Alignment measurements of HL-LHC superconducting quadrupole cryo-assemblies at CERN

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- Measurement requirements
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- Final reference system definition
- Fiducialization of the final cryo-assemblies
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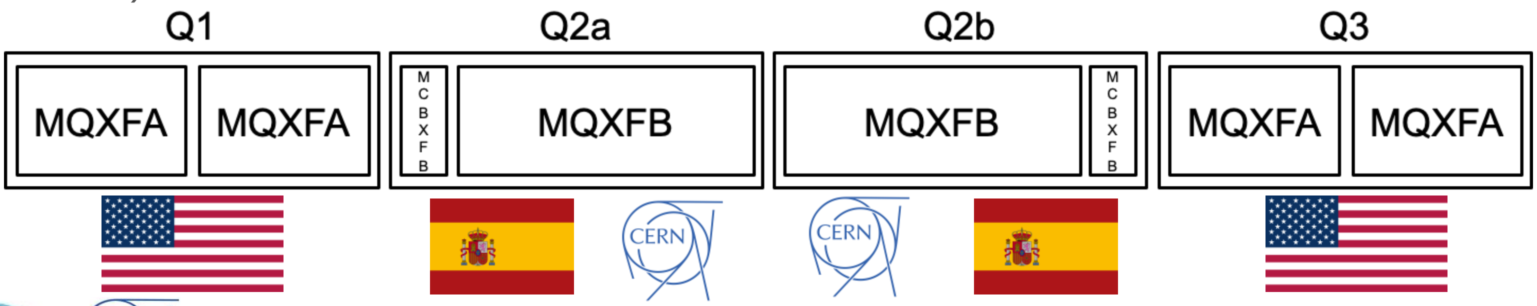
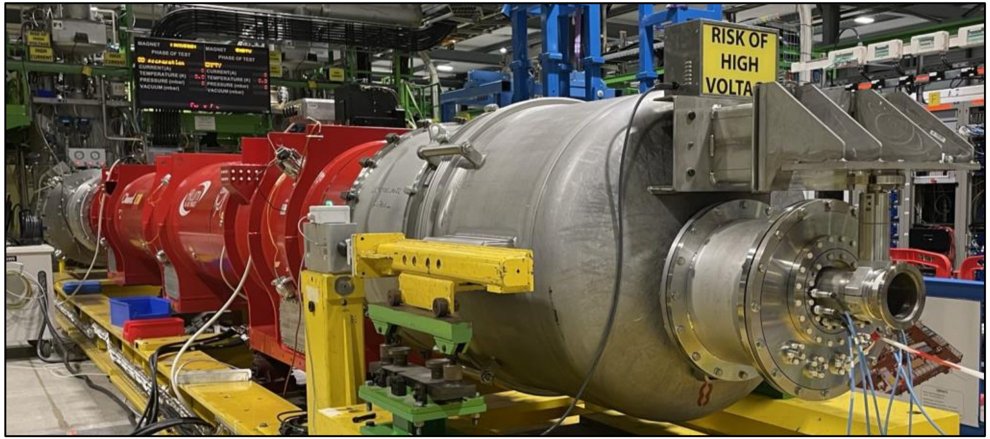
Introduction

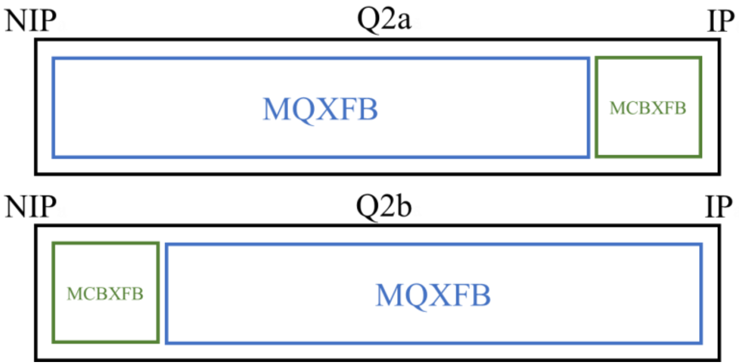
- High-Luminosity LHC (**HL-LHC**) is a major upgrade of the **Large Hadron Collider** at CERN, aiming to **increase the beam luminosity** by a factor 10. Increased luminosity means **more collisions** and, therefore, a higher probability of measuring rare phenomena.
- One of the HL-LHC work packages is the upgrade of the **magnets for the insertion region** (WP3), including new low-β superconducting **Nb_3Sn quadrupoles** (MQXF)
- The quadrupole section (Q1 to Q3) consists of 150-mm aperture, superconducting quadrupole magnets with a nominal gradient of 132 T/m, coming into two version:
  - **MQXFA**, manufactured by US-AUP and having a magnetic length of **4.2 m** (Q1 and Q3 cryo-assemblies)
  - **MQXFB**, manufactured by CERN and having a magnetic length of **7.2 m** (Q2 cryo-assemblies)
- The Q2 cryo-assemblies also have nested orbit dipole correctors manufactured by CIEMAT (MCBXFB)



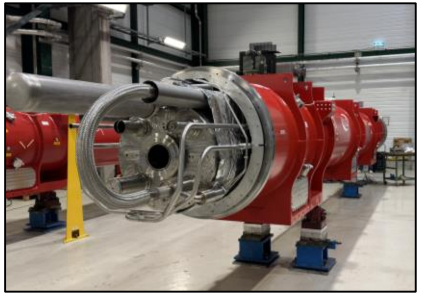
Status of the Q2 magnet production

- **Series production** of the MQXFB quadrupole **60 % complete**, with the most recently manufactured magnet, MQXFB07, ready to be assembled in the cold mass.
- In parallel, series production of the **Q2 cold masses (LMQXFB)** has started:
  - Three cold masses fully tested at 1.9 K and nominal current: LMQXFB01, LMQXFB02, LMQXFB04
  - One cold mass under cold test at the moment: LMQXFB06





Q2 measurement workflow



MQXFB production → **Cold mass production** → **Cryostating** → **Final assembly**

MQXFB production

Coil pack insertion → Centering → Loading

- **Transfer function and field quality**

Cold mass production

- **Pre-alignment of the cold mass with gravity**
- **Transfer function and field quality**
- **Magnetic axis measurement**
- Mechanical fiducialization of cold mass

Cryostating

- Insertion of cold mass in vacuum vessel
- Mechanical fiducialization of vessel
- Installation of FSIs

Final assembly

- **Warm magnetic axis measurement**
- **Transfer function and field quality at cold**
- **Fiducialization at cold (magnetic and mechanical)**

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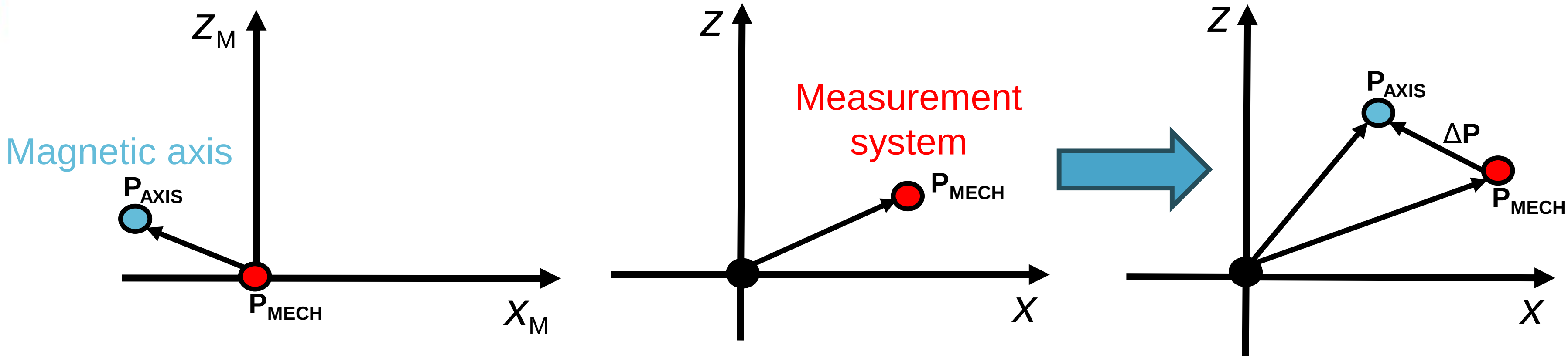
Magnetic axis fiducialization

- **Determination of** magnetic axis and field angle with respect to a set of **fiducial markers** defining the mechanical reference frame.

View from transverse plane



Determination of magnetic axis position in a local reference frame centered on the transducer

Determination of the absolute transducer position in the external reference frame

Coordinate transfer and determination of absolute coordinates of magnetic axis

N.B: z_M axis coincident with gravity

- Origin
- Measurement system
- Magnetic axis

Measurement requirements

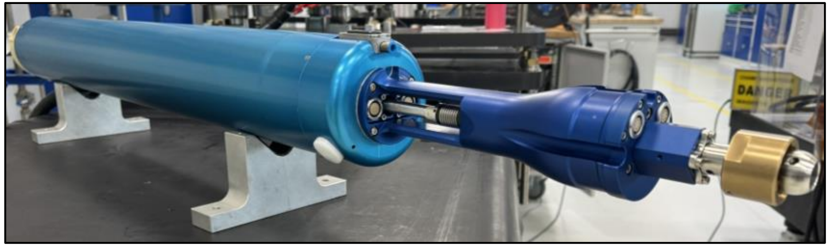
Measurement uncertainty requirement values for different magnet types (3σ)

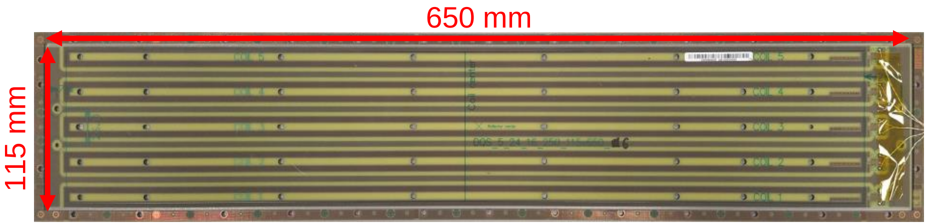
Magnet Type	Transverse center		Roll		Long. center		Mag. length	Mag. length
	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)	Warm (mm)	Cold (mm)
D1, D2, MCBXFB, MCBRD	0.6	NA	0.3	0.2	5	5	5	5
Q1, Q2, Q3	0.4	0.2	0.3	0.2	5	5	5	5
MCBXFA, CP	0.4	0.4	0.3	0.3	4	10	5	3

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

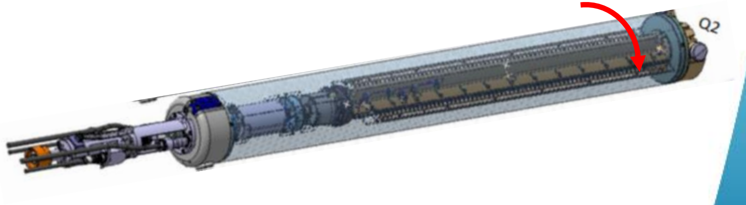
Measurement of the bare cold masses

Rotating coil scanner





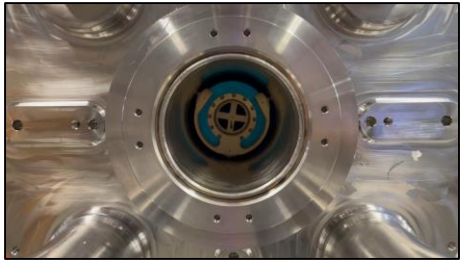
- Measurements performed at room temperature by a **rotating coil scanner (or mole),** at 10 A DC. PCB **~2.33 m²** surface, **50 mm** radius, **600 mm** active length.
- Multi-purpose tool for **field quality** measurements and **alignment** measurements.
- **Standard rotating coil measurement** performed at different longitudinal positions (every 600 mm, 13 positions).
- Each point obtained by **combining four measurements** to compensate for systematics: ±10 A, CW/CCW rotation direction.
- **PCB leveled to gravity** before each measurement through onboard tilt sensor. Mole held in position via **pneumatic brake** for better stability.



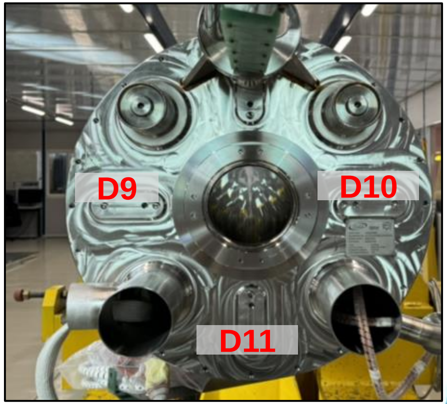
[2] M. Pentella, C. Petrone, Room temperature measurements of the MQXFB magnets and LMQXFB cold masses (Q2) (EDMS 2901463)

Measurement of the bare cold masses

Alignment measurements

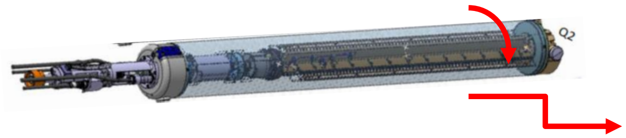


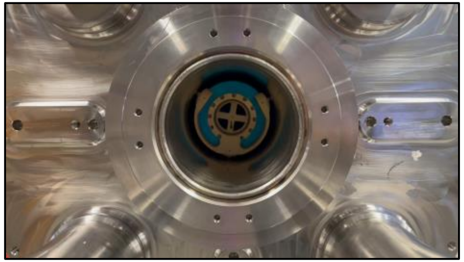
- **Magnetic axis** position w.r.t. rotation axis obtained from **feed-down**
  - C_2 over C_1 for MQXFB.
  - C_{11} over C_{10} for MCXFB.
- **Rotation axis** measured by laser tracker (Leica AT930), through an onboard 0.5” retroreflector positioned on the PCB center.
- **Roll angle** obtained by the phase of the main field w.r.t. gravity.
- Measurements expressed in a **reference frame** defined by the three fiducials on the two cold mass endplates (and gravity). The **origin** is the center of the three fiducials on the quadrupole connection side (CS side).
- N.B: the **mechanical axis** is defined by the **cold bore tube** (CBT) position



Measurement of the bare cold masses

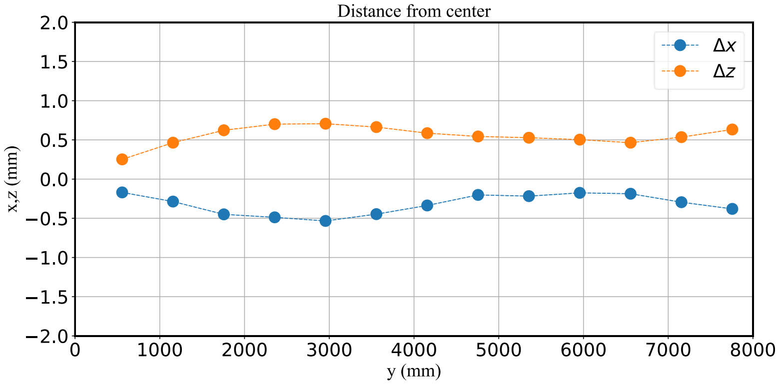
Alignment measurements





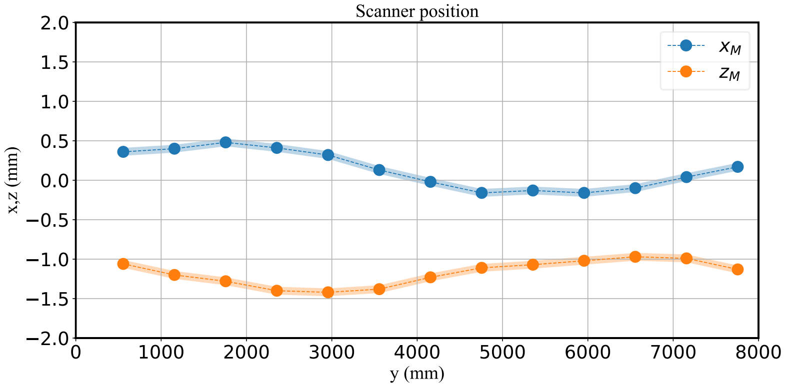
Magnetic measurement

- **Magnetic center uncertainty** – ~0.005 mm (1σ)
- **Roll angle uncertainty** – 0.07 mrad (1σ)



Optical measurement

- **Total uncertainty:** 0.05 mm (1σ)
- **Longitudinal positioning uncertainty**: 0.02 mm (1σ)
- **Fit quality of rotation center**: 0.01 mm (1σ)



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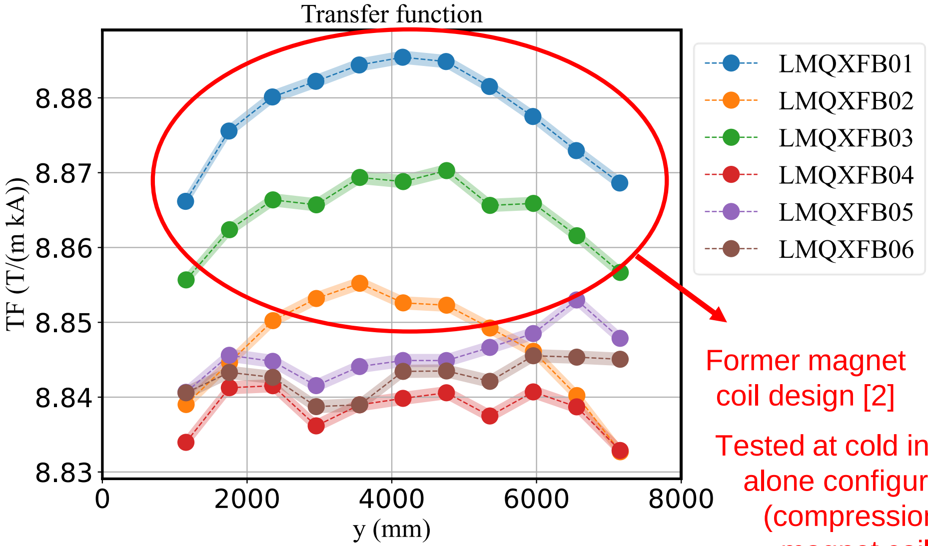
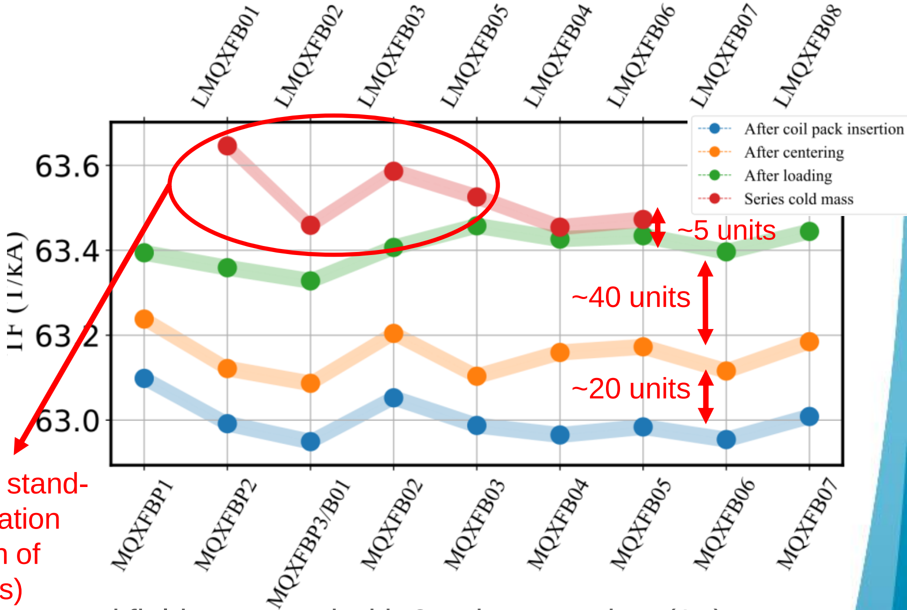
Measurement of the bare cold masses

Field profiles and integrated transfer functions





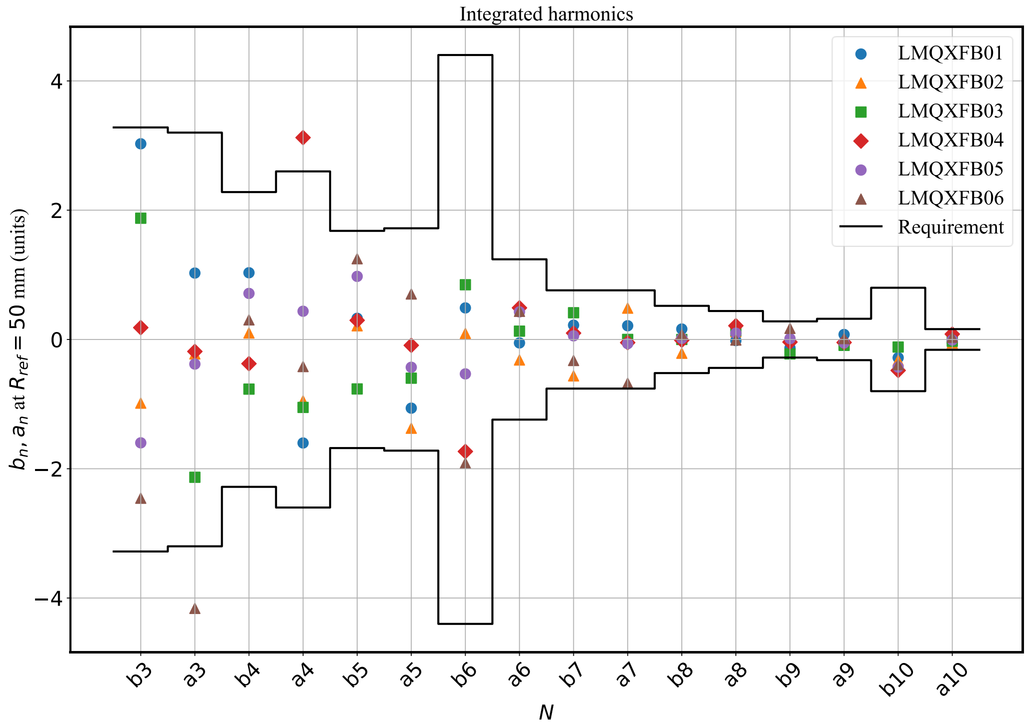
Tested at cold in stand-alone configuration (compression of magnet coils)

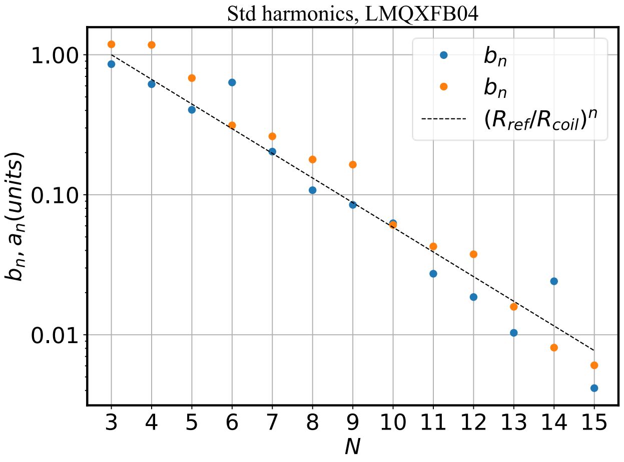
- **Transfer function** measured with **1-unit uncertainty** (1σ). Integrated field measured with 3-unit uncertainty (1σ).
- The **longitudinal field profile** can be correlated with the **coil's geometrical shape**, and used for **quality control** [2].
- **Each manufacturing step increases the magnet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

Field harmonics





- **Harmonics** are used as quality control during production (integral and local).
- If low-order harmonics are **off tolerance**, the **magnet is shimmed** (2-3 units), based on the measurement performed after loading.
- **Harmonics change with different assembly steps** and they generally decrease. After the loading, harmonics variations are negligible.
- Resolution up to 0.01 units.

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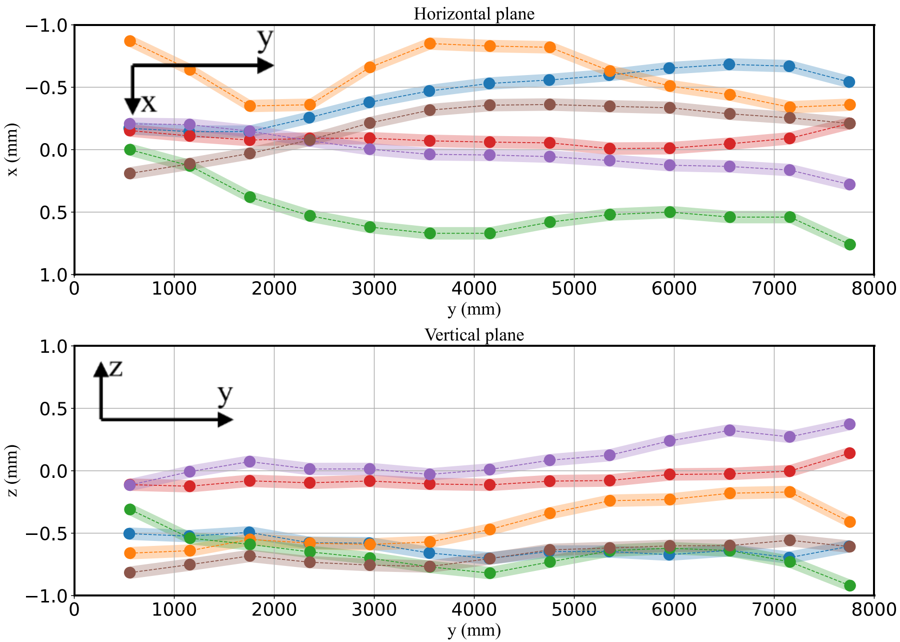
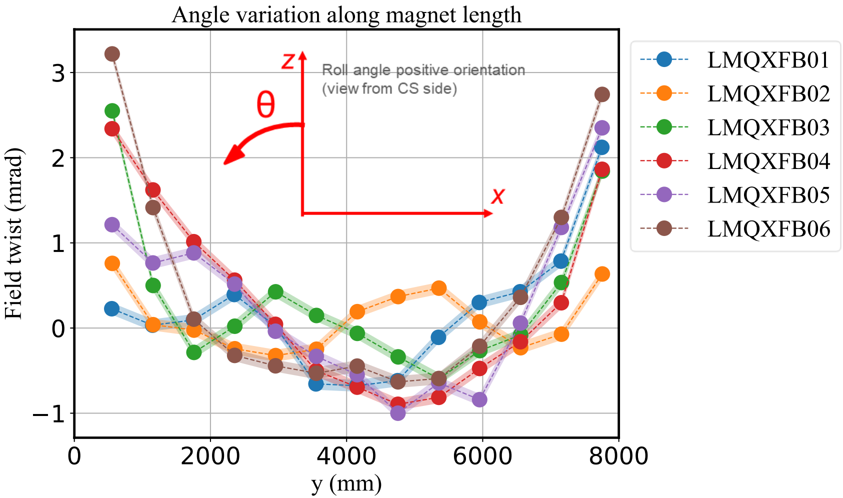
Measurement of the bare cold masses

Alignment measurements – Magnetic axis and roll

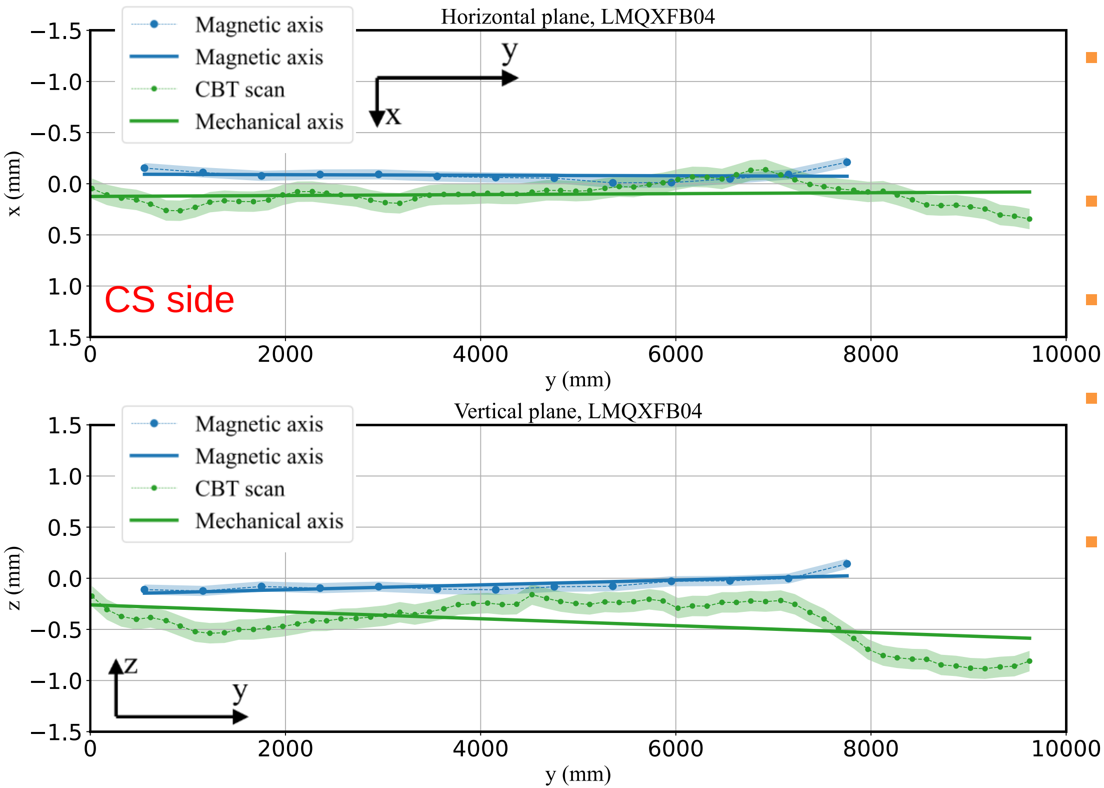




- **Alignment measurements** allow the **spotting** of **local defects** in the magnet coils. Therefore, they are another useful tool for quality control of cold mass production.

Measurement of the bare cold masses

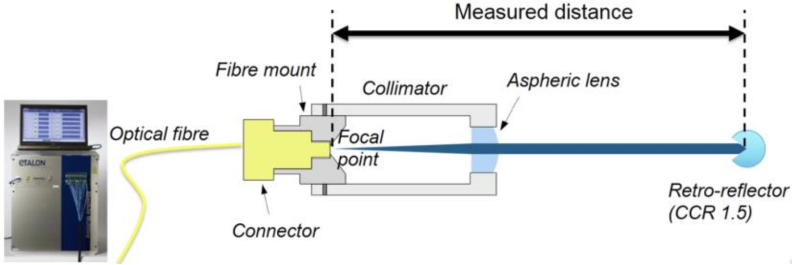
Alignment measurements – Mechanical axis



- The **mechanical axis** is defined as the **best-fit line** of the **cold bore tube** (CBT)
- CBT scanned using a **mechanical mole**.
- Relationship between the **magnetic** and **mechanical** axis established.
- **Mechanical** and **magnetic** axes do not coincide**,** and their offset must be known.
- The offset between the **magnetic** and **mechanical axis** is monitored at different stages of the cold mass production

[4] Source CBT Scan: H. Prin, M. Parent, EDMS 3014691

Cryostating



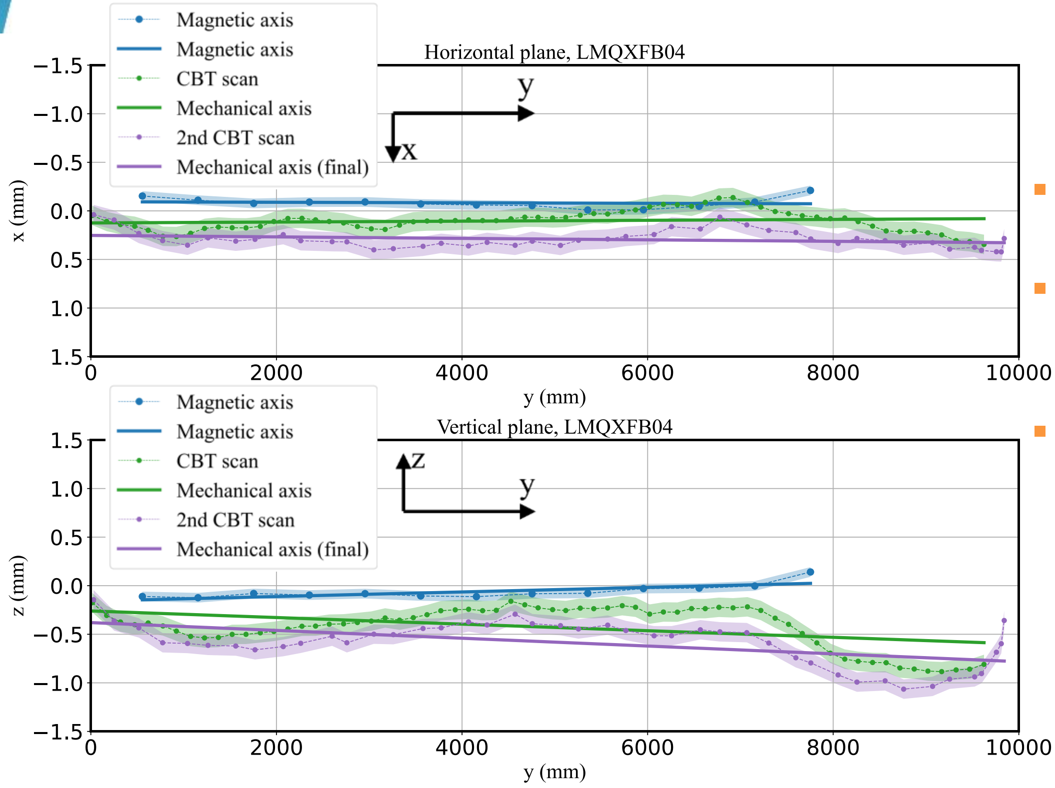
FSI retroreflector

- The manufactured **cold mass** is sent to **cryostating**, where it is inserted in the **vacuum vessel**
- The **FSIs** (Frequency Scanner Interferometers), for the **internal monitoring** of the cold mass position in the vessel, are installed
- The entire **assembly vessel/cold mass** is fiducialized. During this phase, the **CBT** is re-measured, and the final reference system is defined

Source:
[5] J. Calmels, V. Rude, EDMS 3129432
[6] V. Rude, https://indico.cern.ch/event/831552/contributions/3484640/

Final reference system definition

Second CBT measurement

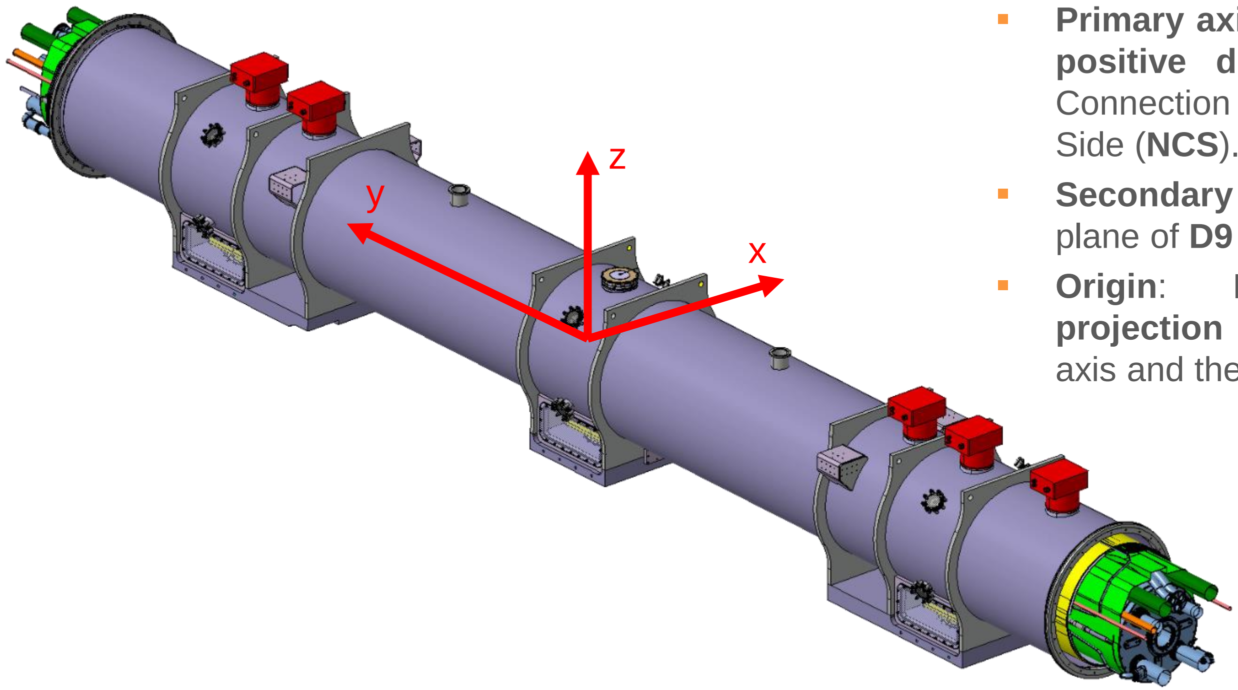


- **Differences** of about **0.1-0.2 mm** between the mechanical axes are visible.
- Behavior observed on all cold masses, likely due to **transport/handling** operations, resulting in an apparent shift.
- **The magnetic axis follows this shift accordingly** (see room temperature final measurement).

[7] Source: J. Calmels, V. Rude, EDMS 3070861

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 foot** on *y*-axis and the *y*-axis

Fiducialization of the final cryo-assembly

Overview

- The **final magnetic** and **alignment measurements** take place on the horizontal test bench in SM18
- **Alignment measurements** are performed by **Single-Stretched Wire** at room temperature (5 A) and 1.9 K (nominal current)
- **Field quality** measurements at 1.9 K performed by rotating coil (see the talk by G. Deferne, ”Rotating-coil Chains for the HL-LHC cryo-magnets”)

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[8] M. Pentella, C. Petrone, Cryogenic temperature measurements of the LMQXFB cold masses (Q2), (EDMS 3019565)

Fiducialization of the final cryo-assembly

Stretched-Wire for alignment measurements

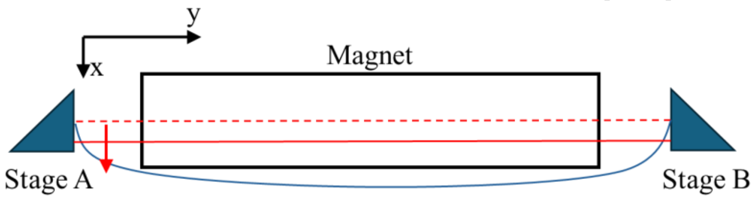
- The Stretched-Wire system is installed with **Stage A** on the **CS side** in order to have the measurement results already with the **correct polarity**. The wire stages are **aligned with gravity** at better than 0.01 mm/m.
- The **wire** is **iteratively aligned** with the magnetic axis. Once the offset w.r.t. the magnetic axis has been zeroed (within tolerance), the position of the wire extremities is measured by laser tracker.

Fiducialization of the final cryo-assembly

Stretched-Wire method – Magnetic axis

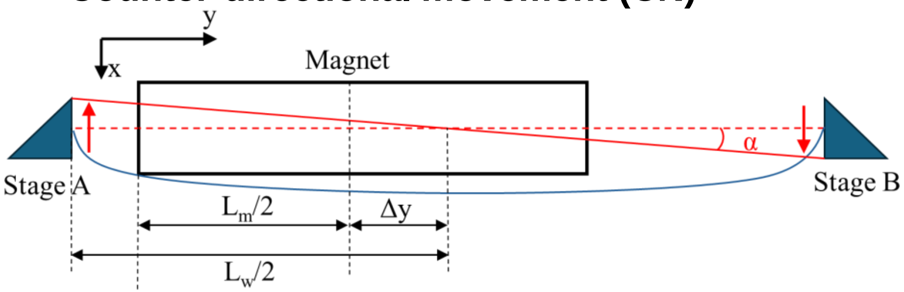
- Alignment of the wire with the magnetic axis performed **iteratively** by **combination** of two different wire movements.
- The **integrated gradient** is measured with a CO movement

Co-directional movement (CO)



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

Counter-directional movement (CN)

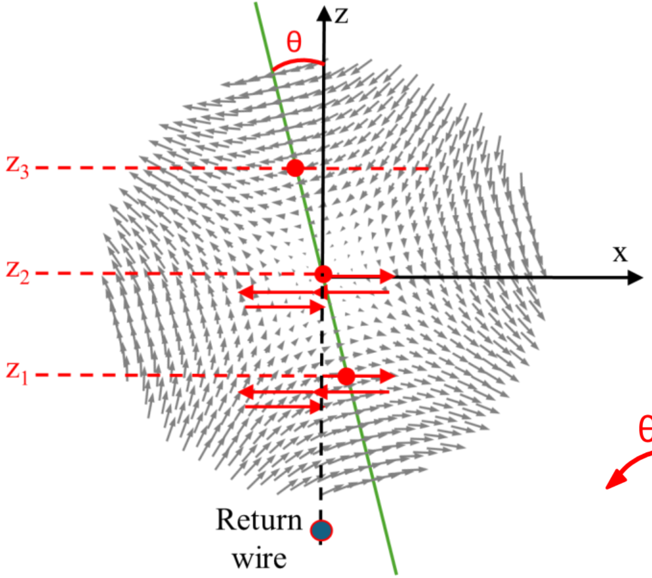


$$\Phi(\alpha_1, \alpha_2) = (GL_m)\,\frac{\alpha_2^2 - \alpha_1^2}{2}\left(\frac{L_m^2}{12} + \Delta y^2\right)$$

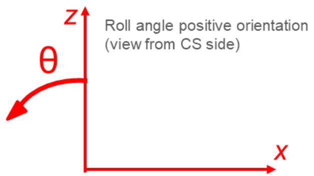
Fiducialization of the final cryo-assembly

Stretched-Wire method – Roll angle

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



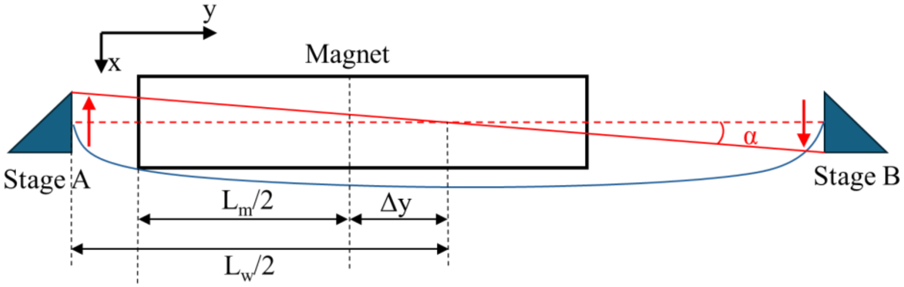
$$\theta_{roll} = \frac{\theta}{2} = -\frac{1}{2}\,\mathrm{atan}\left(\frac{x}{z}\right)$$



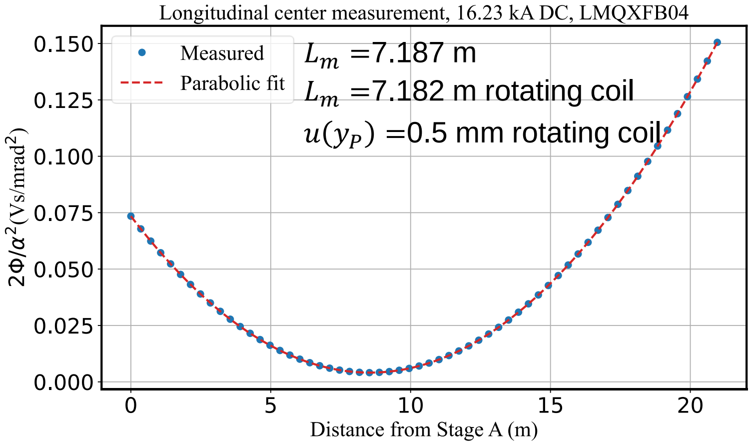
Fiducialization of the final cryo-assembly

Stretched-Wire method – 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, $y_P = \Delta y$

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

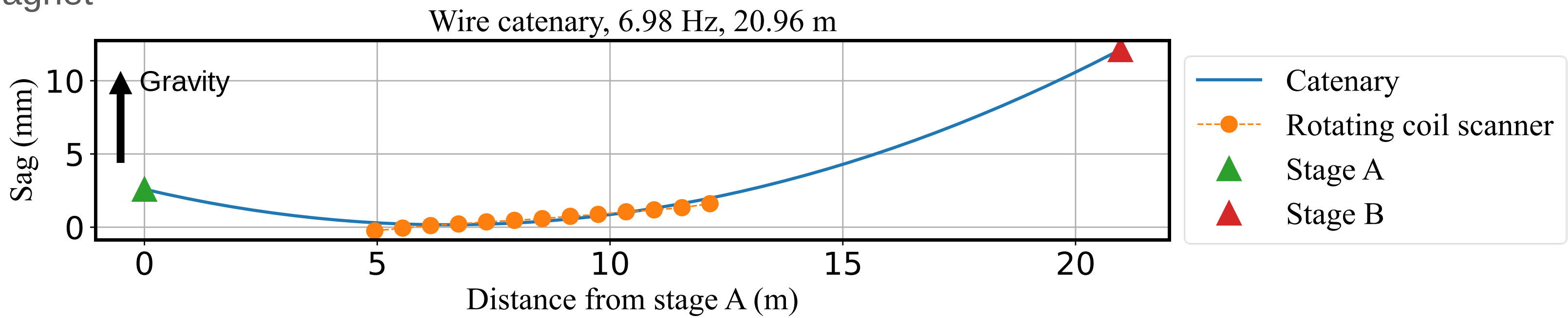
- Difference with rotating coil mainly related to the adopted **longitudinal profile model (field roll-off).** Rotating coil value given as result.

[9] C. Petrone, M. Pentella, S. Russenschuck, D. Caiazza, "Advancements with the Stretched-Wire System at CERN", in preparation for submission

Fiducialization of the final cryo-assembly

Stretched-Wire method – Sagitta correction

- On typical 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).
- Such low resonance frequencies also impact the induced voltage acquisition. After moving between two positions, **wire kept stationary** for about 4 s to **dampen transient mechanical oscillations**. Adopting this strategy improved the **gradient measurement repeatability** by a factor 5.
- In addition, due to setup constraints, the wire stages are positioned with a **strong asymmetry** w.r.t. magnet

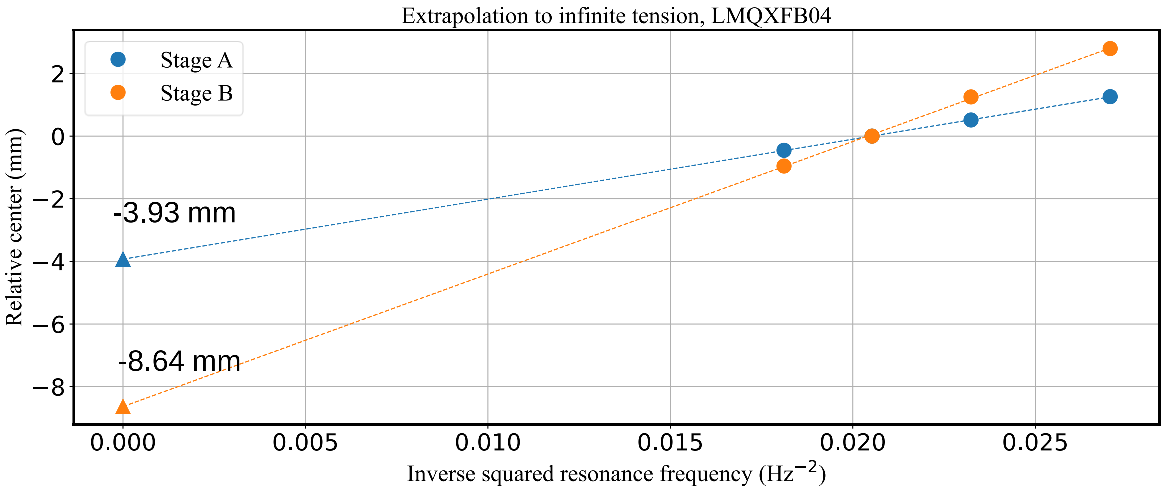


$$z(y) = \frac{g}{2}\left(\frac{\pi}{\omega_R L}\right)^2 y^2 + \frac{1}{y_B}\left(z_B - z_A - \frac{g}{2}\left(\frac{\pi}{\omega_R L}\right)^2 y_B^2\right) y + z_A$$

Fiducialization of the final cryo-assembly

Stretched-Wire method – Sagitta correction

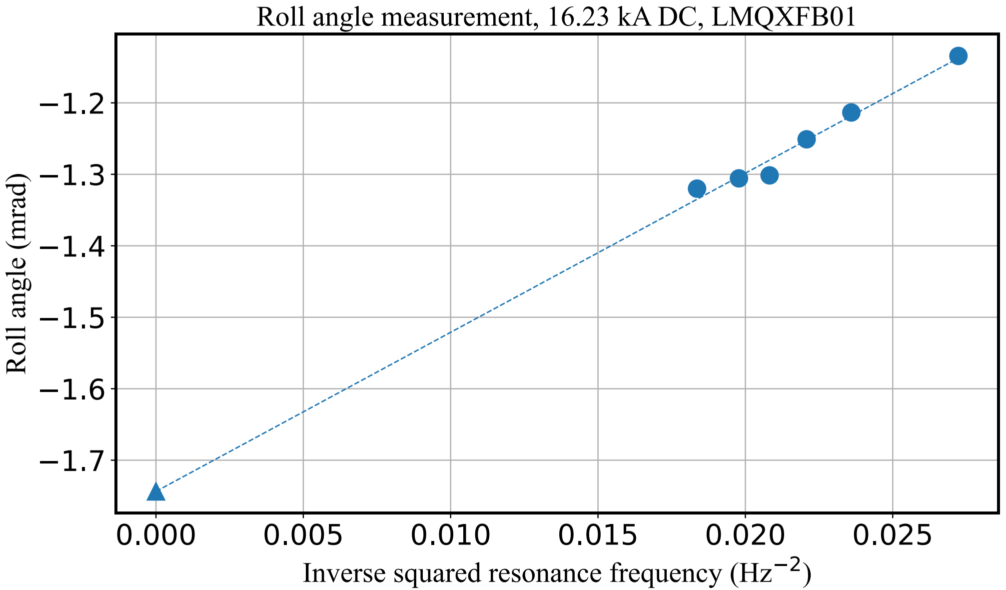
- **Offset** due to wire sagitta (or sag) corrected by performing the measurements at different wire tensions and **extrapolating at infinite tension**.
- Extrapolation performed by using the **wire mechanical resonance frequency** for better accuracy.
- **Method 1**: **Vibrating wire mode**. A small current is injected in the wire and the frequency is swept to detect the maximum amplitude of the oscillations.
- **Method 2**: **Wire shaking**. Stages moved sharply in the field in the *x*-direction. This triggers oscillations at the resonance frequency, determining an induced voltage at the wire loop terminals.
- Uncertainty on the order of 0.01-0.03 Hz.



Fiducialization of the final cryo-assembly

Stretched-Wire method – Sagitta correction

- A dependency on the wire tension is visible also on the roll angle



- **Roll** angle obtained by **linear extrapolation**.
- Unexpected behavior and investigation is ongoing about the cause. We consider a 0.1 mrad uncertainty (1σ).

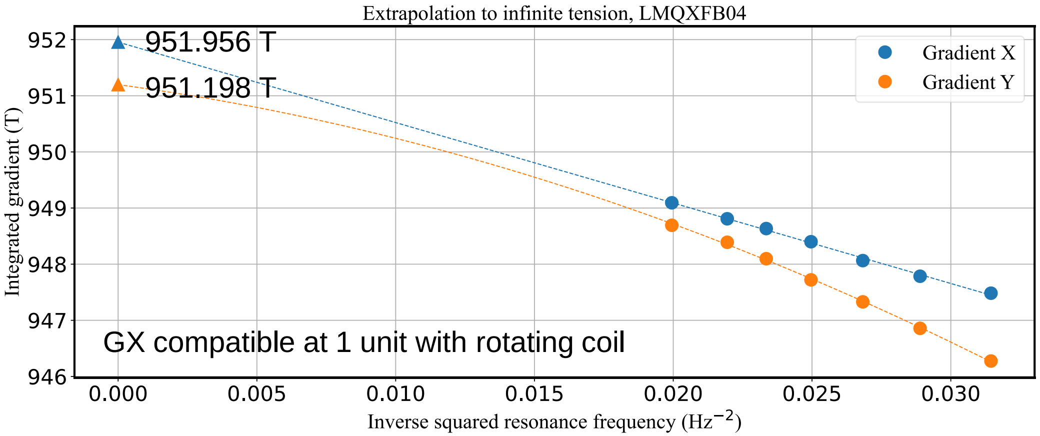
Fiducialization of the final cryo-assembly

Stretched-Wire method – Impact of finite tension on measured gradient

- Beside gravity, another contribution to the wire deformation is given by **magnetic forces**.
- The wire relative susceptibility is on the order of -10^{-6}: **normally**, forces are **negligible**.
- However, the combined effect of a **high field gradient** (~1000 T) and **long wires** (~21 m), determines **magnetic forces deforming the wire.** $F \propto \chi G^2 x$
- The global effect is a **repulsive force**, given the wire diamagnetism, on both axes. Measured integrated gradient underestimated by 30 units (up to 50 units), with wire steps of 20 mm.

Parameter	Value	
Wire length (m)	20.96	
Integrated gradient (T)	951.956	
Resonance frequency (Hz)	7.08	at 900 g
Step (mm)	20	
Expected measured gradient (T)	949.184	
Deformation (mm)	0.029	

Total estimated deformation
0.077 mm Hz^{-2} /Tm

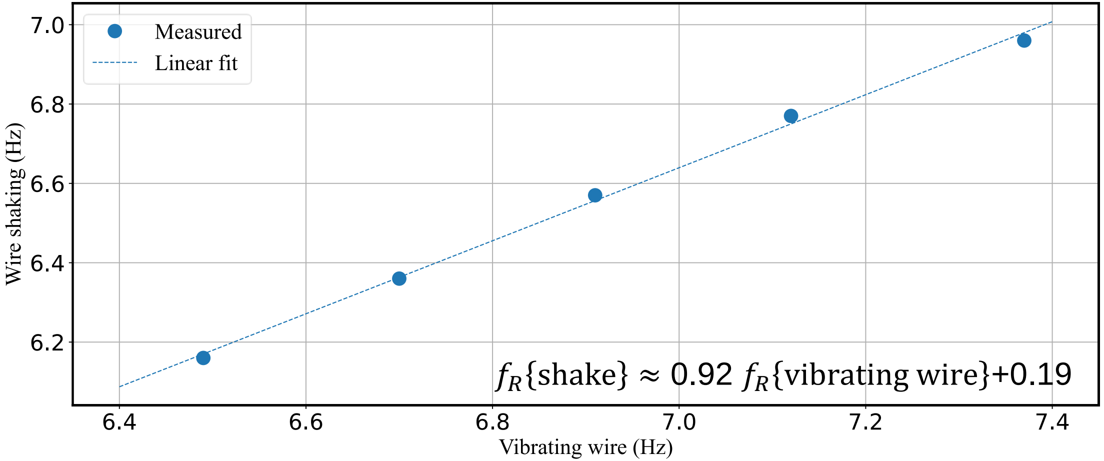


- **Linear fit on *x*-axis. Parabolic fit on *y*** (sag + wire magnetization).
- **Negligible impact on measured axis.**

Fiducialization of the final cryo-assembly

Stretched-Wire method – Resonance frequency measurement

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



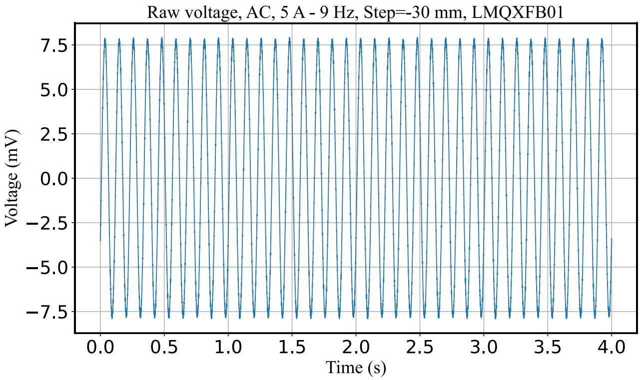
- In theory, **no impact expected on extrapolation – scaling factor**, intercept remains the same
- In practice, the residual 0.19 Hz impacts the extrapolation up to 0.2 mm for **asymmetric stage-magnet configuration,** on the farther stage (stage B for the Q2s). Impact on the gradient less than 1 unit.

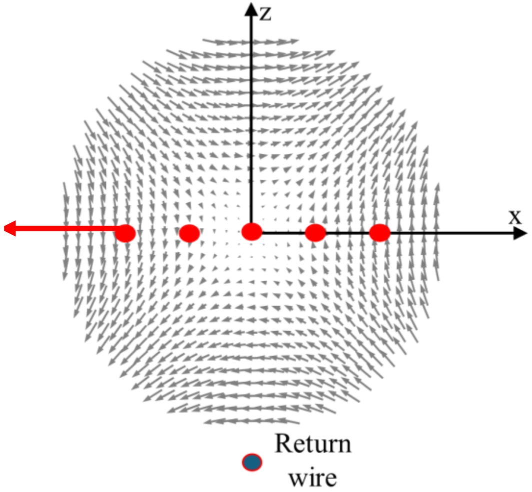
- **Choice**: vibrating wire method for resonance frequency determination, with wire on the axis. Wire re-aligned with the axis every time it is untensioned.

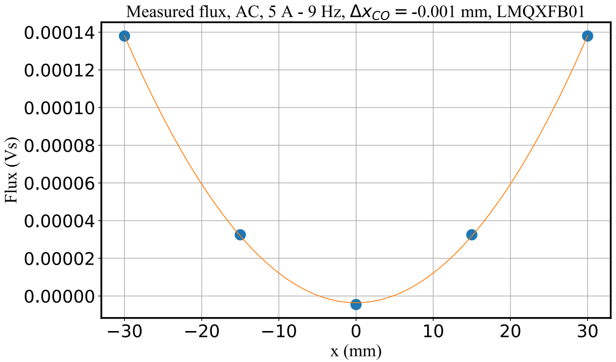
Fiducialization of the final cryo-assembly

AC measurements – SSW at room temperature

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



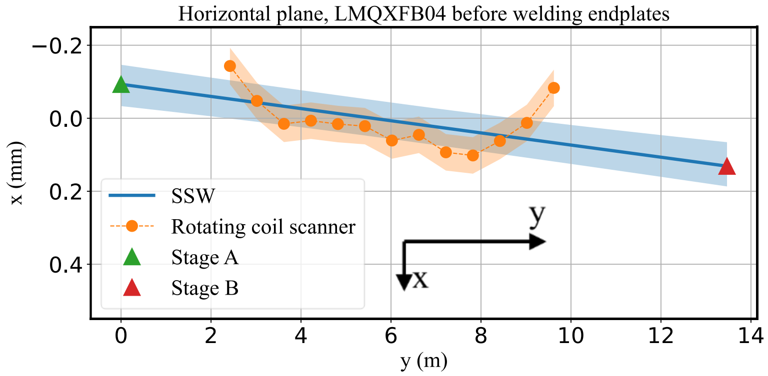


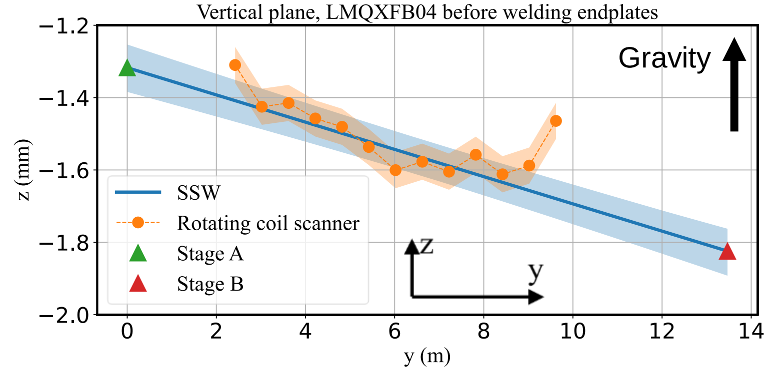


- **Flux value** at a given position obtained by **FFT of the measured flux** and **selecting** the **tone** corresponding with the **magnet's excitation current**.
- **Same formulae used for the DC case are valid**. The measured points are fitted with parabolas.

Fiducialization of the final cryo-assembly

AC measurements – Validation against rotating coil scanner





Parameter	SSW Value	SSW unc. (1-σ)	Rot. coil scanner Value	Rot. coil scanner unc. (1-σ)	Req. (1-σ)
x (mm)	0.01	0.05	0.02	0.05	0.13
z (mm)	-1.54	0.07	-1.52	0.05	0.13
Roll (mrad)	0.06	0.10	0.02	0.07	0.10
Yaw (mrad)	0.01	0.01	0.01	0.00	
Pitch (mrad)	-0.04	0.01	-0.03	0.00	

[10] M. Pentella et al. , "Field-axis measurement of an AC-powered magnet by a Single-Stretched Wire", IMEKO WC 2024, Hamburg

- Similar uncertainty values also for **cold measurements**

Fiducialization of the final cryo-assembly

Uncertainty budget

- Values comparable with [10]

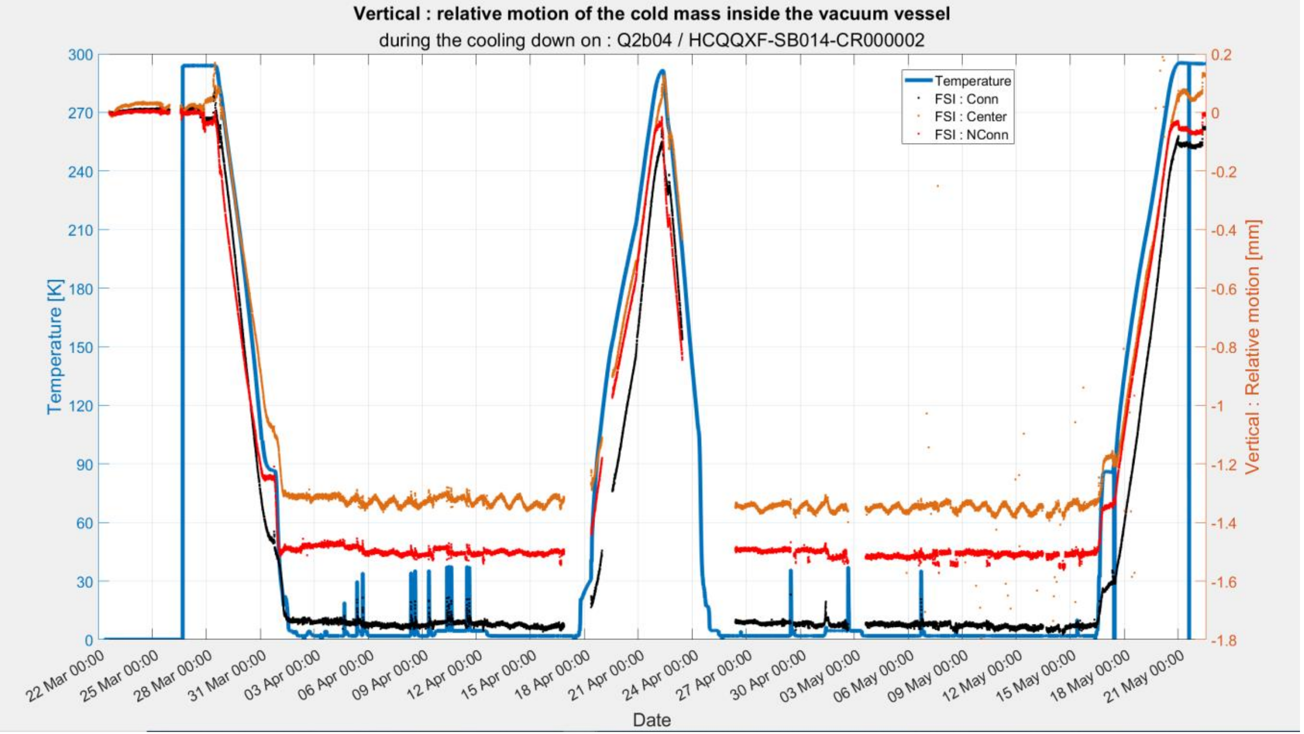
With reference to a 20-m wire

Parameter	Uncertainty (1σ)	
	Warm (5 A AC, 9 Hz)	Cold (16.23 kA DC)
Center CO (mm)	0.005	0.005
Center CN (mm)	0.05	0.01
Roll angle (mrad)	0.1	0.1
Resonance frequency (Hz)	0.02	0.02
Sag correction (mm)	0.05	0.05
Magnet longitudinal center (mm)	5	0.5
Magnetic length (mm)	10	5
Integrated gradient (T)	NA	0.2
Optical survey (mm)	0.05	0.05

[10] L. Bottura, M. Buzio, S. Pauletta, N. Smirnov, "*Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments*", IMTC 2006

Fiducialization of the final cryo-assembly

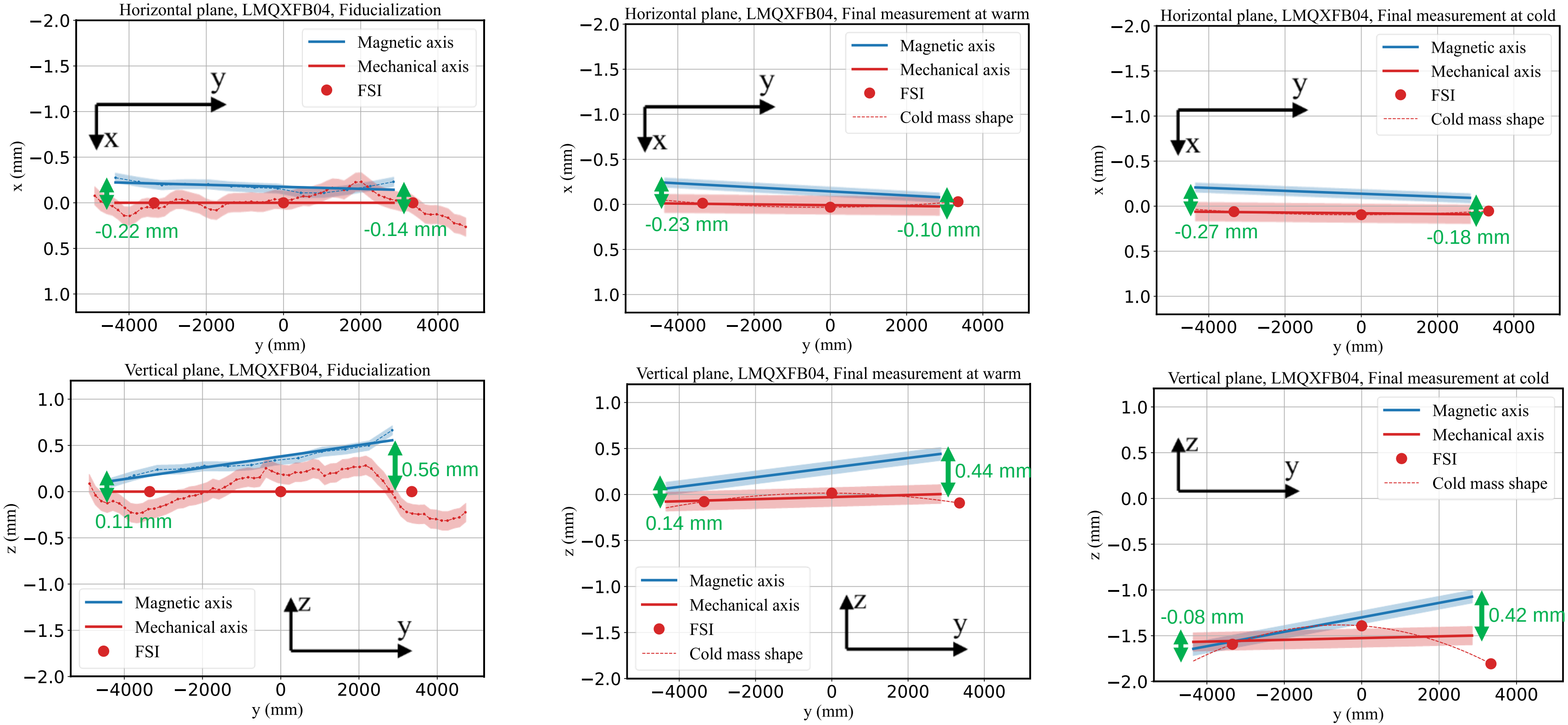
Internal monitoring



[9] J. Calmels, V. Rude, EDMS 3139144

Fiducialization of the final cryo-assembly

Series measurement of LMQXFB04 – Magnetic axis



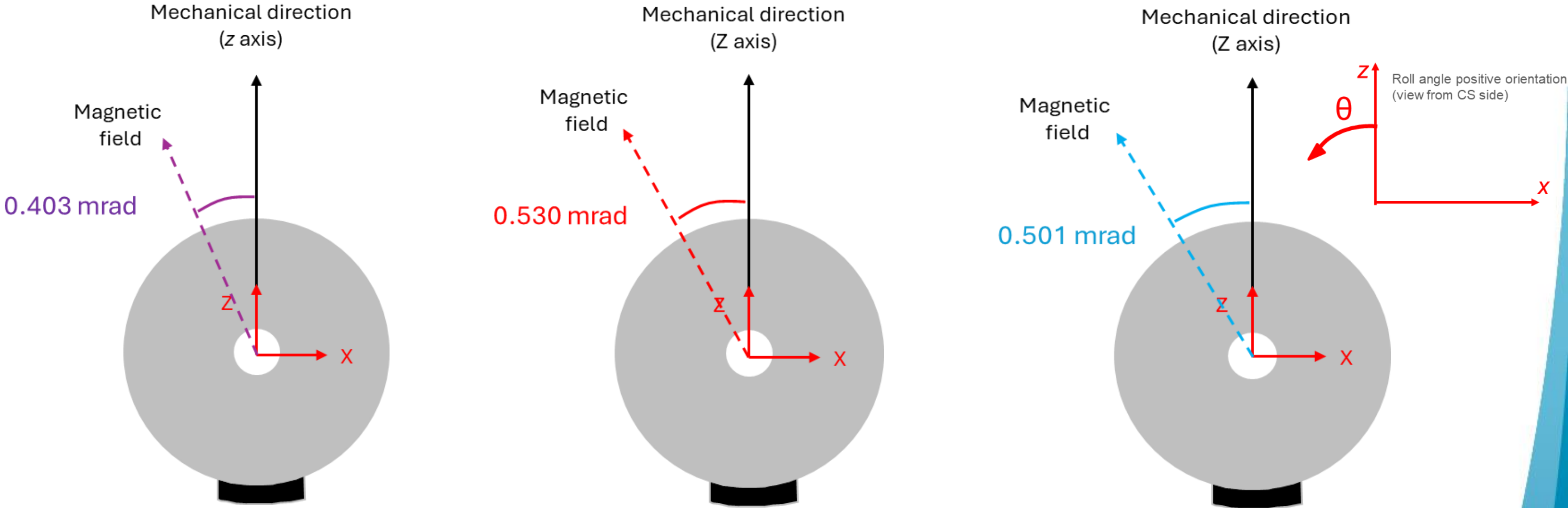
N.B: measurement performed after the cold test

Cold-to-warm vertical variation (integral)

- -1.61 mm (**magnetic**)
- -1.55 mm (**mechanical**)

Fiducialization of the final cryo-assembly

Series measurement of LMQXFB04 – Roll angles



Fiducialization | **SSW at room temperature (final)** | **SSW at cold, nominal current (final)**

Conclusions

- **Alignment measurements** of superconducting accelerator magnets consist of several steps to be carried out at warm and cold. **Measurement procedures** were developed and implemented with the alignment and metrology team through a proactive and fruitful collaborative effort.
- **Rotating coil** and **stretched-wire** system are complementary tools, showing comparable performance for alignment measurements.
  - **Rotating coils** are multi-purpose instruments used for a fine **longitudinal scan of the magnet**. This is particularly useful during the production process for quality control).
  - The **stretched-wire** system is the **reference for cold measurements**, providing integral information about field strength and magnetic axis, whereas rotating coil scanners are more challenging to operate.
- With the measurement procedures fully established, we are sailing at full mast through the series measurement campaign.
- Some of the lessons learned with Q2s will be useful for the HL-LHC corrector package (CP). First series measurement at cold for CP scheduled in the coming weeks.

Thank you for your attention.
Any questions?