New Rotating-coil Chains for the HL-LHC Cryomagnets

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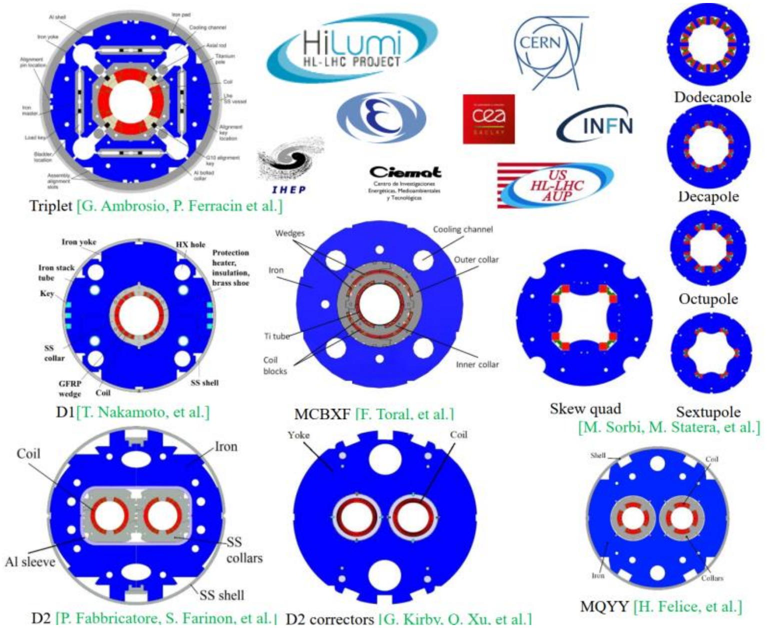
Introduction

- **High-Luminosity LHC upgrade**
  - WP3 “IR Magnets”: **SC magnets** based on different technologies (Nb_3Sn for high field, NbTi CCT or nested, super-ferric for correctors)
- **48** series cryo-assemblies to be **magnetically measured at cold** on SM18 **horizontal test benches**



Courtesy E. Todesco

Main characteristics of HL-LHC main magnets for Insertion Regions to be measured on horizontal benches											
Cryo-assembly Function	**Denomination**	**Cold Mass**	**Number of apertures**	**Aperture diameter**	**Field at nominal current**	**Gradient at nominal current**	**Magnetic length**	**Integrated field at nominal current**	**Integrated gradient at nominal current**	**Units needed**	**Spare units**
				mm	**T**	**T/m**	**m**	**Tm**	**T**		
Triplet	Q1/Q3	LMQXFA	1	150	n.a.	132.6	4.2	n.a	556.9	16	4
Triplet	Q2a/b	LMQXFB	1	150	n.a.	132.6	7.15	n.a.	948.1	8	2
Separation dipole	D1	LMBXF	1	150	5.6	n.a	6.26	35	n.a	4	2
Recombination dipole	D2	LMBRD	2	105	4.5	n.a	7.78	35	n.a	4	2
Correctors package	CP	Order n = 2, 3, 4, 5, 6,	1	150						4	2

MM Requirements and Systems

MM requisits from injection to nominal current												
Cryo-assembly Function	Denomination	Cold Mass	Integrated gradient / field			Integrated multipoles			Magnetic axis	Roll angle	Longitudinal centre	Magnetic length
			Precision	Accuracy	R_{ref}	Up to n	Precision	Accuracy	Precision	Precision	Precision	Precision
			units	units	mm		units	units	mm	mrad	mm	mm
Triplet	**Q1/Q3**	MQXFA	1	10	50	10	0.05	0.1	0.2	0.2	5	5
Triplet	**Q2a/b**	MQXFB	1	10	50	10	0.05	0.1	0.2	0.2	5	5
Separation dipole	**D1**	MBXF	1	10	50	11	0.05	0.1	n.a.	0.2	5	5
Recombination dipole	**D2**	MBRD	1	10	35	11	0.05	0.1	n.a.	0.2	5	5
Correctors package	**CP**	Order n = 2	10	50	50	10	0.1	0.5	0.4	4	5	3
Correctors package	**CP**	Order n = 3, 4, 5, 6,	50	100	50	12	0.5	1	0.4	4	5	3

Source CERN LHC-M-ES-0016 Edms 2436024

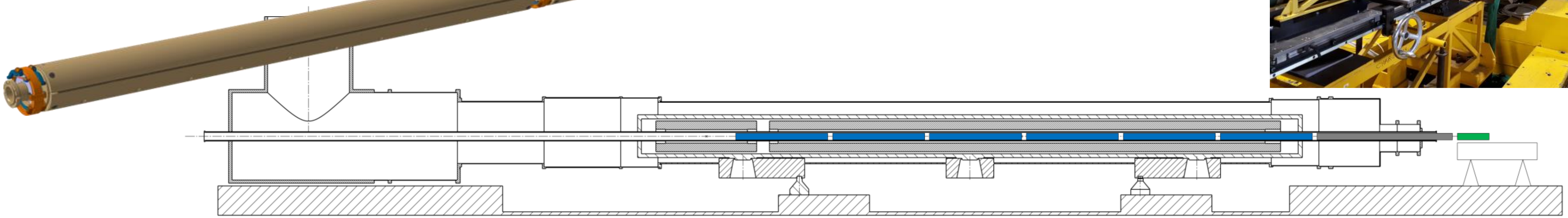
End of cold tests mid-2027
Target: **3 days / magnet for magnetic measurements**

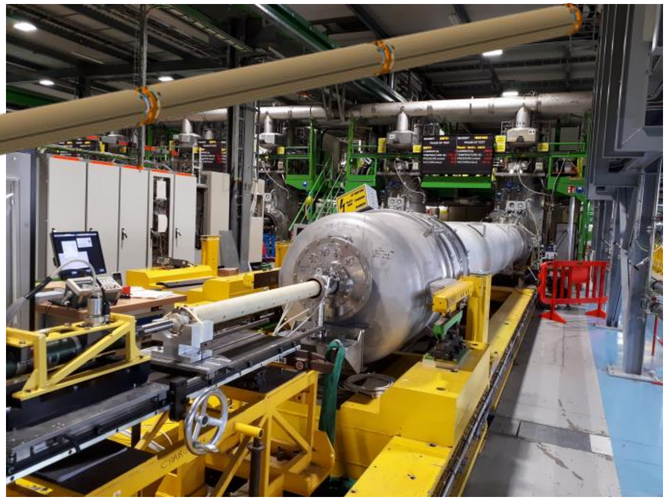
Required magnetic measurements systems

- **Integrated field gradient/strength**
  - **Single Stretched Wire (SSW) at nominal level** - Reference @ CERN since LHC
  - **Rotating-coils Chains at various excitation cycles (machine, stair step, ramp rate)**
- **Integrated and local field quality**
  - **Rotating-coils Chains at various excitation cycles (machine, stair step, ramp rate)**
- **Field axis, angle and longitudinal centre**
  - **Single Stretched Wire (SSW)** *(see Mariano Pentella's IMMW23 presentation)*
  - **Rotating-coils Chains** for longitudinal magnetic centre

Rotating Coils Chains

A **rotating-coil chain** (previously named “shaft” for the LHC) is an **assembly of several rotating coil segments mechanically connected**





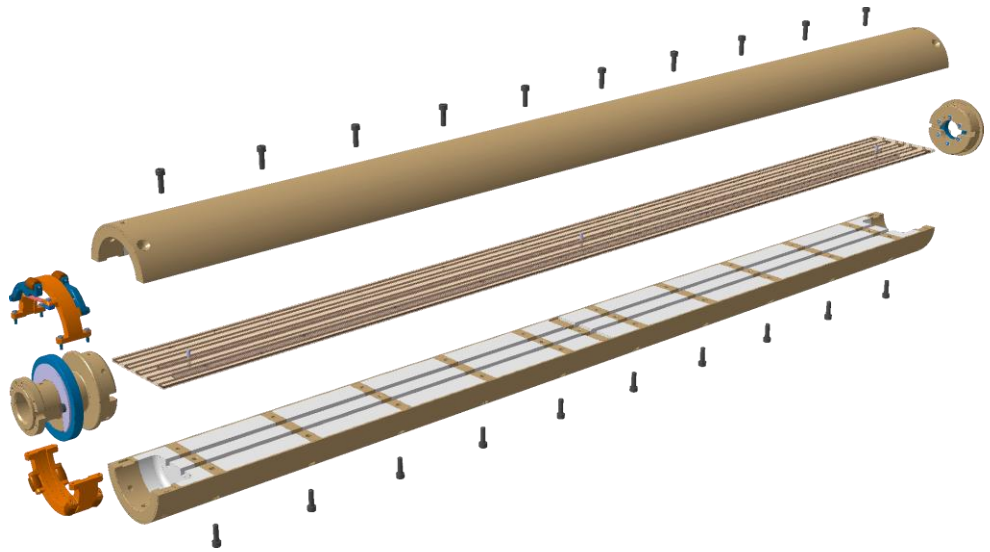
- **Pros**
  - Integral and local field measured continuously during current cycles (main field and harmonics)
  - Standard resolution in time = 1 Hz
  - Magnets of ~10 m in length measured at once
- **Cons**
  - Price proportional to the number of segments

- **3 chain configurations**
  - For Q1, Q2 & Q3 magnets : 6 segments ∅103 mm (2 units)
  - For D1 and CP correctors packages : 5 segments ∅ 103 mm (2 units)
  - For D2 magnets : 7 segments ∅ 66 mm (2 units)

The segments

Based on a **new design** with respect to LHC:

- **PCB boards** instead of hand-wound coils
- **Half-shells made of composite material** instead of machined ceramic-tubes cores



- Pros:
  - Lower overall price
  - Easier assembling and calibration
  - Better bucking

Different diameters and lengths are needed to cover the **HL-LHC WP3 magnets**

- **2 types of segments**
  - diameter 103 mm and length 1.3 m
  - diameter 66 mm and length 1.2 m

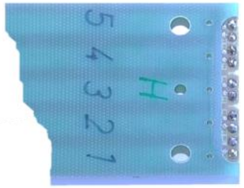
→ ~50 segments needed (spares included)

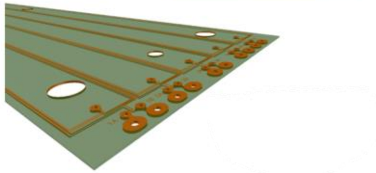
Half shells + PCB sandwiches

Half-shells:

- Prototype in carbon fibre: too large torque required due to eddy currents at high field (>3 T)
- Design change to use EPGM
  - Mechanical tolerances on shells manufacturing ≈ 0.2 mm

PCBs characteristics					
For segments diameter	Number of coils	Total number turns	Layers	Design magnetic length	Design coils area
mm				m	m^2
103	5	4	2	1.290	0.049529
66	5	4	2	1.195	0.055439



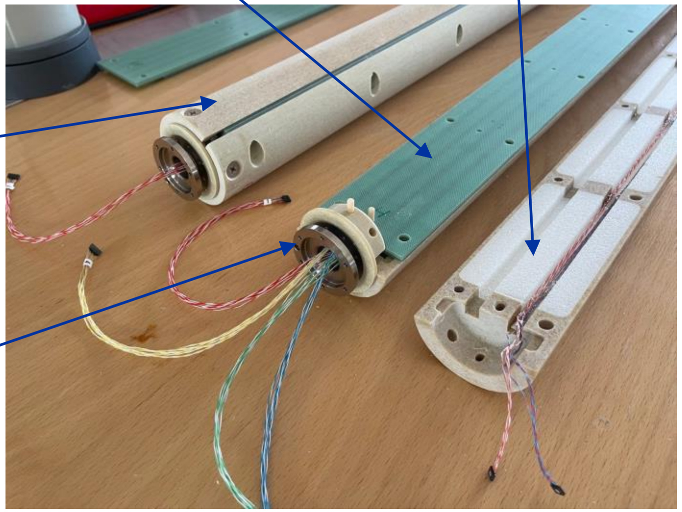


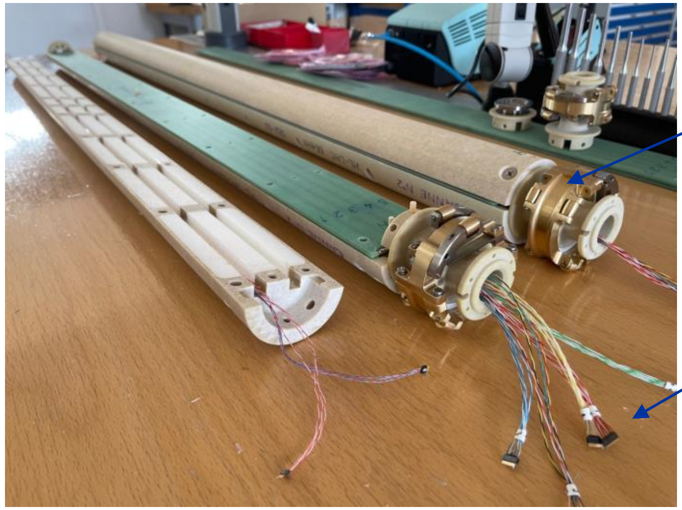
PCB board (CERN)

ROHACELL filling (Mfr. RESARM / BELG)

EPGM half-shells (Mfr. RESARM / BELG)

Titanium bellow





Roller with ceramic ball-bearing

Cables with nano connectors

PCBs calibration – coil area

- <u>Performed on raw PCBs</u> by coil voltage integration while manually flipping the PCBs inside the reference dipole magnet
- Reference field mapped by NMR homogeneity < 1 unit
- Calibration typical relative repeatability: $2{\cdot}10^{-5}$

$$A_{coil} = \frac{\psi}{B}$$

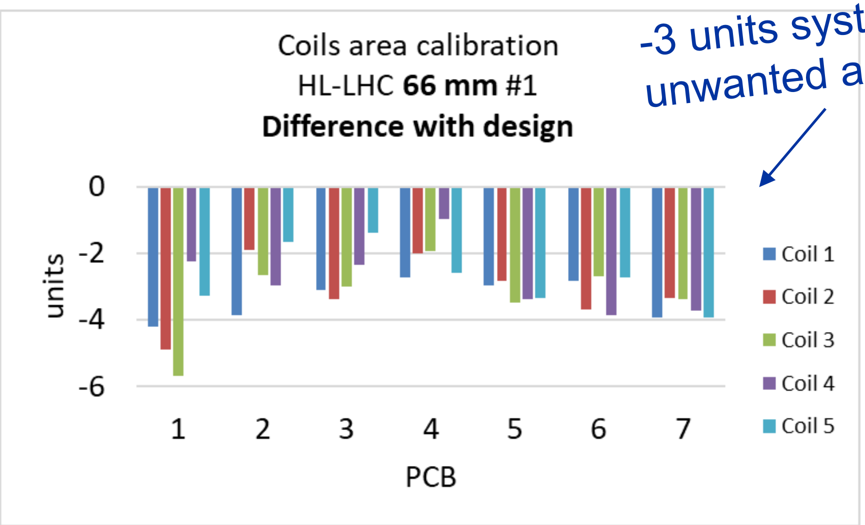
A_{coil} = coil effective surface [m^2]

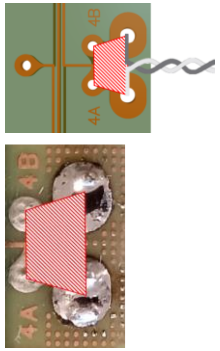
Ψ = measured integrated flux [Wb]

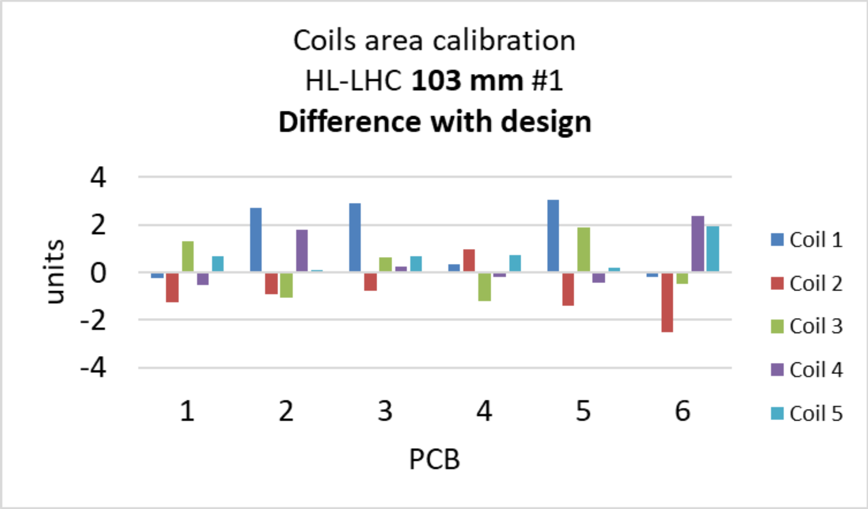
B = magnetic field [T]

Reference dipole bench RefDip1

-3 units systematic difference: unwanted area from design





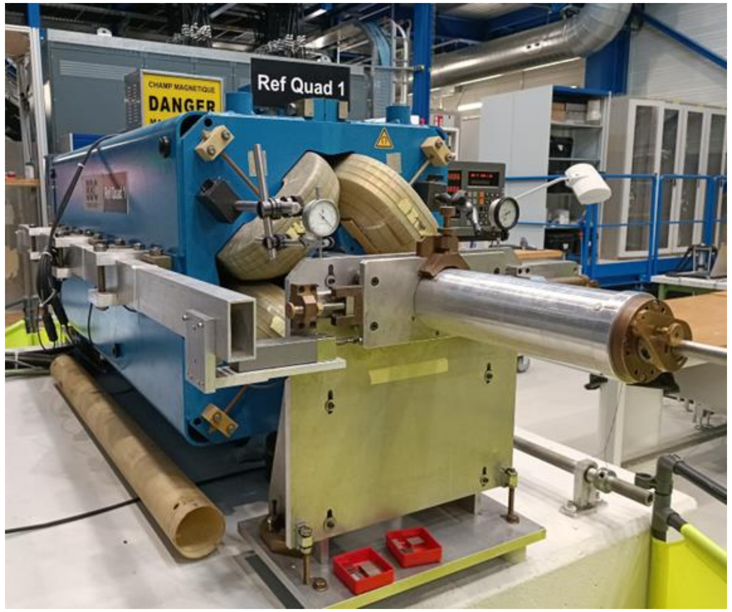


Examples of coils area calibration of PCBs for HL-LHC

Segments calibration – coils radius

- Performed on assembled segments
  - Previous method : flux measurement by accurate lateral displacement of the segment in our **reference quadrupole** magnet
    - Complex process, accuracy of manual lateral displacement ~1um

- **NOT POSSIBLE** for HL-LHC 103 mm segments - **diameter incompatible with magnet aperture**

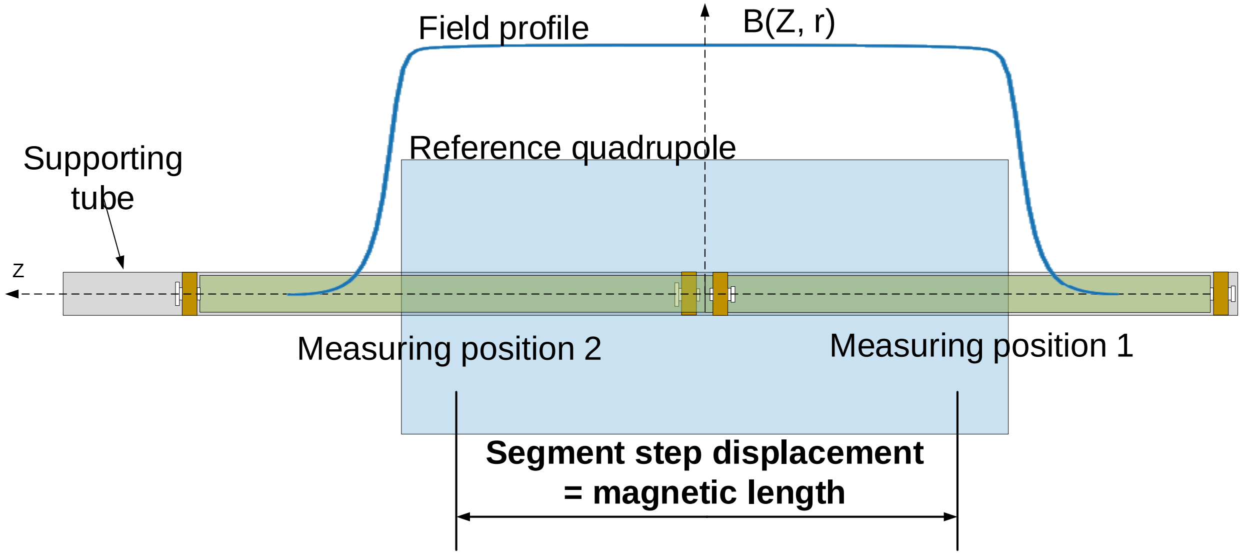


Reference quadrupole bench RefQuad1

→ **New method necessary**

Coils radius calibration – principle

- "**Integrated flux measurement** by rotating the segment in a quadrupole magnet **calibrated with Single Stretched Wire systems** with segment displacement to cover the field profile"
  - *Proof of principle by **Andrea Fontanet Valls** for her master thesis «Innovative calibration method for rotating-coil magnetometers", 2022)*



- *Radius from flux according to:*

$$R_{cal} = \frac{L_m \Psi_2}{A_{coil} \int G dl}$$

R_{cal} = calibrated radius [m]

L_m = coil magnetic length from design [m]

$\int Gdl$ = magnet integrated gradient from SSW [T]

A_{coil} = coil effective surface from calibration in the dipole [m^2]

Ψ_2 = measured integrated flux of 2^{nd} harmonic [Tm^2]

- **Pros:**
  - Flux acquisition in similar conditions as real measurement
  - Simpler than the old method – using standard measurement equipment
  - Not sensitive to transversal off-centering (1 mm ~ 10^{-5})
- **Cons:**
  - Non-uniform sensitivity along the coils given by the field profile and the coils length

Coils radius calibration – the new bench

- **Reuse of reference quadrupole**
  - Field profile total length ≈ 2.3 m
  - 125 mm diameter aperture
  - 13.338 T integrated field at I_{nom}
- **New sliding structure for rotation unit**
  - 3 m stroke
  - Linear encoder : positioning accuracy better than 0.1 mm
- **Standard acquisition as other rotating coil systems** using 5 FDIs and the FFMM software

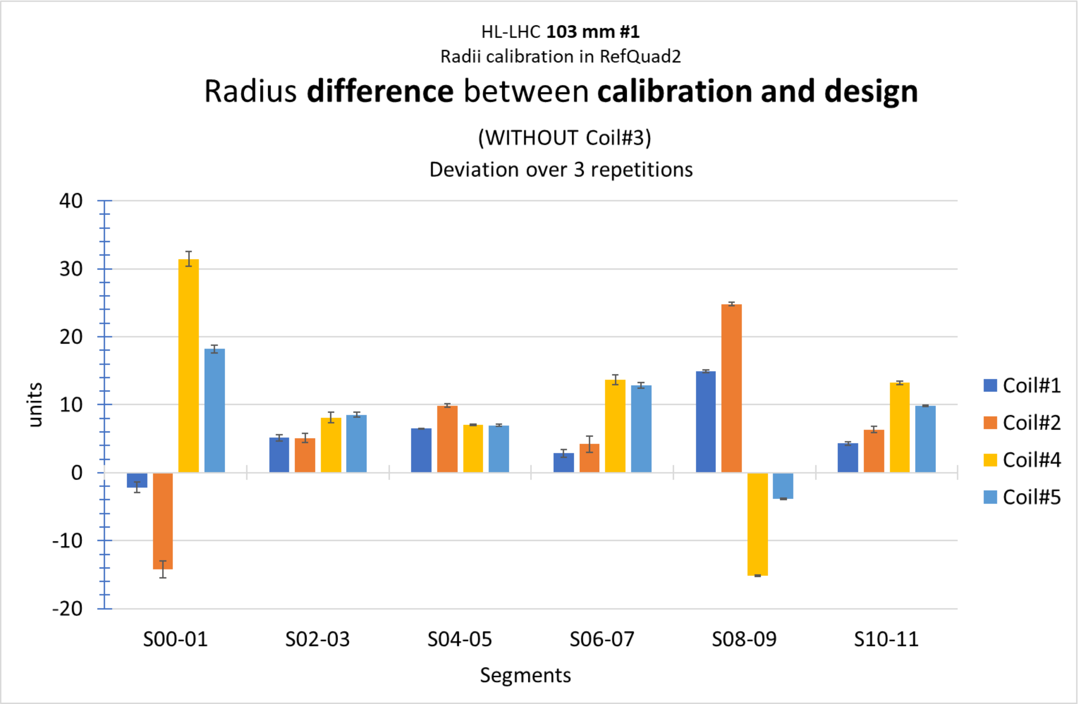
The radii calibration bench in bdg 311 installed on RefQuad2 magnet

The sliding rotation unit

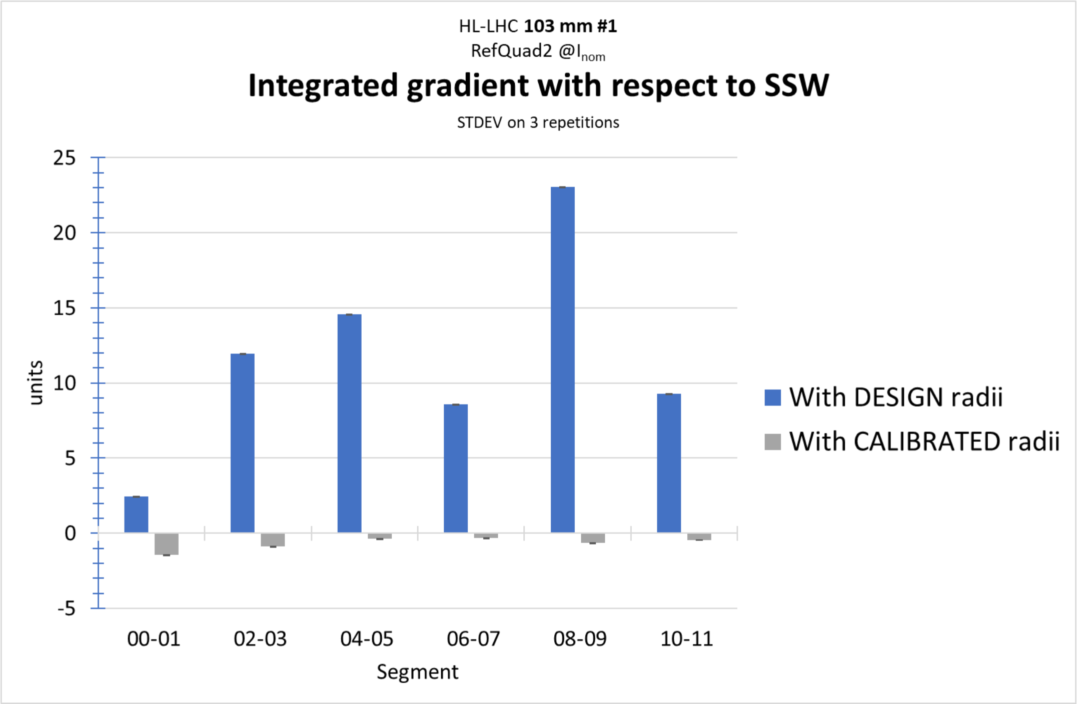
Standard CERN acquisition system

Coils radius calibration – some results

- **Coils chain 103 mm #1**
  - Calibration uncertainty over 3 repetitions < 1 unit



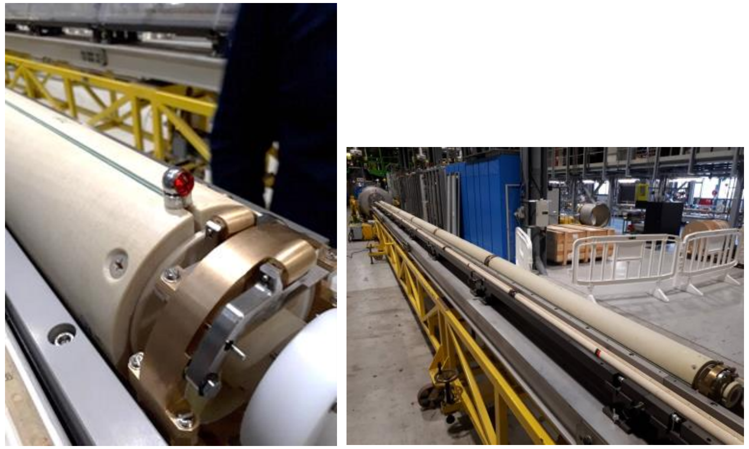
Coils radii calibration



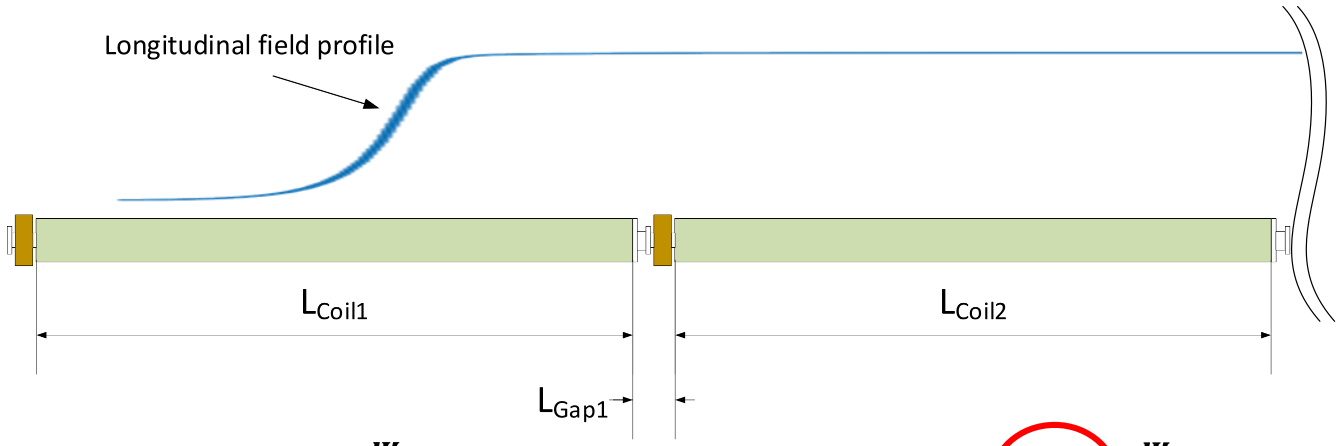
Integrated field verification using coil 1

Integrated field measurements - gap compensation

- **Principle**
  - Integrated field measured with a coil chain reconstructed by:
    - **Geometrical measurements of each gap** between coils with a laser tracker (uncertainty ~0.1 mm)
    - **Correction of missing flux** due to gaps
      - **Extension of the measurement** of the adjacent segment

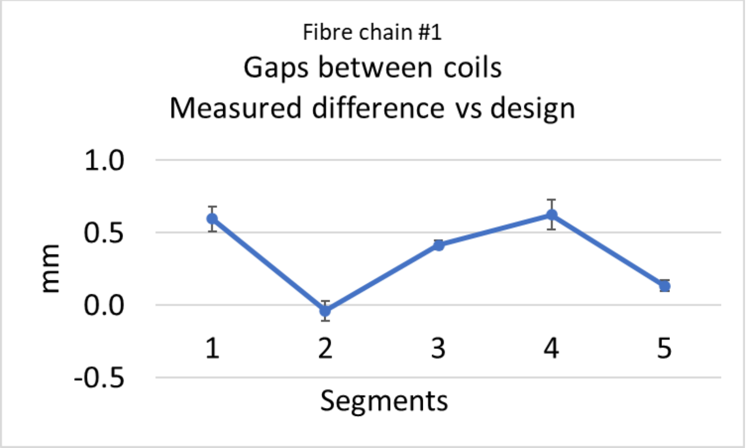


Measurement of the gap between PCBs



$$\int Gdl_1 = L_{Coil_1} \frac{\Psi_{2(1)}}{A_{coil} R_{coil}}$$

$$\int Gdl_2 = (L_{Coil_2} + L_{Gap_1}) \frac{\Psi_{2(2)}}{A_{coil} R_{coil}}$$



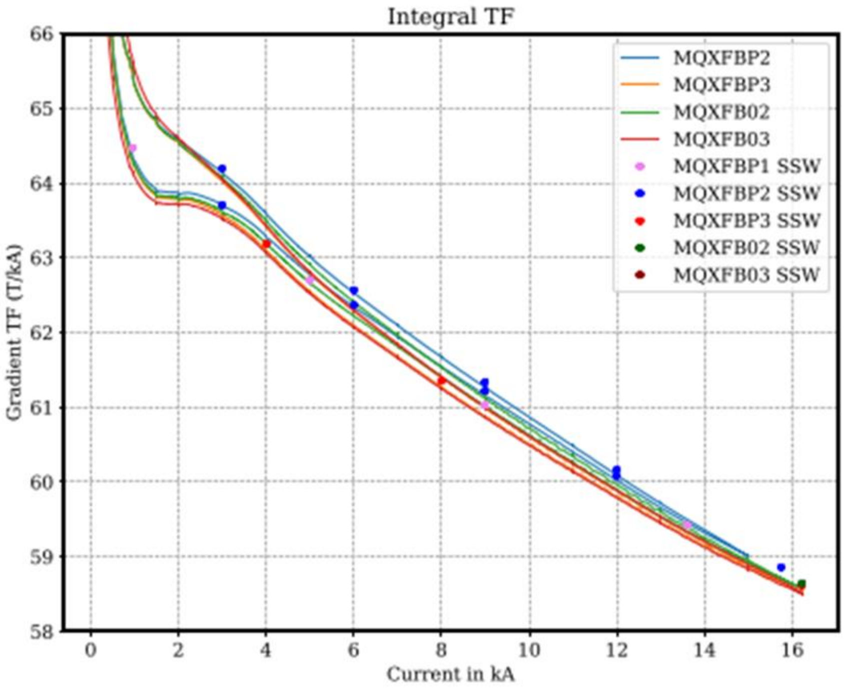
Cumulated error between PCBs w/r to design over total chain length (8300 mm) = 1.7 unit

Integrated field measurements – verification vs SSW

- Since the LHC, **SSW systems** are the **reference** at CERN for **field integral**
  - Global wire systems uncertainty on HL-LHC magnets @ cold : <5 units (3σ) (*see M. Pentella's presentation*)

Integrated gradient difference between **rotating coils chains** and **SSW**		
Chain	**Magnet**	**units**
Prototype - NOT CALIBRATED, BASED ON DESIGN	MQXFBP3	-16.0
Chain 103 mm #1	LMQXFB04	-0.8
Chain 103 mm #1	LMQXFA01	1.0
Chain 103 mm #1	LMQXFBP3	1.1

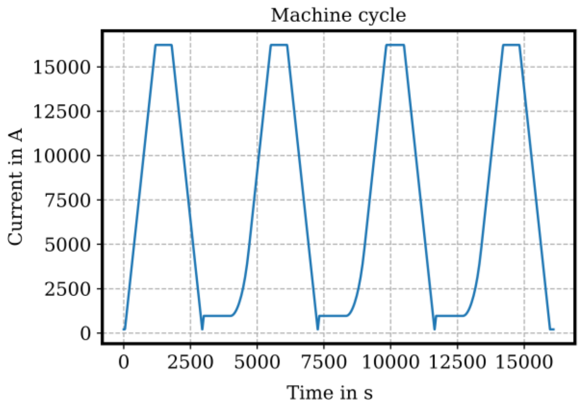
Q2 with LMQXFB04 magnet under test with SSW and coils chain



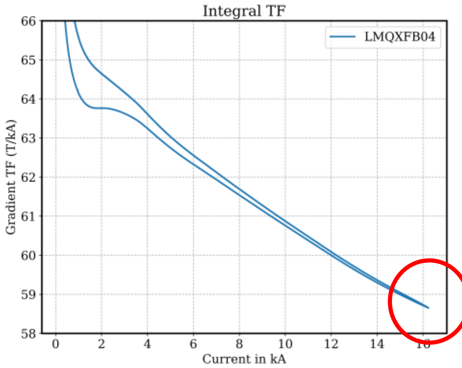
Integrated TF measured by coils chain and SSW

Examples of measurement results

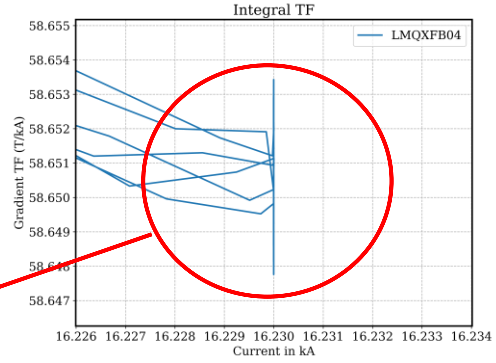
- Magnet **LMQXFB04**,
- Coils chain: 103 mm #1
- Typical precision over 3 consecutive **machine cycles**
  - Integrated TF : **< 0.5 unit**
    Harmonics : **< 0.01 unit**



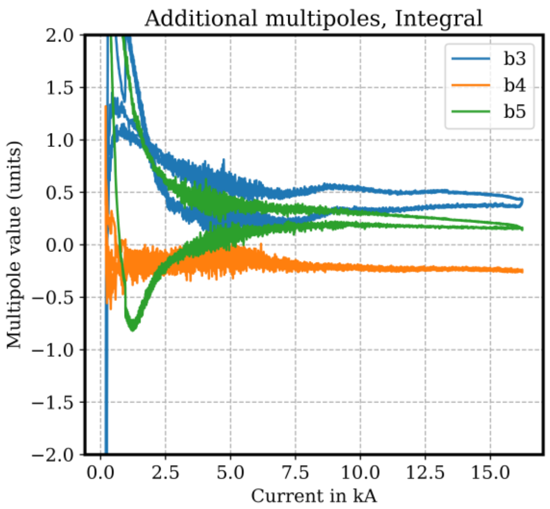
Current cycles

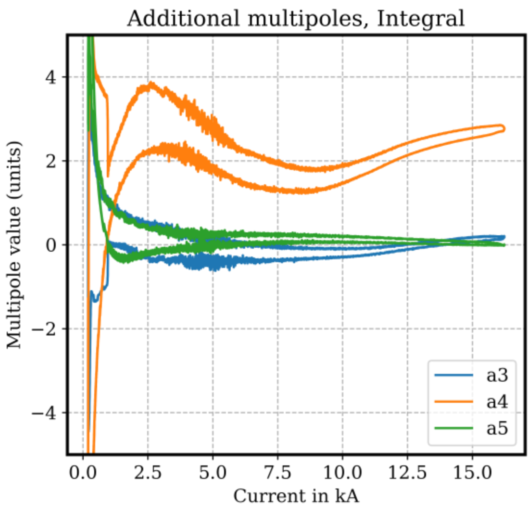


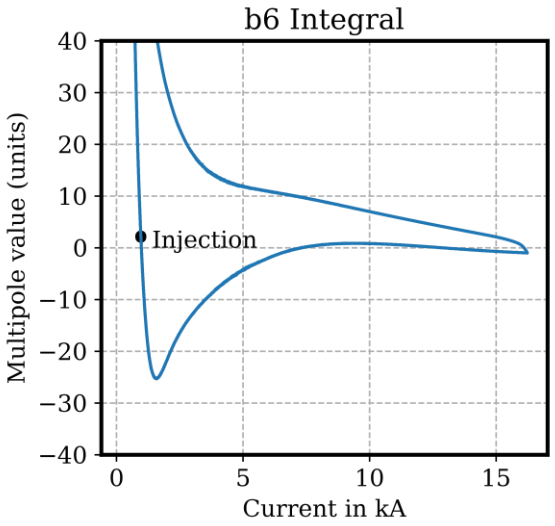
Integrated gradient TF versus current



Int. Grad. TF during plateau @ I_{nom}







Some integrated harmonics

Conclusion

- **New rotating-coil chains design validated**
- **New coils radii calibration bench in operation**
  - Method validated
  - To be checked for segments with other geometries (Ø66 mm segments campaign ongoing)
- **Segments and chains production - status September 2024:**
  - ∅66 mm
    - 2 chains in calibration phase
  - ∅103 mm
    - 1 chain for Q1/Q2/Q3 in operation
    - Components ordered and awaiting delivery for 3 more chains (2 spares included)
- **HL-LHC measurement campaign**
  - Q2, Q3 and D1 prototypes campaign about to be completed, CP before end of year
  - Q2 series magnets started
  - Accuracy and precision according to HL-HC beam dynamics requirements – next tests will provide more statistics

Thank you

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