Strategy concerning magnetic measurements both at “warm” and at “cold”

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TE/MSC/MM and WP3

Review of HL-LHC Alignment and Internal Metrology– 26th-29th August 2019

Outline

- Quantities to be measured and related requirements
- Measurement techniques and systems
  - Rotating-coil scanner (so called “mole”)
  - Rotating-coil chain (so called “long shaft”)
  - Single stretched wire
- Magnetic-measurement tests for alignment
  - Magnet
  - Cold-mass
  - Cryo-assembly
  - Final test at operating conditions
- Conclusions

Quantities to be measured and required accuracy

Example for Q1/Q3 and Q2

Integral quantities [1]

Integrated field	$\pm 1 \cdot 10^{-4}$ of nominal
Magnetic length	<±1 mm
Average field angle	<0.5 mrad
Magnetic axis	±0.2 mm
Longitudinal magnetic center	<±1 mm

Local quantities (longitudinal scan)

Gradient	$\pm 1 \cdot 10^{-4}$ of nominal
Magnetic center	±0.2 mm
Magnetic angle	<0.5 mrad

[1] "LMQXFA COLD MASS - FUNCTIONAL REQUIREMENTS SPECIFICATION", US-HiLumi-doc-64 1686197 v.0.7, LHC-LMQXFA-ES-0001

Measurement techniques

- There are several measurement techniques
  - can be classified according to:
    - Integral or local measurement
    - At ambient (“warm”) or at cryogenic temperature (“cold”)

- We will mainly focus on:

a) Rotating-coil scanner
   - Continuous rotation in DC mode
   - Stepwise in AC mode

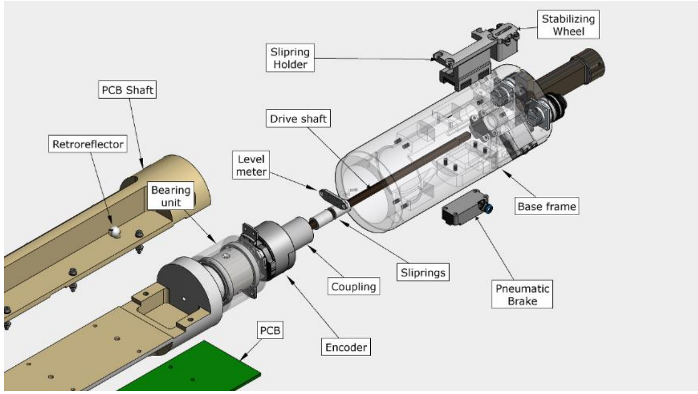
b) Long rotating-coil chains
   - Many segments in series covering the full length of the magnet

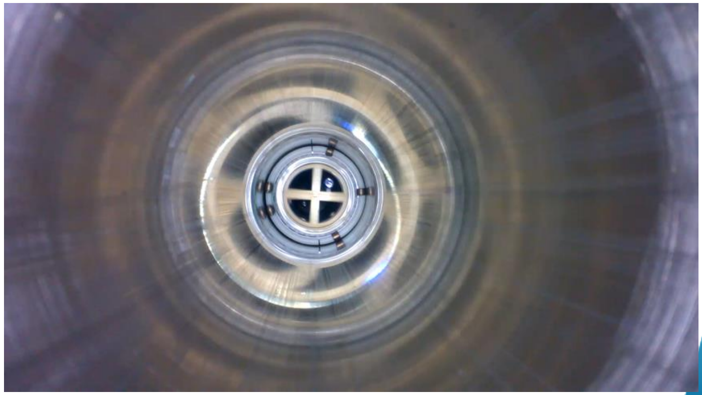
c) Stretched wire
   - Different operation modes

Rotating-coil scanner

- A suitable set of search coils is positioned into the magnet aperture
- The coils are rigidly rotated around an axis parallel to the longitudinal axis of the magnet
- The angular position of the coil in the transverse plane is measured by means of a rotary encoder and a tilt sensor
- The flux intercepted by the coils between two angular positions is measured by means of an integrator (~10^{-5})
- Combination of signals from different coils can improve the precision
- The harmonic coefficients are extracted by processing the flux measurements and by applying the sensitivity factors (calibration)

- **The tilt angle (phase of main harmonic) and magnetic center offset wrt to rotation axis (feed-down) can be retrieved from the harmonics**
- **The rotation axis can be measured by tracking two rotating targets by means of a laser tracker, and then referenced to external points**





Rotating coil scanner: accuracy

Gradient	**$1*10^{-3}$ of nominal (limited by calibration)**	
new development	**$1*10^{-4}$**	**with accurate PCB**
Magnetic center	**~50 µm**	**[3]**
Field angle	**<0.1 mrad**	**[6]**
Longitudinal magnetic center	**2-3 mm**	**[5]**
new development	**~1 mm**	**if retroreflector on PCB**

[3] L. Bottura, M. Buzio, S. Pauletta and N. Smirnov, "Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments," IEEE Instrumentation and Measurement Technology Conference Proceedings, Sorrento, 2006, pp. 765-770

[5] J. DiMarco et al., "Alignment of production quadrupole magnets for the LHC interaction regions," in IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, pp. 1325-1328, June 2003.

[6] A. Jain, “Overview of Magnetic Measurement Techniques”, US Particle Accelerator School on Superconducting Accelerator Magnets Santa Barbara, California, June 23-27, 2003

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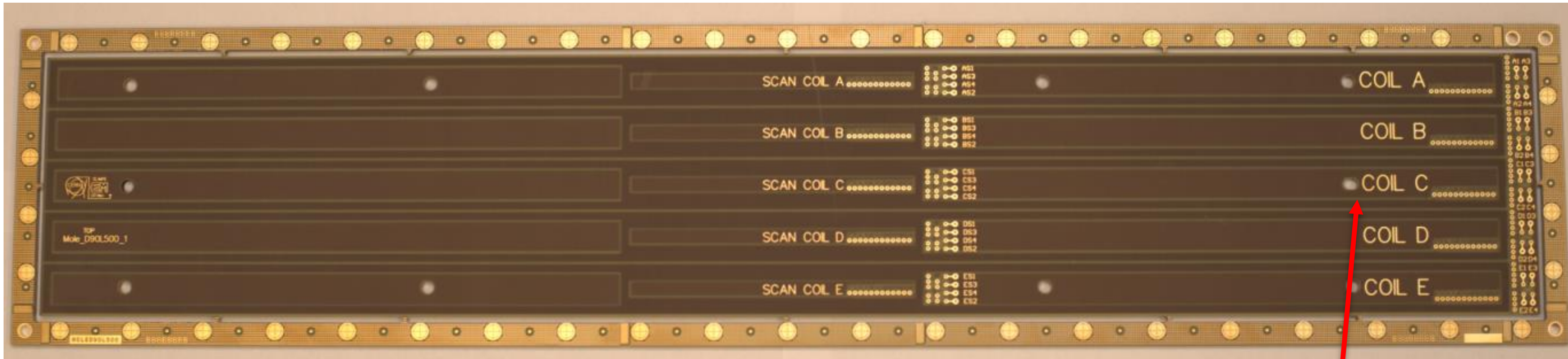
Rotating-coil scanner: PCB



	Equivalent surfaces [m²]				
	Coil A	Coil B	Coil C	Coil D	Coil E
PCB 1	1.87298	1.87291	1.87285	1.87278	1.87302
PCB 2	1.87303	1.87288	1.87292	1.87276	1.87299
PCB 3	1.87307	1.87293	1.87284	1.87284	1.87297
Design	1.8727				

	Relative diff wrt design value [10^{-4}]				
	Coil A	Coil B	Coil C	Coil D	Coil E
PCB 1	1.49	1.11	0.81	0.44	1.7
PCB 2	1.77	0.95	1.19	0.34	1.55
PCB 3	2	1.23	0.75	0.75	1.44
Average	**1.17**				

PCB alignment holes:

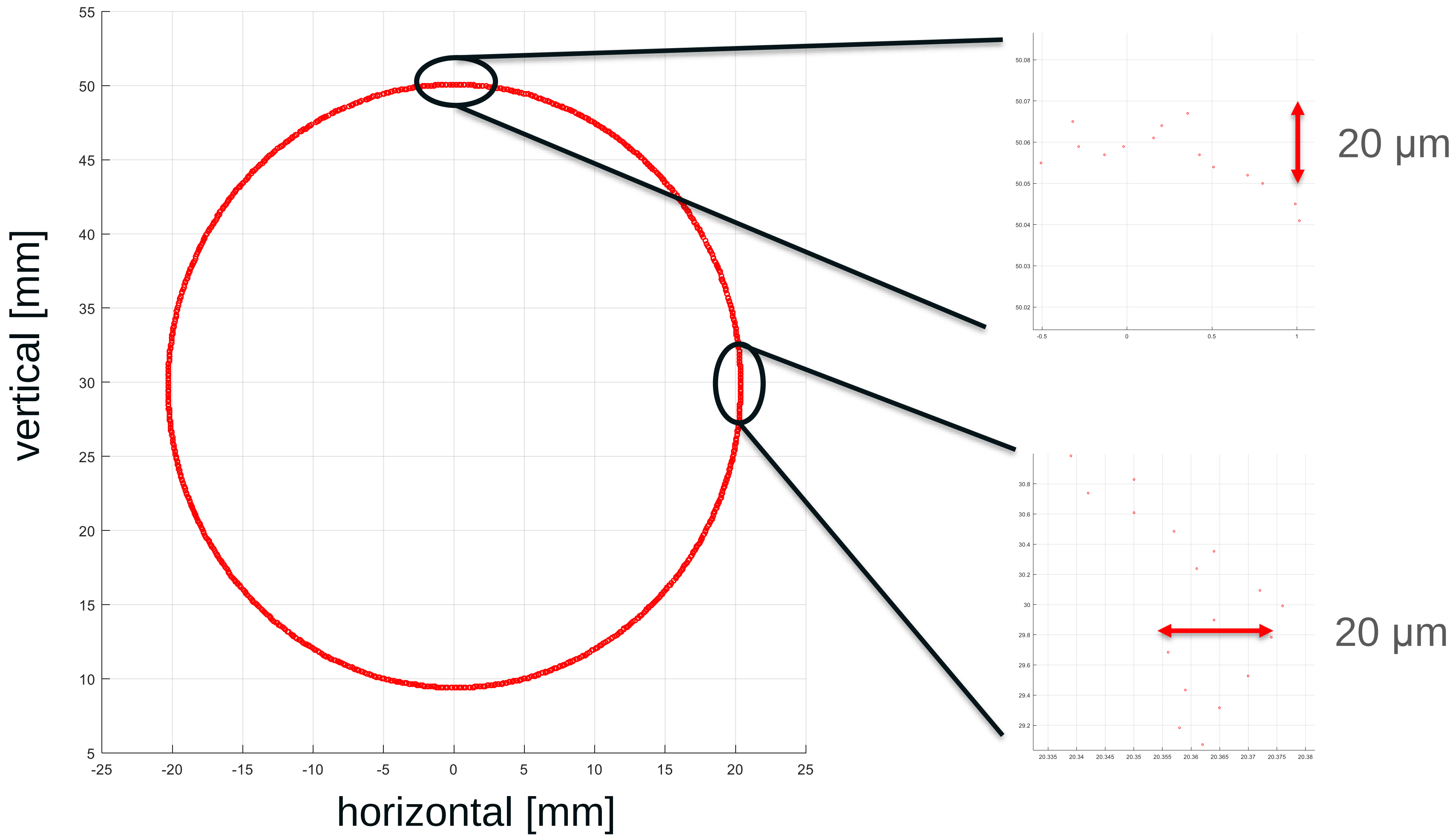
Precisely machined with a special tool for placing them at an accurate distance from the coil windings. A retroreflector can be positioned there.

Coil surfaces:

Accurate at $1 \cdot 10^{-4}$ level, no calibration needed. We will check if these results will be confirmed on PCB from other production batches

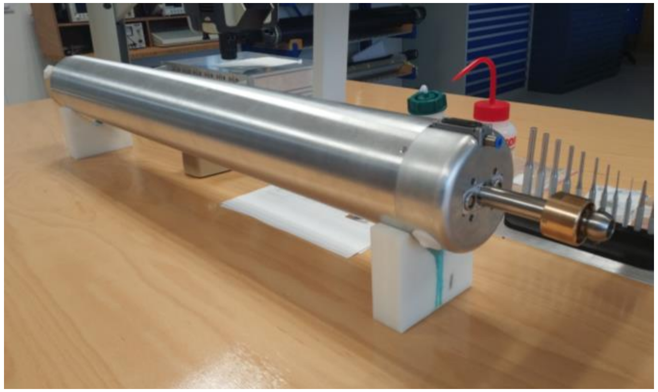
Rotating-coil scanner – rotating target

Tracking of the rotating target by using the Leica LTD 500



Rotating-coil scanner: status

- The prototype system has been fully validated
- The final system is under test on the MQXFBP1
- Other systems will be procured according to needs



Rotating-coil scanner: validation

Prototype system on our reference quadrupole

Local (3-σ repeatability)			
Type / Quantity	Single measurement	Repeated instertions	
Harmonics [2,3]	0.01	0.01	[units]
Gradient [3]	0.6 [1]	0.6 [1]	[units]
Angle	0.05	0.08	[mrad]
Axis location	0.02	0.05	[mm]

Integral		
Type / Quantity	Combination of multiple measurements	
Harmonics [2,3]	0.01	[units]
Gradient [3]	2 [1,4] (cross check wrt wire - accuracy)	[units]
Angle	~0.1 (under evaluation for long magnets)	[mrad]
Axis location	~0.1 (under evaluation for long magnets)	[mm]

[1] With gradient coil (difference of two external coils)

[2] $R_{ref} = R_{meas} = 42.7$ mm

[3] Relative to main field @ $R_{meas} = 0.16$ T

[4] Influenced by coil positioning

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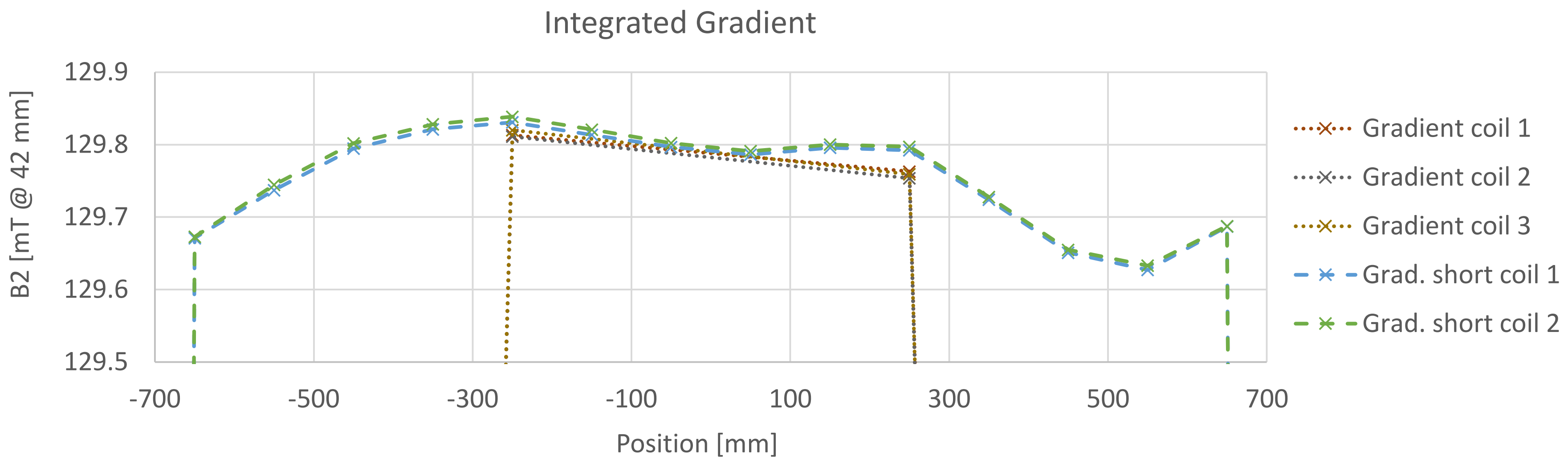
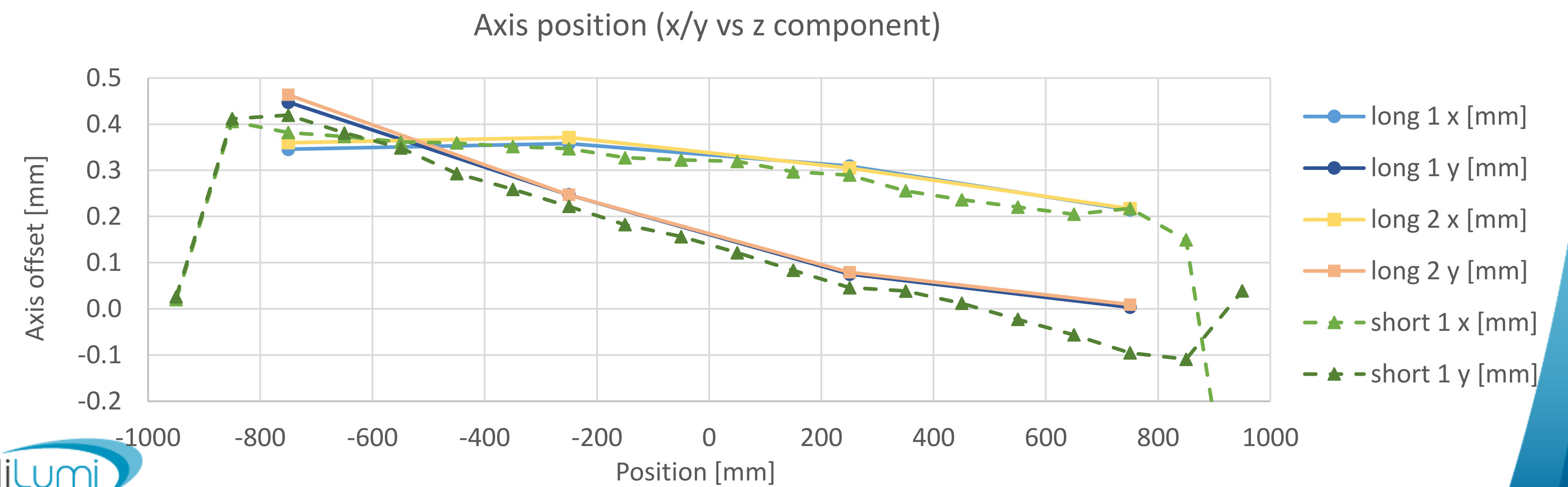
Rotating-coil scanner: validation

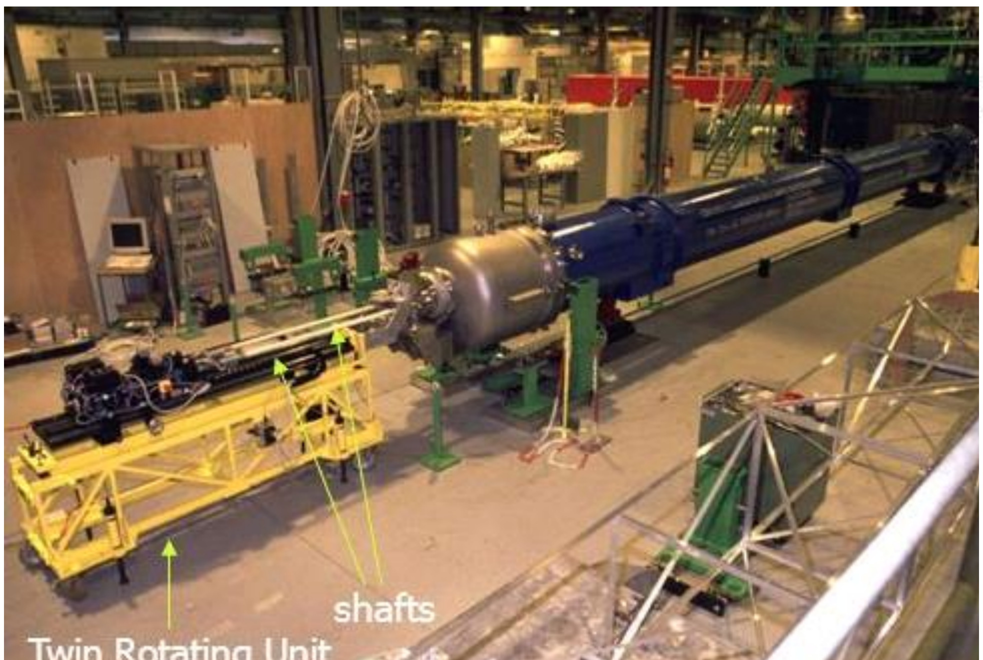
Prototype system on our reference quadrupole





Rotating-coil chains

- 15-m-long “shafts” have been used for LHC dipoles
- Al_2O_3 tubes with 3 rectangular pick up coils
- Titanium bellows for absorbing the bending by keeping the torsional stiffness
- Accuracy: 10^{-4} central field



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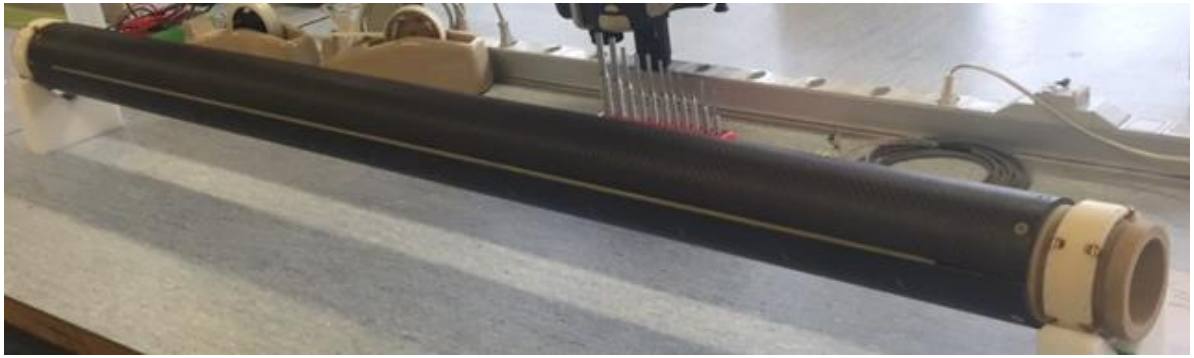
Rotating-coil chains: new development



Carbon fiber shell

- Total weight 4 kg

PCB

- 5 radial coils
- 90-mm width
- 1.3-m length

- Tilt angle <0.35 mrad
- Dipole bucking ~800
- Quadrupole bucking ~600

surface (m2) :	1.44749	1.44720	1.44738	1.44722	1.44731
ecart (%0)	0.0	-0.2	-0.1	-0.2	-0.1
radius(mm)	40.075	20.031	0.000	-20.031	-40.075

- It is the “first brick” for a long multi-segment shaft for full-length HL-LHC magnets
- In-situ calibration of relative angles [7]
- Retroreflectors on each PCB
- The last segment is visible from outside

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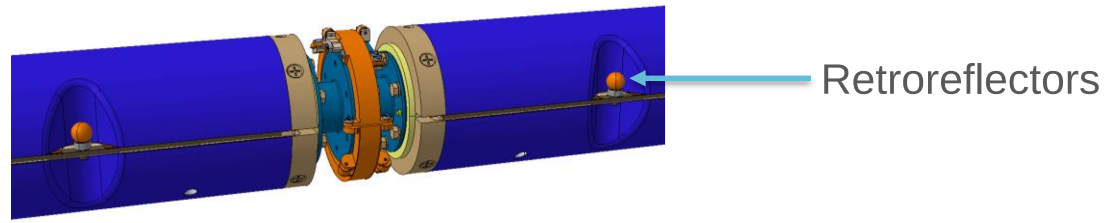
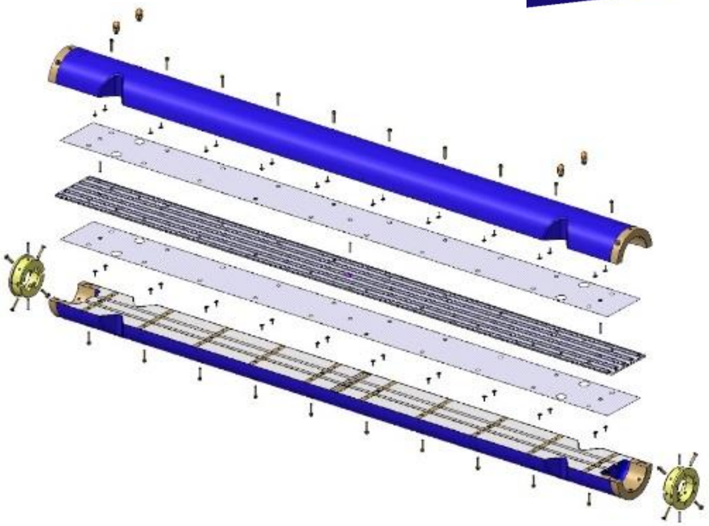
[7] L. Fiscarelli et al., “Calibration of rotating coil arrays for particle accelerator magnet testing”, XX IMEKO World Congress Metrology for Green Growth September 9−14, 2012, Busan, Republic of Korea

Rotating-coil chains: new development





- Modules with length of 1.4 m (1.3 m active)
- Carbon-fiber shells for stiffness and low weight
- Pickup coils made from printed circuit boards (PCB)
- **Retroreflectors on each module directly linked to the PCBs (best accuracy)**
- **One retroreflectors is always visible outside the anti-cryostat**

- The measurement shafts have been designed
  - First 10 modules are under procurement (shells are the most critical component)
- The anti-cryostat is under production (prototype for Q2 proto)

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Rotating coils – scanner vs chain

- Scanner
  - Compact instrument (easy transport, can be used where the magnet is assembled)
  - Small number of search coils to be produced and calibrated
  - Translation and positioning system needed
  - On-board encoder and tilt sensor
  - Slow: a complete scanning of a long magnet requires several hours (single field level)

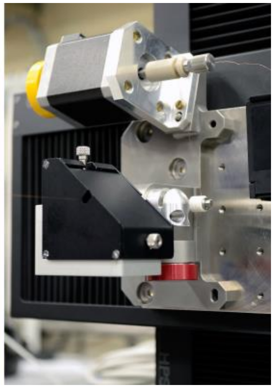
  ⟶ **Tests at ambient temperature**

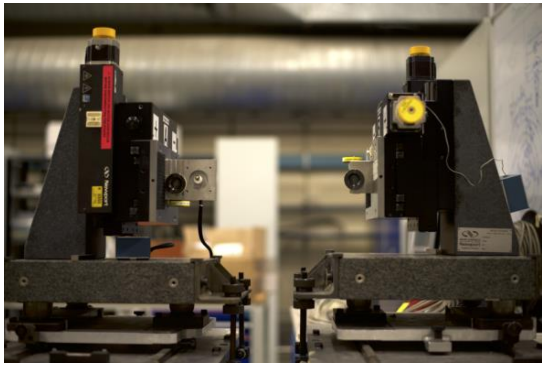
- Long chains
  - Longer than the magnet under test
  - Complementary tools required for insertion/removal/holding
  - Large number of search coils to be fabricated and calibrated
  - Diameter, length and position of segments are specific to a magnet family
  - Fast: once installed they provide central field, integral field, tilt angle, harmonics at ~1 Hz
  - The rotation axis of inner segments cannot be referenced to external points

  ⟶ **Tests at cryogenic temperature**

Stretched wire

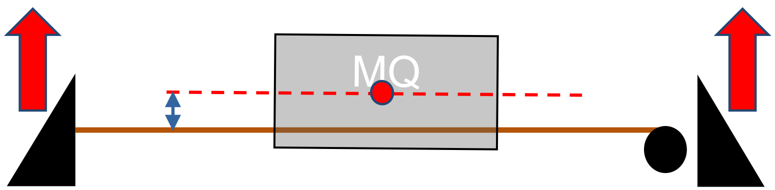
- A conducting wire is stretched along the magnet aperture and displaced with high accuracy (~1 μm)
- The flux intercepted by the wire between two positions (~30 mm) is measured by means of an integrator (~10^{-5})
- The wire can be positioned on the magnetic axis by imposing symmetries
- **The position of the wire can be precisely measured by a laser tracker and then related to the fiducials**
- The wire sag is not negligible on long quadrupoles. Its effect can be corrected (extrapolation at infinite tension)
- Co-directional and counter-directional displacements are possible
- At ambient temperature, the magnet can be powered with AC current for improving the sensitivity





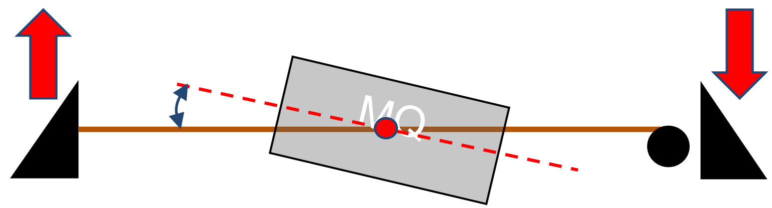
Stretched wire: modes

Co-directional displacements



- Integrated gradient
- Magnetic axis
- Average field (roll) angle

Counter-directional displacements



- Pitch and yaw angles
- Longitudinal magnetic center

Stretched wire: accuracy

Integrated gradient	~$1 \cdot 10^{-4}$ of nominal	[2], [4]
Magnetic axis	50-100 µm	[3]
Average field angle	<0.1 mrad	[4]
Longitudinal magnetic center	2-3 mm	[5]

[2] L. Walckiers , "Magnetic measurement with coils and wires", CERN Accelerator School CAS 2009: Specialised Course on Magnets, Bruges, 16-25 June 2009, CERN-2010-004, pp. 357-385

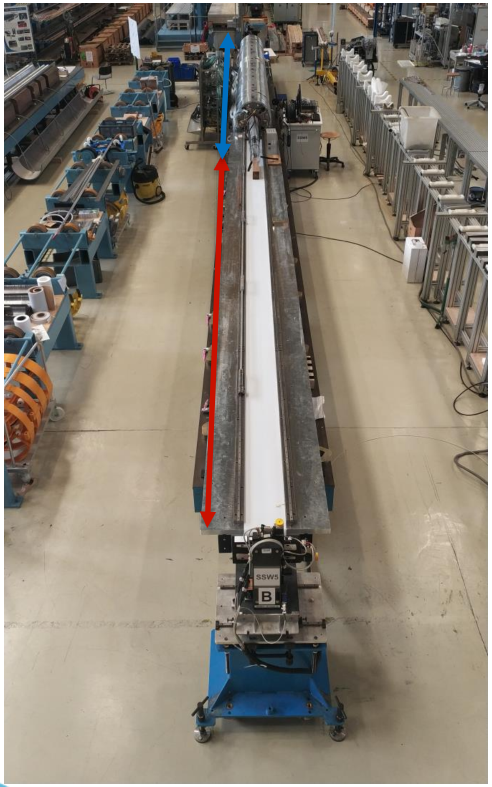
[3] L. Bottura, M. Buzio, S. Pauletta and N. Smirnov, "Measurement of magnetic axis in accelerator magnets: critical comparison of methods and instruments," IEEE Instrumentation and Measurement Technology Conference Proceedings, Sorrento, 2006, pp. 765-770

[4] G. Deferne, M. Buzio, N. Smirnov, J. DiMarco, "Results of magnetic measurements with the Single Stretched Wire (SSW) System on a LHC prototype main lattice quadrupole and LHC preseries dipoles", 13th International Magnetic Measurement Workshop, May 19-22, 2003, Stanford, California

[5] J. DiMarco et al., "Alignment of production quadrupole magnets for the LHC interaction regions," in IEEE Transactions on Applied Superconductivity, vol. 13, no. 2, pp. 1325-1328, June 2003.

Stretched wire: status

- Two systems are available for general use
- For HL-LHC
  - 2 systems have been procured (under assembling)



MQXFBP1 at warm on the assembly bench

First test 17.12.2018				
Quantity		1-σ		
Gx (Tm)	0.6282	0.0003	5	units
Gy (Tm)	0.6304	0.0015	24	units
X (mm)	0.053	0.030		mm
Y (mm)	0.005	0.024		mm

Second test 01.04.2019				
Quantity		1-σ		
Gx (Tm)	0.6193	0.0003	5	units
Gy (Tm)	0.6184	0.0010	16	units
X (mm)	0.052	0.011		mm
Y (mm)	-0.037	0.022		mm

In this setup the extra length of the wire outside the magnet reduces the precision

MM tests for alignment

1. Magnet

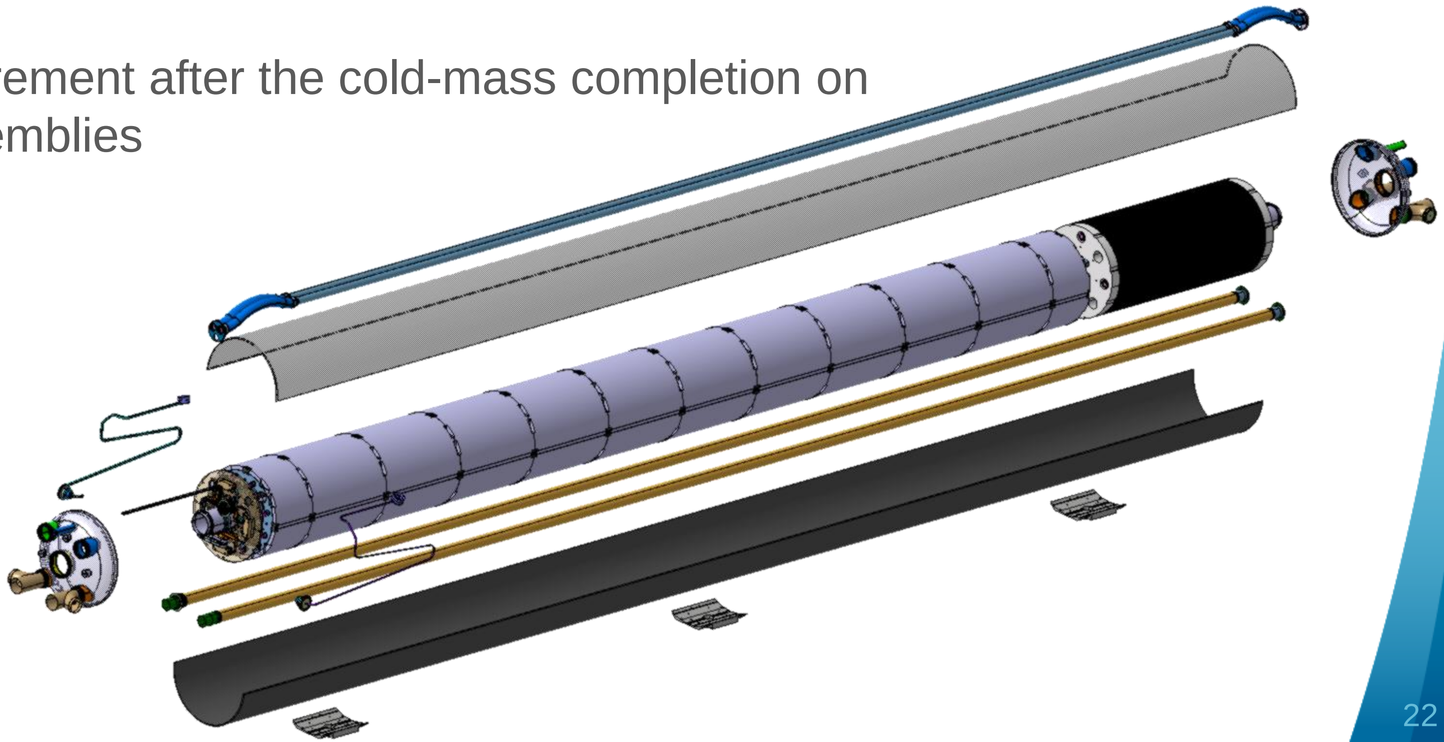
- Single magnet on the assembly bench

  - Rotating-coil scanner
    - Example for MQXF
      - Coil-pack assembly: local field quality
      - After centering: local field quality
      - After loading: integral field, local and **integral angle**, local and integral field quality

  - Temporary reference points on the two ends will be used for transferring the angle measurement from the magnet assembly bench to the cold-mass assembly bench

2. Cold-mass

- Main magnet + corrector(s) on the assembly bench
  - Each magnet already measured and angles referred to the temporary reference points
    - Discussion on-going for D2 (double aperture magnets and double aperture correctors)
  - Intermediate measurement on a sub set of magnets before welding the end cover (rotating-coil scanner or wire TBD)
  - Measurement after the cold-mass completion on all assemblies



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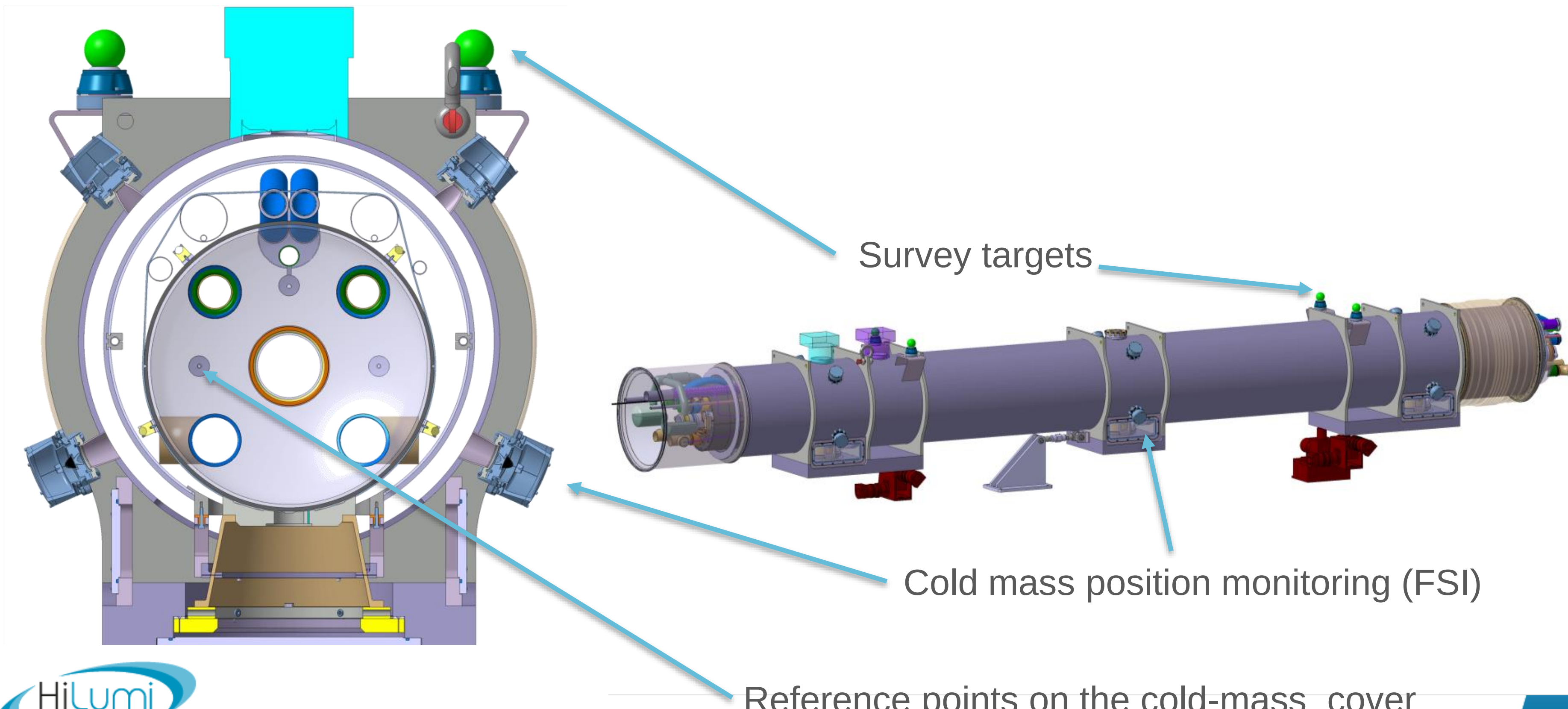
3. Cryo-assembly

- Cold-mass in the vessel

  - No adjustments→ no measurements during the assembling
  - Measurement of axis and angle after completion at warm on all assemblies
    - Stretched wire should be enough



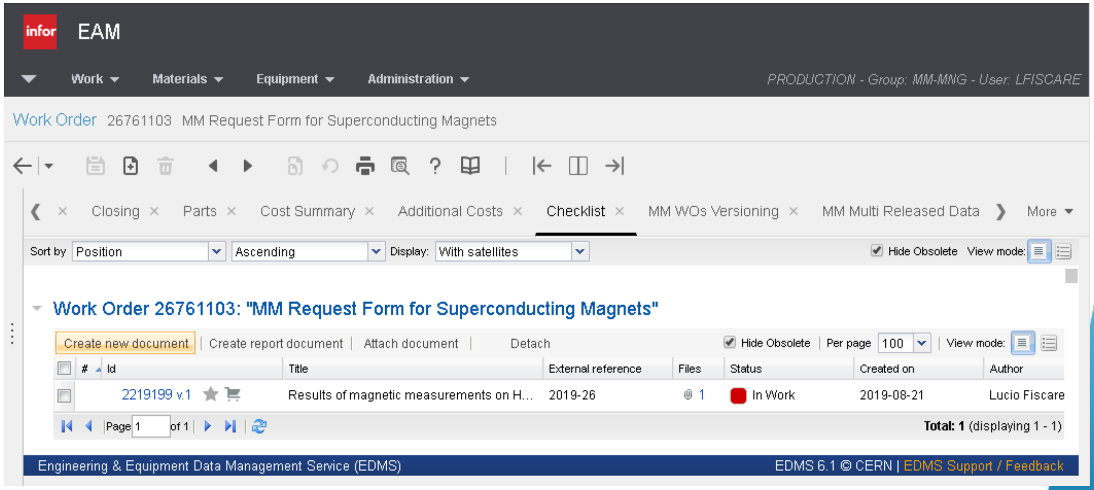
4. Final test in SM18

- Cryo-asembly at operating conditions (cold, nominal field)
  - All cryo-assemblies will be tested
  - Aperture equipped with anti-cryostats
  - Measurement by using stretched wire
    - integrated gradient
    - axis
    - angle
  - Measurement by using rotating-coil chains
    - magnetic length
    - longitudinal center

Documentation

- MTF
  - Equipment folder
  - Manufacturing step
  - Excel measurement report

- INFOR
  - “MM request”
  - Work order - equipment
  - Results in a EDMS document



Conclusions

- We have identified the techniques according to requirements
- New development has been carried out to cope with specific needs
- Readiness of systems
  - Stretched wire systems are available
    - Tests ongoing
  - Rotating-coil scanner ready
    - First unit under test on MQXFBP1
    - Other systems for other magnet families will be procured
  - Rotating-coil shaft chains
    - Under procurement
- Work flow for each magnet family is under development
  - Some aspects will be clarified with the construction of the prototypes
- Collaboration and information exchange between MM-survey is important
  - WGA meetings

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