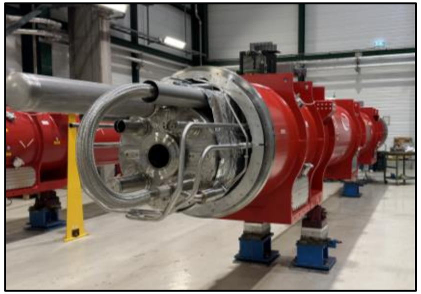
Magnetic axis measurements of the superconducting quadrupoles (Q2) at CERN

Carlo Petrone, Mariano Pentella, Piotr Rogacki, Lucio Fiscarelli, Guy Deferne, Susana I. Bermudez, Herve Prin, Nicolas Bourcey, Vivian Rude, Julia Calmels, Patrick Bestmann, et al..

14th HL-LHC Collaboration Meeting – Genoa – 7 ÷ 10 October 2024

Q2 Magnetic measurements workflow



MQXFB assembly → **Cold mass assembly** → **Cryostating** → **Cryo-assembly**

MQXFB assembly

- Coil pack insertion
- Centering
- Loading

Cold mass assembly

Pre-alignment field angle with gravity **before** feet and endplates welding[1]

Transfer function and field harmonics

Magnetic axis measurement at ambient temperature (180)

Cryostating

Insertion of cold mass in vacuum vessel

Mechanical fiducialization of vessel

Installation of FSIs

Cryo-assembly

Transfer function and field quality at cold[2]

Magnetic axis measurement at ambient and cold temperatures (SM18)

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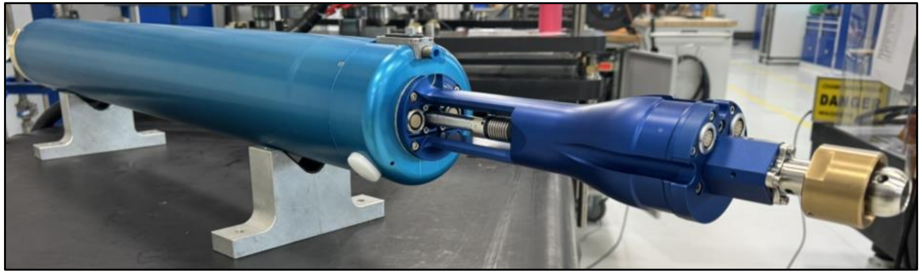
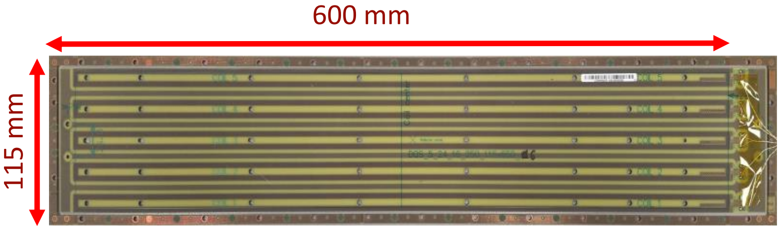
[1] H. Prin: Status of cold mass activities

[2] L. Fiscarelli: Field quality update

Measurement method: rotating-coil scanner



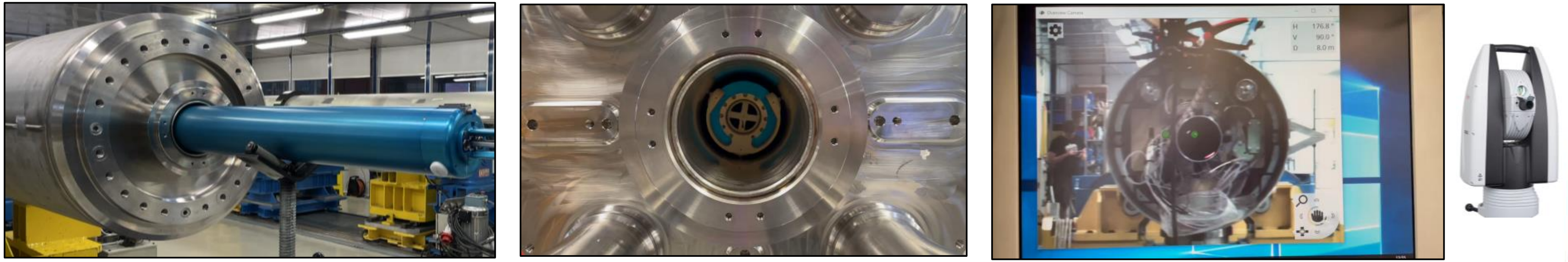


PCB: 2.33 m^2 as surface

Rotating-coil scanner (ambient temperature)

- The **harmonic coefficients** (C_2 and C_1 used for the field center) are extracted by combining **four** measurements to compensate for systematics (**±10 A**, CW/CCW rotation direction) and applying **sensitivity factors**.
- The field **roll angle** and the **magnetic center** frame referenced to **gravity** through the onboard **tilt sensor**, while a pneumatic brake increases mechanical stability.

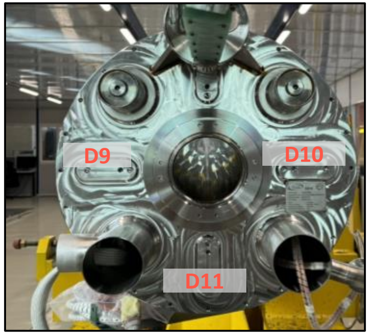
Cold-mass measurement procedure

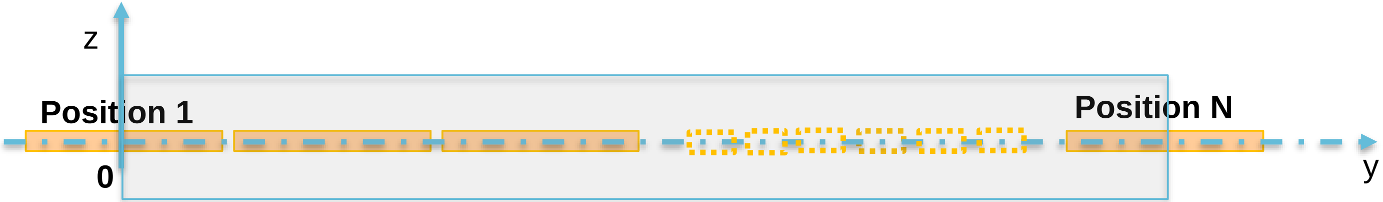


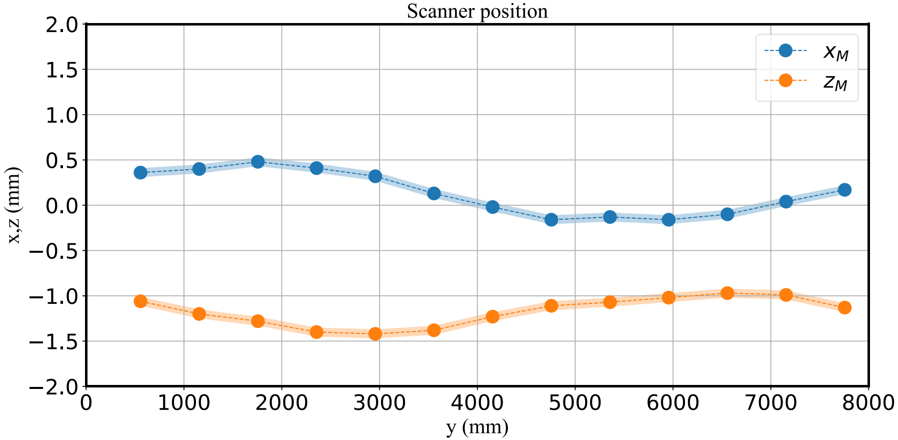
- The mechanical **rotation** axis is measured using a **laser tracker**, detecting a reflector rotating solidly with the printed circuit board (PCB).
- Measurements expressed in a **reference frame** defined by the three fiducials on the two cold mass endplates (and gravity).

Procedure: Room temperature measurements of the MQXFB magnets and LMQXFB cold masses (EDMS 2901463)

Cold-mass measurement procedure

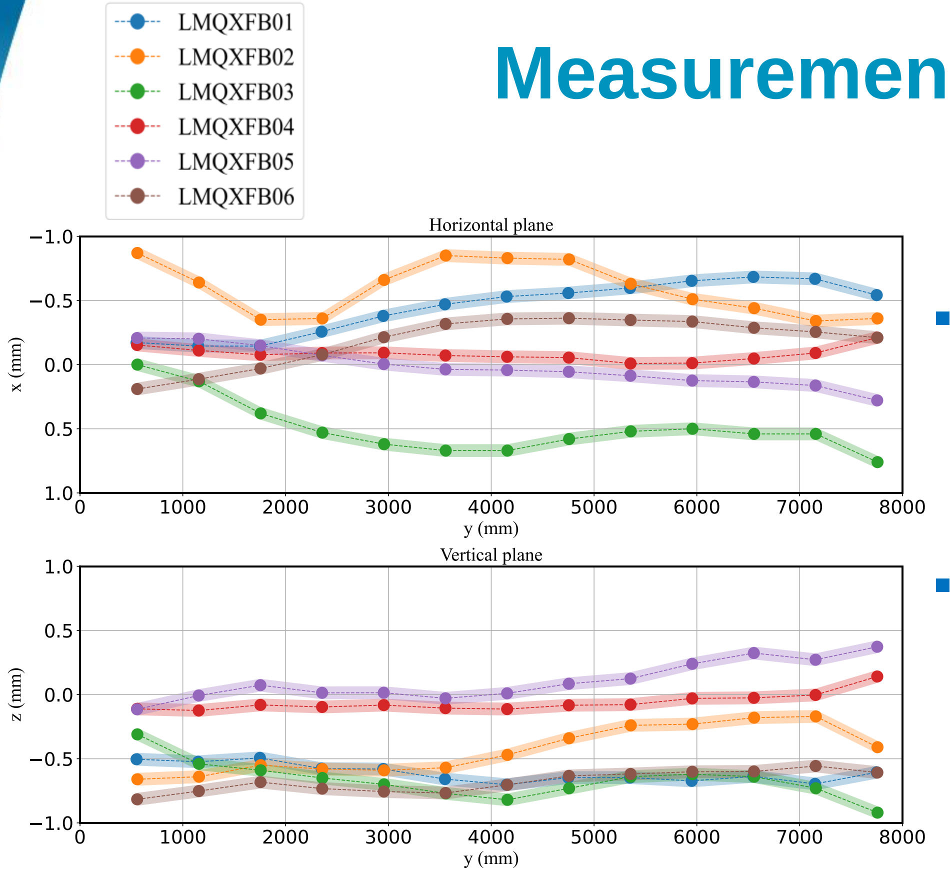






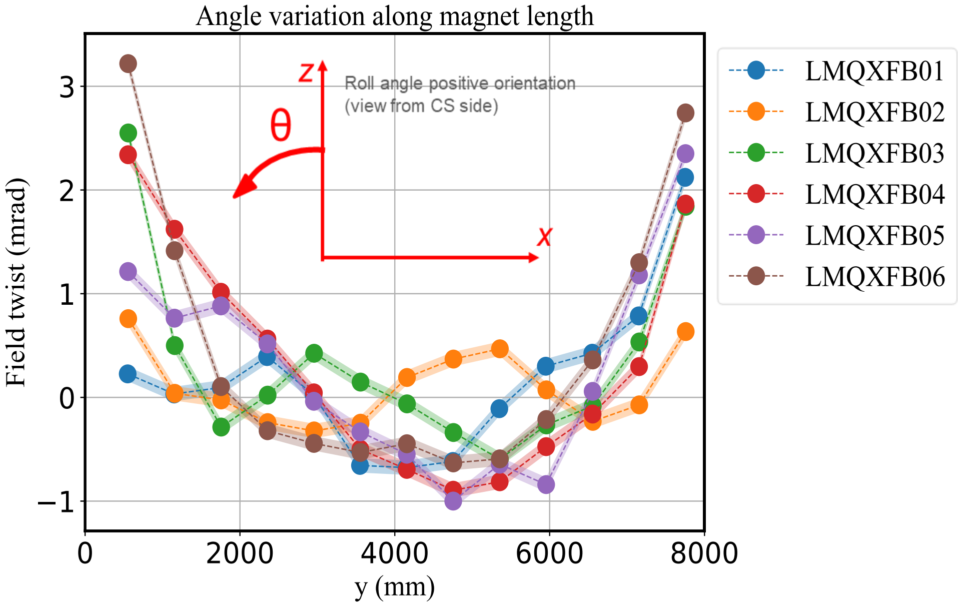
- Measurement performed at different longitudinal positions (magnetic axis).
- The **origin** is the center of the three fiducials on the quadrupole connection side.

Measurement results



- Magnetic axis measured over the 13 longitudinal positions of **6 cold masses**.
- The **reference frame** is referring to the cold masses D9, D10, and D11 points on both endplates.

Measurement results

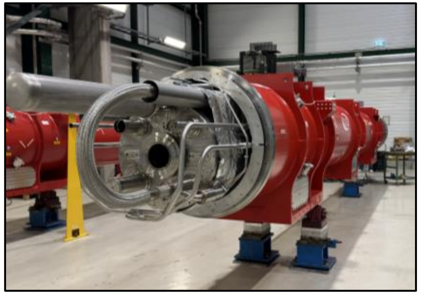


- Magnetic field angle measured w.r.t. gravity.
- The **integral** field angle smaller than 1 mrad on all cold masses:

Field angle integral [mrad]	
LMQXFB01	0.27
LMQXFB02	-0.10
LMQXFB03	-0.20
LMQXFB04	-0.04
LMQXFB05	-0.28
LMQXFB06	-0.68

Ambient temperature results are uploaded on MTF

Q2 Magnetic measurements workflow



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Presentation outline

Cryo-assembly

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Magnetic axis measurement at ambient and cold temperatures in SM18

[1] H. Prin: Status of cold mass activities

[2] L. Fiscarelli: Field quality update

Magnetic axis of the cryo-assembly

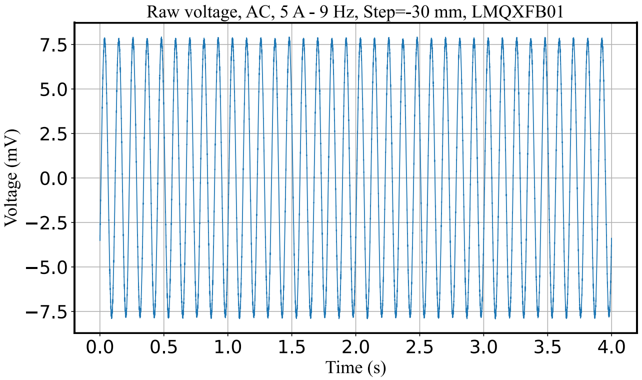
Stretched-Wire for alignment measurements

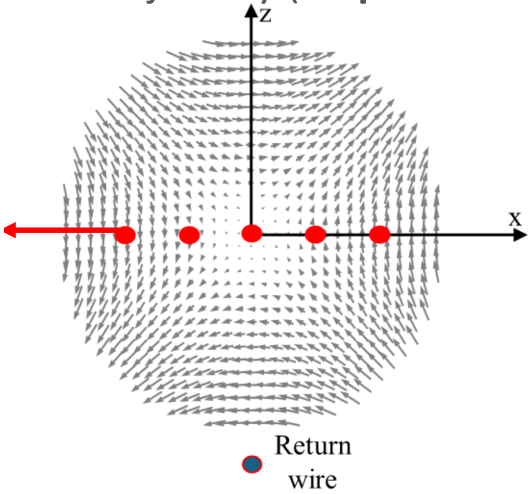
- Rotating coil scanner cannot be used.
- The Stretched-Wire system is installed with **Stage A** on the **CS side and aligned with gravity** at over 0.01 mm/m.
- Axis measurements at **cryogenic and ambient temperature** are performed also to assess the vertical mechanical variation (~ 1.5 mm).

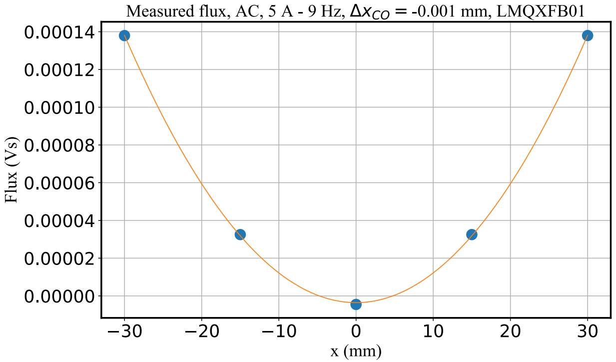
Measurement method: single stretched wire

AC measurements – SSW at ambient temperature

Measurements performed at **5 A AC, 9 Hz**, with the wire used in **stationary mode** moving on a discretized trajectory (**stop-wait-measure**)



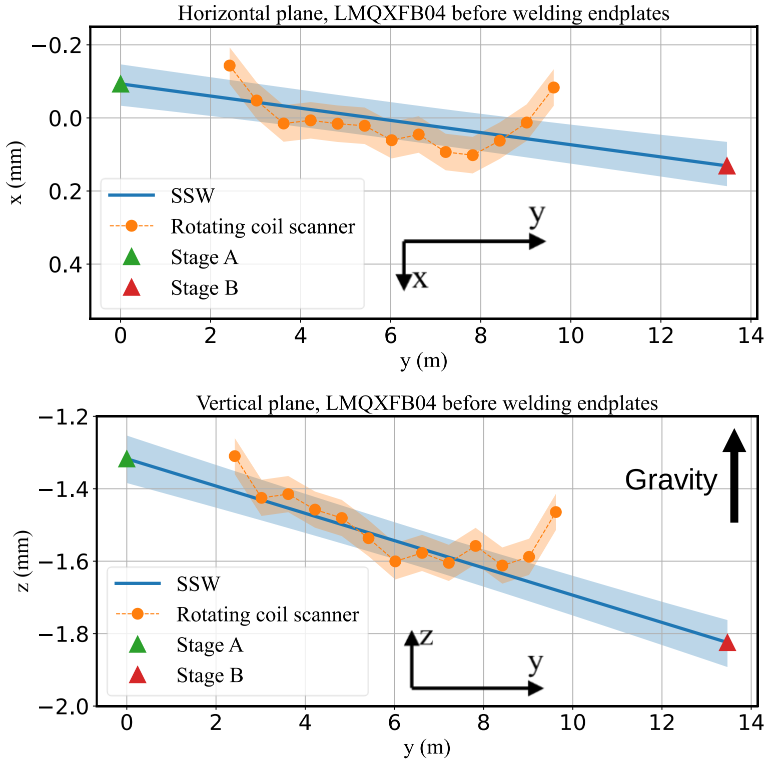




- **Flux value** at a given position obtained by **FT of the measured flux** and **selecting** the **tone** corresponding with the **magnet's excitation current**.
- The measured points are fitted with **parabolas**.

Measurement method: single stretched wire

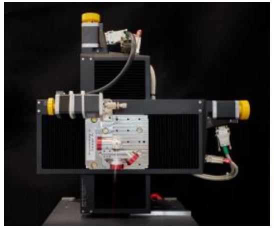
AC measurements – Validation against rotating coil scanner



Parameter	SSW Value	SSW unc. (1-σ)	Rot. coil scanner Value	Rot. coil scanner unc. (1-σ)
x (mm)	0.01	0.05	0.02	0.05
z (mm)	-1.54	0.07	-1.52	0.05
Roll (mrad)	0.06	0.10	0.02	0.07
Yaw (mrad)	0.01	0.01	0.01	0.00
Pitch (mrad)	-0.04	0.01	-0.03	0.00

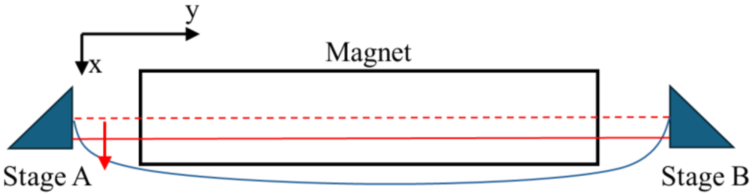
Measurement method: single stretched wire

DC measurements – SSW at cryogenic temperature



- Alignment of the wire with the magnetic axis performed **iteratively** by combining two **different** wire movement types (CO and CN).
- Knowledge about **longitudinal magnet position** is crucial for setting up wire stages movement appropriately, especially with an **asymmetric setup.**

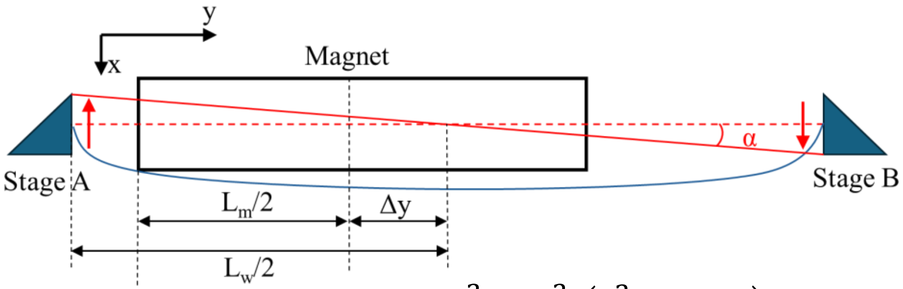
Co-directional movement (CO)



$$\Phi(x_1, x_2) = (GL_m)\,\frac{x_2^2 - x_1^2}{2}$$

The **integrated gradient** is measured with a CO movement.

Counter-directional movement (CN)

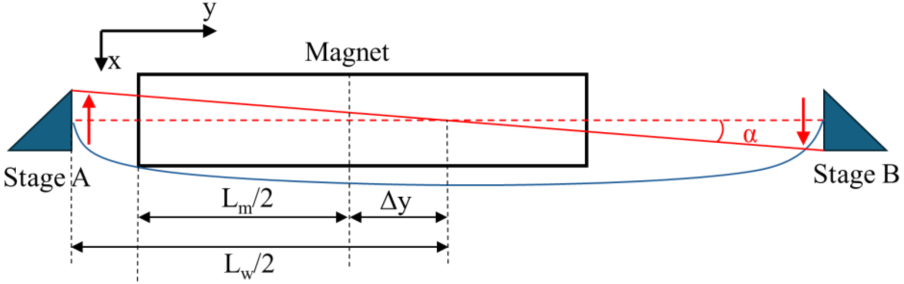


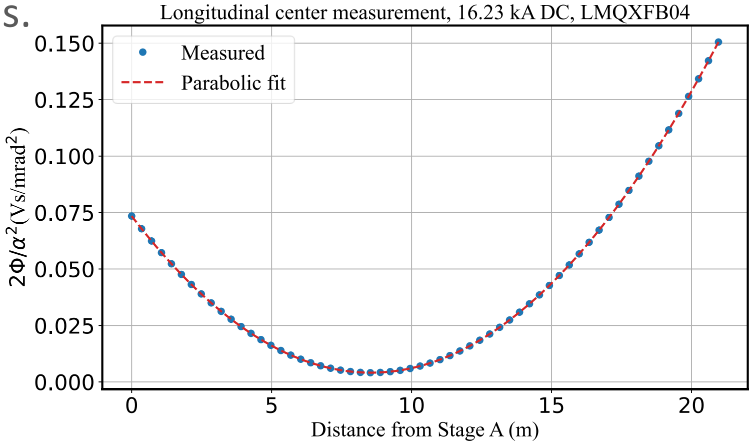
$$\Phi(\alpha_1, \alpha_2) = (GL_m)\,\frac{\alpha_2^2 - \alpha_1^2}{2}\left(\frac{L_m^2}{12} + \Delta y^2\right)$$

Measurement method: single stretched wire

Longitudinal center and magnetic length

- The **longitudinal center position** is measured by a sequence of CN movements, with the pivot position y_P moving along the longitudinal axis.





$$\Phi(0,\alpha) = (GL_m)\frac{\alpha^2}{2}\left(\frac{L_m^2}{12} + \Delta y^2 - y_P\Delta y\right)$$

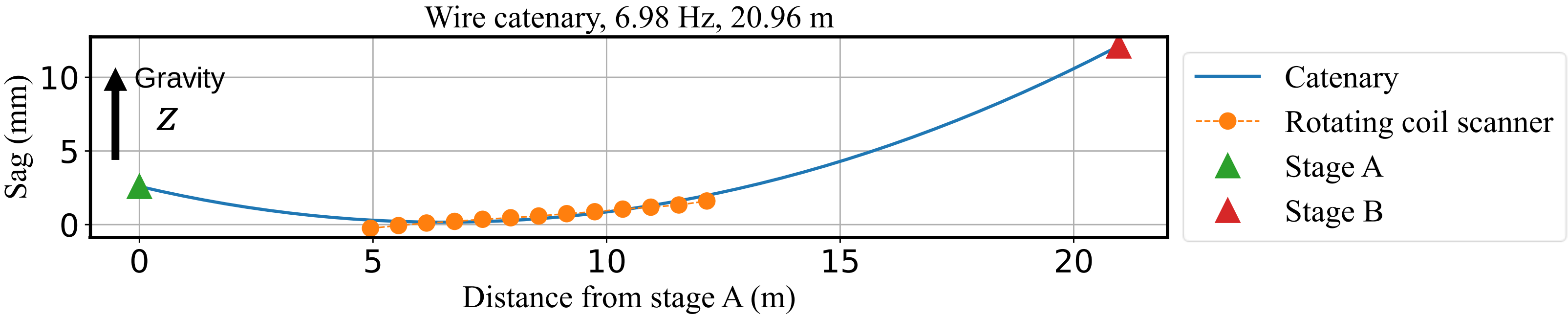
- $\Phi(0,\alpha)\frac{2}{\alpha^2}$ describes a parabola with its minimum in $y_P = \Delta y$
- When the pivot point corresponds with the longitudinal center, $y_P = \Delta y$

$$L_m = \pm\sqrt{12\frac{\Phi(0,\alpha)}{(GL_m)}\frac{2}{\alpha^2}}$$

Measurement method: single stretched wire

Sagitta correction

$$z(y) = \frac{g}{2}\left(\frac{\pi}{\omega_R L}\right)^2 y^2 + \frac{1}{y_B}\left(z_B - z_A - \frac{g}{2}\left(\frac{\pi}{\omega_R L}\right)^2 y_B^2\right) y + z_A$$

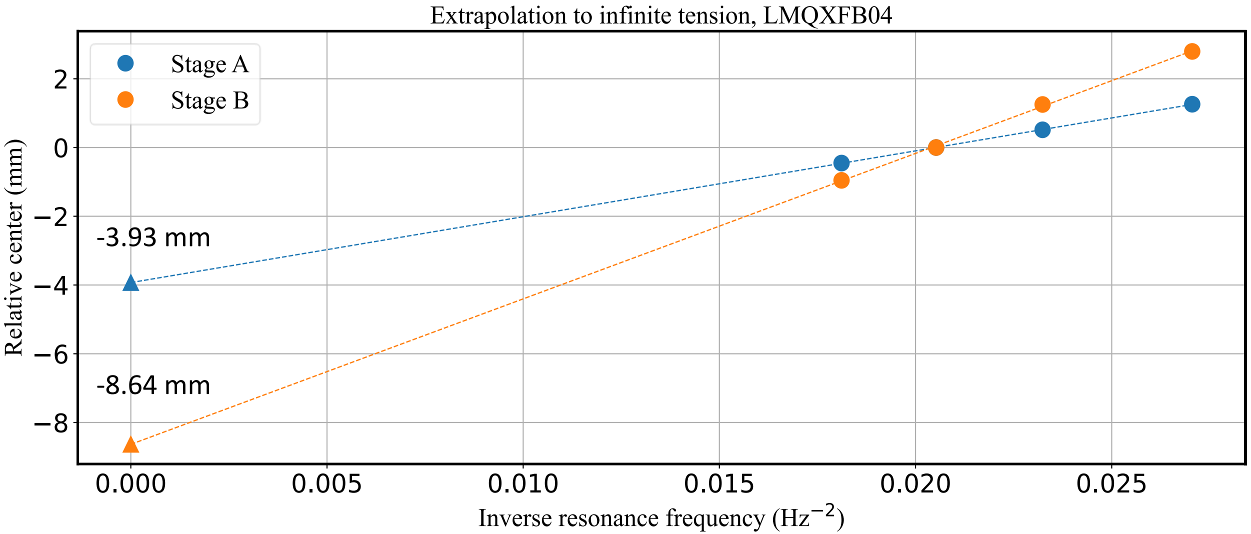


- On wire lengths of **21 m** used in this measurement setup, resonance frequencies span between **5.6 and 7.4 Hz** (**650 g to 950 g** tension on a **0.125-mm CuBe** wire).

- Precise measurement of the wire resonance frequency ω_R is required

Measurement method: single stretched wire

Sagitta correction

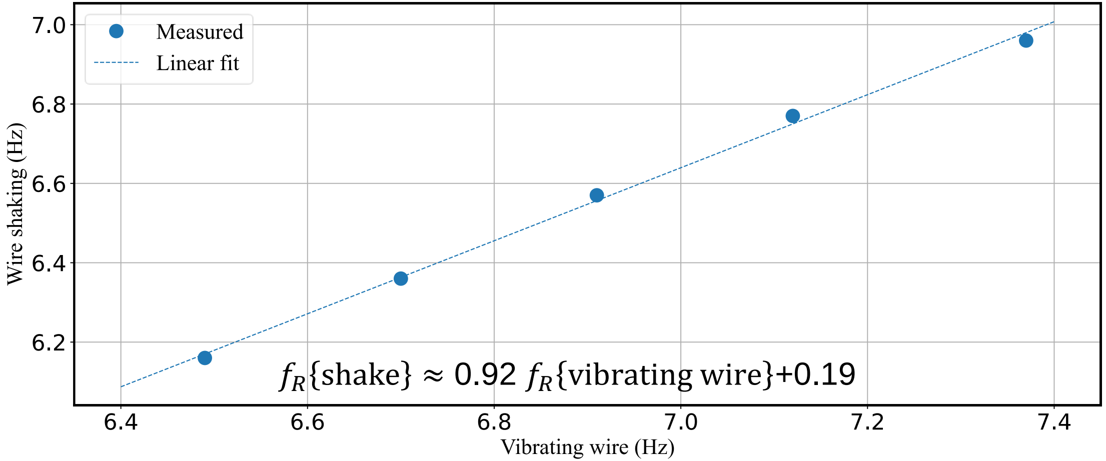


- **Offset** due to wire sagitta (or sag) corrected by performing the measurements at different wire tensions and **extrapolating at infinite tension**.
- **Precise measurement of the wire resonance frequency: un**certainty ~ 0.01-0.03 Hz.

Measurement method: single stretched wire

Resonance frequency measurement

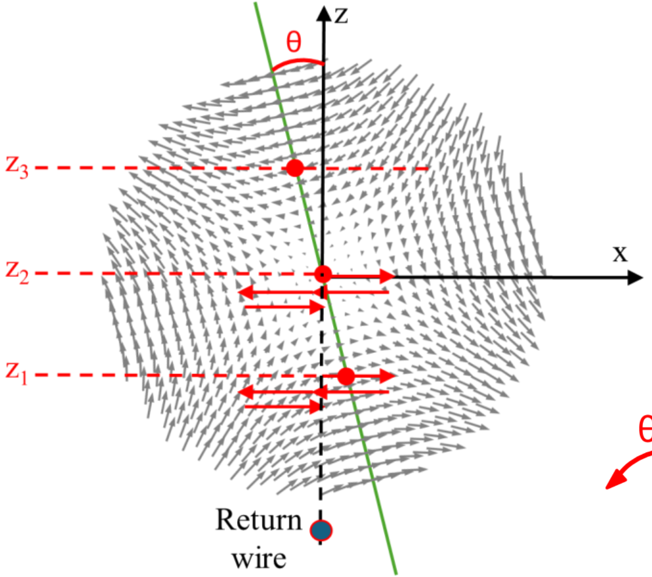
- The **wire susceptibility**, thus **magnetic forces**, also impact the measurement of the wire **resonance frequency**. The plot of the **frequencies** measured by **wire shaking** against the wire measured with the **vibrating wire** in the **lower field region** (wire located around the axis)

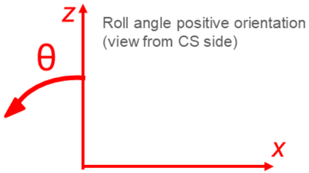


- In practice, the **residual 0.19 Hz impacts** the extrapolation up to 0.2 mm for **asymmetric stage-magnet configuration** on the farther stage (stage B for the Q2s).
    - **Choice**: vibrating wire method for resonance frequency determination

Measurement method: single stretched wire

- **Roll angle** measured by **linear interpolation** of horizontal centers at different vertical coordinates

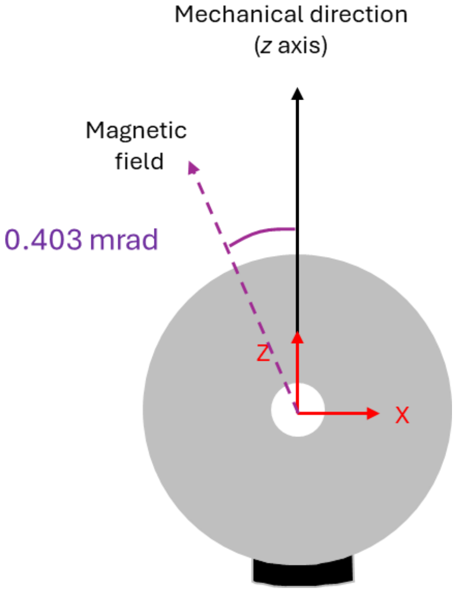




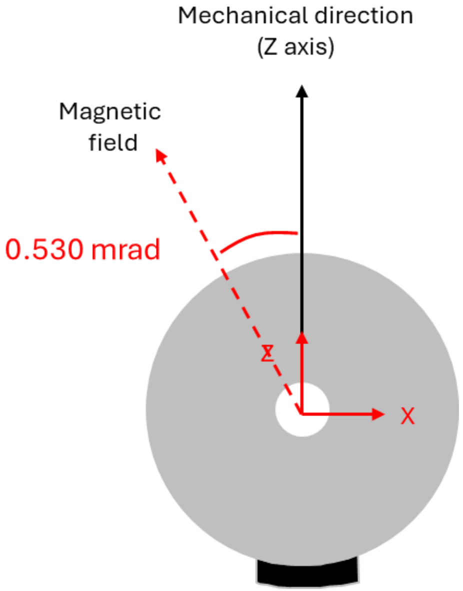
Roll angle positive orientation
(view from CS side)

$$\theta_{roll} = \frac{\theta}{2} = -\frac{1}{2}\,\mathrm{atan}\left(\frac{x}{z}\right)$$

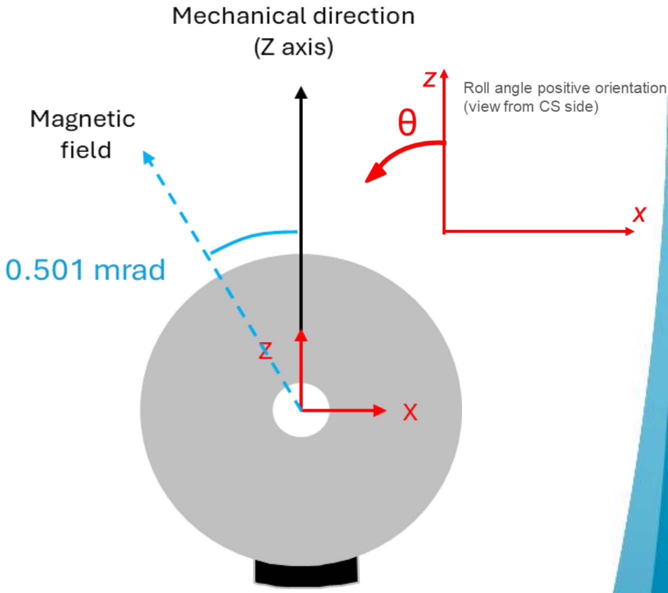
Measurement of LMQXFB04 – Roll angles



Rotating coil scanner (180)



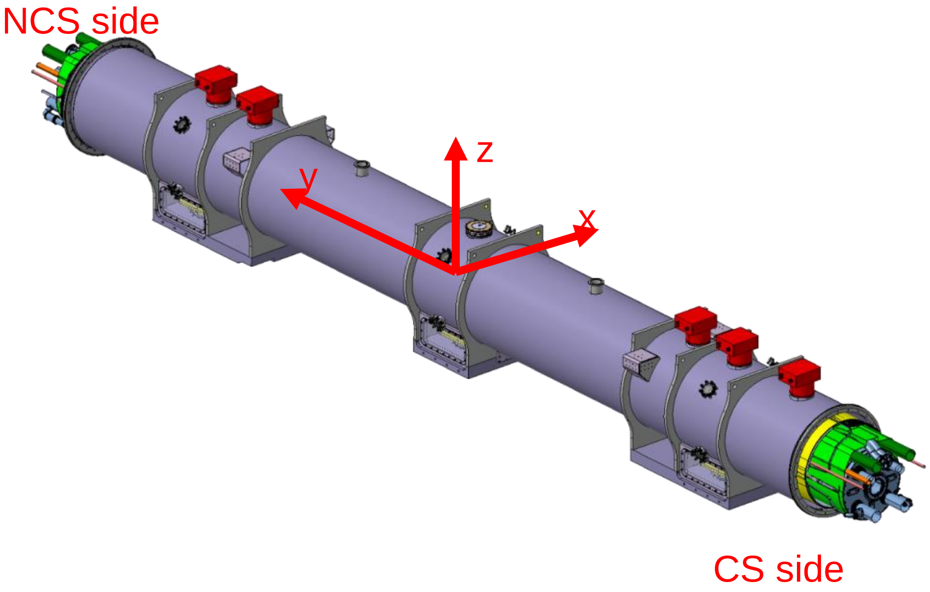
SSW at room temperature (final)



SSW at cold, nominal current (final)

Final reference system definition

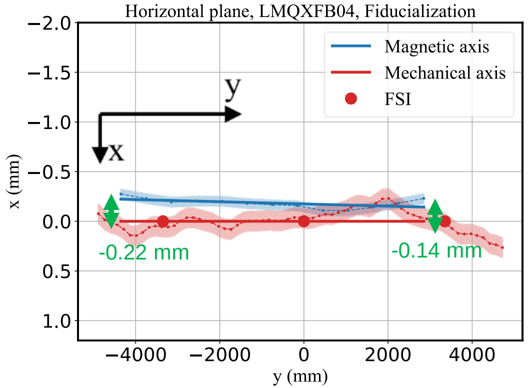
Final reference system

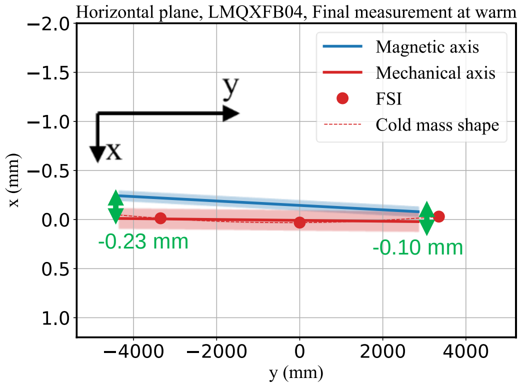


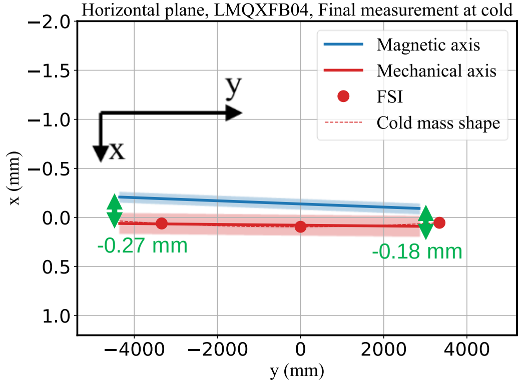
- **All final measurement** results expressed in a reference frame where**:**
  - **Primary axis *y* – best-fit line of CBT**, with **positive direction** from the quadrupole Connection Side (**CS**) to Non-Connection Side (**NCS**).
  - **Secondary axis *z* – Normal vector** to the plane of **D9 and D10**, on CS and NCS side
  - **Origin**: **Intersection** between the **projection of the central cold support** on *y*-axis and the *y*-axis

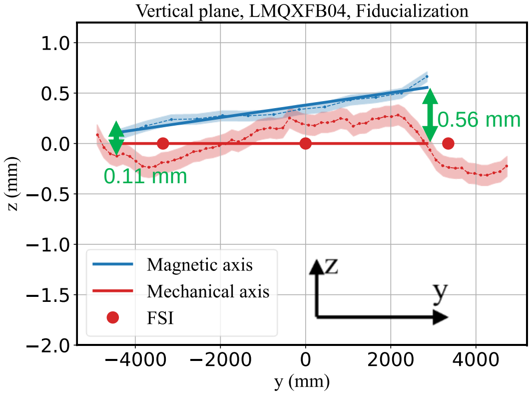
Measurement of LMQXFB04 – Magnetic axis

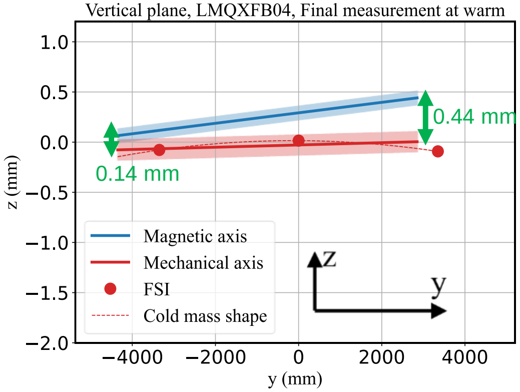
N.B: measurement performed after the cold test

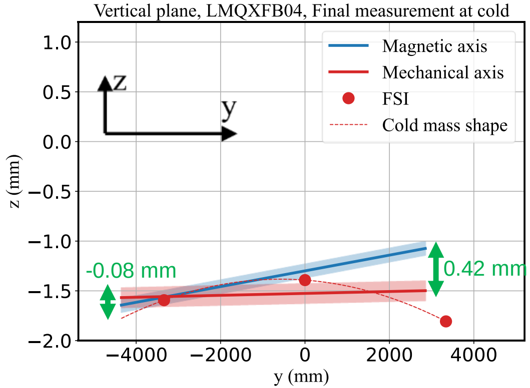






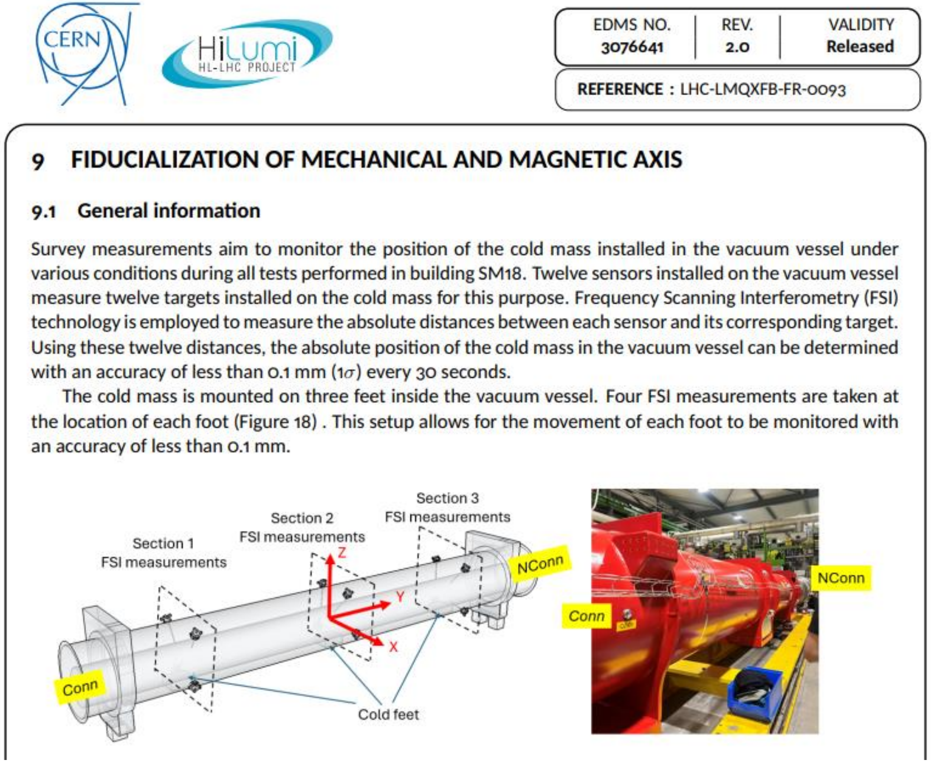






Cold-to-warm vertical variation: -1.61 mm (**magnetic) and** -1.55 mm (**mechanical**)

Magnetic measurement reports



EDMS NO.	REV.	VALIDITY
3076641	2.0	Released

REFERENCE : LHC-LMQXFB-FR-0093

9 FIDUCIALIZATION OF MECHANICAL AND MAGNETIC AXIS

9.1 General information

Survey measurements aim to monitor the position of the cold mass installed in the vacuum vessel under various conditions during all tests performed in building SM18. Twelve sensors installed on the vacuum vessel measure twelve targets installed on the cold mass for this purpose. Frequency Scanning Interferometry (FSI) technology is employed to measure the absolute distances between each sensor and its corresponding target. Using these twelve distances, the absolute position of the cold mass in the vacuum vessel can be determined with an accuracy of less than 0.1 mm (1σ) every 30 seconds.

The cold mass is mounted on three feet inside the vacuum vessel. Four FSI measurements are taken at the location of each foot (Figure 18) . This setup allows for the movement of each foot to be monitored with an accuracy of less than 0.1 mm.

- Measurement results of the magnetic axis are compiled in a report synergically with the metrology teams.
- Over last year gained experience in treating and transmitting data acquired.

Conclusions

- **The longitudinal magnet scan is performed using the rotating coil scanner**. This is also used for quality control during the production process (180).

- The **stretched-wire** system is the **reference for cold measurements**, providing integral information about field strength and magnetic axis (SM18).

- **Alignment measurements** consists of several steps.

- The alignment and metrology team developed and implemented measurement procedures through a proactive and fruitful collaborative effort.

Thank you

HIGH LUMINOSITY LHC

14th

HL-LHC COLLABORATION MEETING

GENOA, ITALY, 7-10 October 2024

Jointly organised by **INFN** and **CERN**, the **14th HL-LHC Collaboration Meeting** will take place in person in **Genoa**, Italy from **7th to 10th October 2024**. This edition will provide the occasion to showcase the successful production and validation of the first series D2 magnets, produced by ASG in Genoa as an in-kind contribution by INFN (Italy), as well as the completion of production of the MgB_2 wires for the superconducting link by ASG.

Based on the traditional programme with plenary and work package parallel sessions, this meeting will serve as a technical update forum for the 8th Cost and Schedule Review, scheduled for 11th to 14th November 2024. The main objectives will be to update all HiLumi collaborators on the advancement of the series production of components for the project, to showcase the status of the IT String test stand installation at CERN, and to update all collaborators on the latest schedule changes.

CERN – Organizing Committee

Oliver Brüning *Project Leader*
Markus Zerlauth *Deputy Project Leader*
Cécile Noels *Project Office & Communications*
Florence Thompson *Project Office & Communications*

INFN – Local Organizing Committee

Andrea Bersani - *Communication Officer*
Barbara Caiffi - *MBRD Deputy Technical Coordinator*
Mirko Corosu - *IT Manager*
Stefania Farinon - *MBRD Technical Coordinator*
Filippo Levi - *Deputy Conference Coordinator*
Alessandra Pampaloni - *Conference Coordinator*
Marco Statera - *HO Corrector Technical Coordinator*

For more details and registration : HL-LHC.Secretariat@cern.ch / hilumilhc.web.cern.ch

Spare Slides

Measurement requirements

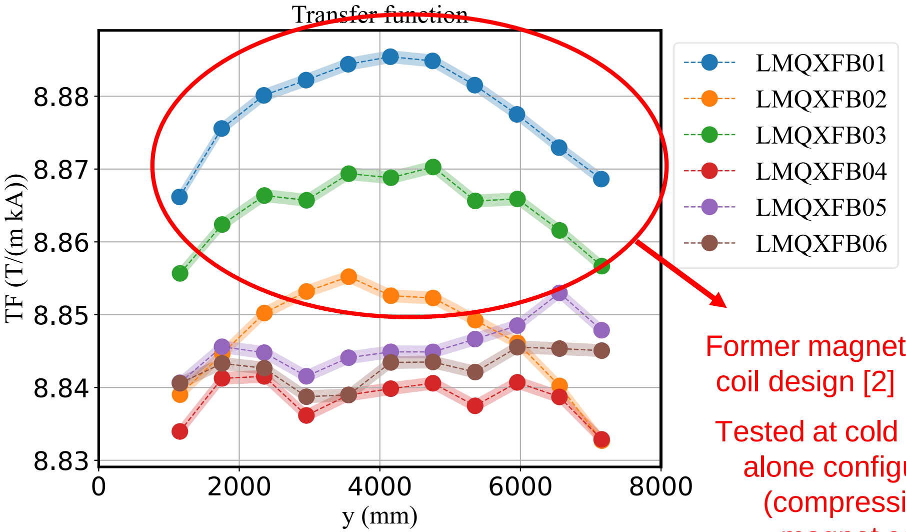
Measurement uncertainty requirement values for different magnet types (3σ)

Magnet Type	Transverse center		Roll		Long. center		Mag. length	Mag. length
	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)
D1, D2, MCBXFB, MCBRD	0.6	NA	0.3	0.2	5	5	5	5
Q1, Q2, Q3	0.4	0.2	0.2	0.2	5	5	5	5
MCBXFA, CP	0.4	0.4	0.3	0.3	4	10	5	3

[1] Source: Engineering specification LHC-G-ES-0023

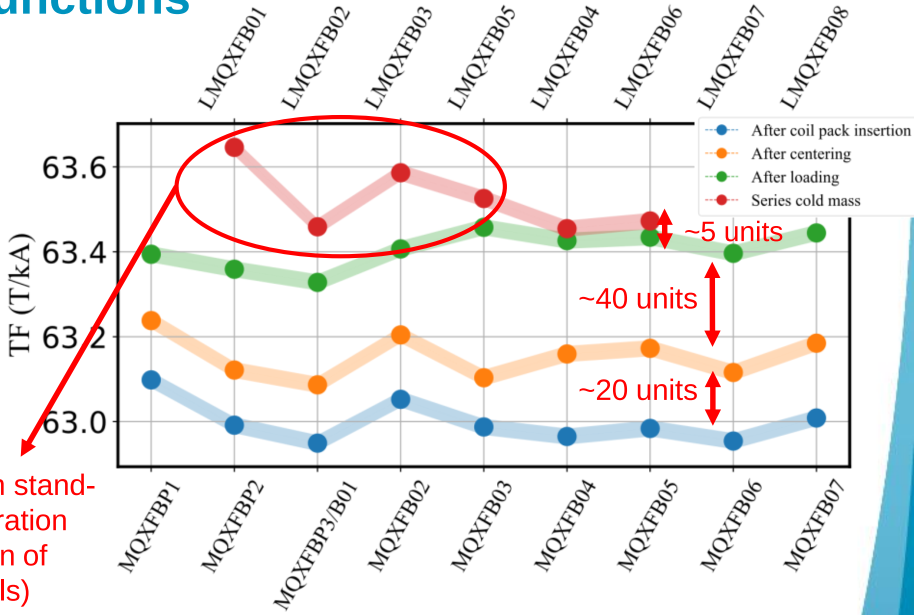
Measurement of the bare cold masses

Field profiles and integrated transfer functions



Former magnet coil design [2]

Tested at cold in stand-alone configuration (compression of magnet coils)



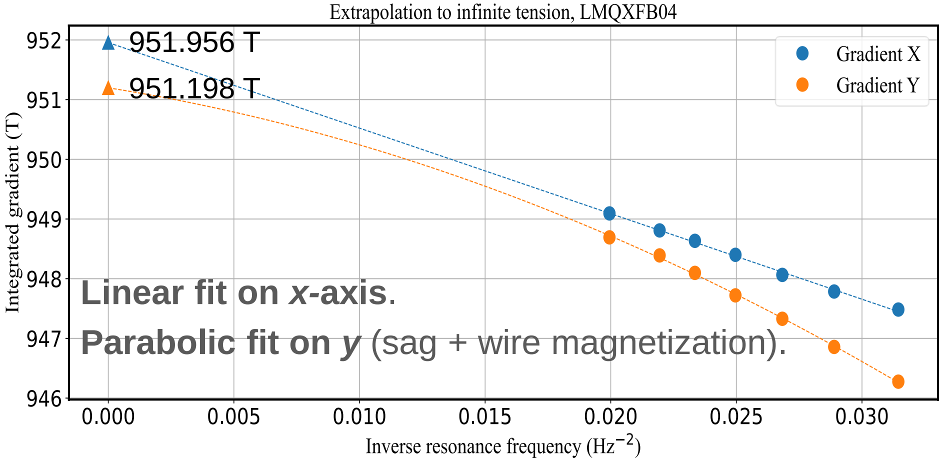
- **Transfer function** measured with **1-unit uncertainty** (1σ). Integrated field measured with 3-unit uncertainty (1σ).
- The **longitudinal field profile** can be correlated with the **coil's geometrical shape**, and used for **quality control** [2].
- **Each manufacturing step increases the magnet transfer function** (compression of magnet coils).

[3] S.I. Bermudez, et al. "Status of the MQXFB Nb3Sn quadrupoles for the HL-LHC." *IEEE Transactions on Applied Superconductivity* 33.5 (2023): 1-9.

Measurement method: single stretched wire

Impact of finite tension on measured gradient

Parameter	Value	
Wire length (m)	20.96	
Integrated gradient (T)	929.547	
Resonance frequency (Hz)	7.38	at 950 g
Step (mm)	20	
Expected measured gradient (T)	927.114	
Deformation (mm)	0.026	



Linear fit on *x*-axis.

Parabolic fit on *y* (sag + wire magnetization).

- Besides gravity, another contribution to the wire deformation is given by **magnetic forces**.
- The wire relative susceptibility determine **magnetic forces not negligible on the wire for this measurements**. The global effect is a **repulsive force** on both axes, given the wire diamagnetism.