MQXFB magnet assembly, including actions to limit peak stress

Jose Ferradas Troitino, Susana Izquierdo Bermudez on behalf of the MQXF collaboration

Acknowledgements: Stephane Triquet, Nicholas Lusa, Attilio Milanese, Juan Carlos Perez, Helene Felice, Ezio Todesco, Arnaud Devred and all the MQXFB/A teams.

12th HL-LHC Collaboration Meeting, Uppsala (Sweden), 19-22 September 2022

Acknowledgement

- US HL-LHC Accelerator Upgrade Project (AUP)
  - BNL: K. Amm, M. Anerella, A. Ben Yahia, H. Hocker, P. Joshi, J. Muratore, J. Schmalzle, H. Song, P. Wanderer
  - FNAL: G. Ambrosio, G. Apollinari, M. Baldini, J. Blowers, R. Bossert, R. Carcagno, G. Chlachidze, J. DiMarco, S. Feher, S. Krave, V. Lombardo, C. Narug, A. Nobrega, V. Marinozzi, C. Orozco, T. Page M. Parker, S. Stoynev, T. Strauss, M. Turenne, D. Turrioni, A. Vouris, M. Yu
  - LBNL: D. Cheng, P. Ferracin, L. Garcia Fajardo, E. Lee, M. Marchevsky, M. Naus, H. Pan, I. Pong, S. Prestemon, K. Ray, G. Sabbi, G. Vallone, X. Wang
  - NHMFL: L. Cooley, J. Levitan, J. Lu, R. Walsh
- CERN: HL-LHC Project
  - A. Ballarino, H. Bajas, M. Bajko, B. Bordini, N. Bourcey, S. Izquierdo Bermudez, H. Felice, S. Ferradas Troitino, L. Fiscarelli, J. Fleiter, M. Guinchard, O. Housiaux, F. Lackner, F. Mangiarotti, A. Milanese, P. Moyret, J.C. Perez, H. Prin, R. Principe, E. Ravaioli, T. Sahner, S. Sequeira Tavares, E. Takala, E. Todesco

Outline

- Introduction
- MQXFB magnet assembly in a nutshell
- Coil pack preparation
- Yoke-shell assembly
- Magnet loading
- Conclusions

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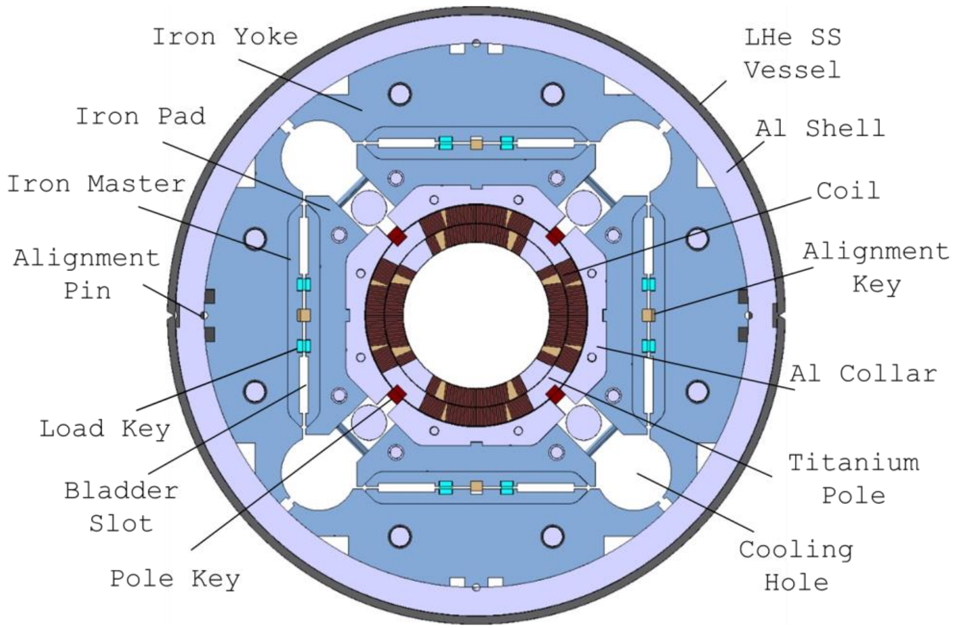
Magnet design – Reminder

- Target: 132.2 T/m; 150 mm coil aperture, **11.3 T B_{peak}.**
- Q1/Q3 (by US-AUP Project), 2 magnets **MQXFA** with 4.2 m L_{m}.
- Q2a/Q2b (by CERN), 1 magnet **MQXFB** with 7.15 m L_{m}.
- Different lengths, same design, very similar assembly procedure and loading target.
- **Three prototypes built** and **tested** up to date: **MQXFBP1, BP2 and BP3.**

Joint short model development program **(MQXFS)** to validate the design.



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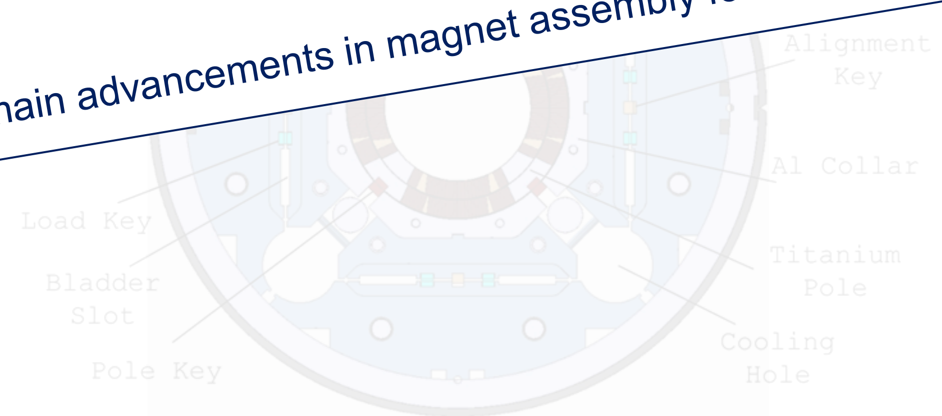
- Different lengths, same de
- Three

What's new since last collaboration meeting?
https://indico.cern.ch/event/1079026

- Following the limited performance of MQXFBP2, the assembly of new magnets was put on hold.
- Three "main axes" were identified to tackle the performance limitation issue, among them the magnet assembly (see *talk from E. Todesco, "Status of WP3 with focus on MQXFB"*).
- A mechanical assembly test, known as MQXFBMT3, was launched to optimize the assembly process and further assess potential issues linked to conductor over-stress. Details were treated in last collaboration meeting.
- Based on all lessons learnt, final green light was given for the assembly of a new magnet in summer 2022: **MQXFB02**.

This presentation will thus focus on the main advancements in magnet assembly for MQXFB02!



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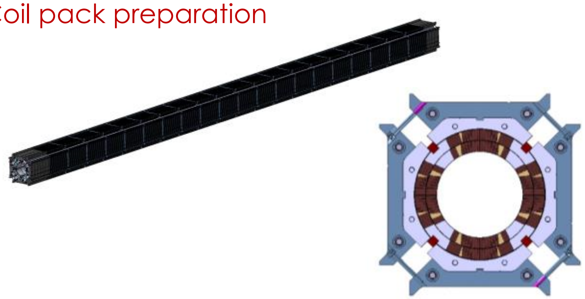
MQXFB magnet assembly in a nutshell

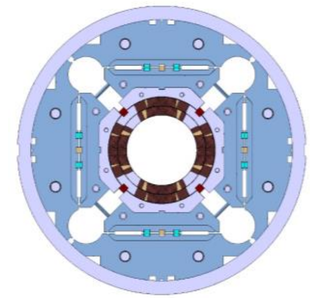
Magnet assembly:

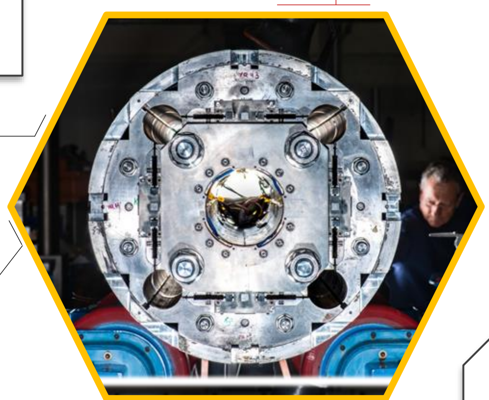
Coils → Coil pack preparation → Insertion in the structure → Centering, az. and long. loading

Coil pack preparation

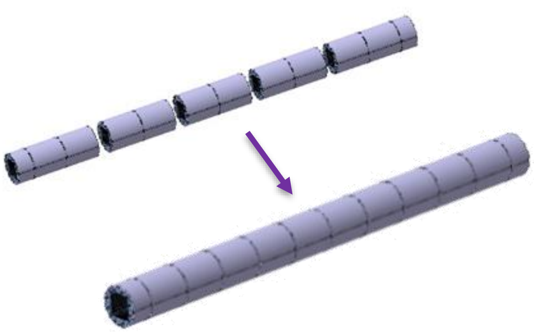


Coil pack insertion and centering

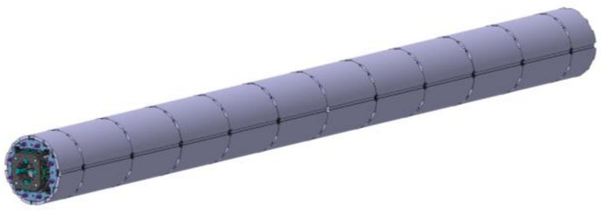




Assembly of the yoke-shell structure



Azimuthal and longitudinal magnet loading



MQXFB magnet assembly in a nutshell

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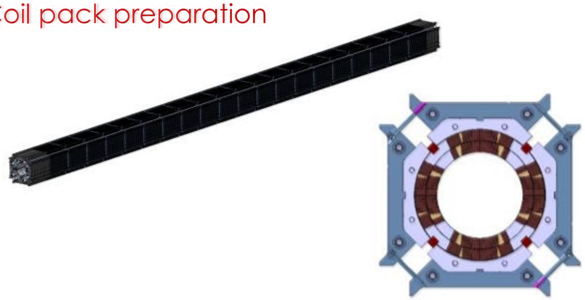
Coil pack preparation



Coil pack insertion and centering

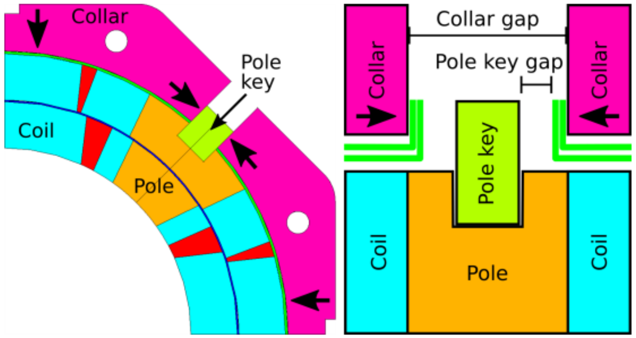
Assembly of the yoke-shell structure

Azimuthal and longitudinal magnet loading

Coil pack assembly

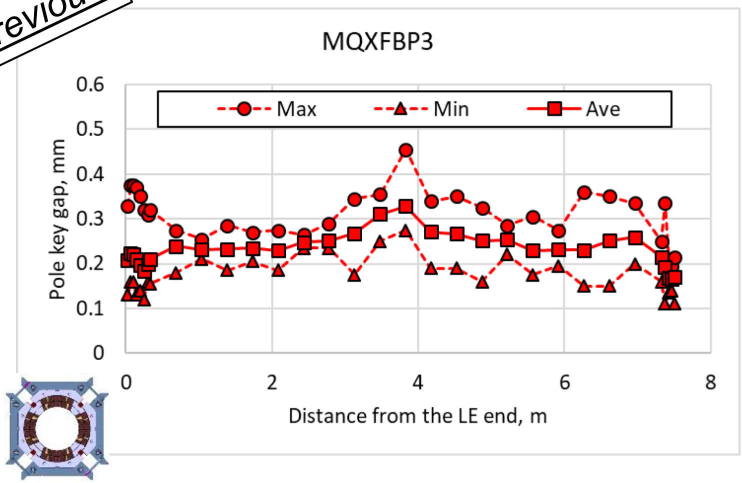
Based on previous magnets experience and the recent findings in MQXFA magnets (see *talk from P. Ferracin, "MQXFA magnet assembly"*):

- **Refined procedures** for the coil pack preparation have been established, including **tighter** geometrical **targets.**
- **Special** attention is now paid to get "our best" of a **square geometry**. Important in terms of magnet mechanics, but also seen in magnetic measurements (change in harmonics during centering).
- **Gap** in the **pole key increased** to **550 µm** per side (previously 300 µm), ensuring **no force interception** at the collar level **all along** the **length**.

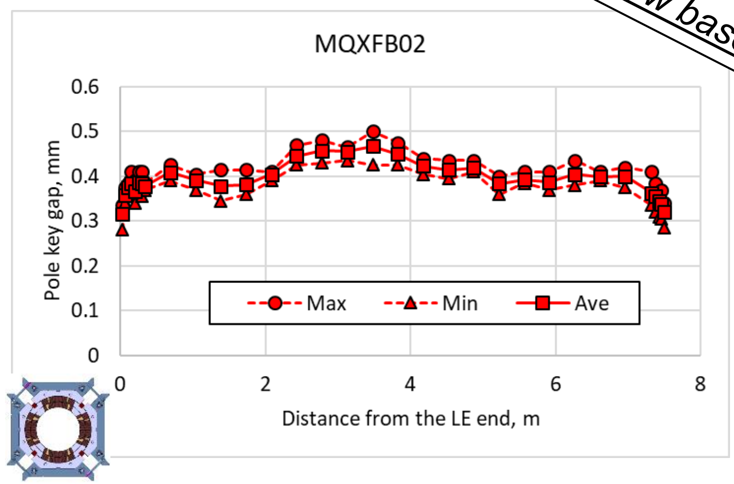


Pole key gap per side

Previous



New baseline



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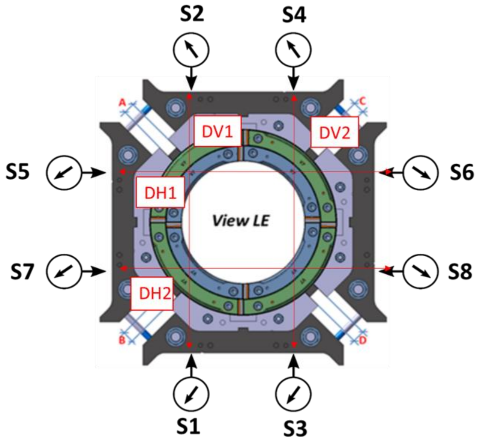
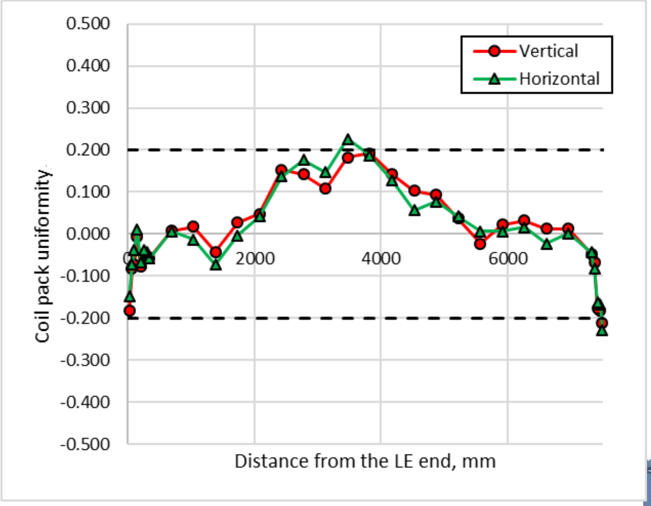
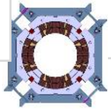
Coil pack assembly

- Coil pack geometry is afterwards **verified** by **external measurements**. Not done for first prototypes.
- Neglecting the coil ends, it has been possible to **keep** the coil pack **squareness*** within **+/- 150 µm over 7 m**.
- As expected, coil size variation is clearly visible in the coil pack shape.

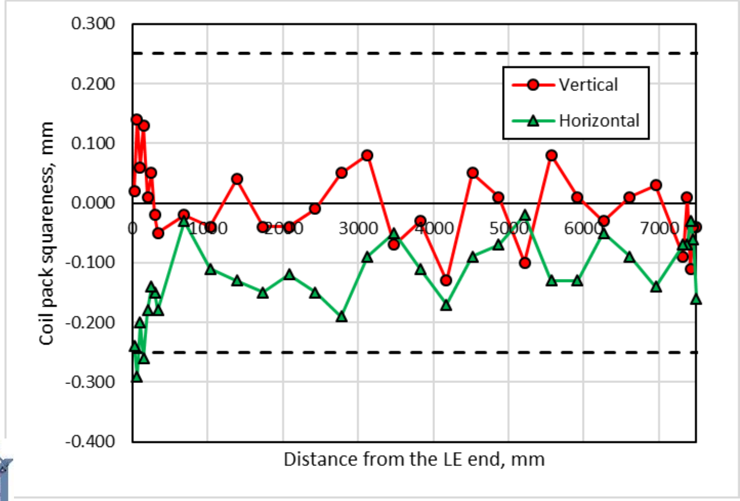


Coil pack uniformity, MQXFB02





Coil pack squareness, MQXFB02



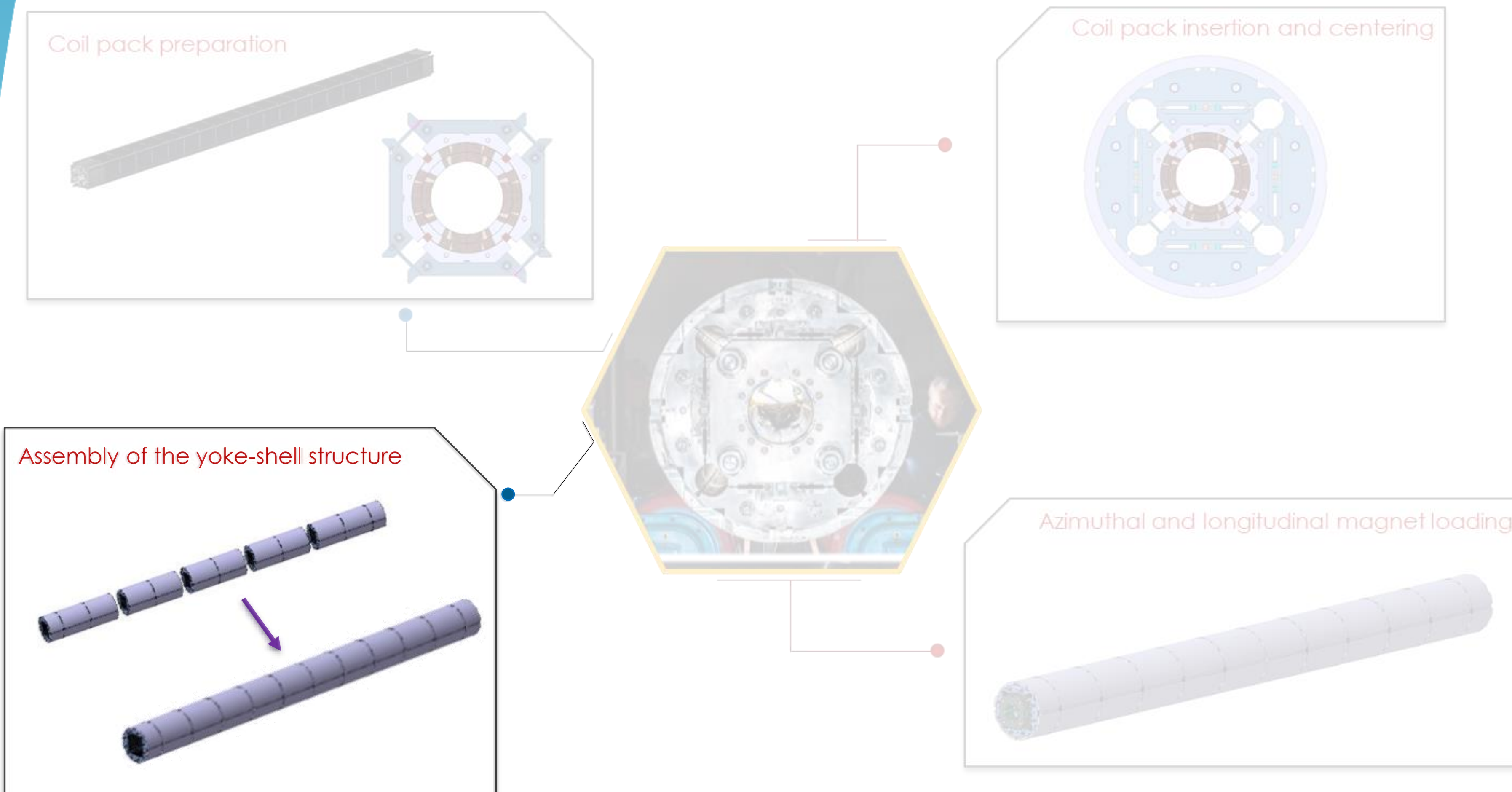
*Defined as:

Uniformity = $\frac{\frac{(DH1+DH2)_i}{2}}{\frac{\sum_{i=1}^{n}(DH1+DH2)_i}{n}}$, or DV // Squareness = $DH1 - DH2$, or DV

MQXFB magnet assembly in a nutshell

Magnet assembly:

Coils → Coil pack preparation → Insertion in the structure → Centering, az. and long. loading



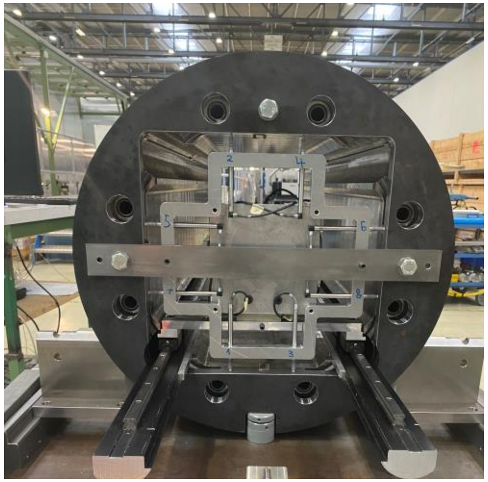
Yoke-shell assembly

As for the coil pack, a series of important improvements (mostly based on MQXFBMT3):

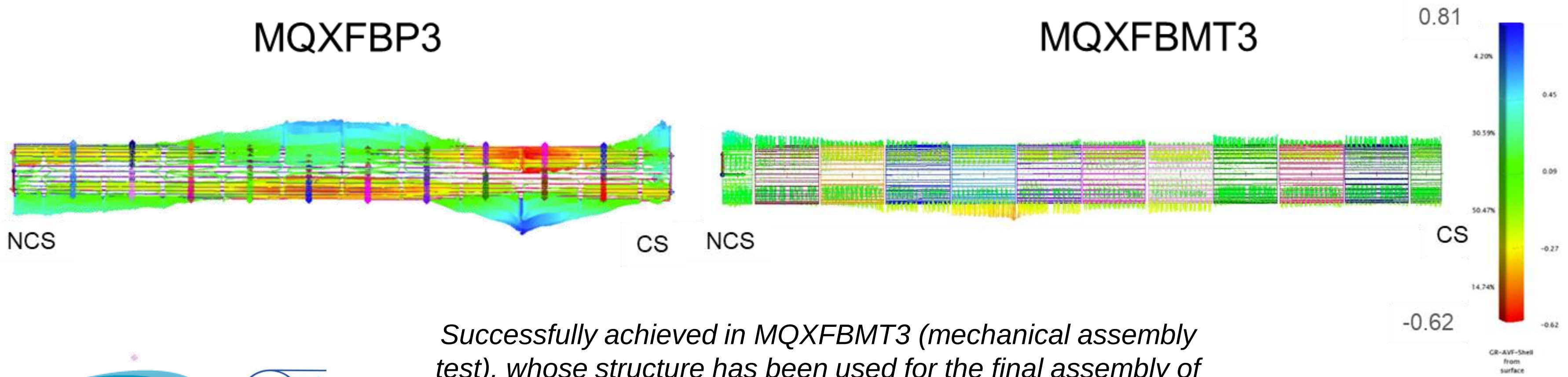
- The **internal cavity dimensions** of each single **module and of the final assembled structure** are **measured** (not done before).
  - Vertical and horizontal yoke cavity dimensions within 385.1 mm – 385.2 mm for MQXFB02.

- In **MQXFBP3**, a **misalignment** in the **horizontal axis** of the magnet structure was **observed** for the **first time**. Max_{dev}-Min_{dev} = 1.4 mm.
  - After **cold mass** completion, **same shape** as after magnet loading. Visible as well in **magnetic measurements** but less pronounced.
  - To the best of our understanding, the **resulting geometry** is **governed** by the **parallelism/alignment** between **matching faces** at the module intersections.

Decision taken to **machine** the **external faces** of the yoke at either side of the module, to **ensure** a proper **connection**.



In-house developed system for cavity measurements.



Successfully achieved in MQXFBMT3 (mechanical assembly test), whose structure has been used for the final assembly of MQXFB02 (except the central module).

MQXFB magnet assembly in a nutshell

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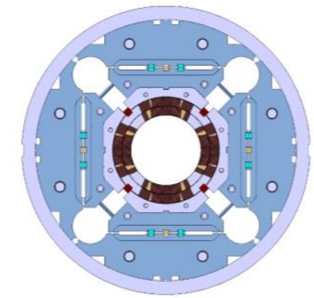
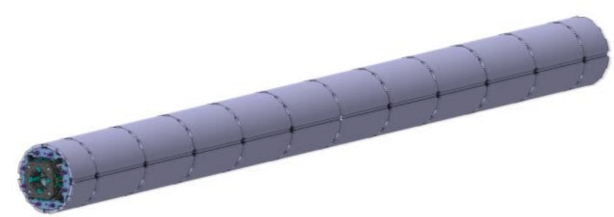
Coil pack preparation

Assembly of the yoke-shell structure

Coil pack insertion and centering

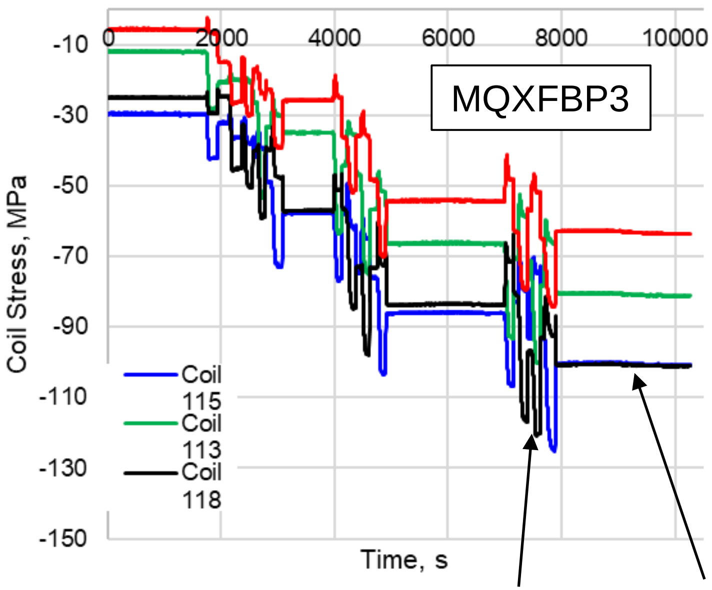


Azimuthal and longitudinal magnet loading



MQXFB magnet pre-load: Context

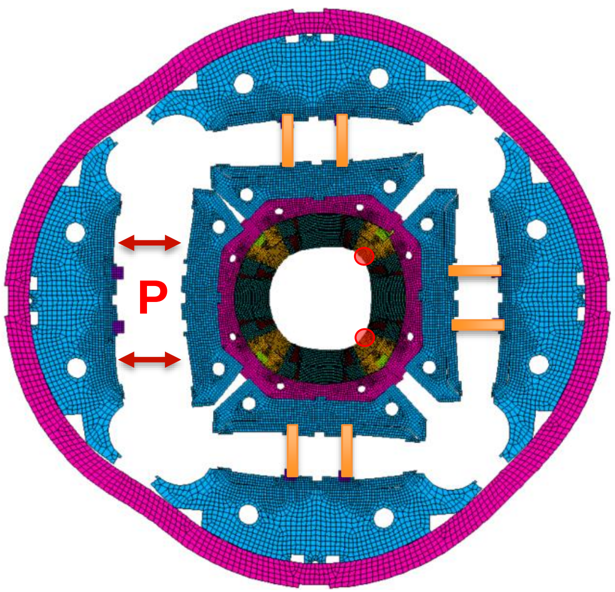
- The three **first prototypes** and **all MQXFS** magnets have been pre-loaded using the master's bladder slots in a **quadrant-by-quadrant** procedure (same for **MQXFA**).
- Using this "**quadrant by quadrant**" sequence, the last bladder operation resulted systematically into a coil **stress overshoot** for long MQXFB magnets in the order of **20 - 40 MPa** (measured in the winding pole).



Bladder operations

Key inserted

$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$

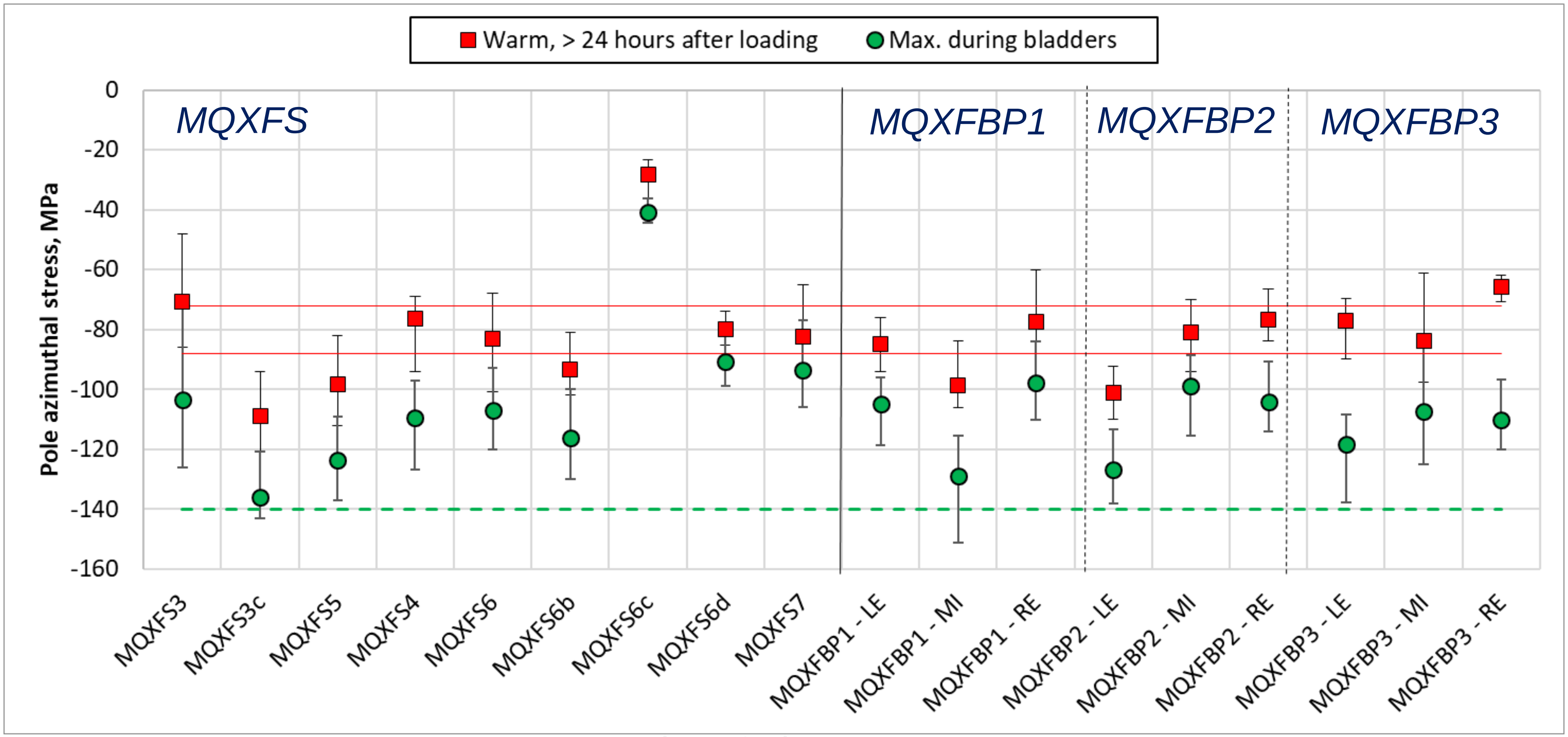


Simulated deformed geometry during a "quadrant by quadrant" bladder operation. The overshoot happens in the coils located opposite to the active bladder.

**For the insertion of the interference keys, we need to open up a space larger than the key thickness (clearance dealing with geometrical tolerances, frictional resistance, etc).*

MQXFB magnet pre-load: Context

- The three first prototypes and all MQXFS magnets have been loaded using the master's bladder slots in a quadrant-by-quadrant operation (similarly to what was shown during centering).



operations inserted *quadrant bladder operation!*

**One should keep in mind that for the insertion of the interference keys, it is straightforwardly necessary to open up a space between masters that is larger than the key thickness (clearance dealing with geometrical tolerances, frictional resistance, etc).*

A clear strategy for refined magnet assembly

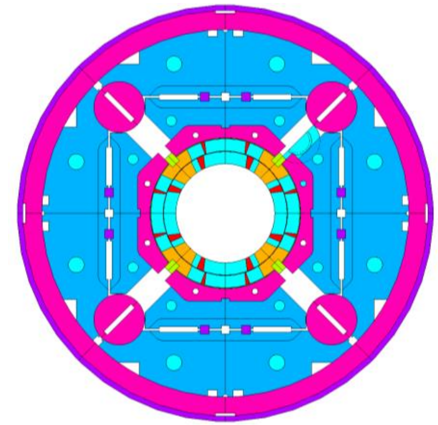
<u>Reminder:</u> In the framework of the MQXFB strategy to tackle the performance limitation seen in first prototypes, the refinement of the magnet assembly was identified as one of the main aspects to be explored. Including: reduction of coil peak stresses during loading, update of the target pre-load levels and revision of the assembly procedures.

- Before putting on hold the assembly of new magnets, MQXFB and MQXFA had identical **target** preload, i.e., **average shell** stress **+58** ± 6 MPa, **average coil stress** (winding pole): **-80** ± 8 MPa.
- In terms of **peak** stress during loading, the maximum measured in MQXFBP2&P3 magnets was **-140 MPa**, which is higher than the -110 MPa set as limit for MQXFA. The same pole stress level was already reached in the successful short model MQXFS5.

- Based on all the novel information gathered since the test of MQXFBP2 → **New** and **more stringent target** values for **MQXFB** magnets:
  - **Average shell** stress (three stations): **+58** ± 6 MPa
  - **Average coil stress** (winding pole, three stations): **-70** ± 10 MPa
  - **Peak coil stress** (winding pole, three stations): **100 MPa**

See talks from:
E. Todesco, “Status of WP3 with focus on MQXFB”
A. Ballarino, “Assessing MQXF conductor limits”
P. Ferracin, “MQXFA magnet assembly”

New pre-load concept

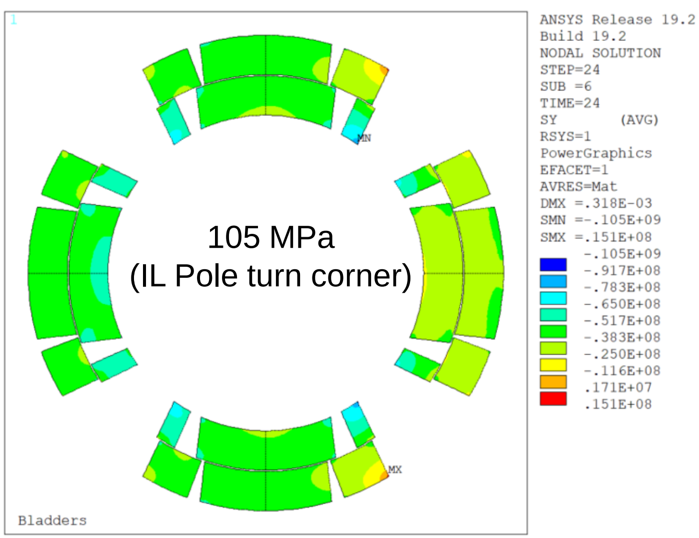


<u>How to decrease the peak stress during assembly to the required levels?</u>

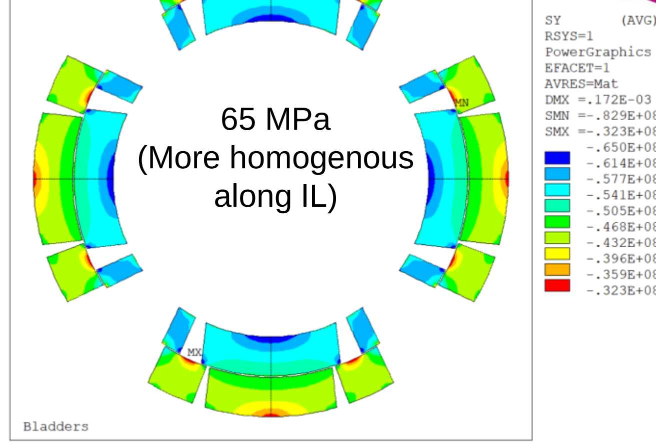
- **Proposal:** A new loading procedure employing a symmetric loading scheme (all quadrants at the time), where new bladders are placed in the cooling hole channels. The latter act directly on the iron yoke, opening up the structure and unloading the coils.

Az. stress during last bladder operation for 80 MPa pole az. stress after key insertion, assuming 0.3 mm clearance to insert the keys

Stress during bladder operations, quadrant by quadrant, bladder slots



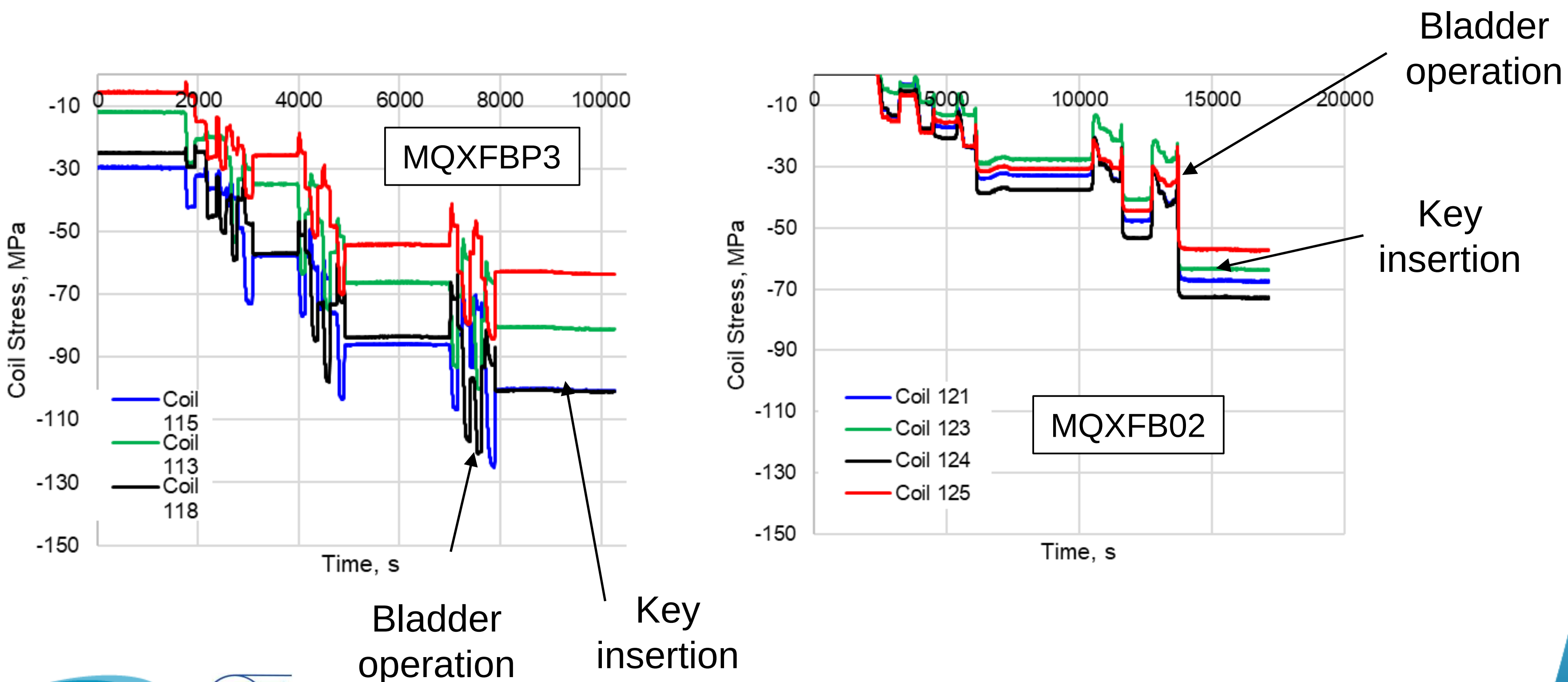
Stress during bladder operations, Symmetric loading, bladder slots + cooling holes



New pre-load concept

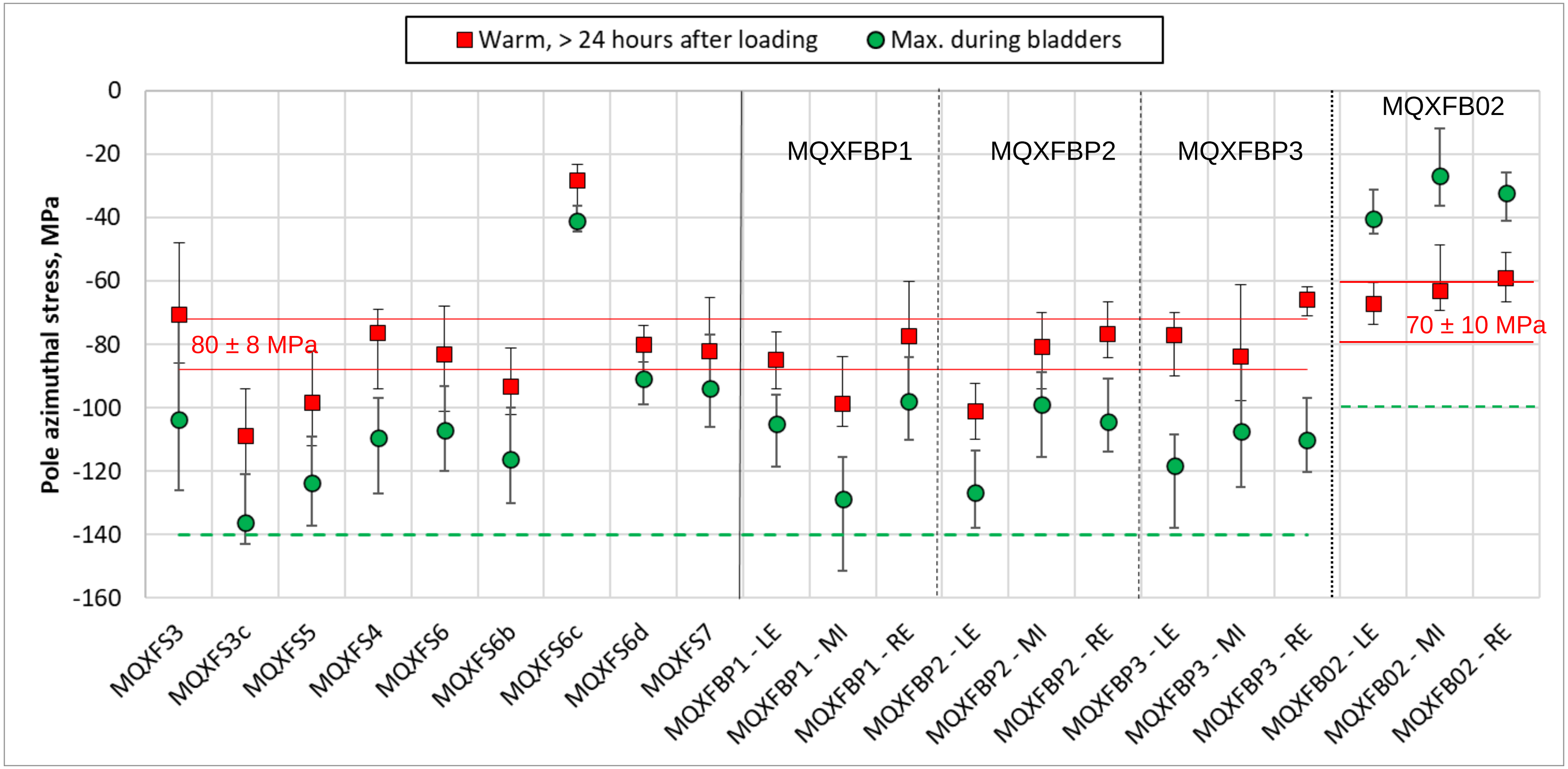
- The new assembly procedure was successfully tested in the full-length mechanical assembly test, MQXFBMT3, last year.
- Also tested in a short model magnet (MQXFS7), proving no detrimental effect on magnet performance.
- Based on the positive results, the new procedure is today the baseline for next magnets.

Applied for the first time in a real MQXFB magnet for MQXFB02!



Room temperature pre-load summary

- New target pre-load and peak stress levels were respected in all measuring locations for MQXFB02.
- For the first time, the measured peak stress level corresponds to the final stress after key insertion. No overshoot.



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Conclusions

- Based on the test results of the two first prototypes, showing a performance limitation, an important effort on refining the magnet assembly process was put in place.

- A **new loading procedure**, with auxiliary bladders in the cooling holes, has been developed and successfully demonstrated in a MQXFS short model and in a full-length MQXFB magnet (firstly with a mechanical assembly test). The new loading method allows to **eliminate the 20-40 MPa overshoot** of coil stress during bladder operations.

  A major improvement in MQXFB magnet assembly!

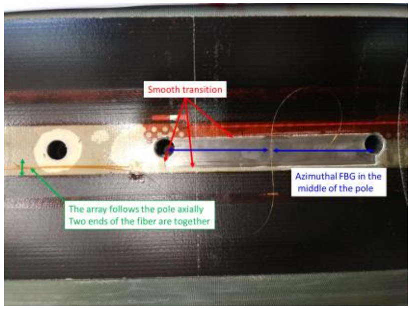
- The pre-load targets have been modified, introducing a more stringent limit of 100 MPa for the peak azimuthal stress measured in the winding pole during assembly. The average pole az. stress after magnet pre-load has been as well decreased by 10 MPa.

- In addition to the new loading procedure and targets, other **relevant modifications in magnet assembly** have been introduced to ensure a sound mechanical response of the system:
  - **Refined coil pack preparation**, allowing for a tightly controlled square geometry of the sub-assembly. In parallel, the pole key gap has been increased to avoid any chance of force interception (lesson learnt from MQXFA07 & 08).
  - **New yoke-shell assembly procedure**, with the objective of ensuring a better alignment of the magnet structure and a homogenous cavity. Measurements of the yoke internal cavity are now systematically performed.

ANNEX

Mechanical instrumentation

Coils instrumented with strain gauges and FBGs

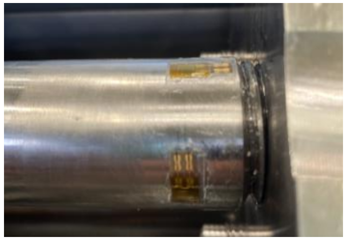


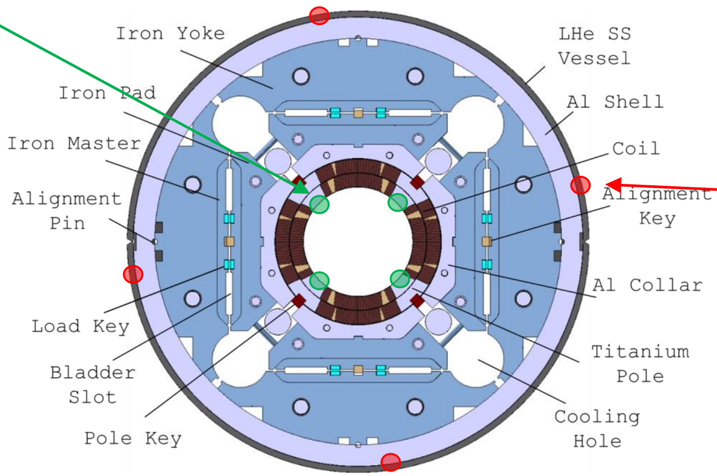
Mechanical behavior monitored. **Strain** is **measured** in:

1. Rods
2. Aluminum shell
3. Coil titanium pole

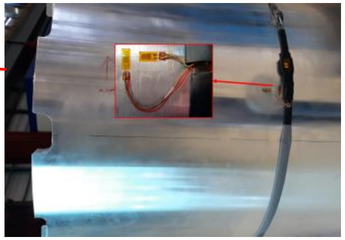
Measurements are performed in 3 longitudinal sections.

Rods instrumented with strain gauges



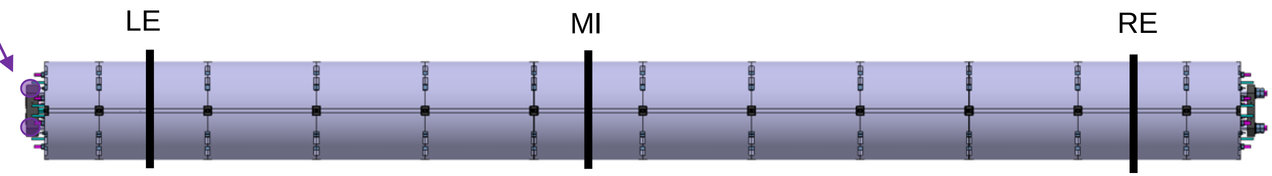


Al-shells instrumented with strain gauges



$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$

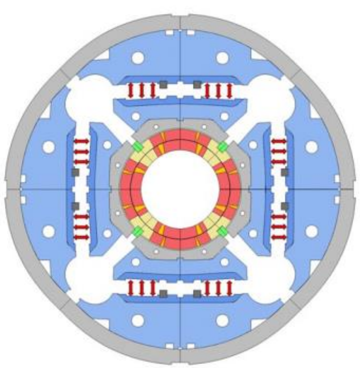
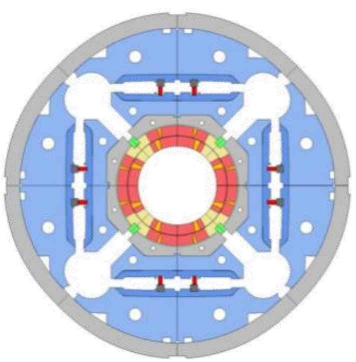
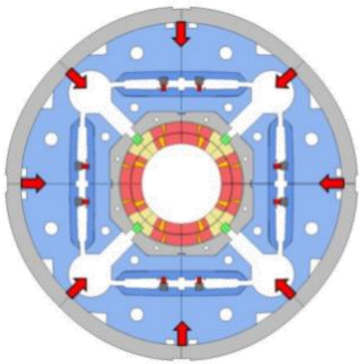
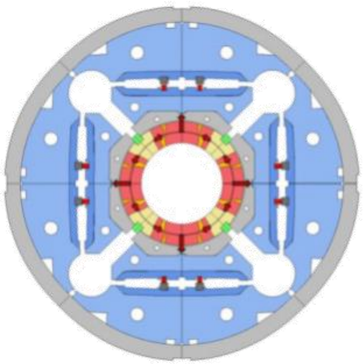
$$\sigma_z = \frac{E}{(1-\nu^2)}(\varepsilon_z + \nu\varepsilon_\theta)$$



MQXFB, three longitudinal measuring locations

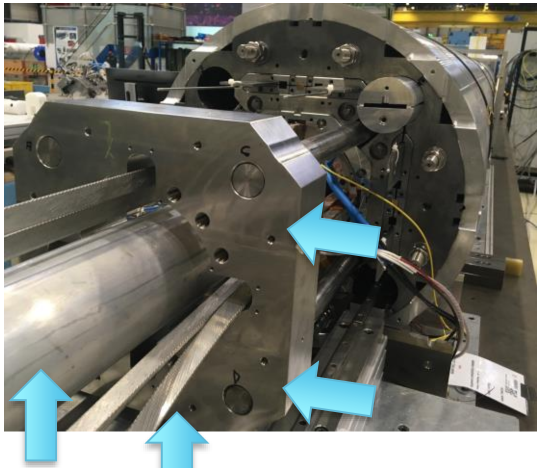
Magnet mechanical concept

- **Shell-based** support **structure**, **bladders** and **keys** technology for the application of a certain coil pre-load.
- Objectives: To react the strong e.m. forces appearing during operation, while minimizing the conductor displacement.

	Bladder pressurization	Key insertion	Cool down	Powering
	Open enough clearance to insert the keys (key size + ≈ 0.3 mm clearance)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic forces
F_θ/F_{em} shell	n. a.	40 %	87 %	93 %
F_θ/F_{em} pole	n. a.	40 %	87 %	10 %
				

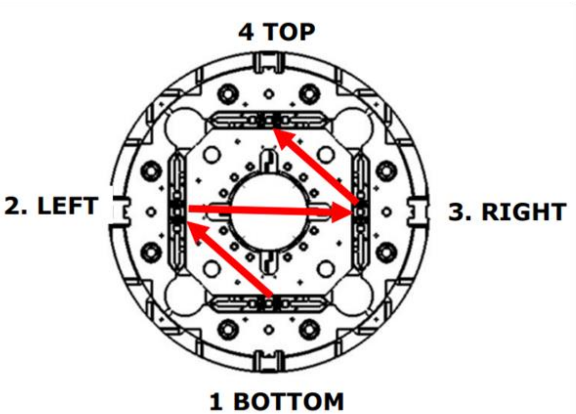
Coil pack insertion and centering

- **Centering** defined as the **installation** of **13.2 mm keys** in **all quadrants**. Done using the "**quadrant by quadrant**" **procedure**. No major changes with respect to previous magnets.
- The **procedure** is **well established**, avoiding some of the issues encountered in the past:
  - **Purging** the **bladder** circuits, for instance, has been found to be an important action that needs to be systematically done.
- <u>Recent lesson learnt from the first Q2 cold mass:</u> Necessary to properly center the end plates at both extremities to avoid any interference with the heat exchanger tubes.

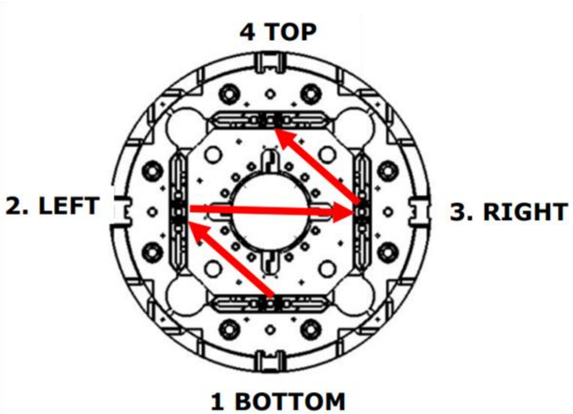


A centering system based on pusher screws has been developed for the end plates.

First stage (13.0 mm)

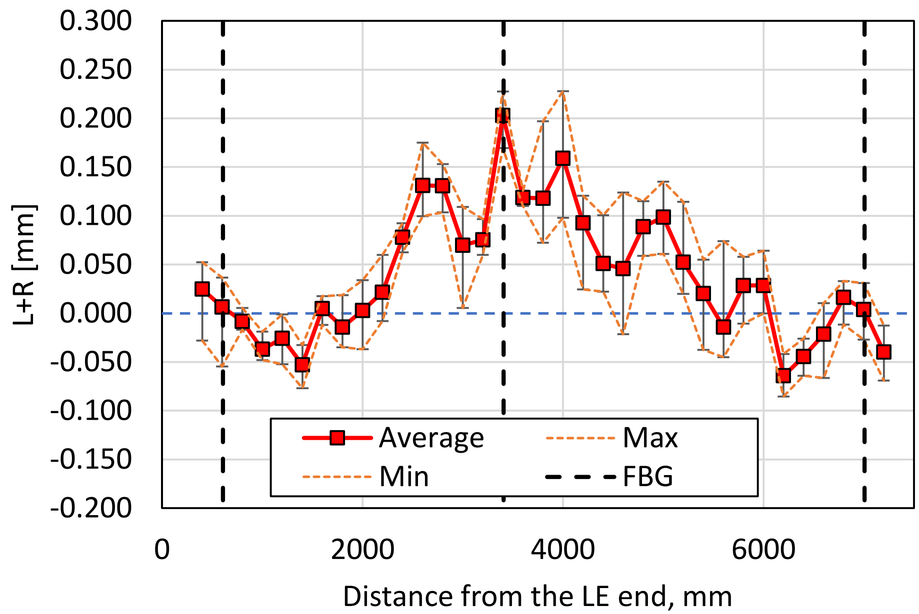


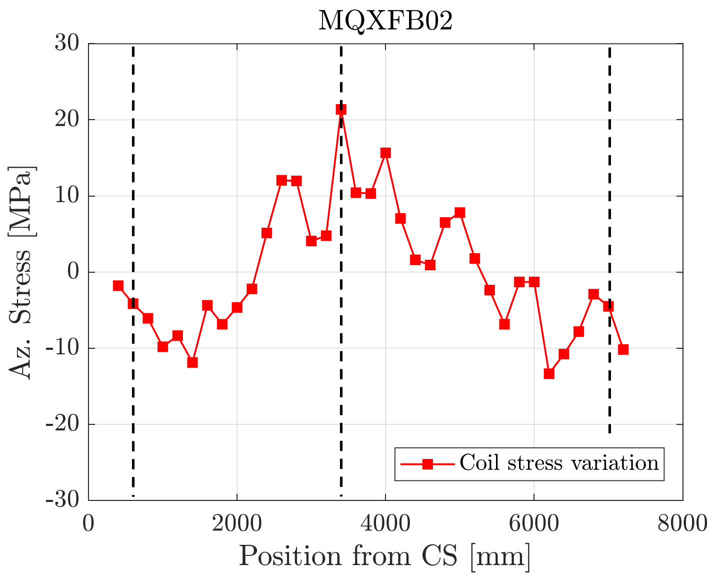
Second stage (13.2 mm)



MQXFB02 -250 um shimming plan

Azimuthal size and expected stress variation along the length (w.r.t. average)

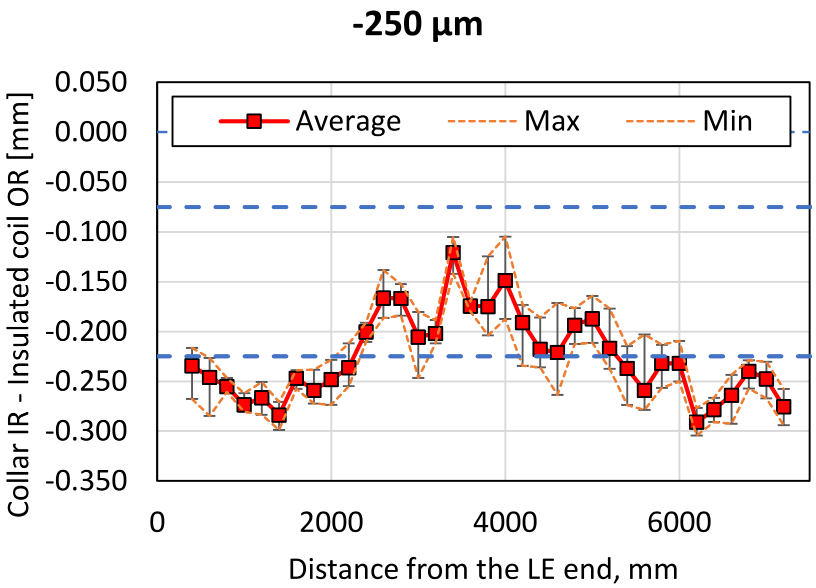


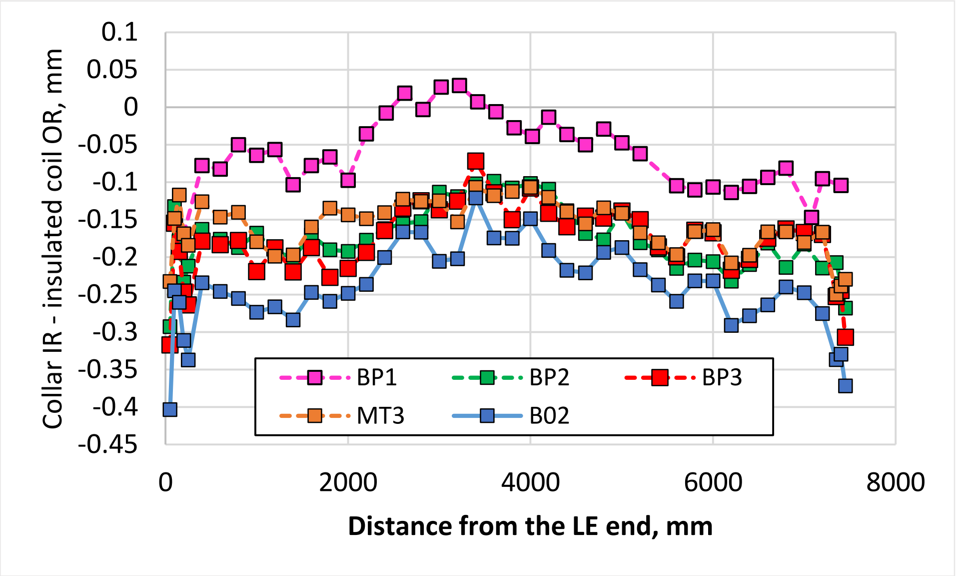


Measurement position covering the point of larger average azimuthal size!

MQXFB02 -250 um shimming plan

Radial size and comparison to previous magnets





Shimming strategy

<u>The importance of the coil size</u>

- When using constant thickness interference keys:

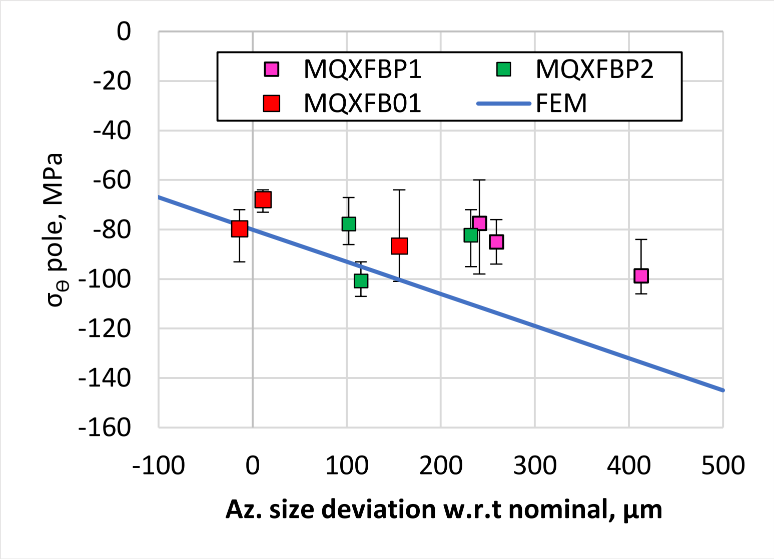
Variation in coil size along the length → Variation in coil stress

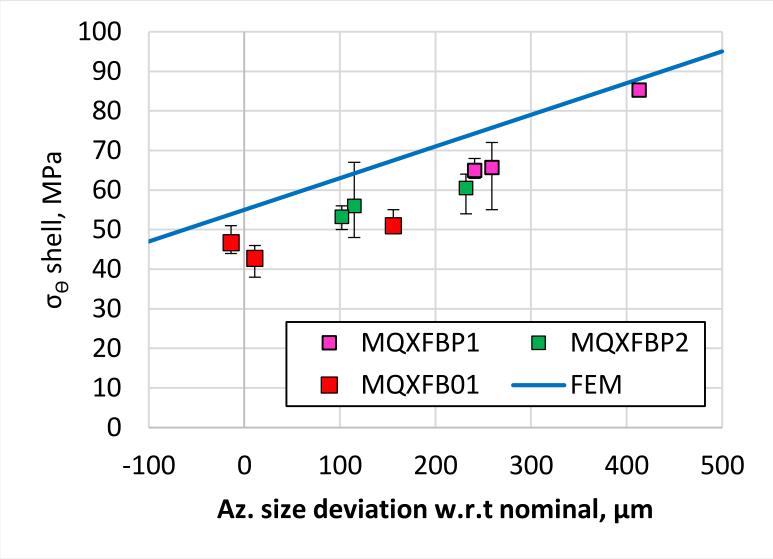
- + 100 µm of total coil arc length increase translates* into:
  - 13 MPa in azimuthal compression at the winding pole
  - 8 MPa in the azimuthal tension at the Al shell

  Values confirmed both in the FE model and in the short model experience

**Assuming that only the average coil size plays a role in the coil stress*

Stress at the end of the loading operations, no creep /stress relaxation included!





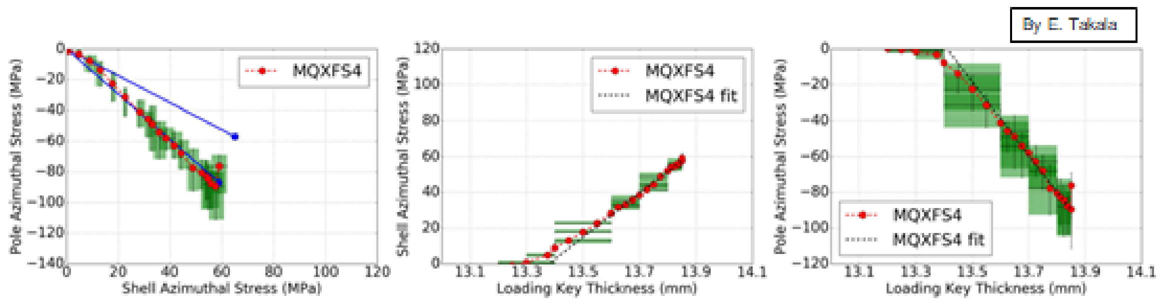
Data processing:

- BP1 – Drift in the FBG readings corrected. Wrong coil sizes used for shimming.
- BP2 – Signals shifted in the LE after centering issue.

Symmetric loading

Magnet assembly and loading
Sensitivity analysis

- +0.100 mm of coil outer radius increase
  - -20 MPa of coil stress variation
  - +12 MPa of shell stress variation
- +0.100 mm of total coil arc-length increase (0.050 per mid-plane)
  - -13 MPa of coil stress variation
  - +8 MPa of shell stress variation
- FE values confirmed in short models, like MQXFS4



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