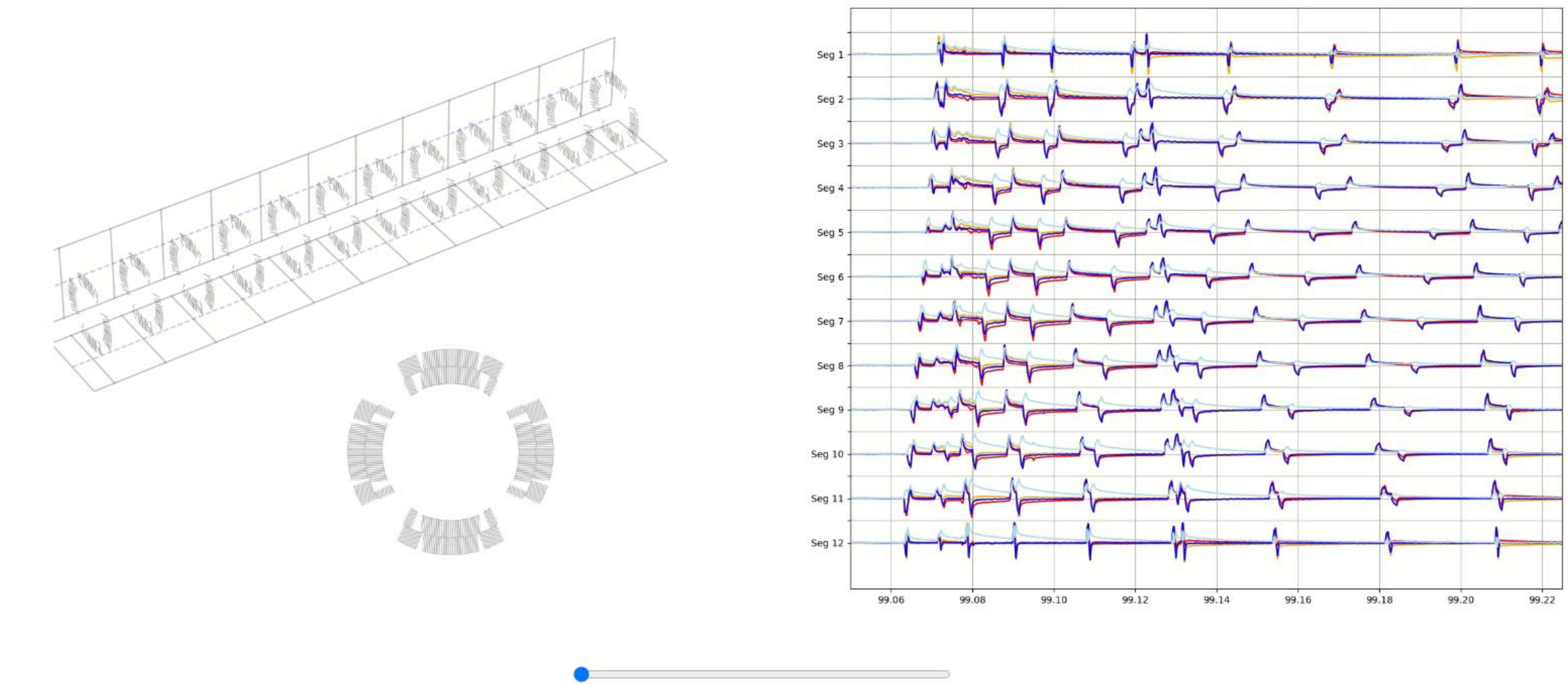


Example of quench localization

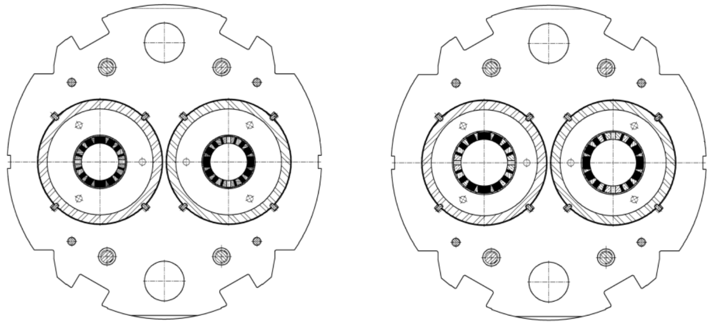


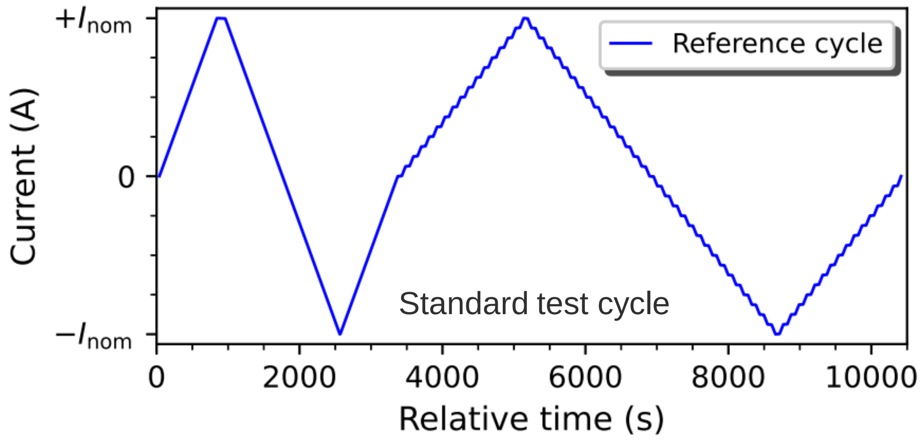
Current: 16.39 kA
File: HCLMQXFBT01-CR000005__G202211291432_na001(0).tdms

Example of flux-jump localization



MCBC and MCBY correctors under special cycling conditions

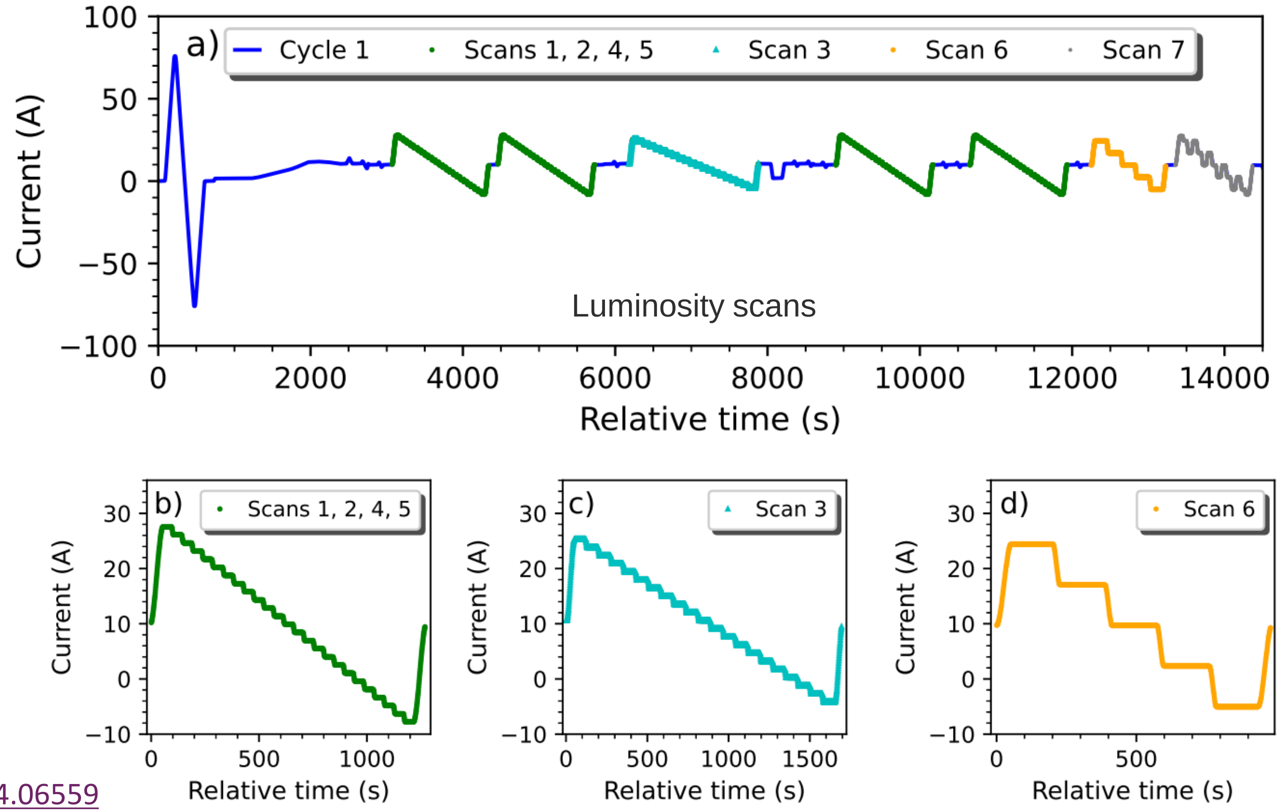




In 2017, the ATLAS experiment performed a **luminosity calibration scan** by powering the orbit correctors whit special cycles.

A **non-linearity** was noticed on the beam position reconstructed from the magnetic model (linear) versus the BPM measurements.

A magnetic measurement campaign was launched.



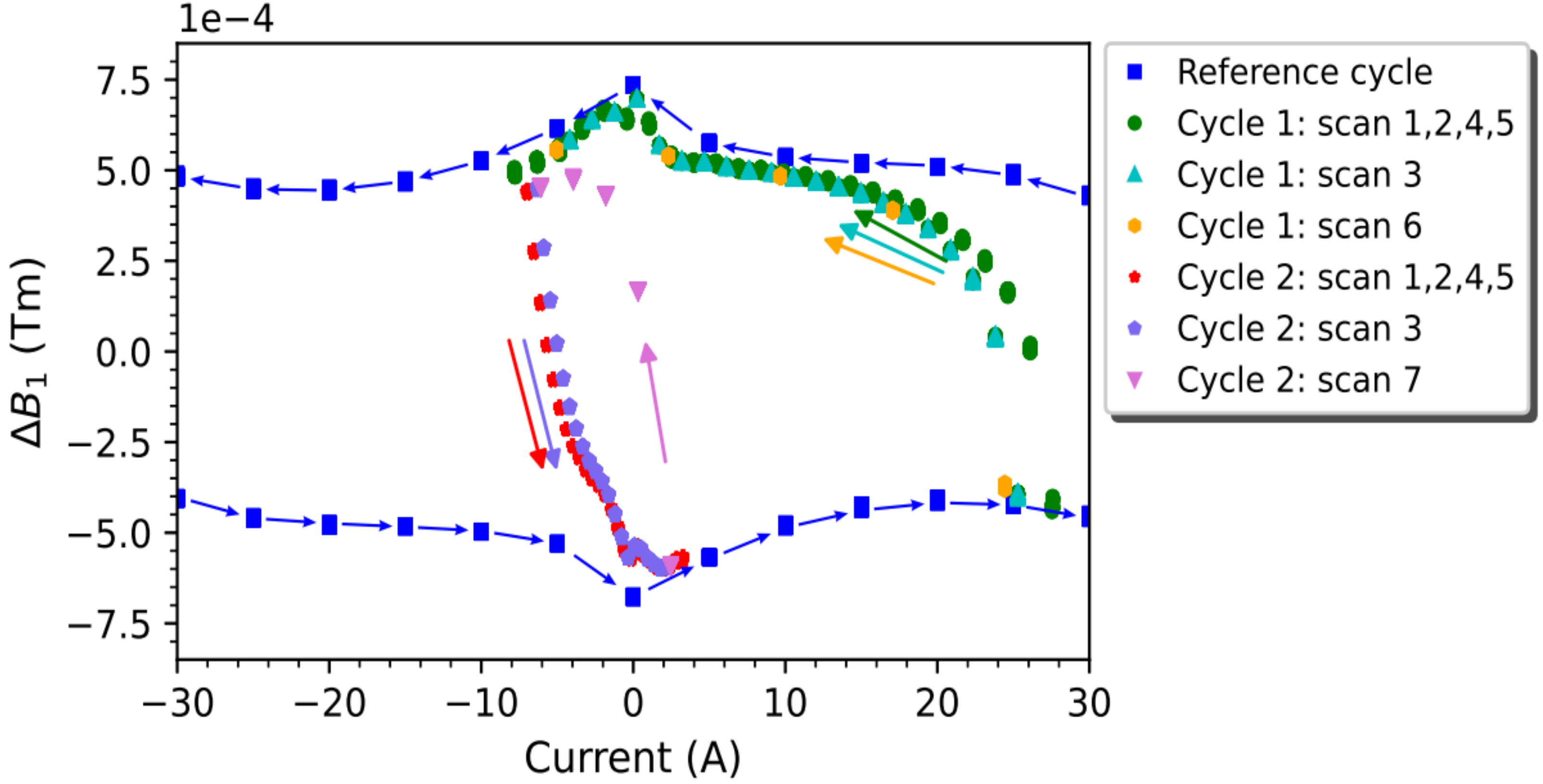
http://arxiv.org/abs/2304.06559

MCBC and MCBY correctors under special cycling conditions

The luminosity-scan cycles were measured and compared to standard test cycles.

Transitions of magnetization branch were identified as the main cause of the non-linearity.

Residuals from linear model

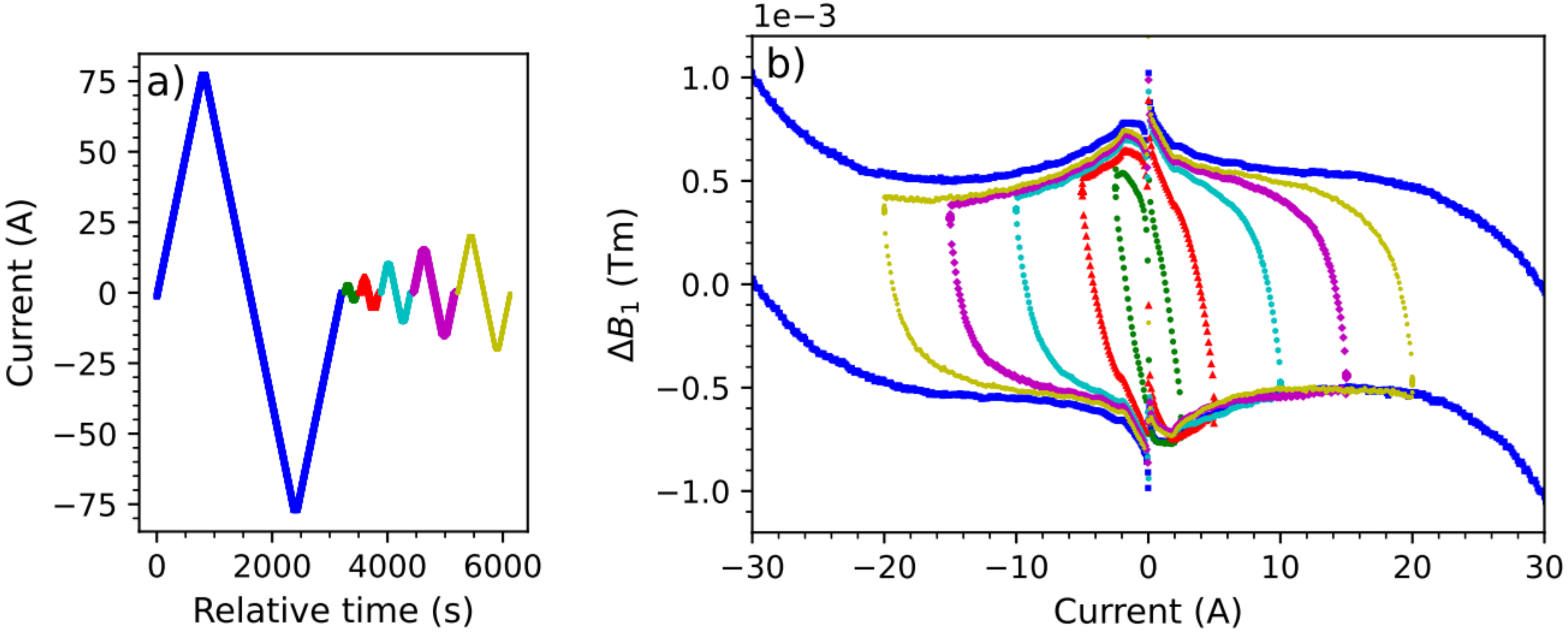


http://arxiv.org/abs/2304.06559

MCBC and MCBY correctors under special cycling conditions

In addition, ad-hoc cycles were performed to study and model the transitions (design of experiments).

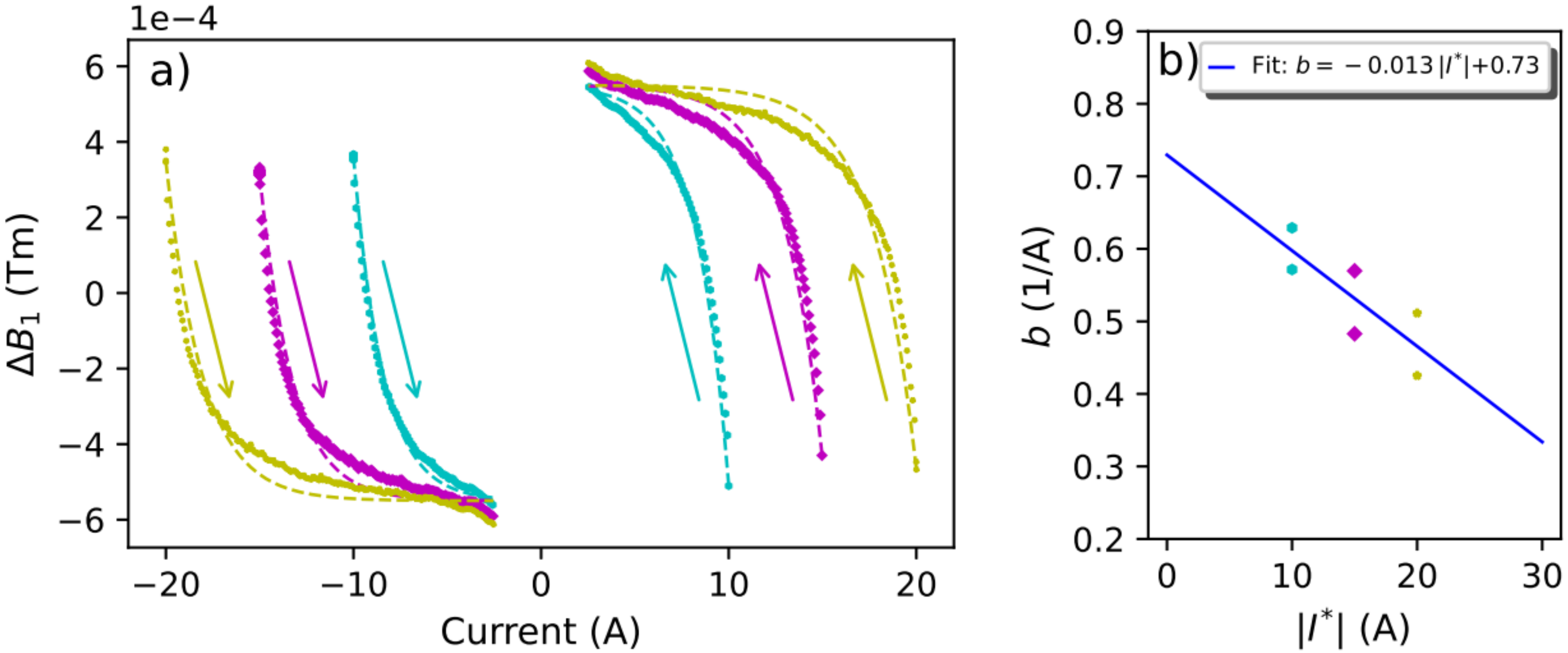
Residuals from linear model



http://arxiv.org/abs/2304.06559

MCBC and MCBY correctors under special cycling conditions

A simple exponential model, with exponent function of the field level, is able to predict the transitions within the required level for the luminosity scans (~0.1 mTm)



ATLAS delivers most precise luminosity measurement at LHC
https://atlas.cern/updates/briefing/run2-luminosity
https://arxiv.org/abs/2212.09379

http://arxiv.org/abs/2304.06559

Accuracy

Typical accuracy on a ~10-m-long magnet:

- **Integrated gradient ~1 unit** by using stretched wire
- **Harmonics ~ 0.05 unit** by using rotating coil
- **Field direction ~0.1 mrad** by using rotating coil or stretched wire
- **Magnetic center <0.1 mm** by using rotating coil or stretched wire
- **Magnetic length ~1 mm / 8 m** by using rotating coil
- **Longitudinal center ~1 mm / 8 m** by using rotating coil

*Stretched wire for integral field, rotating coils for local or integral field

Thank you
for your attention

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Multipoles

In a region of space

- free of magnetic sources (currents or magnetic materials)
- where the longitudinal component of B is constant

B(x,y) can be simply described by a **series of scalar coefficients** B_1, A_1, B_2, A_2, B_3, A_3,... The so-called **harmonics**, or **multipoles**.

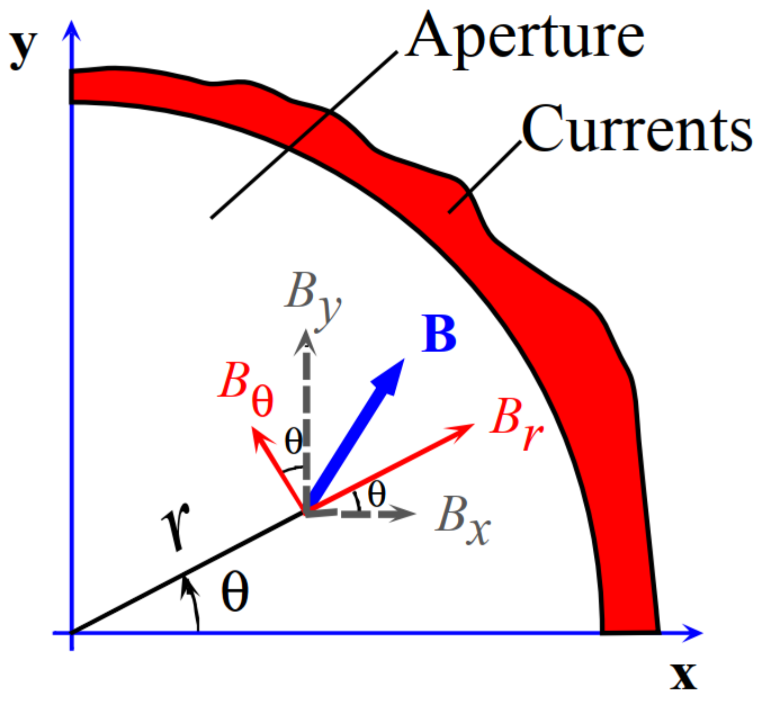
$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \sin(n\theta) + A_n \cos(n\theta)]$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \cos(n\theta) - A_n \sin(n\theta)]$$

R is a reference radius and the units are ***tesla***

Or by using the complex notation

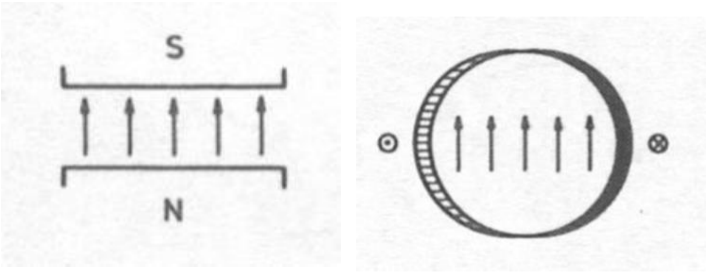
$$B_y + iB_x = \sum_{n=n_0}^{\infty} B_n + iA_n \left(\frac{x+iy}{R}\right)^{n-1}$$

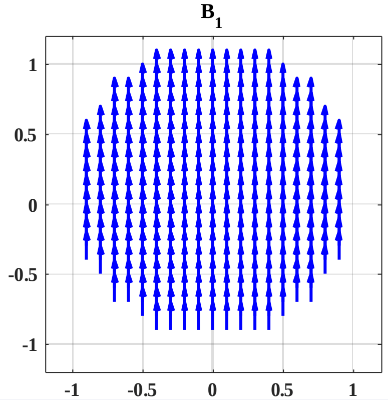


View from the Lead End of the Magnet

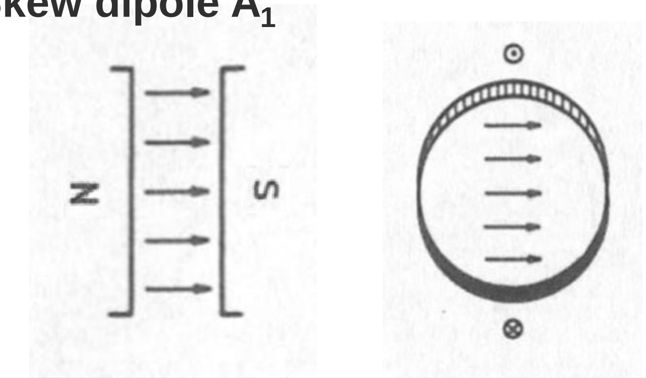
A. Jain, CERN Academic Training Program 2003

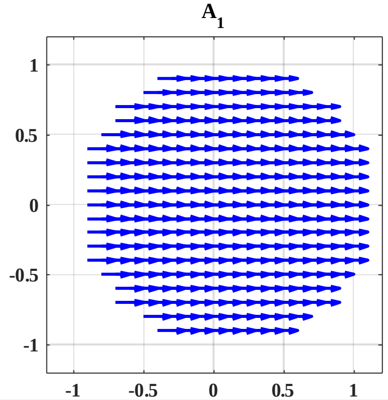
Normal dipole B_1



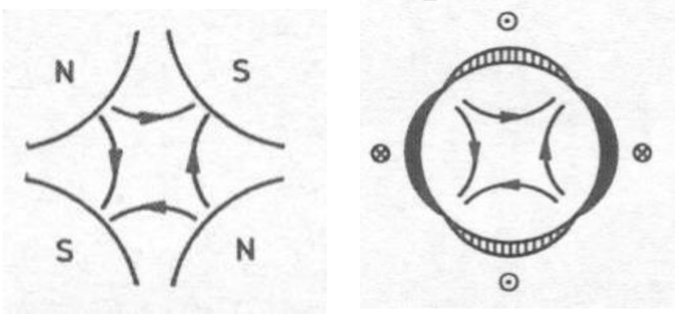


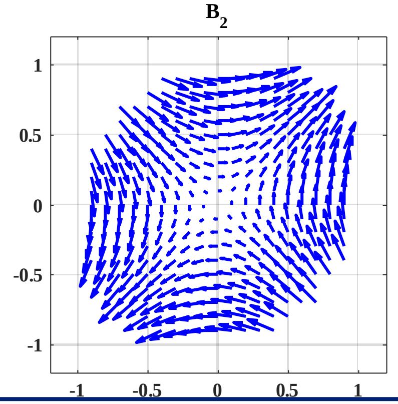
Skew dipole A_1



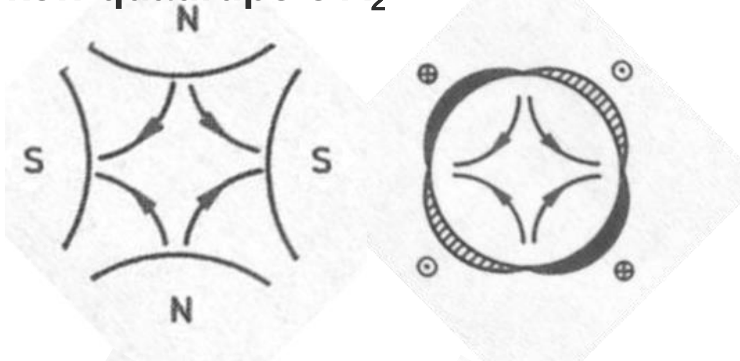


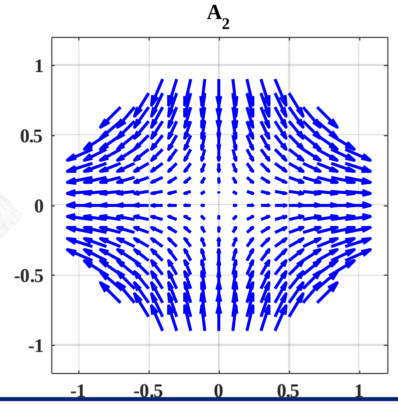
Normal quadrupole B_2



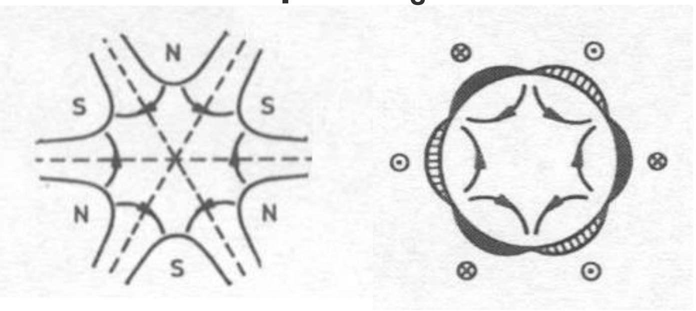


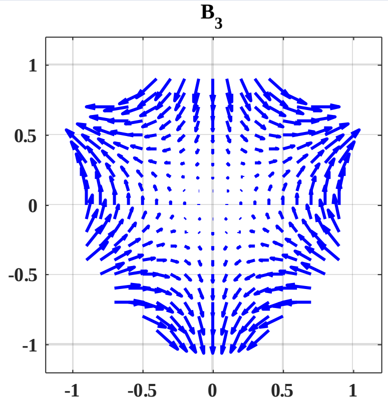
Skew quadrupole A_2



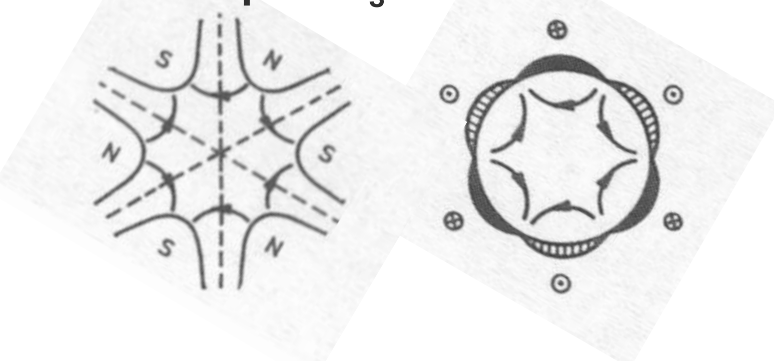


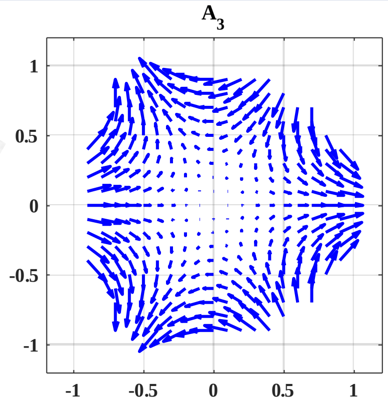
Normal sextupole B_3





Skew sextupole A_3





Normalized multipoles

By assuming that the magnet is mainly generating one field component (main field), we can factorize

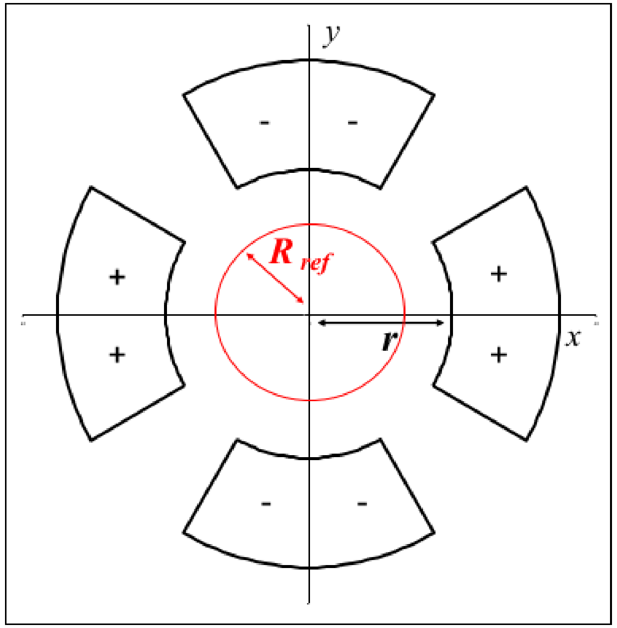
- the main field component (B_1 for dipoles, B_2 for quadrupoles, …)
- 10^{-4} to get numerical values ~1 (unit) since the expected deviations from the ideal field are ~0.01%

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

The coefficients b_n, a_n are called **normalized multipoles** given in *units* at the reference radius R_{ref}

- $\mathbf{b_n}$ are the **normal** multipoles
- $\mathbf{a_n}$ are the **skew** multipoles

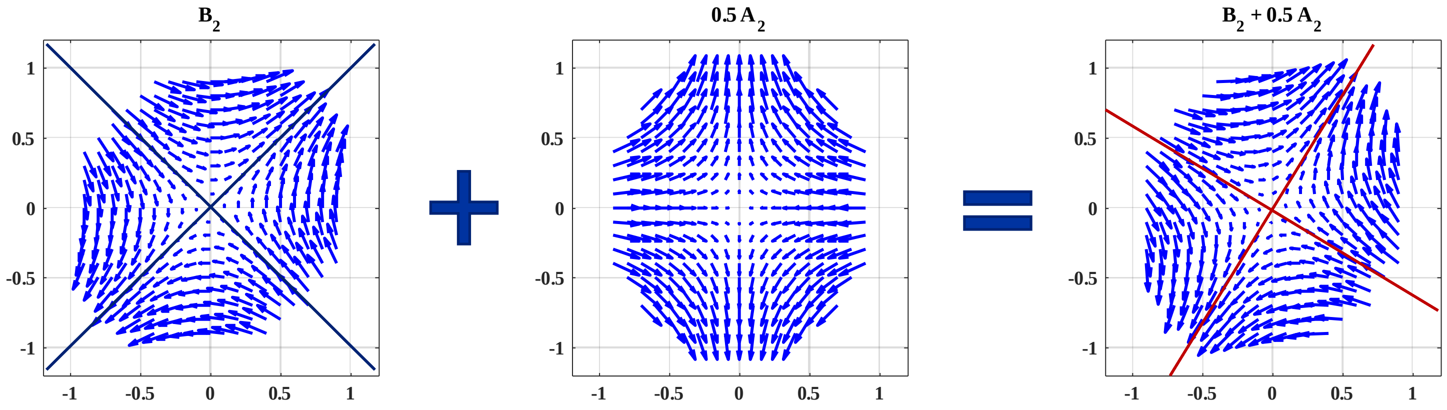
In general, only a small set of coefficients (**n<15**) is sufficient to have an accurate description of the field in the region of interest.



The reference radius is usually chosen as 2/3 of the aperture radius.

Properties of multipoles

- An error on the angle of the main field can be seen as the presence of the skew coefficient of the same order (**rotation**)



- An error on the magnetic center can be seen as the presence of the normal/skew coefficient of order n-1 (**feed-down**)