# MQXFS4
# Warm Magnetic Measurements and Analysis

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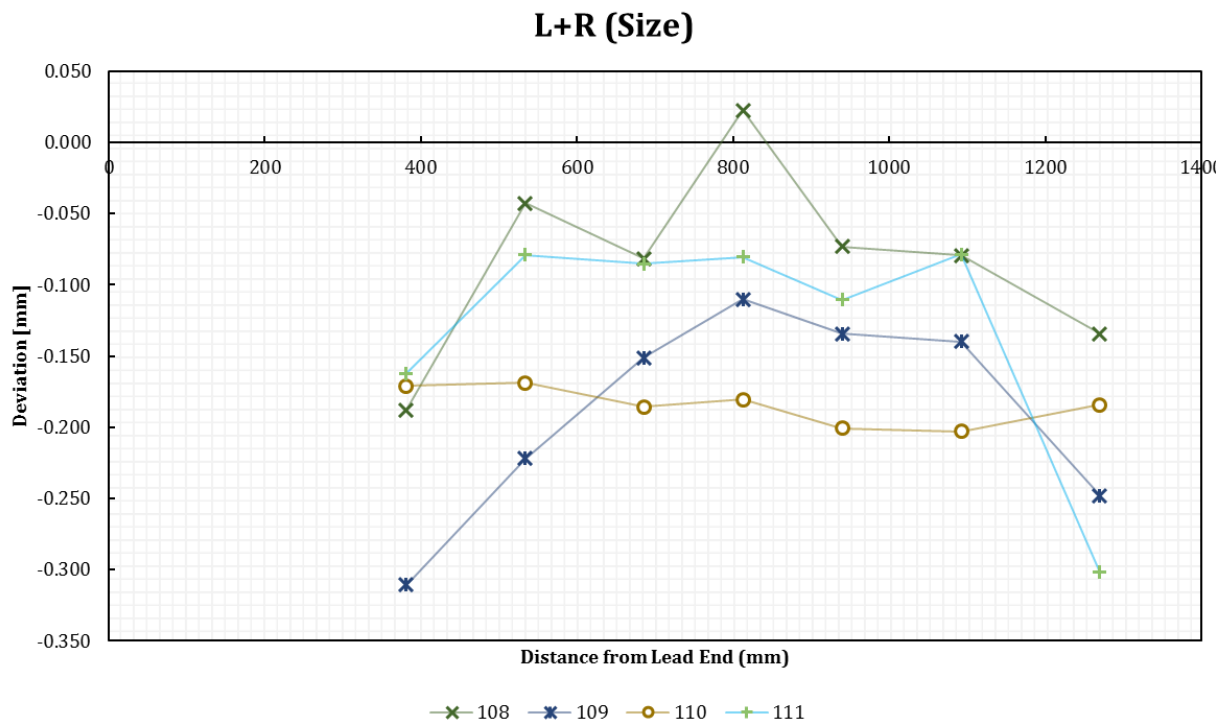
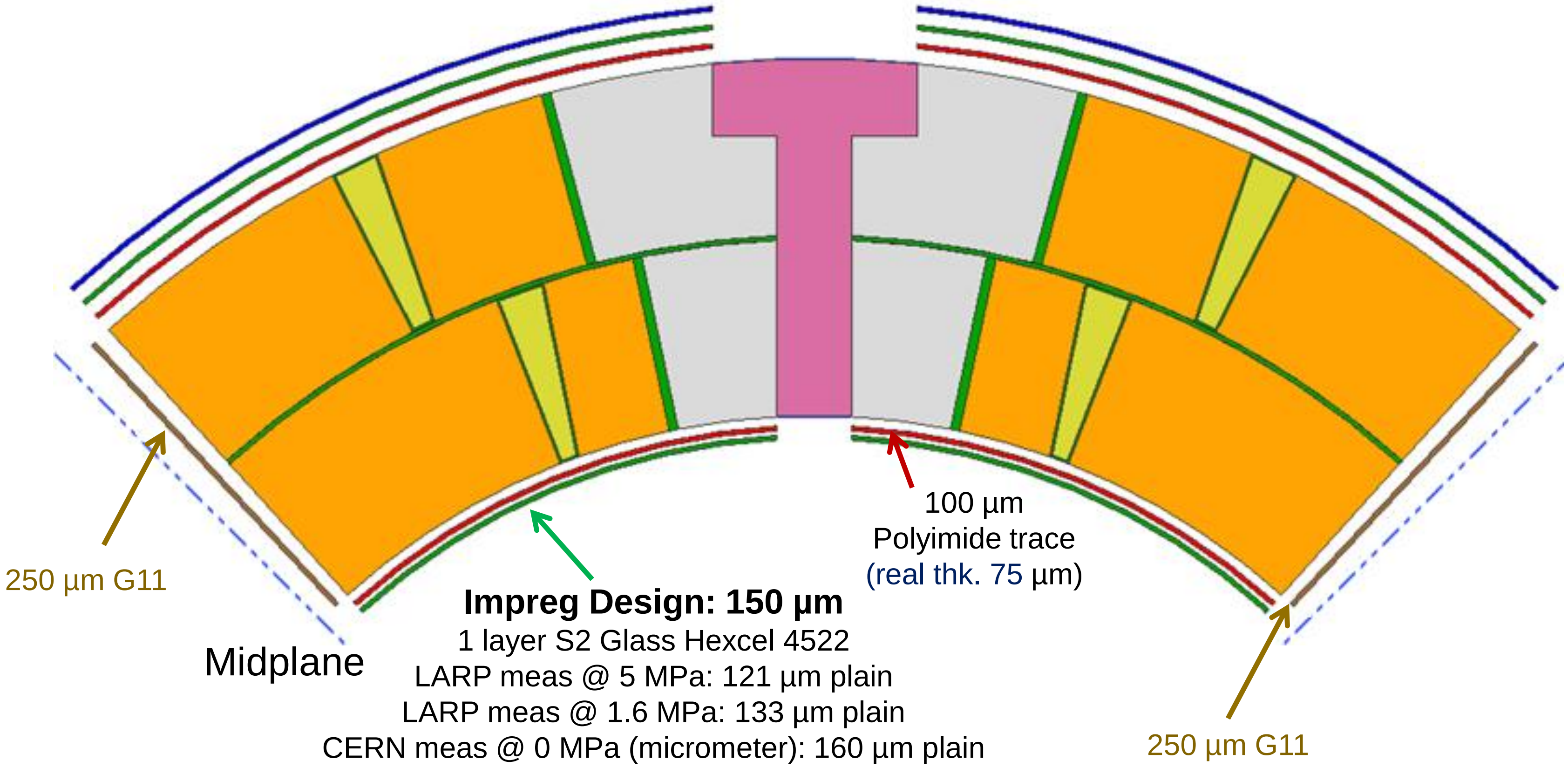
# MQXFS4 – Coil Geometry




- Coil size within $\pm 50\ \mu m$
- Coil 110 is one of the most regular coils we did.
- The different inner layer QH configurations might have an impact on field quality.

| COIL | Inner Diameter Configuration | L+R (mm) | Assumed (mm) |
|---|---|---|---|
| **C108** | **Standard IL trace** | -82 | -100 |
| **C109** | **Standard IL trace** | -188 | -200 |
| **C110** | **Pressed encapsulated trace** | -185 | -200 |
| **C111** | **Laminated encapsulated trace** | -128 | -150 |

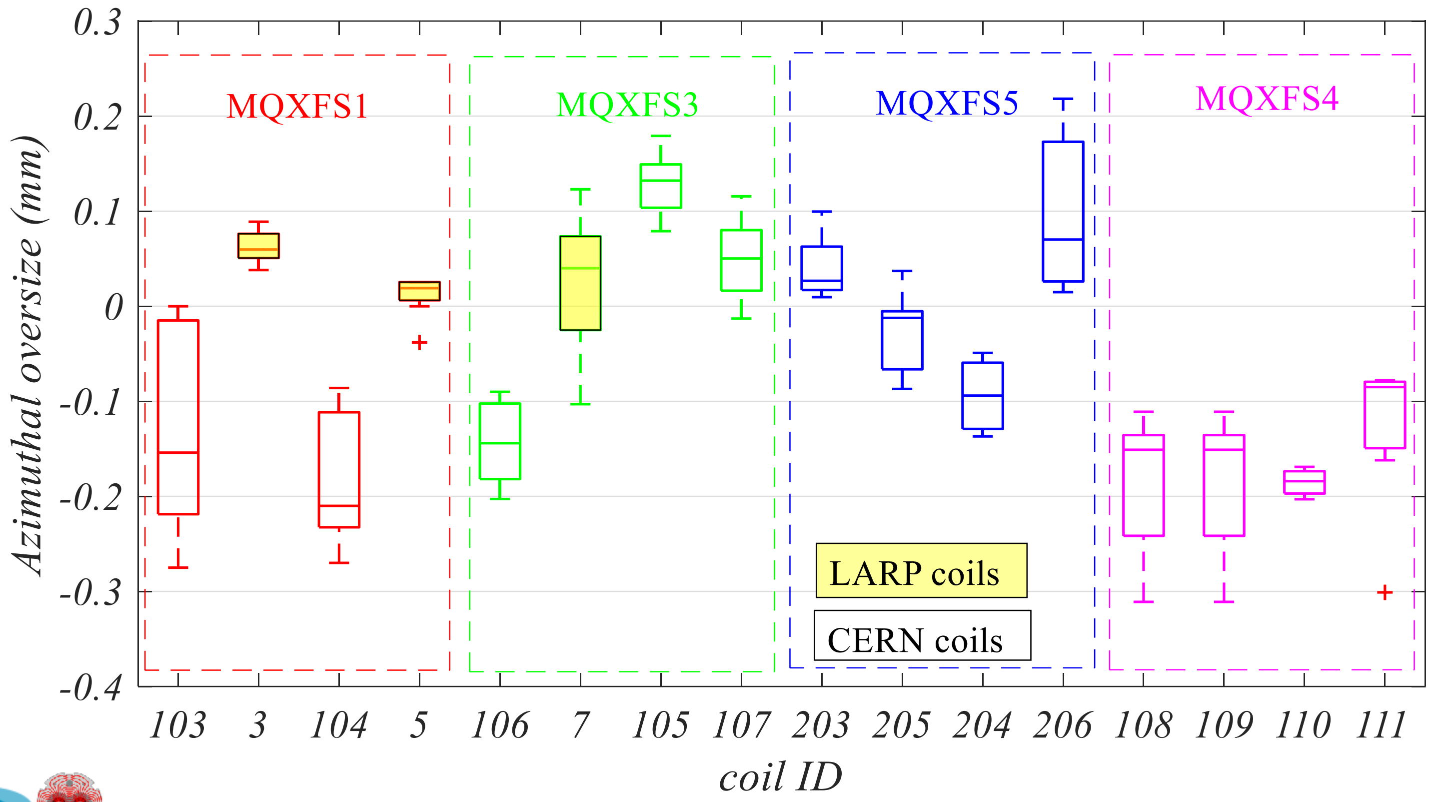
# Inner Layer Diameter Insulation Lay Out



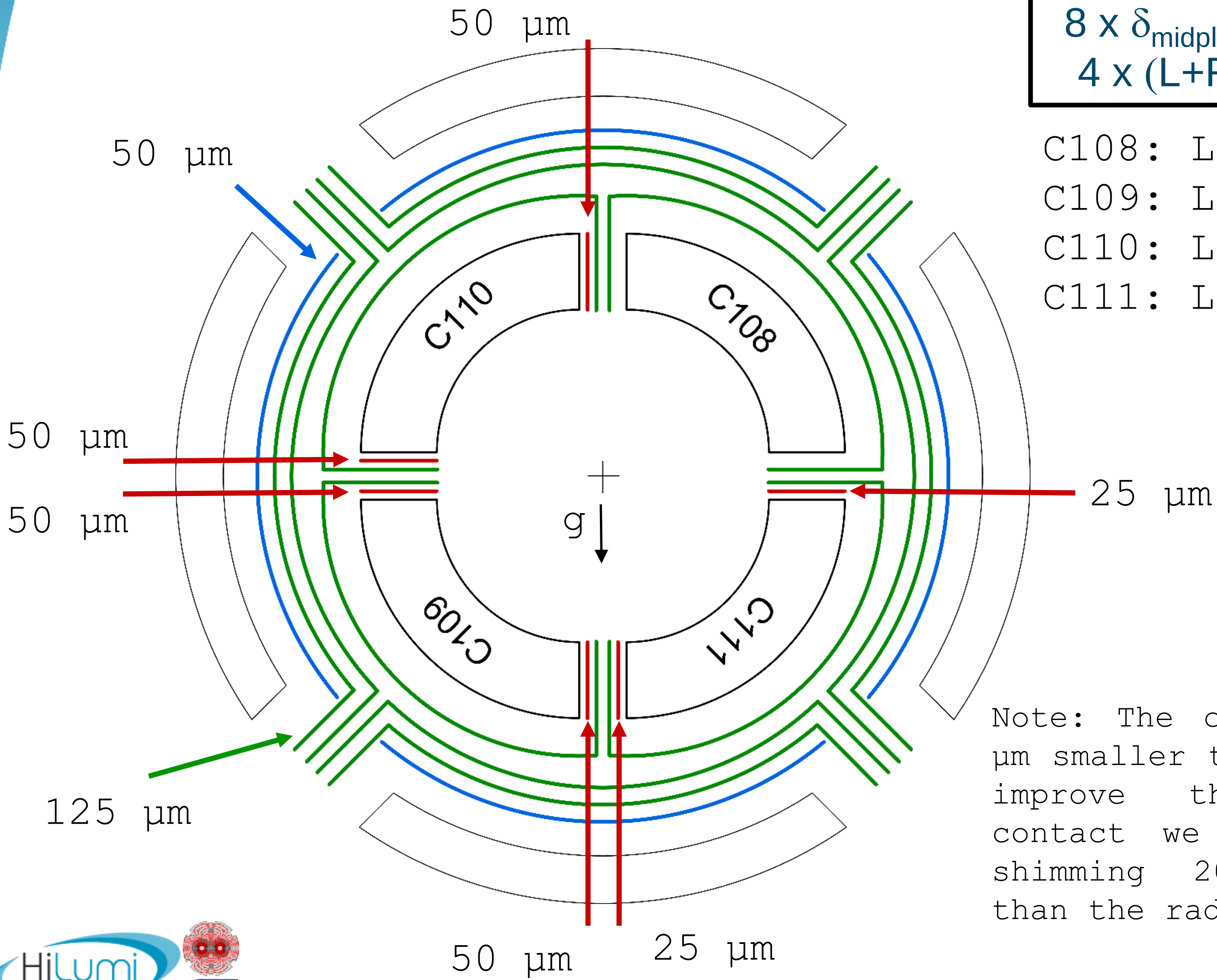

| COIL | Inner Diameter Configuration | Polyamide trace Nom/real (µm) | S2 glass Type/Nom/real (µm) |
|---|---|---|---|
| **C108** | **Standard IL trace** | 100/75 | S2 Glass Hexcel 4522/150/120-160 |
| **C109** | **Standard IL trace** | 100/75 | S2 Glass Hexcel 4522/150/120-160 |
| **C110** | **Pressed encapsulated trace** | 100/125 | S2 Glass Hexcel 4522/150/120-160 |
| **C111** | **Laminated encapsulated trace** | 100/125 | S2 Glass Hexcel 4522/150/120-160 |

# Overview on coil size for assembled magnets

- MQXFS4 is the magnet with the lowest difference among coils in terms of azimuthal oversize
  - Difference among coils on the magnet assembly still needs to be compensated by radial or azimuthal shimming.



# Coil Pack Assembly




$$8 \times \delta_{midplane} = 2\,\pi \times \delta R_{OR}$$
$$4 \times (L+R) = 2\,\pi \times \delta R_{OR}$$

C108: L+R = - 100 μm
C109: L+R = - 200 μm
C110: L+R = - 200 μm
C111: L+R = - 150 μm

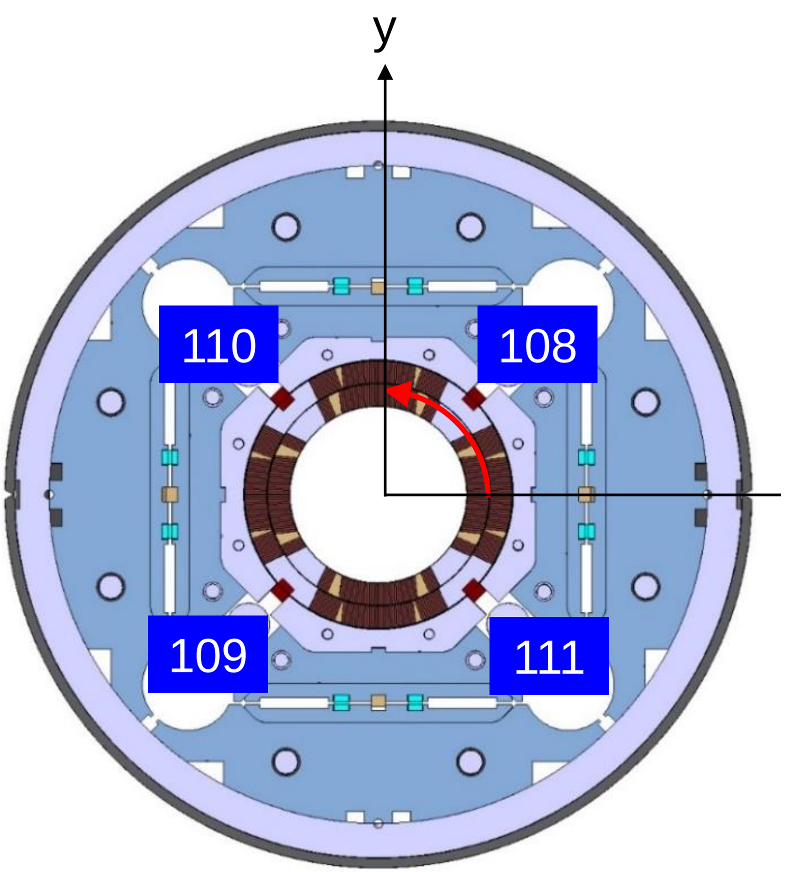
| L+R (μm) | $dR_{OR}$(μm) |
|---|---|
| 50 | 31.831 |
| 100 | 63.662 |
| 150 | 95.493 |
| 200 | 127.324 |
| 250 | 159.155 |
| 300 | 190.986 |

Note: The coil pack is 63 μm smaller than nominal. To improve the collar/coil contact we apply a total shimming 200 μm smaller than the radial distance.

# Reference Axis For Magnetic Measurements

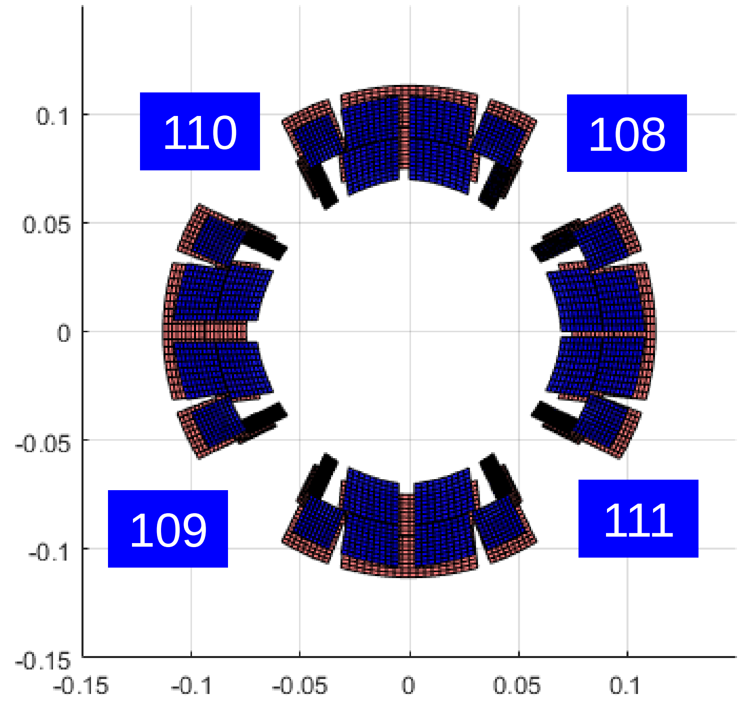
*Magnet and coil positioning*

*(magnetic reference axis)*




Parameter Set - [mm]:

| | overSize | midShim | orDelta | dThick |
|---|---|---|---|---|
| C108 | -0.05 | 0.000 | 0 | 0 |
| C110 | -0.1 | 0.050 | 0 | 0 |
| C109 | -0.1 | 0.050 | 0 | 0 |
| C111 | -0.075 | 0.025 | 0 | 0 |

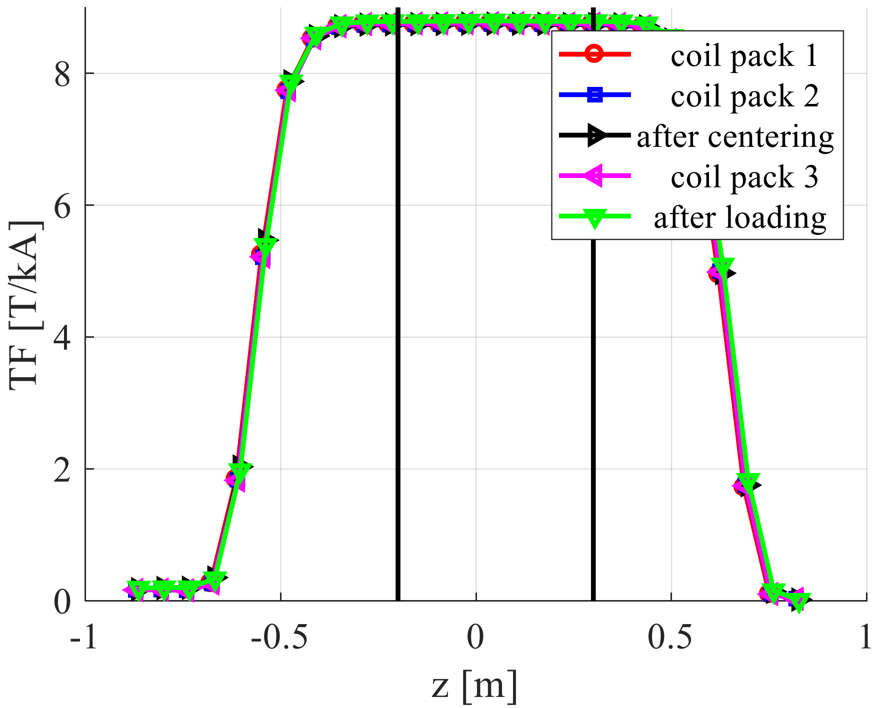


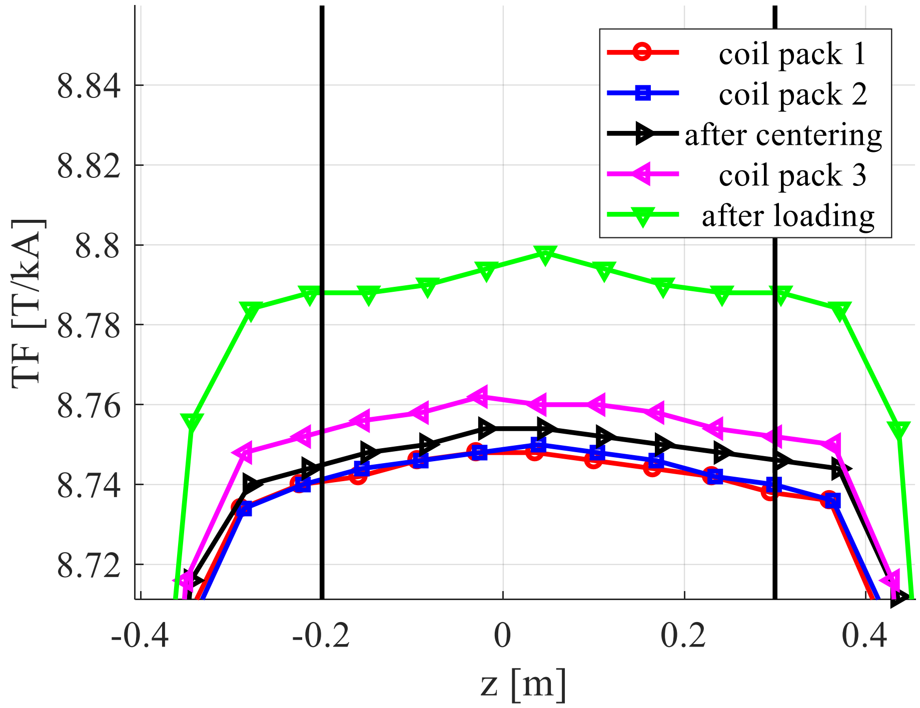
# Assembly History and Measurements

- Assembly of Coil Pack 1.
- **Magnetic Measurements on Coil Pack 1.**
- We realized that the material of the key is the Japanese High Radiation Material instead of G10 (baseline) → Decision to dismount and re-assembly using the right material for the key.
- Assembly of Coil Pack 2
- **Magnetic Measurements on Coil Pack 2**
- Centering of Coil Pack 2 in the structure.
- **Magnetic Measurements on Coil Pack 2 after centering.**
- During the initial loading, large unbalance of the strain in one of the coils → Decision to dismount and inspect. Default on the gluing of the strain gauges. Gauges were re-glued and issue disappeared.
- Assembly of Coil Pack 3
- **Magnetic Measurements on Coil Pack 3.**
- Centering of Coil Pack 3 in the structure.
- Magnetic measurements on the magnet after centering were not done for schedule constrains.
- Loading of Coil Pack 3.
- **Magnetic Measurements on Coil Pack 3 after centering.**

# Transfer Function

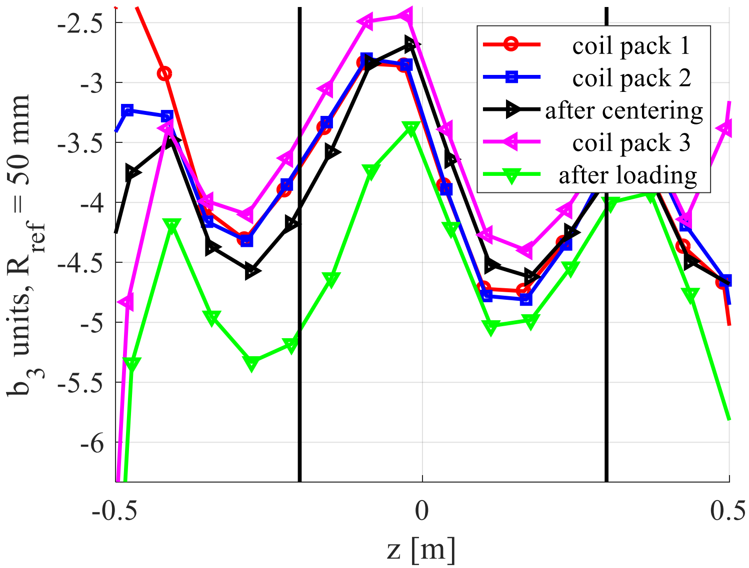
- 35 units increase on the main field due to the loading.
- 10 units variation on the main field in the straight section after loading.
  - This is around 2 times the measured longitudinal variation on the main field in MQXFS5.

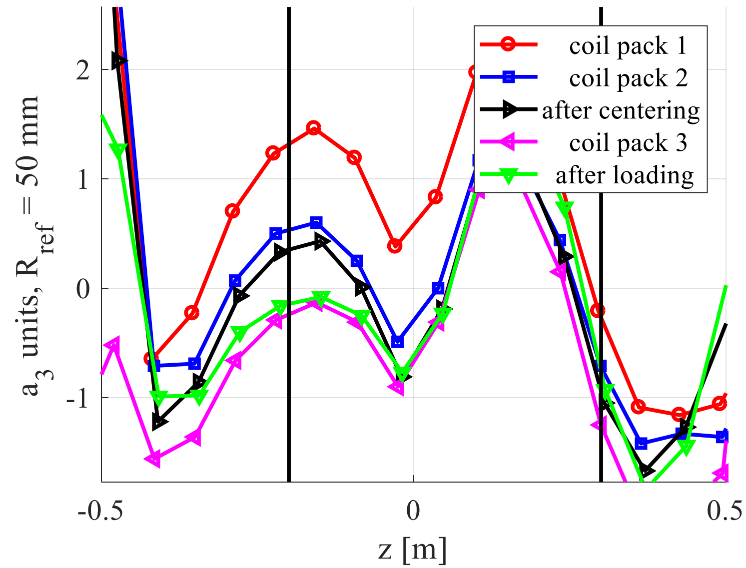


# $b_3/a_3$

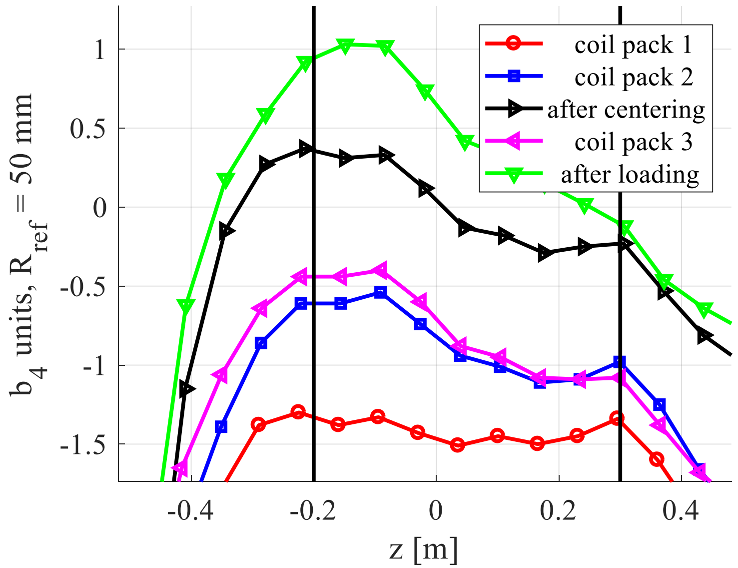
- Almost 1 unit of variation in $a_3$ between coil pack 1 and 2, even if the same shims and procedure was used (only the pole-collar key material changed)
- Small variation on the harmonics on the coil pack 2 after centering, consistent with previous magnets.
- 1 unit variation on $b_3$ with the centering + loading
- Shape of the harmonics is the same for all measurements.

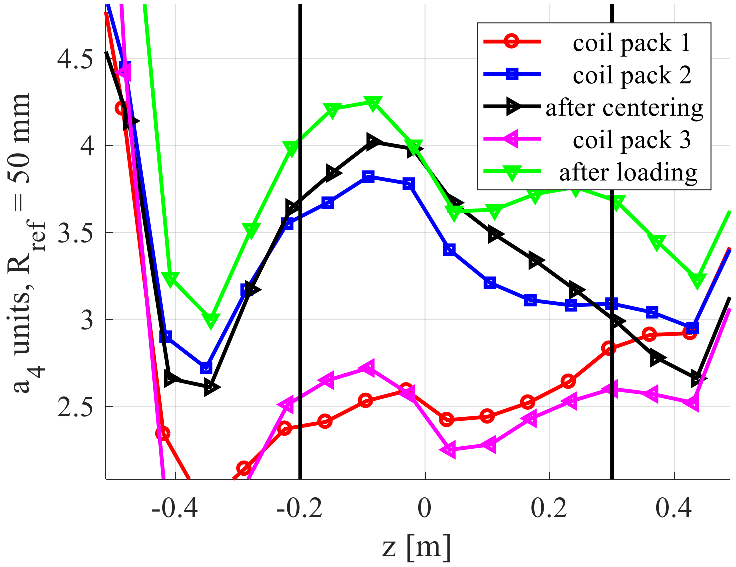


# $b_4/a_4$

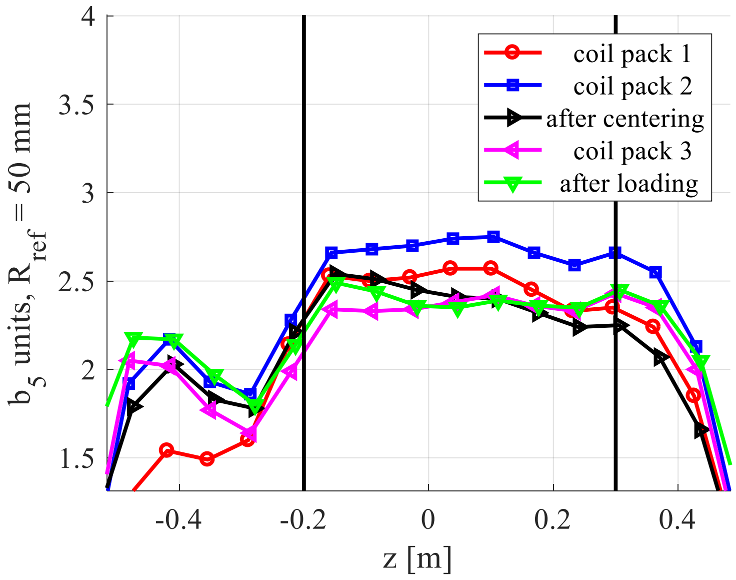
- Around 1 unit of variation in $b_4$ and $a_4$ between coil pack 1 and 2, even if the same shims and procedure was used (only the pole-collar key material changed)
- Almost 1 unit of variation in $b_4$ with the centering
- Around 1.5 unit variation on $b_4$ & $a_4$ with the centering + loading
- Coil pack 3 is as coil pack 2 in terms of $b_4$ and as coil pack 1 in terms of $a_4$.

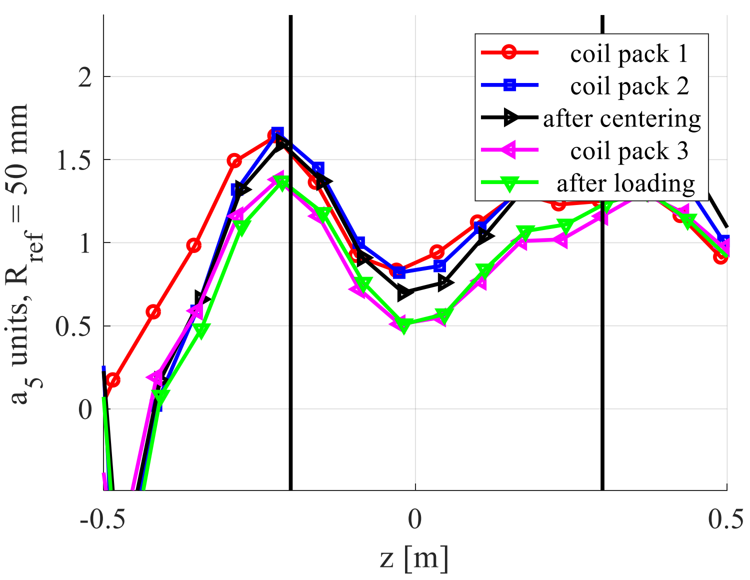


# $b_5/a_5$

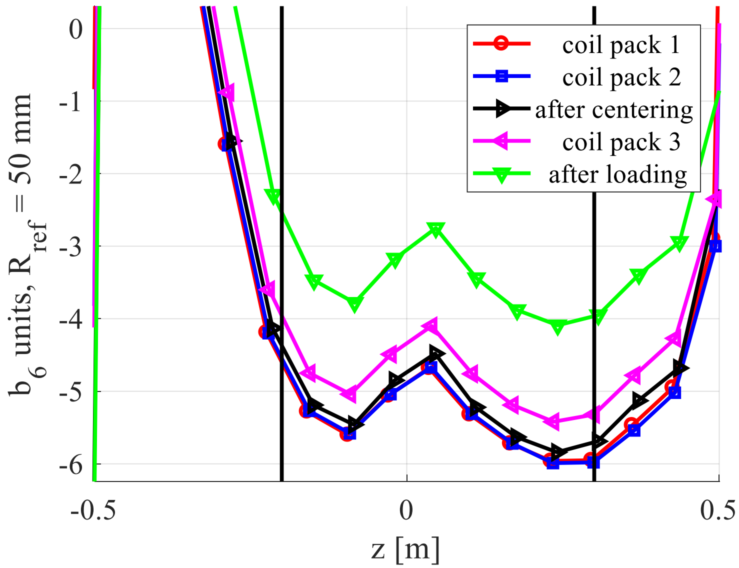
- $b_5$ and $a_5$ are not affected with the centering + loading
- Around 0.2 units difference on $b_5$ for the different coil packs assemblies.
- $b_5$ is very close for coil pack 1 and 2, 0.3 units smaller for coil pack 3.

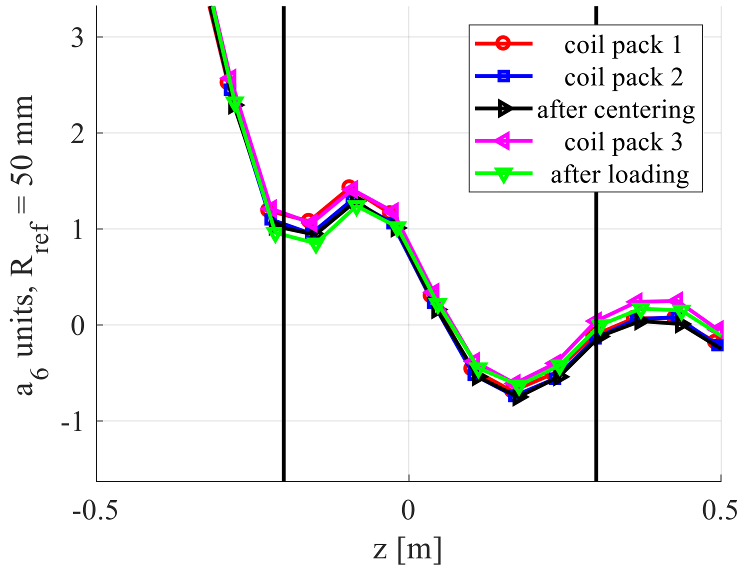


# $b_6/a_6$

- $b_6$ is very close for coil pack 1 and 2, 0.5 units larger for coil pack 3.
- $b_6$ increases by 1 unit due to the centering + loading. This is consistent with the previous magnets and expected due to the computed ANSYS deformation.



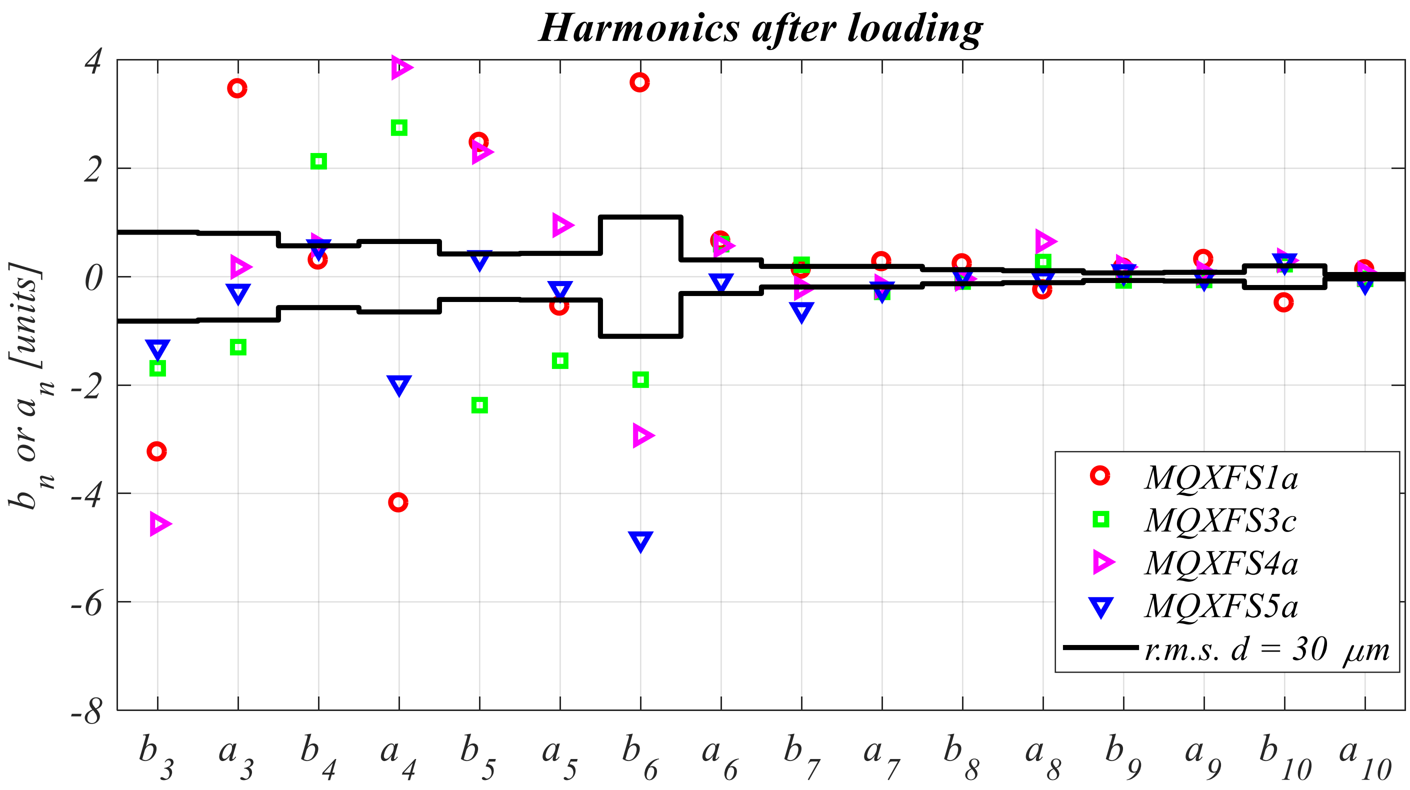



# Summary

| MQXFS4a – Geometric. Average in the straight section | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coil pack + Pad assembly 1 (927) | | Coil pack + Pad assembly 2 (927) | | After centering (927) | | Coil pack + Pad assembly 3 (927) | | After loading (927) | |
| | (warm) | | (warm) | | (warm) | | (warm) | | (warm) | |
| | TF T/m/kA | int T/kA | TF T/m/kA | int T/kA | TF T/m/kA | int T/kA | TF T/m/kA | int T/kA | TF T/m/kA | int T/kA |
| | 8.743 | 10.396 | 8.744 | 10.436 | 8.750 | 10.495 | 8.756 | 10.447 | 8.791 | 10.547 |
| Lm (mm) | 1189 | | 1193 | | 1200 | | 1193 | | 1200 | |
| n | bn | an | bn | an | bn | an | bn | an | bn | an |
| 3 | -3.88 | 1.05 | -3.87 | 0.30 | -3.88 | 0.25 | -3.54 | -0.18 | -4.56 | 0.18 |
| 4 | -1.41 | 2.49 | -0.85 | 3.39 | 0.06 | 3.59 | -0.76 | 2.46 | 0.58 | 3.86 |
| 5 | 2.36 | 1.21 | 2.56 | 1.22 | 2.32 | 1.16 | 2.26 | 0.94 | 2.30 | 0.95 |
| 6 | -4.94 | 0.59 | -4.94 | 0.51 | -4.71 | 0.54 | -4.36 | 0.64 | -2.93 | 0.57 |
| 7 | -0.29 | -0.13 | -0.25 | -0.22 | -0.23 | -0.17 | -0.20 | -0.26 | -0.21 | -0.18 |
| 8 | -0.06 | 0.53 | -0.05 | 0.61 | -0.07 | 0.65 | -0.04 | 0.51 | -0.04 | 0.65 |
| 9 | 0.13 | 0.17 | 0.14 | 0.11 | 0.15 | 0.11 | 0.15 | 0.11 | 0.18 | 0.07 |
| 10 | 0.26 | 0.05 | 0.24 | 0.05 | 0.25 | 0.05 | 0.26 | 0.06 | 0.30 | 0.06 |
| 11 | -0.11 | -0.05 | -0.11 | -0.05 | -0.09 | -0.05 | -0.10 | -0.06 | -0.09 | -0.04 |
| 12 | -0.04 | -0.01 | 0.01 | -0.01 | 0.00 | -0.02 | 0.00 | -0.02 | 0.00 | 0.01 |
| 13 | 0.06 | 0.00 | 0.06 | 0.16 | 0.02 | 0.19 | 0.02 | 0.07 | 0.04 | 0.18 |
| 14 | -0.74 | -0.03 | -0.73 | -0.03 | -0.72 | -0.02 | -0.75 | -0.02 | -0.75 | -0.02 |
| 15 | 0.00 | -0.02 | -0.01 | -0.02 | -0.01 | -0.02 | -0.01 | -0.01 | 0.00 | -0.02 |

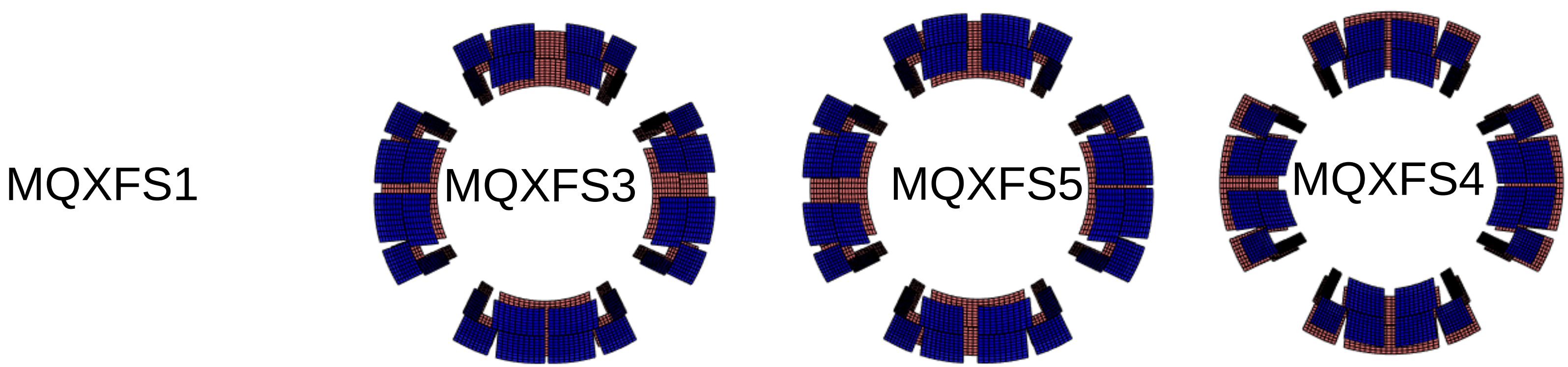
# Geometric harmonics after loading

- Large $b_3$ → Magnetic shims installed to correct it.
- Our typical high $a_4/b_5$ is also present in MQXFS4



# Field errors at warm after magnet loading

- ***$b_3$*** and ***$a_3$***:
  - Asymmetric shimming explains about half of the contribution measured in MQXFS1.
  - In MQXFS3 and MQXFS5, sextupole errors relatively small.
  - The large measured $b_3$ in MQXFS4 cannot be explained through coil shimming.
- ***$b_4$*** and ***$a_4$***
  - Asymmetric shimming explains measured contribution in MQXFS1 and MQXFS5.
  - Larger errors than expected in MQXFS3 and MQXFS4.
- ***$b_5$*** is 1-2 units larger than predicted in all the magnets, whereas ***$a_5$*** is close (within 1 unit) to the computed values.

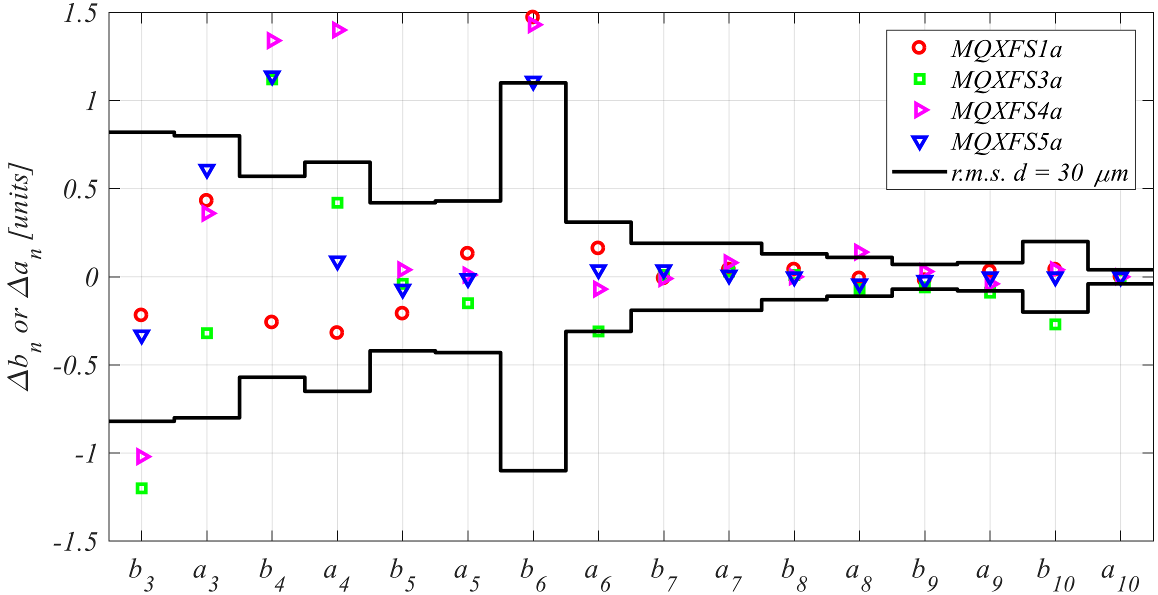



| n | MQXFS1a | | | | MQXFS3a | | | | MQXFS5a | | | | MQXFS4a | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Measured | | Computed | | Measured | | Computed | | Measured | | Computed | | Measured | | Computed | |
| | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ |
| **3** | -3.24 | 3.46 | -1.53 | 1.52 | -1.69 | -1.3 | 0.67 | -0.67 | -1.3 | -0.27 | -0.68 | 0 | -4.56 | 0.18 | -0.32 | 0.10 |
| **4** | 0.3 | -4.18 | 0 | -4.64 | 2.13 | 2.75 | 0 | -0.72 | 0.55 | -1.96 | 0 | -0.72 | 0.58 | 3.86 | 0.00 | 0.32 |
| **5** | 2.47 | -0.55 | 0.69 | 0.69 | -2.37 | -1.55 | -1.33 | -1.33 | 0.35 | -0.22 | 1.33 | 0 | 2.30 | 0.95 | 0.57 | 0.19 |

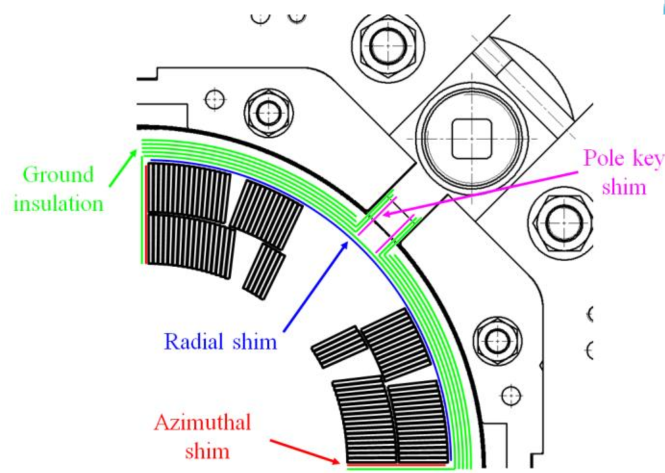
# Change of harmonics due to loading

- Larger variation on $a_4/a_8$ than in previous assemblies.
- Due to coil deformation during loading, 1 unit increased of $b_6$ due to magnet loading is expected, in agreement with the measurements.
- Small change of the rest of harmonics with magnet loading, independent of the coil to structure alignment conditions before magnet loading.
  - Dominant source of field errors is the coil geometry and not its alignment on the magnet structure.

*Change on field errors (after loading – before loading)*




| Magnet | Pole-key alignment for measurements before loading? |
|---|---|
| MQXFS1 | Yes |
| MQXFS3 | No |
| MQXFS5 | No |
| MQXFS4 | No |

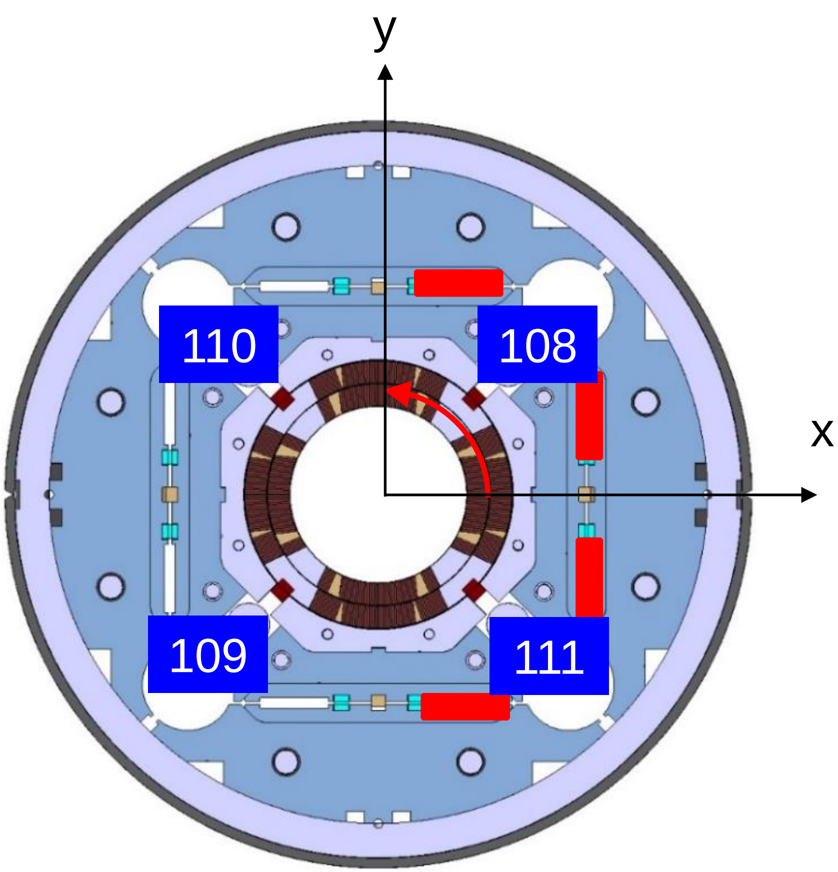



Remark: Before loading conditions not identical for all assemblies:
- MQXFS1a: coil pack centered in the magnet structure
- MQXF3a: coil pack (without magnetic pads)
- MQXFS4a and MQXFS5a: coil pack + magnetic pads

# Magnetic Shimming MQXFS4

*Magnet and coil positioning*

*(magnetic reference axis)*

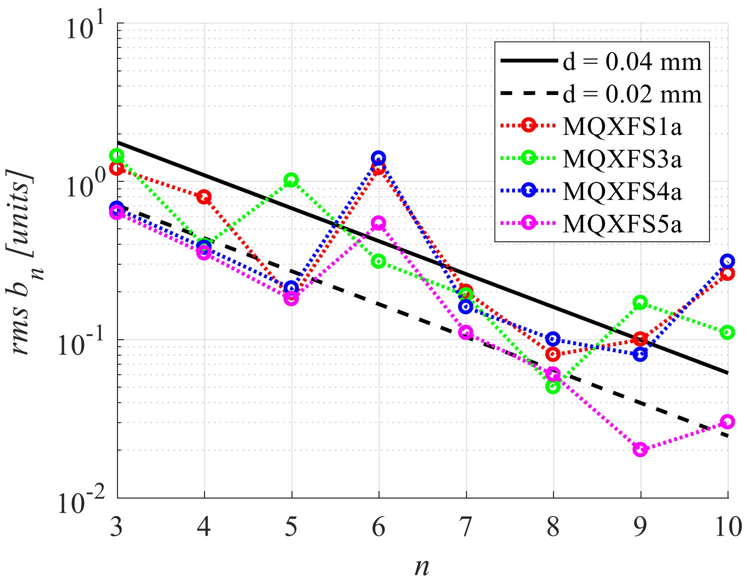


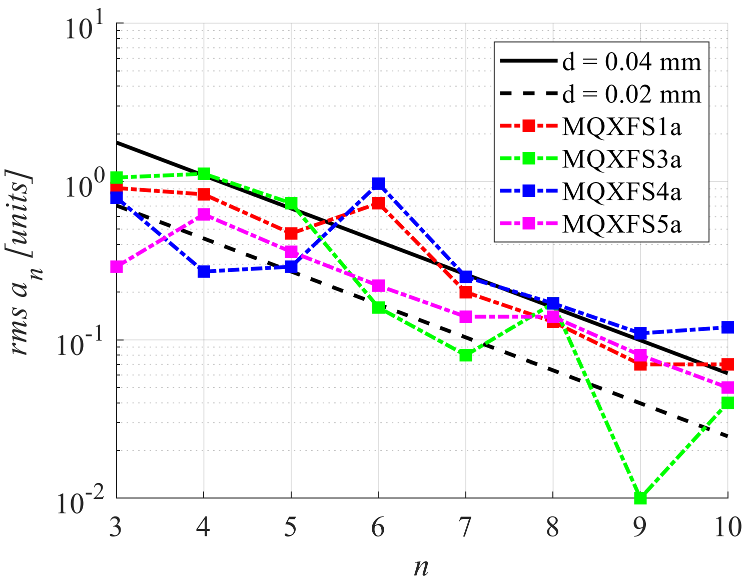

| Correction capabilities using 9x58 mm shim in the bladder slots | | |
|---|---|---|
| Order | bn | an |
| 3 | 3.42 | 0.00 |
| 4 | 0.00 | 0.00 |
| 5 | 0.11 | 0.00 |

*See slides from Lucio Fiscarelli for the impact of magnetic shims at cold*

# Coil Waviness

- Field homogeneity is measured along magnet axis, using ~ 100 mm probe.
- The spread on the measurements along the magnet axis, indicate a 0.02-0.04 mm precision on the longitudinal position of the conductors block.
- This spread is similar to what is obtained for the LHC dipoles and previous $Nb_3Sn$ magnets [1].



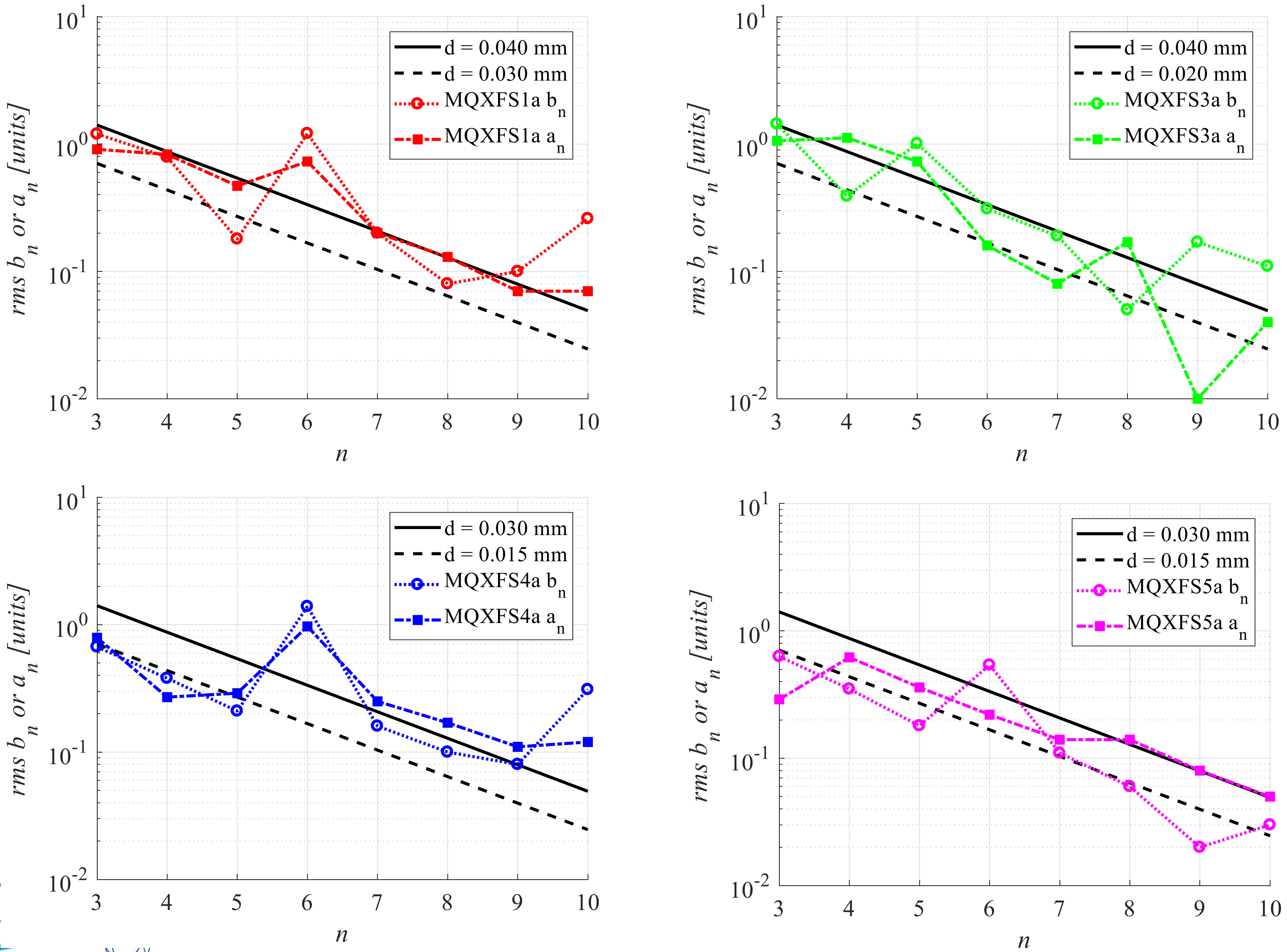





[1] F. Borgnolutti, *et al.*, "Reproducibility of the Coil Positioning in Nb3Sn Magnet Models Through Magnetic Measurements", *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1100-1105, 2009.

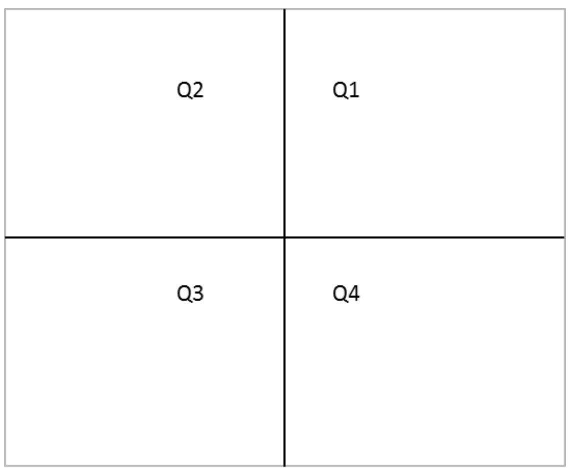
# Additional slides

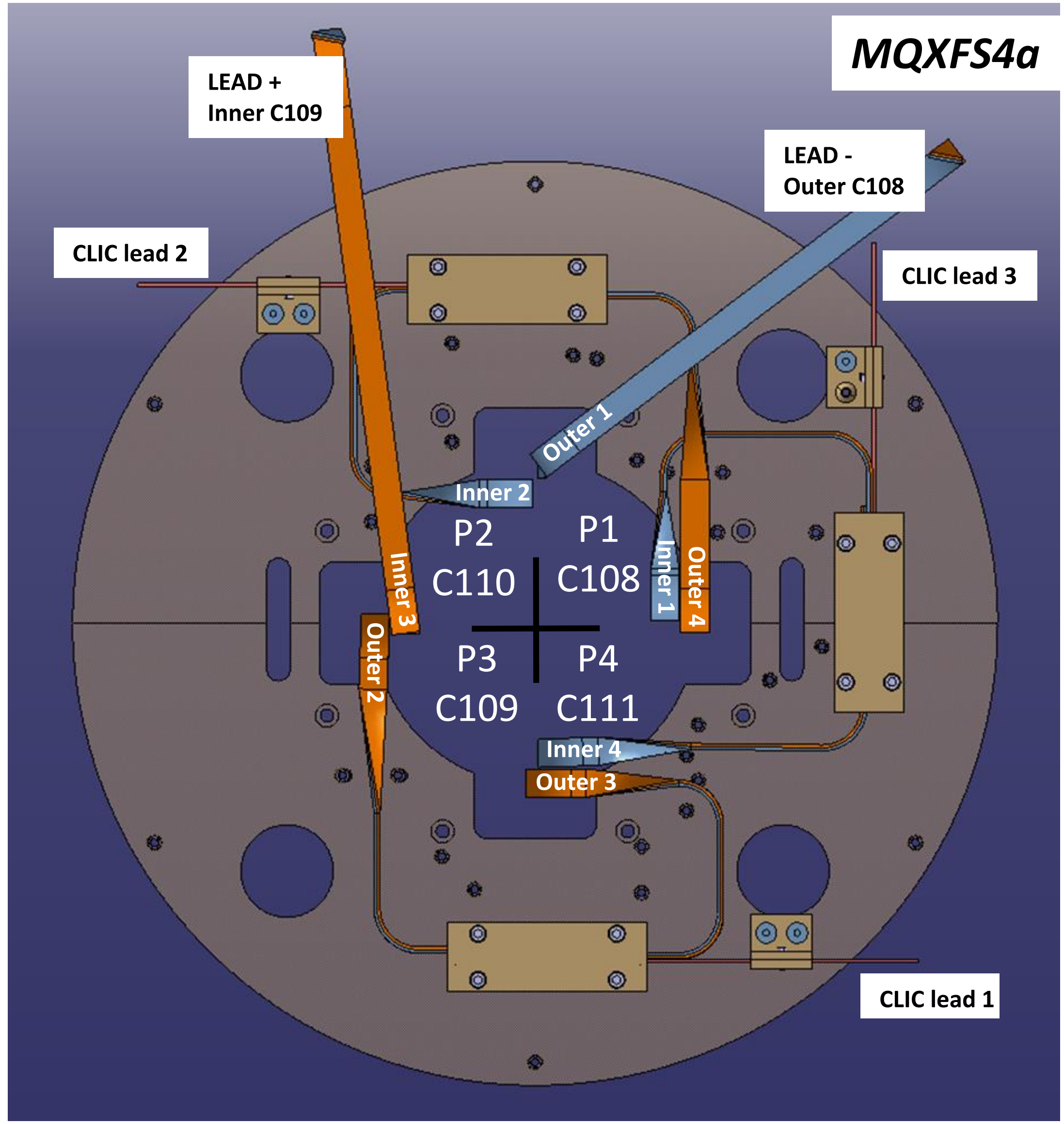
# Coil waviness



Interconnection Scheme
EDMS 1936345

In the magnetic measurements reference frame, C108 is in Q1




Connexion order:

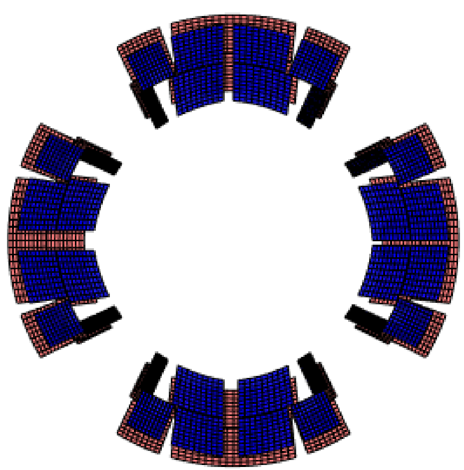
- eP1/iP1---iP4/eP4---iP2/P2e---eP3/P3i +
- e108/108i---i111/111e---i110/110e---e109/109i +

| MQXFS4a – Coil wavines | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coil pack + Pad assembly 1 (927) | | Coil pack + Pad assembly 2 (927) | | After centering (927) | | Coil pack + Pad assembly 3 (927) | | After loading (927) | |
| | (warm) | | (warm) | | (warm) | | (warm) | | (warm) | |
| | TF units | | TF units | | TF units | | TF units | | TF units | |
| | 4.73 | | 5.05 | | 3.92 | | 4.62 | | 4.12 | |
| | | | | | | | | | | |
| n | bn | an | bn | an | bn | an | bn | an | bn | an |
| 3 | 0.68 | 0.66 | 0.72 | 0.62 | 0.74 | 0.62 | 0.70 | 0.71 | 0.67 | 0.79 |
| 4 | 0.07 | 0.18 | 0.21 | 0.30 | 0.27 | 0.32 | 0.29 | 0.20 | 0.38 | 0.27 |
| 5 | 0.30 | 0.26 | 0.28 | 0.27 | 0.23 | 0.31 | 0.25 | 0.29 | 0.21 | 0.29 |
| 6 | 1.30 | 1.05 | 1.30 | 1.03 | 1.30 | 1.02 | 1.34 | 1.01 | 1.39 | 0.97 |
| 7 | 0.20 | 0.31 | 0.21 | 0.30 | 0.18 | 0.26 | 0.19 | 0.29 | 0.16 | 0.25 |
| 8 | 0.14 | 0.15 | 0.12 | 0.18 | 0.11 | 0.18 | 0.12 | 0.16 | 0.10 | 0.17 |
| 9 | 0.09 | 0.09 | 0.09 | 0.10 | 0.09 | 0.11 | 0.09 | 0.10 | 0.08 | 0.11 |
| 10 | 0.29 | 0.14 | 0.30 | 0.14 | 0.31 | 0.13 | 0.30 | 0.13 | 0.31 | 0.12 |
| 11 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 |
| 12 | 0.03 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.07 | 0.07 | 0.02 | 0.02 |
| 13 | 0.05 | 0.06 | 0.07 | 0.09 | 0.05 | 0.04 | 0.09 | 0.14 | 0.04 | 0.03 |
| 14 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.05 | 0.04 | 0.03 | 0.04 |
| 15 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.04 | 0.01 | 0.01 |

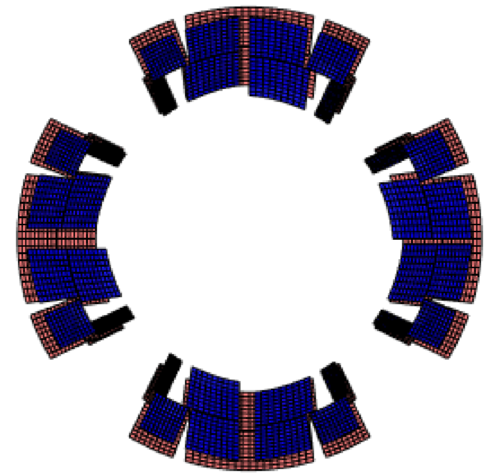
# Inner layer heaters asymmetry

- The difference on inner heater layout is not helping to explain anything.

| n | MQXFS4a – Excluding Inner Layer Heaters asymmetry | | | | MQXFS4a - Including Inner Layer Heaters asymmetry | | | |
|---|---|---|---|---|---|---|---|---|
| | Measured | | Computed | | Measured | | Computed | |
| | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ | $b_n$ | $a_n$ |
| 3 | -4.56 | 0.18 | -0.32 | 0.10 | -4.56 | 0.18 | -0.32 | 0.10 |
| 4 | 0.58 | 3.86 | 0.00 | 0.32 | 0.58 | 3.86 | 0.00 | -1.23 |
| 5 | 2.30 | 0.95 | 0.57 | 0.19 | 2.30 | 0.95 | 0.58 | 0.19 |



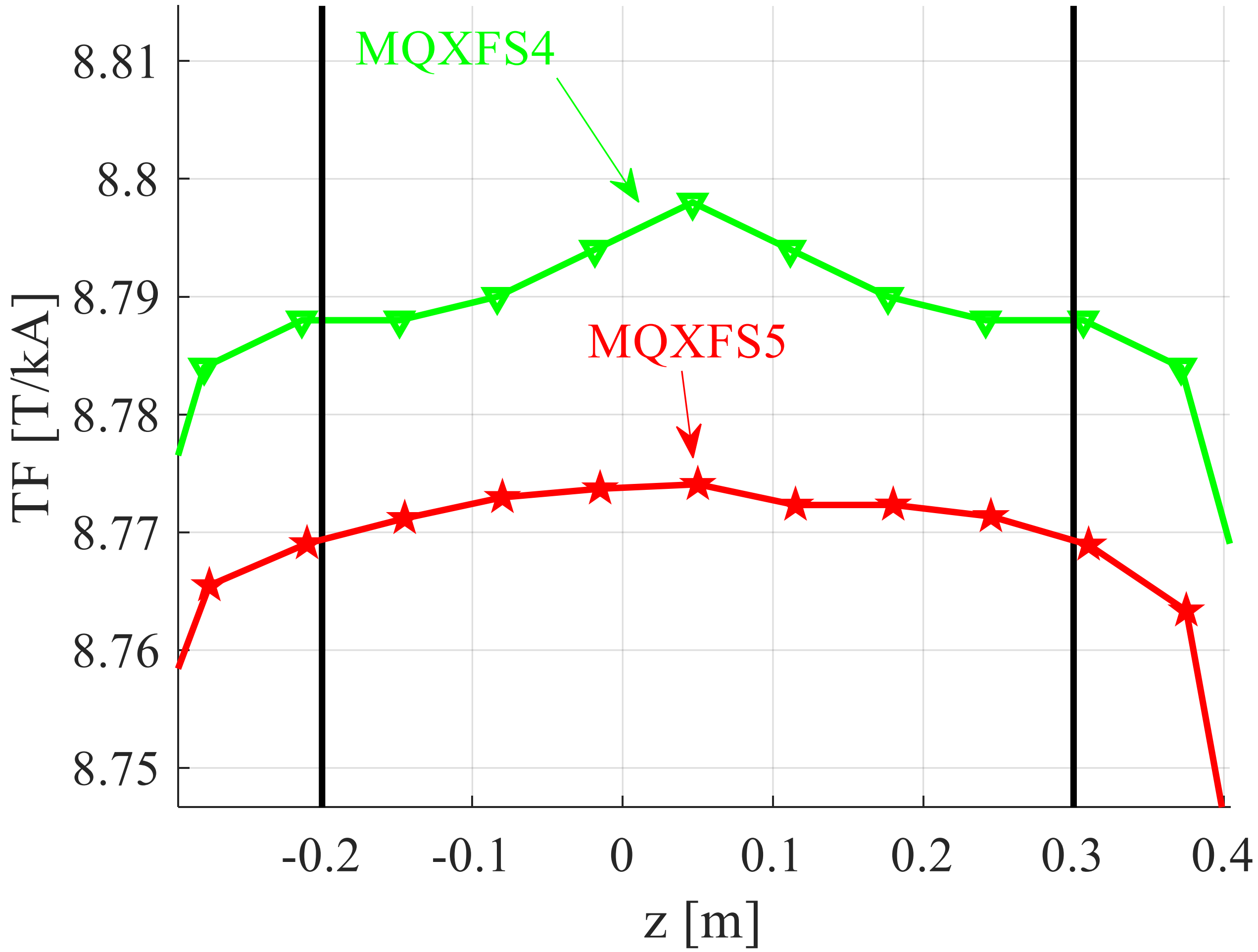
| | overSize | midShim | orDelta | dThick |
|---|---|---|---|---|
| C108 | -0.05 | 0.000 | 0 | 0 |
| C110 | -0.1 | 0.050 | 0 | 0 |
| C109 | -0.1 | 0.050 | 0 | 0 |
| C111 | -0.075 | 0.025 | 0 | 0 |



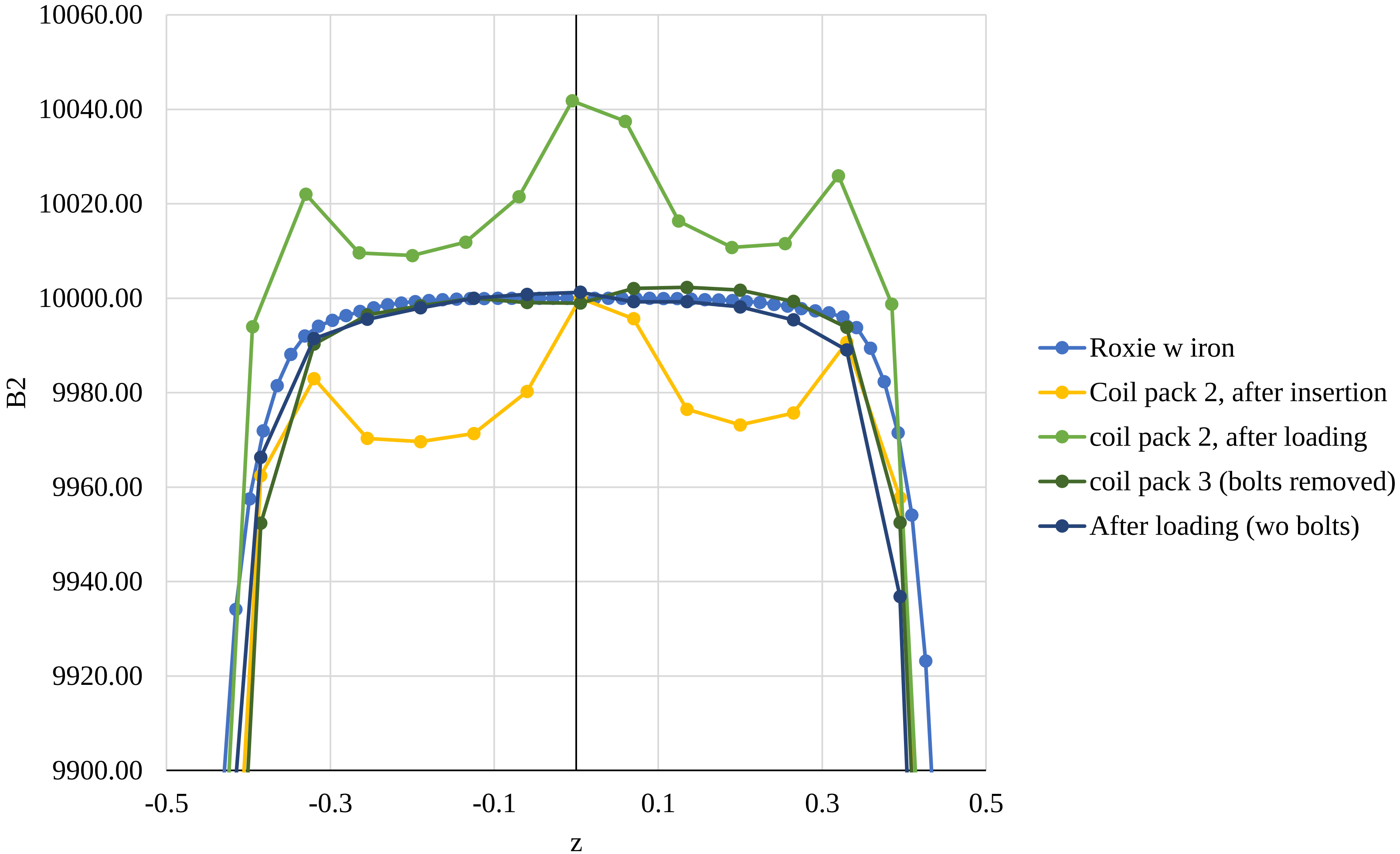
| | overSize | midShim | orDelta | dThick |
|---|---|---|---|---|
| C108 | -0.05 | 0 | 0 | 0 |
| C110 | -0.1 | 0.05 | 0 | -0.05 |
| C109 | -0.1 | 0.05 | 0 | 0 |
| C111 | -0.075 | 0.025 | 0 | -0.05 |

HiLumi HL-LHC PROJECT CERN

# Comparison TF



# MQXFS5



10060.00
10040.00
10020.00
10000.00
9980.00
9960.00
9940.00
9920.00
9900.00
B2
-0.5
-0.3
-0.1
0.1
0.3
0.5
z
Roxie w iron
Coil pack 2, after insertion
coil pack 2, after loading
coil pack 3 (bolts removed)
After loading (wo bolts)