Assembly of the Nb_3Sn MQXFB Quadrupole for HL-LHC

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Acknowledgements: Susana Izquierdo Bermudez, Nicholas Lusa, Stephane Triquet, Sylvain Mugnier, Paolo Ferracin, Jose Ferradas Troitino

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Outline

- Introduction
- MQXFB assembly and measurables
- Observables during loading
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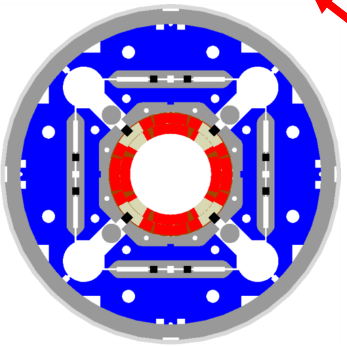
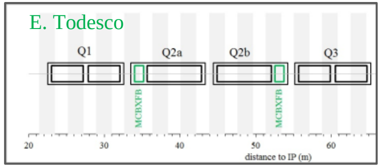
HL–LHC Nb_3SN magnets

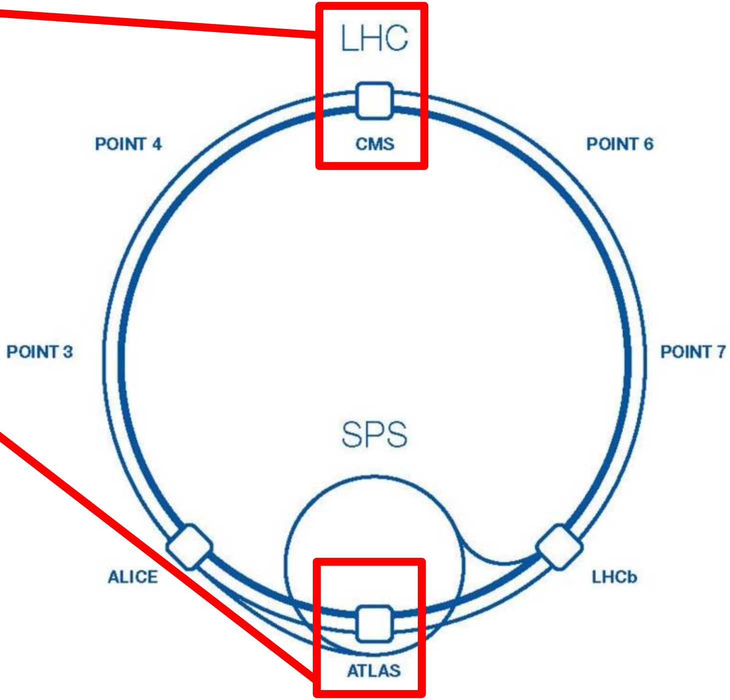
MQXF



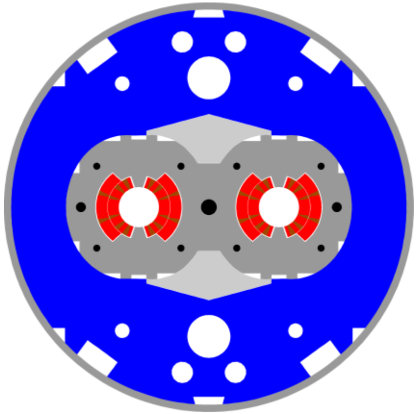
30 large aperture (20 MQXFA + 10 MQXFB) and more powerful quadrupoles around ATLAS and CMS to decrease the beam size and increase the integrated luminosity by a factor 10

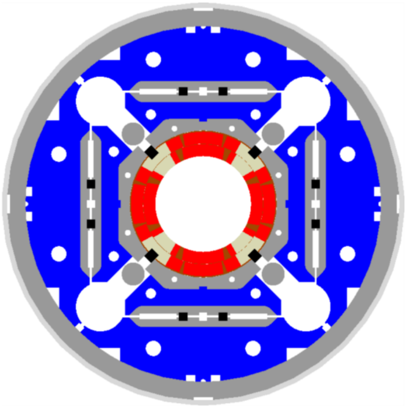
Construction of pre-series and series magnets on-going, joint effort between CERN and US-AUP





MQXF Nb_3SN magnets challenges – material properties





LHC MB

HL-LHC MQXF

NbTi→ ductile material

Extrusion + drawing

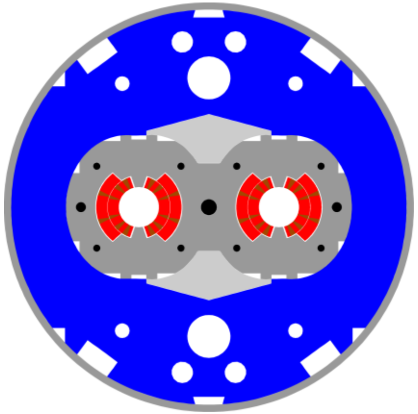
- ***T_C*** *is ~* ***9.2 K*** *at 0 T; B_{C2} is ~ 14.5 T at 0 K*
- *Deff ~ 5 µm*

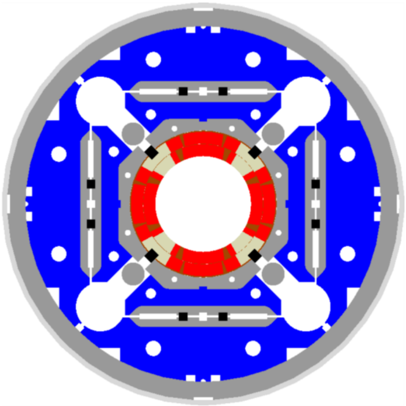
Nb_3Sn→ intermetallic compound

Brittle, strain sensitive, formed at ~650℃

- ***T_C*** *is* ***~ 18 K*** *at 0 T; B_{C2} is* ***~ 28 T*** *at 0 K*
- *Deff ~ 50 µm*

MQXF Nb_3SN magnets challenges – current density





LHC MB

NbTi, B_p = 8.6 T

Eq. coil width: 27 mm

J_{strand} = 475/616 A/mm^2

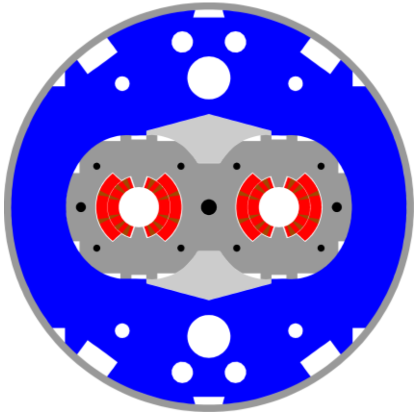
HL-LHC MQXF

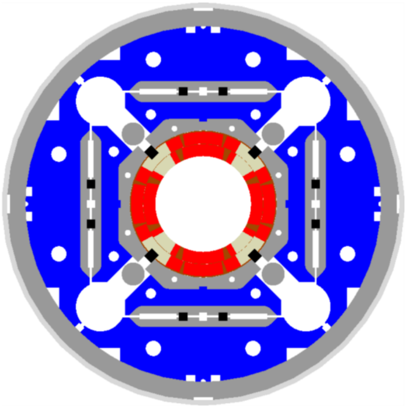
Nb_3Sn, B_p = 11.3 T

Eq. coil width: 36 mm

J_{strand} = 715 A/mm^2

MQXF Nb_3SN magnets challenges – e.m. forces





LHC MB

NbTi, B_p = 8.6 T

F_x = 3.4 MN/m

$\sigma_{\theta,em}$ = 50-60 MPa

F_z = 265 kN

HL-LHC MQXF

Nb_3Sn, B_p = 11.3 T

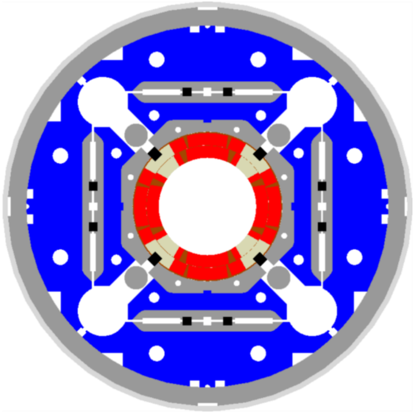
Fx = 6.8 MN/m

σθ,em = 100-110 MPa

Fz = 1200 kN

≈ 2 times more force/stress than in the LHC-MB dipoles, in a brittle conductor

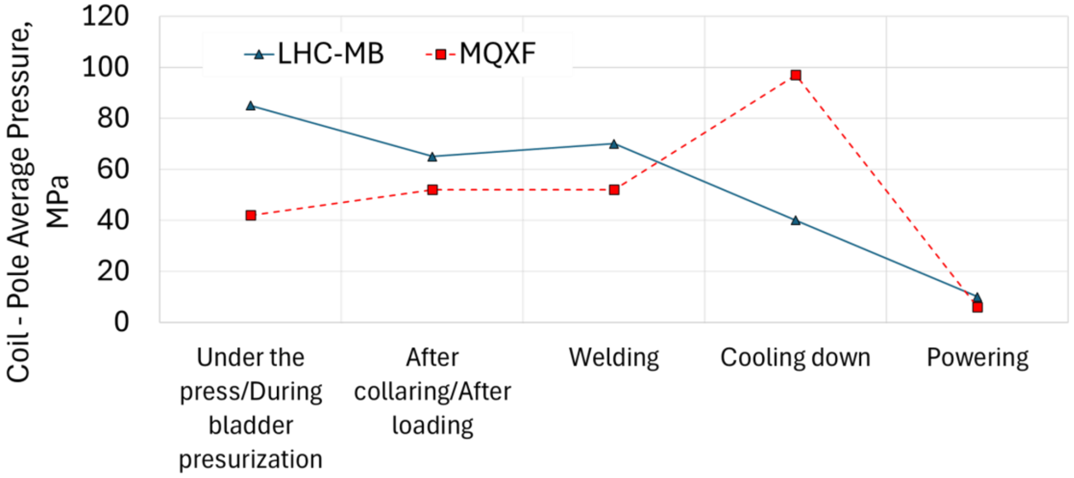
F_x per half magnet; F_z per aperture



Large electromagnetic forces in a brittle conductor calls for an innovative structure.

MQXF structure

- **MQXF** structure is based on **aluminium shell** pre-loaded with **bladders and keys**
    - **≈ 50 %** of the **pre-load** during **room temperature assembly** (bladder pressurization and key insertion)
    - **≈ 50 %** increase of **pre-load** during **cool down** due to the difference of thermal contraction between the outer aluminum shell and the rest of the magnet
- **LHC MB** components shrink differently, and there is significant **reduction of pre-load during cool down**



A superconducting magnet is a complex electro-magnetic-mechanical system, and with the HL-LHC MQXF, it marks the first time magnets with this innovative structure, utilizing Nb_3Sn conductors, are being installed in an accelerator.

Objective: Can we monitor production with simple tools while ensuring the required preload?

Outline

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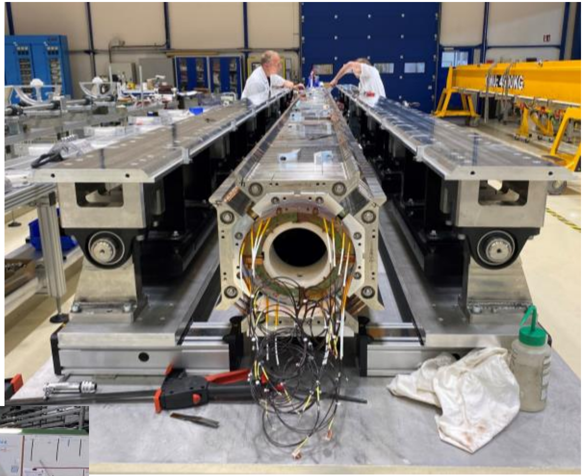
- MQXFB assembly and measurables
- Observables during loading
- Assembly correlations

MQXFB assembly - Coil pack sub-assembly

When 4 coils are ready, we start the **coil pack assembly.**

In this phase:

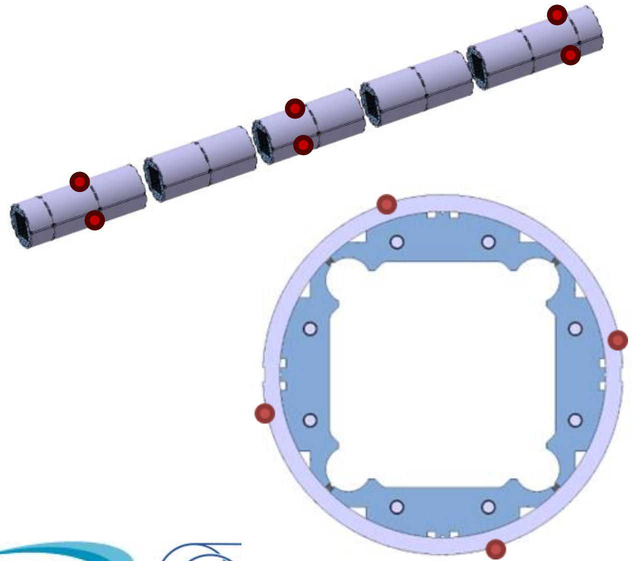
- Coils dimensions are measured, and the difference in size among the them is compensated with radial and azimuthal shims of polyimide
- The dimensions of the coil pack is measured with LVDT
- Coils are instrumented with optical fibers



MQXFB assembly - Yoke-shell sub-assembly

The yoke and shells are assembled in moduli and then combine to form a structure

- Here the cavity dimension are measured with LVDT
- The shell is instrumented with strain gauges



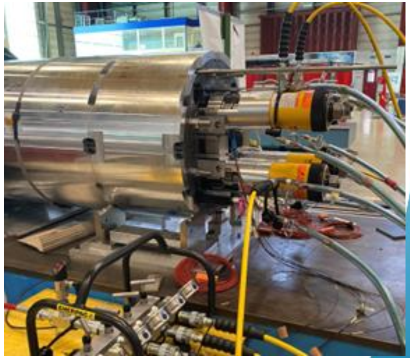
MQXFB assembly - Loading

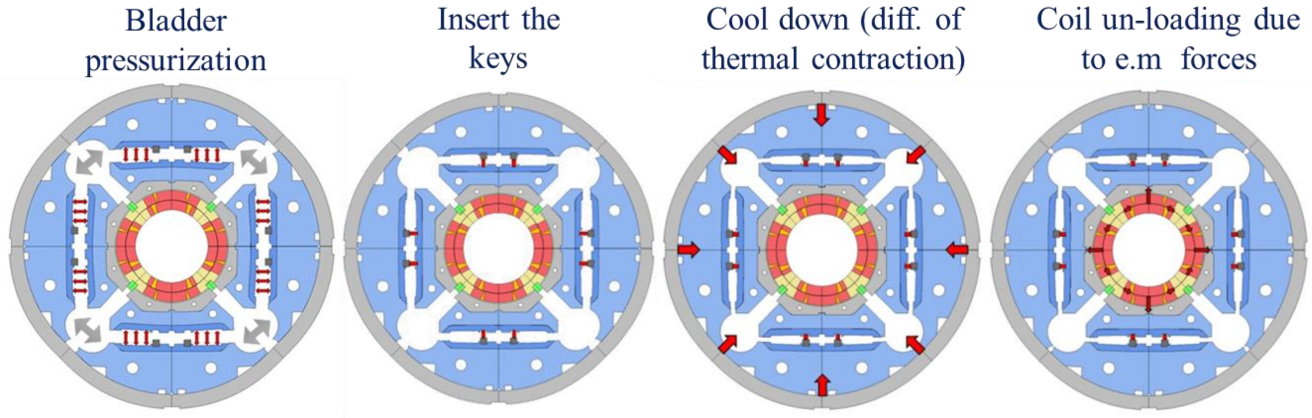
The two sub assemblies are combined, and the magnet is ready for the loading:

- **Azimuthal loading**, using the bladders and keys procedure.
- **Axial loading**, pulling the rods with the hydraulic pistons.

During loading, the strain (stress) in and pole, shell and rods is constantly monitored via strain optical fibers and gauges.

We also monitor the piston pressure used and the rods displacement.





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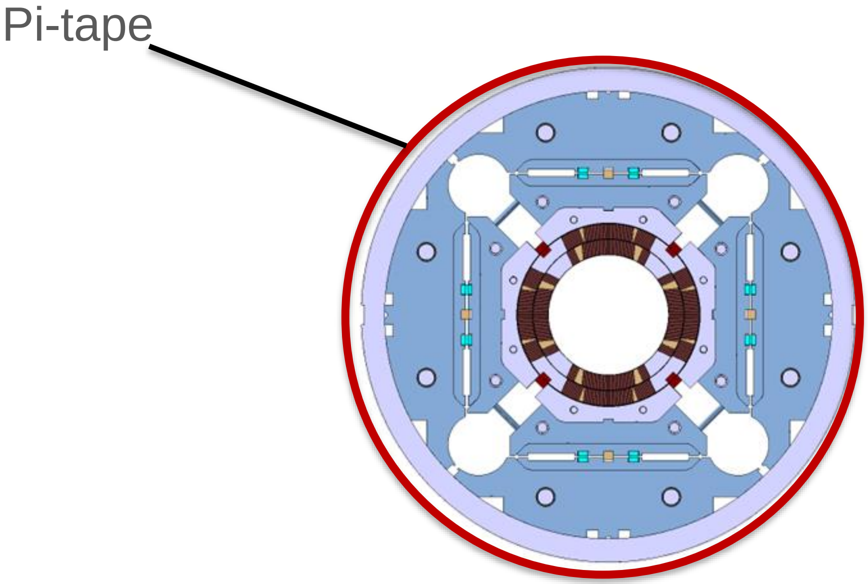
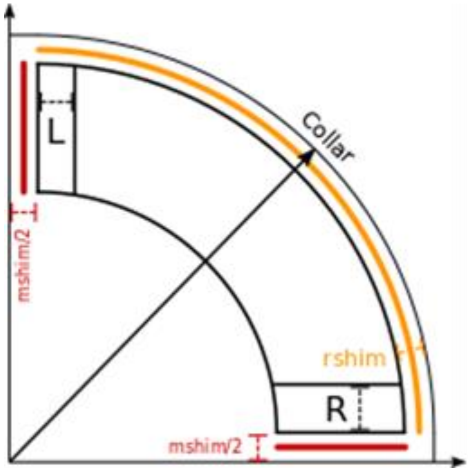
Delta_l_shell

- **Delta_l_shell** is the difference between the external length of the shell after loading and the external length of the shell after the coil pack insertion in the yoke shell structure, before loading.



Delta_l_coil

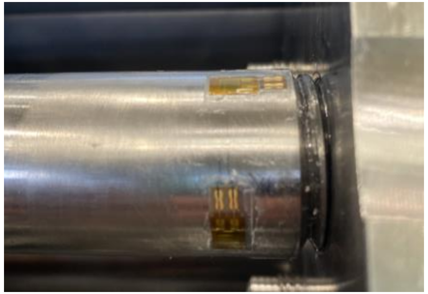
- **Delta_l_coil** is the coil pack radial size deviation from the nominal (the collar inner surface distance from origin) adding the dimention of the final key size and removing the nominal one.
- The key size can vary between 13.6 and 13.85 mm
- The **nominal key** is **13.8 mm**

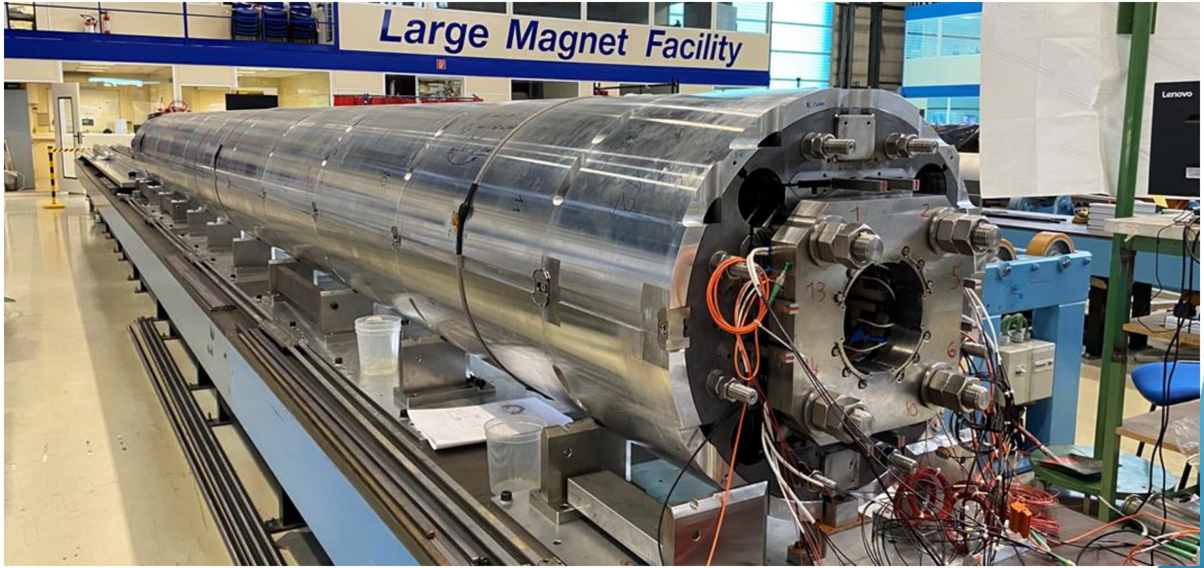


$$\Delta R = \frac{2(\mathrm{L} + \mathrm{R} + \mathrm{mshim})}{\pi} + \mathrm{rshim} + \mathrm{final\ key} - 13.8$$

Mechanical instrumentation

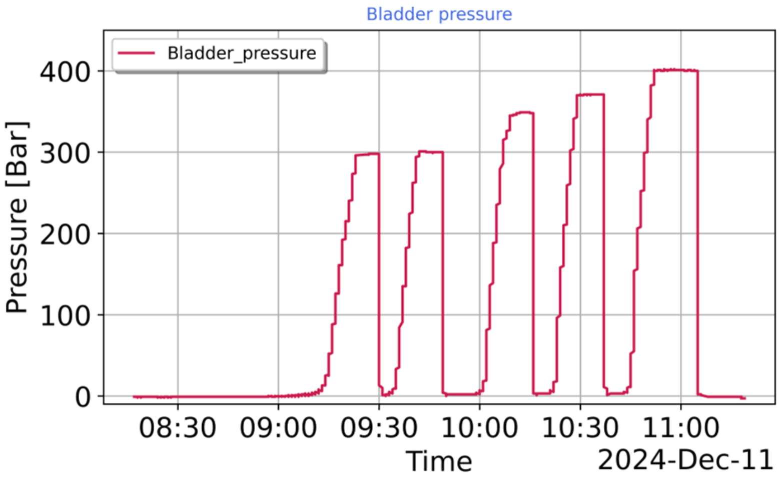
- Strain gauges are installed in the Al-shell, in three longitudinal positions
- Fiber optics are installed in the coils, also in three longitudinal position
- Each rod is instrumented with strain gauges

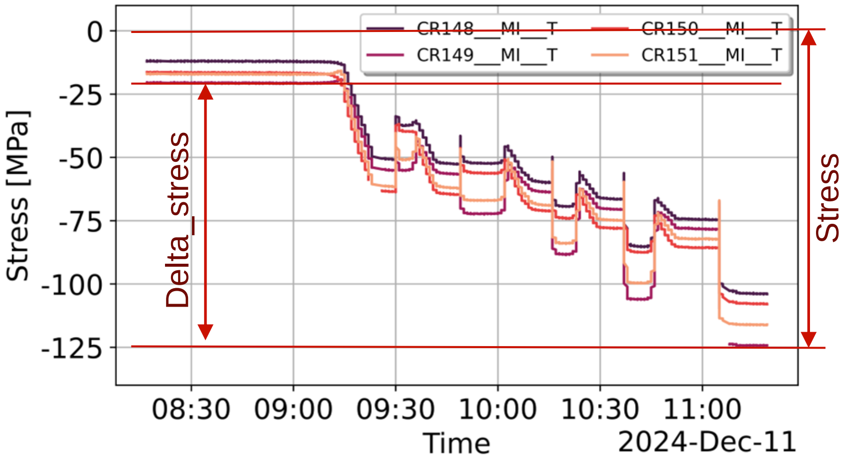




Observables during loading

- Strain is monitored during loading
  - One can look at the final stress in the coil (stress), or the increase on stress during loading (delta_stress)



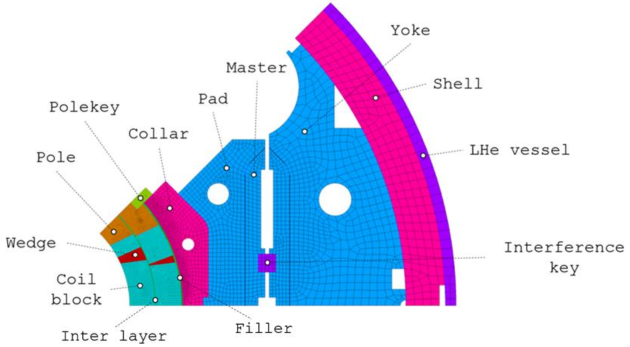


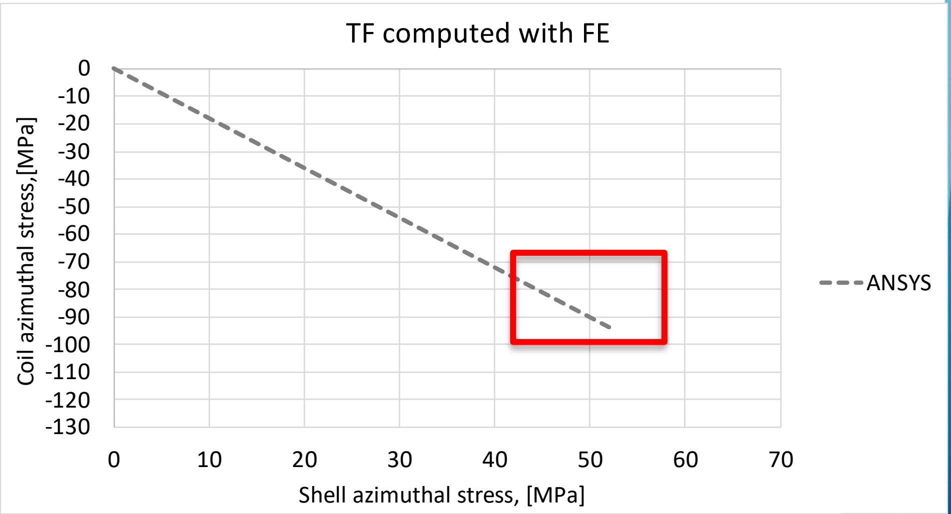
FE model

The expected TF is calculated via FEA analysis and thanks to the model we can predict.

It is a 2D static analysis in which the main steps of the loading are modelled:

- Initial step (no keys)
- Centering
- Loading





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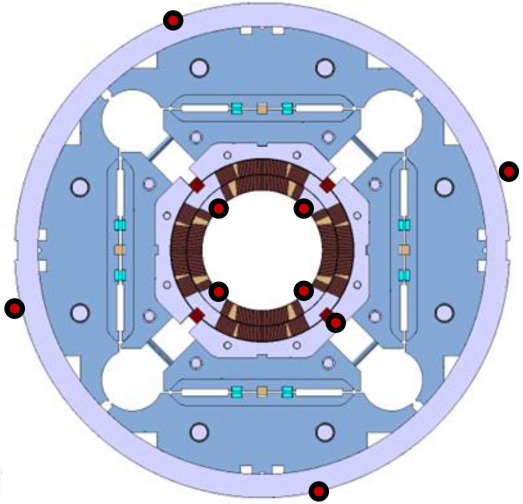
Azimuthal loading

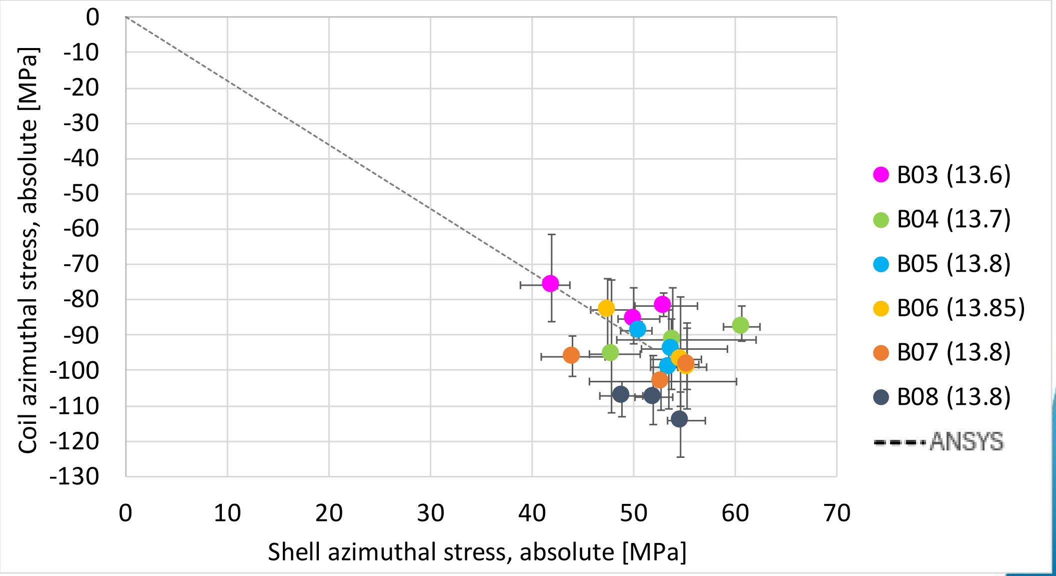
The **transfer function(TF)** between coil stress and pole stress is a tool that we use to ensure that

- both components are operating within their acceptable stress limits
- the expected target preload is reached

Looking at the absolute data we have a large spread for both shell and coil:

- Shell stress from ~40 to~65MPa
- Coil stress from ~-60 to ~-125MPa



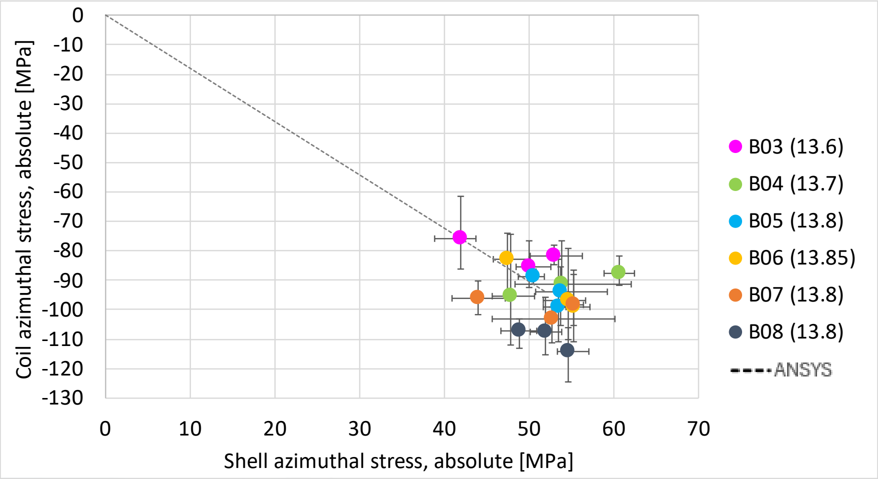


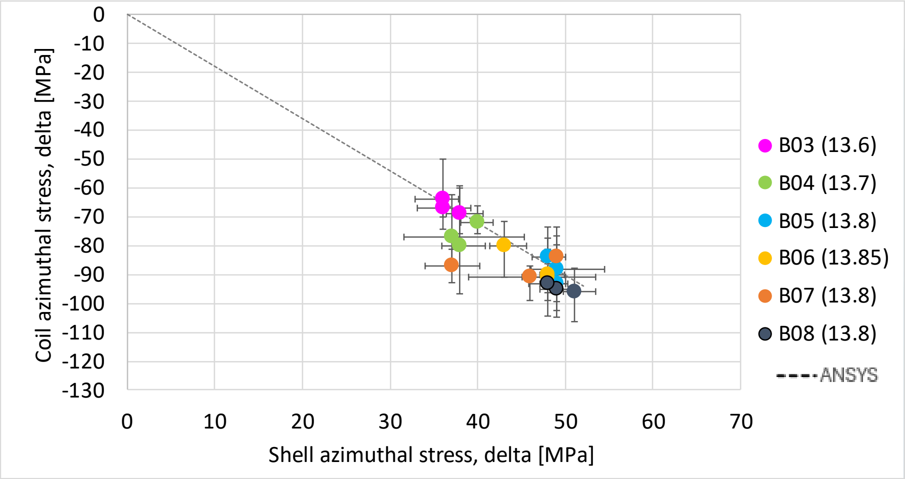
Azimuthal loading

The graphs show the TF for the absolute measurements and the delta.

The delta stress in the shell and in the coil look better than the absolute values.

- Shell stress from ~35 to~55MPa
- Coil stress from ~-50 to ~-100MPa
- The measured data are consisted with the computed one
- Magnets with smaller key result as less preloaded (not always the case with the absolute values)



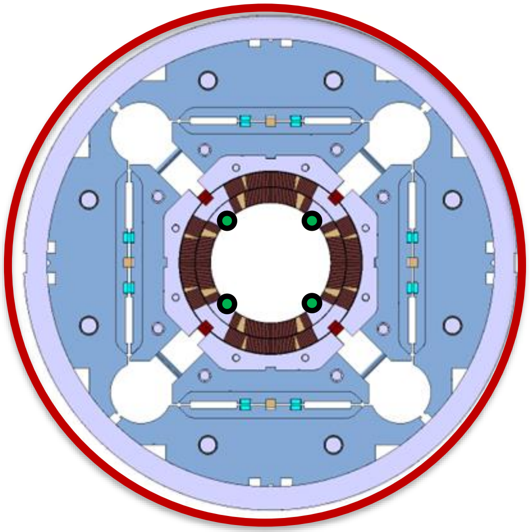


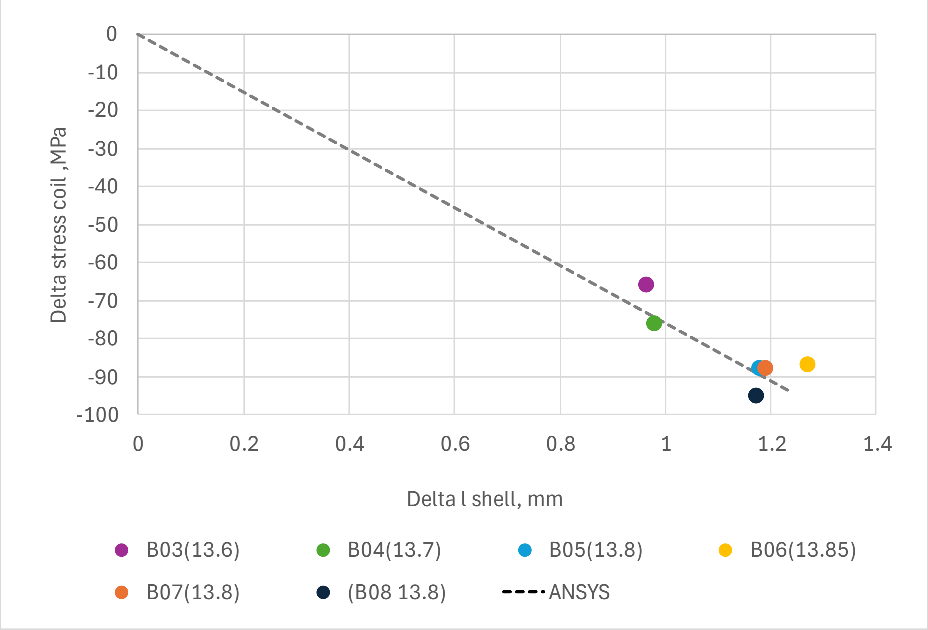
Azimuthal loading

From now, the graphs shows the delta stress for both coil and shell.

Azimuthal loading

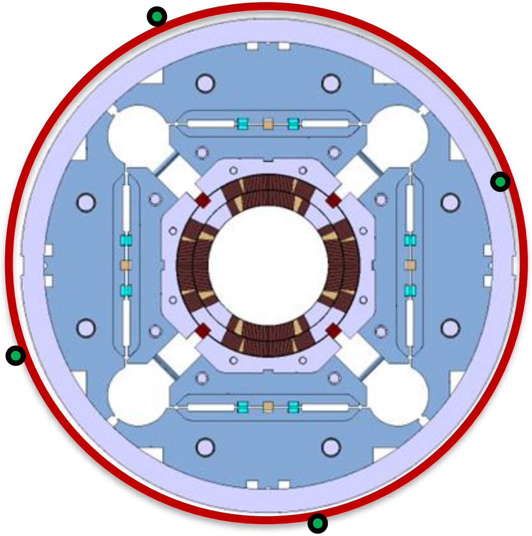
- Good correlation between the increase on the outer magnet developed length with the loading (Delta l shell) and the increase of coil stress during loading
- Good agreement with the FE model

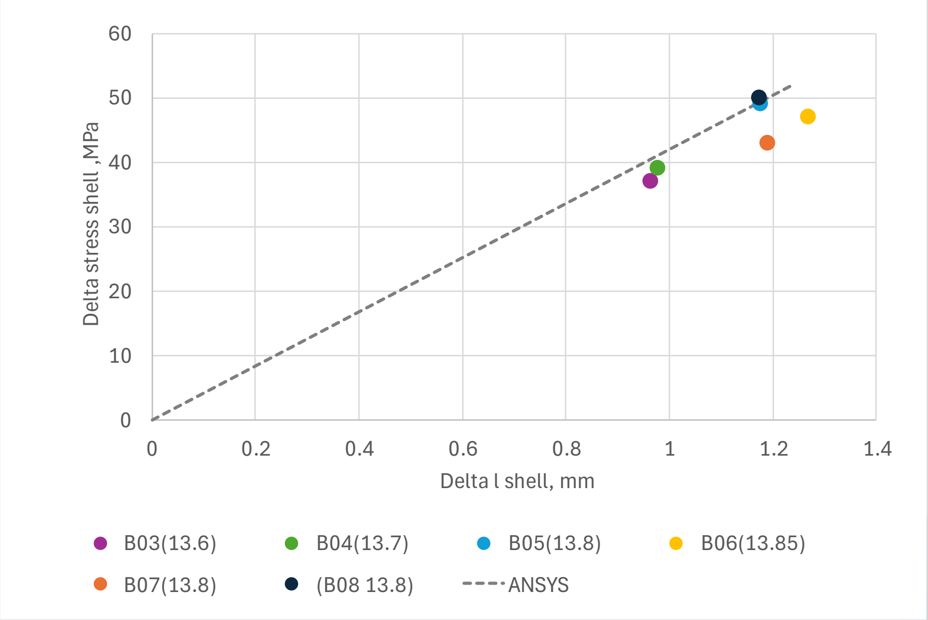




Azimuthal loading

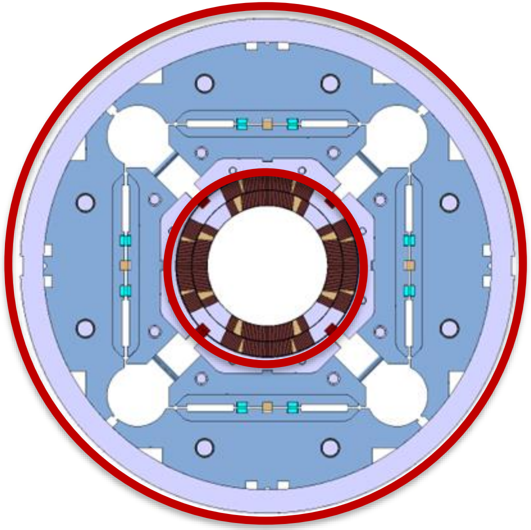
- Good correlation between the increase on the outer magnet developed length with the loading (Delta l shell) and the increase of shell stress during loading (delta stress shell)
- Good agreement with the FE model

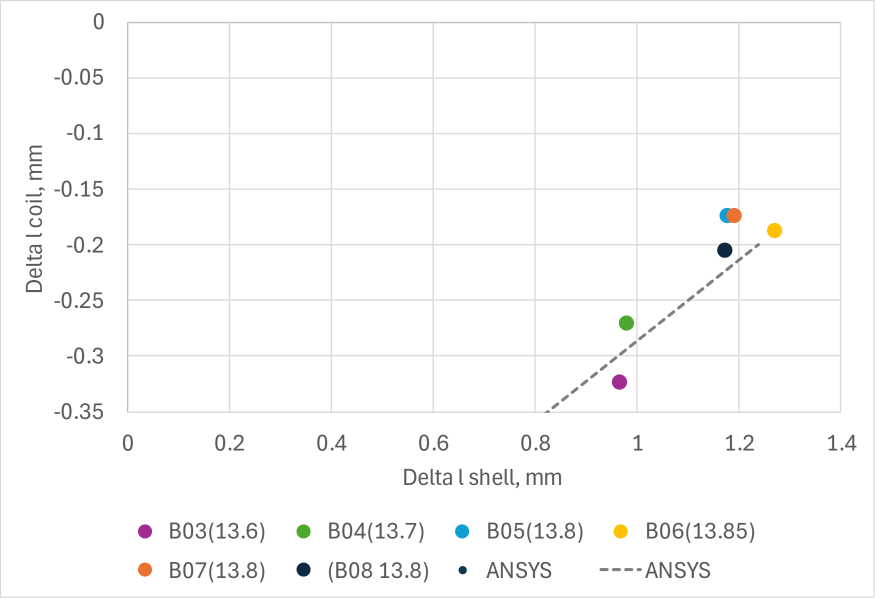




Azimuthal loading

- Good correlation between the increase on the outer magnet developed length with the loading (Delta l shell) and the equivalent increase of coil excess including the loading keys (delta l coil)
- Good agreement with the FE model

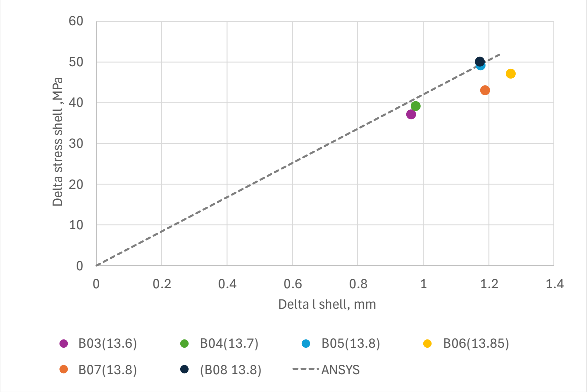


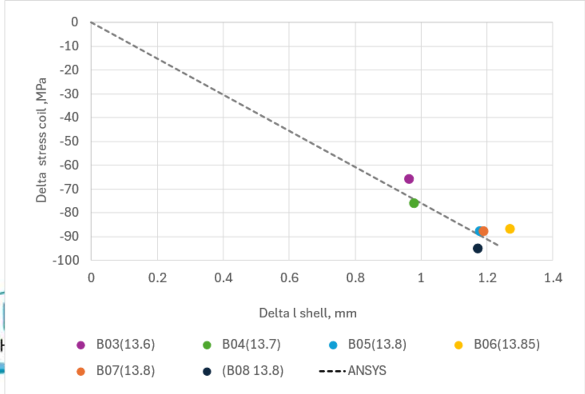


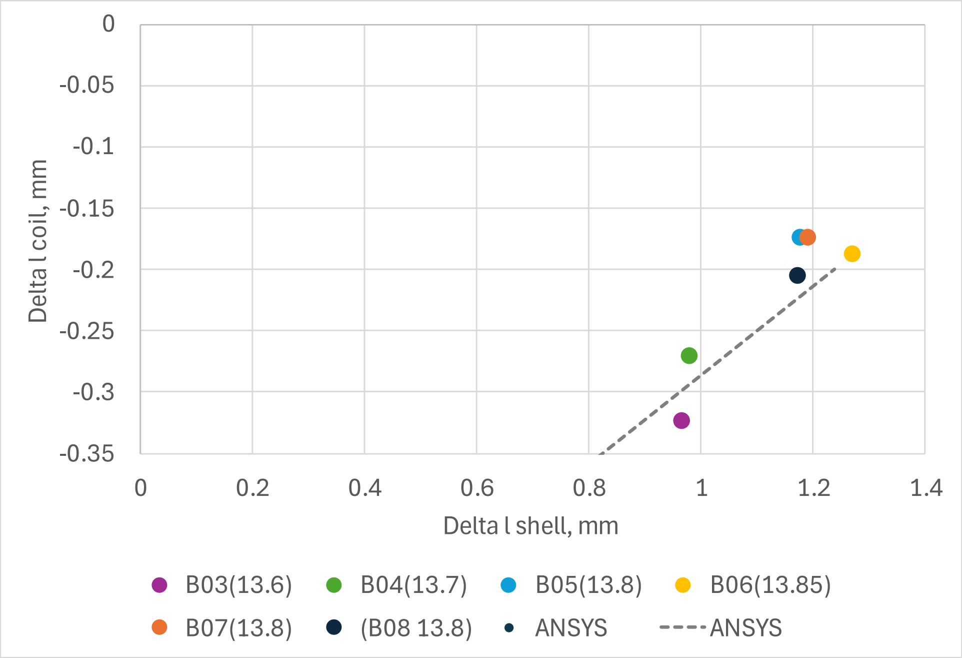
**The ANSYS line is computes as if the delta_l_coil has a deviation from nominal equal to zero, so it is just dependent on the key size. The line has then an assumed offset because the coil pack is smaller than nominal*

Azimuthal loading

- Thus, with geometrical measurements, we can have a good assessment of the level of azimuthal preload in the coil!







Axial loading

Rods instrumentation overview:

- **Strain gauges** placed on the rods
- **LVDT** used to monitor the rods displacement
- **Pressure sensor** to monitor the piston pressure during loading

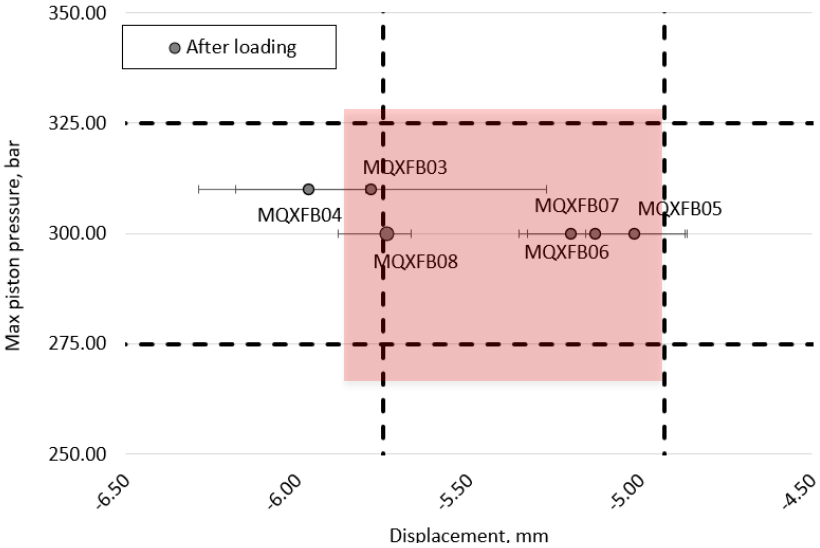
Strain target: **650 ± 50 μstrain after loading** for MQXFB (for all the magnets we are in the ± 50 μstrain windows).

The equivalent targets for pressure and displacement to guarantee 650 ± 50 μstrain are:

1. Pressure target: **300 ± 25 bar**
2. Displacement target: **-5.33 ± 0.4 mm**

Combing the targets of pressure and displacement, we can identify a 'safe' window to guarantee the strain target.

Starting from B08, rods are not instrumented anymore



Conclusion

- Geometrical measurements are a powerful tool to assess the level of the azimuthal and axial coil pre-load

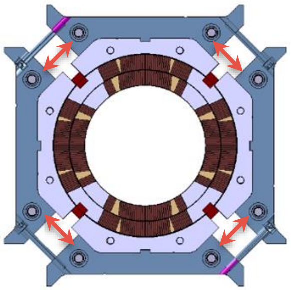
- The accumulated experience with MQXFB from assembling 80% of the magnets for HL-LHC shows that can we monitor production with simple geometrical measurements while ensuring the required preload.

Thank you!

Additional slides

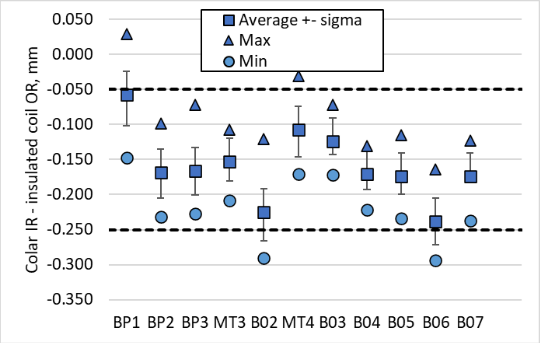
Coil pack sub-assembly

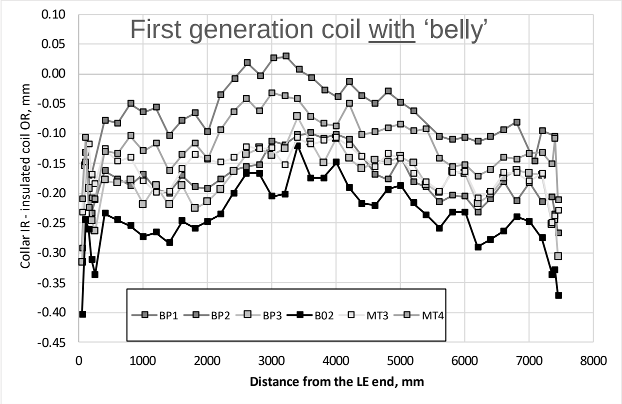
Coil pack sub-assembly

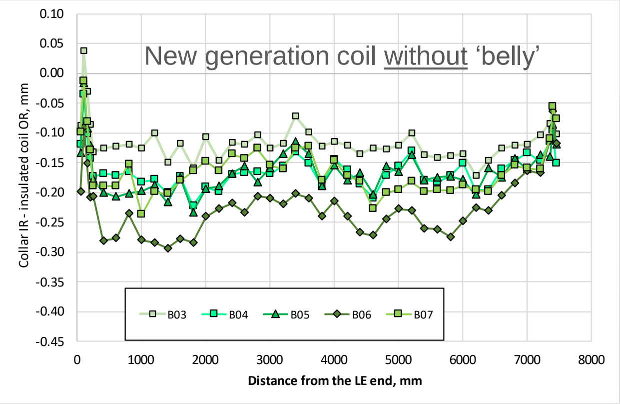


The gap between collars and insulated coils with respect to the nominal dimension gives information about the **coil pack radial size**.

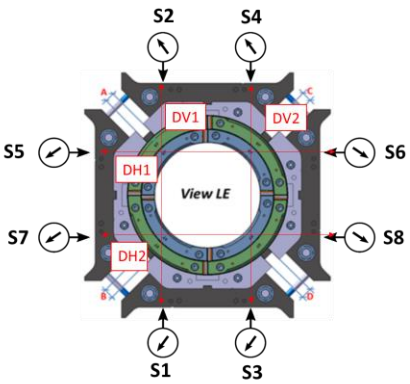
- The magnets with the new generation don't have the 'belly' (larger azimuthal size in the longitudinal center of the coil), and they have very similar sizes.
- The size of the coil pack can be now controlled up to 0.05 mm. For example, B06 is smaller (0.075mm) on purpose, to have the ends' size similar to the previous magnet.







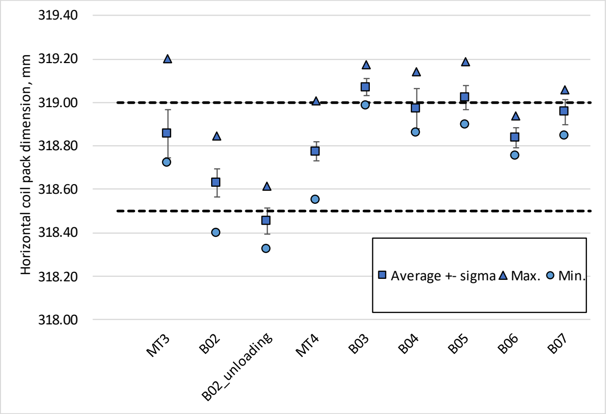
Coil pack sub-assembly

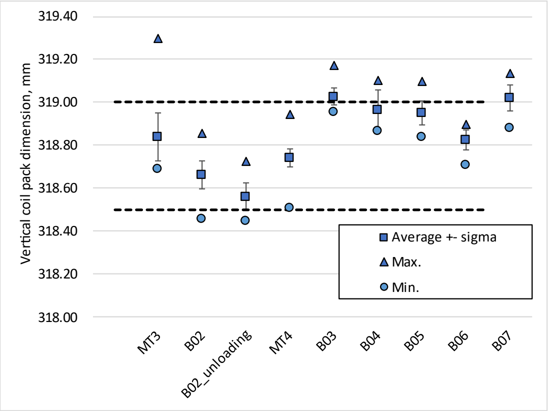


The coil pack is measured horizontally and vertically before the insertion in the structure.

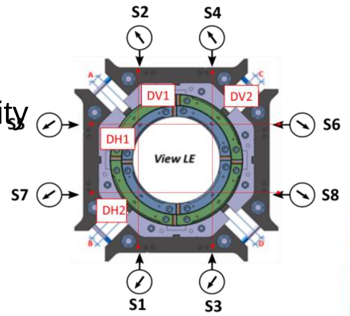
- The differences in the **dimensions** of the coil pack are the same as the one seen in the coil pack radial size (Ex. B06 0.075mm smaller)

Dimensions





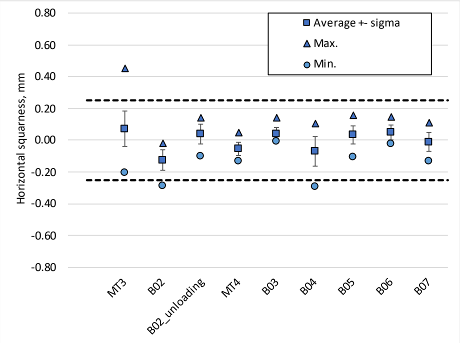
Coil pack sub-assembly

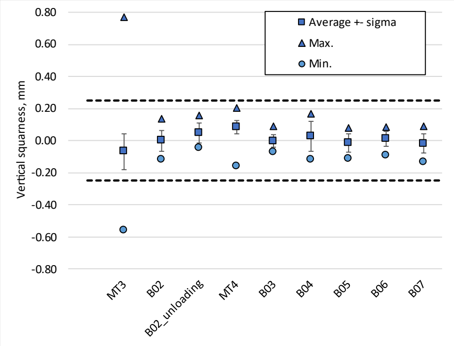


From the measurements it is possible to derive **squareness** ,defied as the difference between the left and right or top and bottom dimensions, and **uniformity**, defied as the average of the vertical or horizontal cavity dimension in each cross-section with respect to the measured average horizontal dimension :

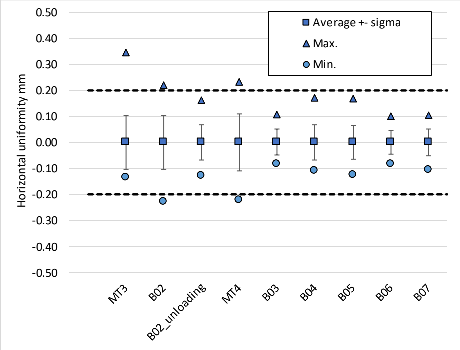
- The **squareness** is consistent with the previous magnets
- The **uniformity** improved with the new generation coils (coils are more uniform along the length now)

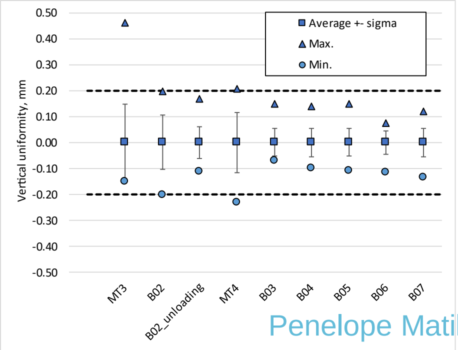
Squareness





Uniformity





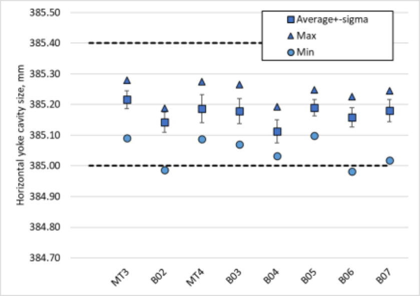
Yoke-shell sub-assembly

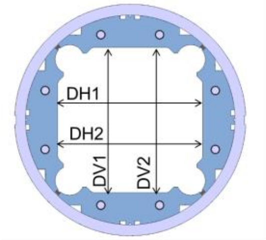
Yoke-shell sub-assembly

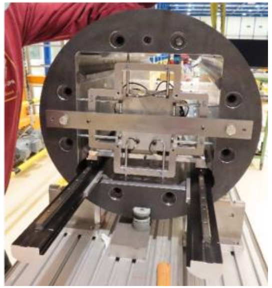
Both the moduli and the final structure are measured to have information about size, squareness and uniformity. Here is presented just the structure analysis.

For the yoke-shell assembly, the magnets are consistent, there is an improvement in the squareness.

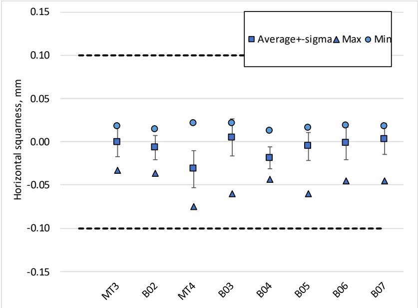
Dimensions

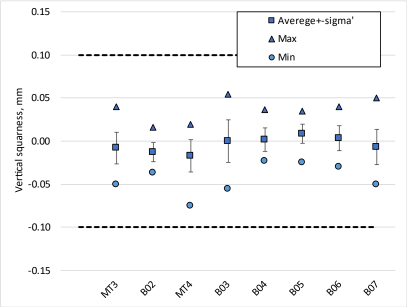




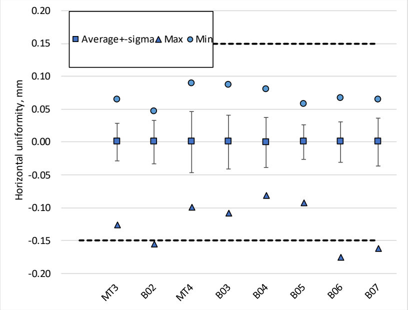


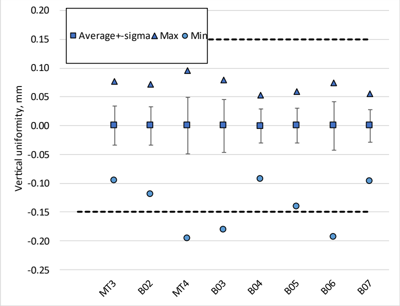
Squareness





Uniformity





Loading

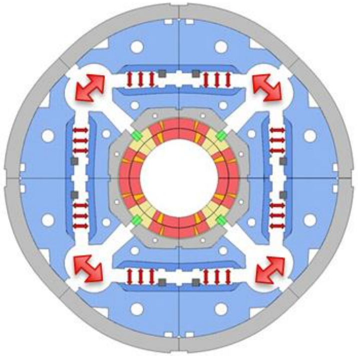
Azimuthal pre-load target (from B03 on)

Loading has the purpose of providing the required pre-stress to the coil to reduce conductor motion.

The target room temperature preload from MQXFB03 is :

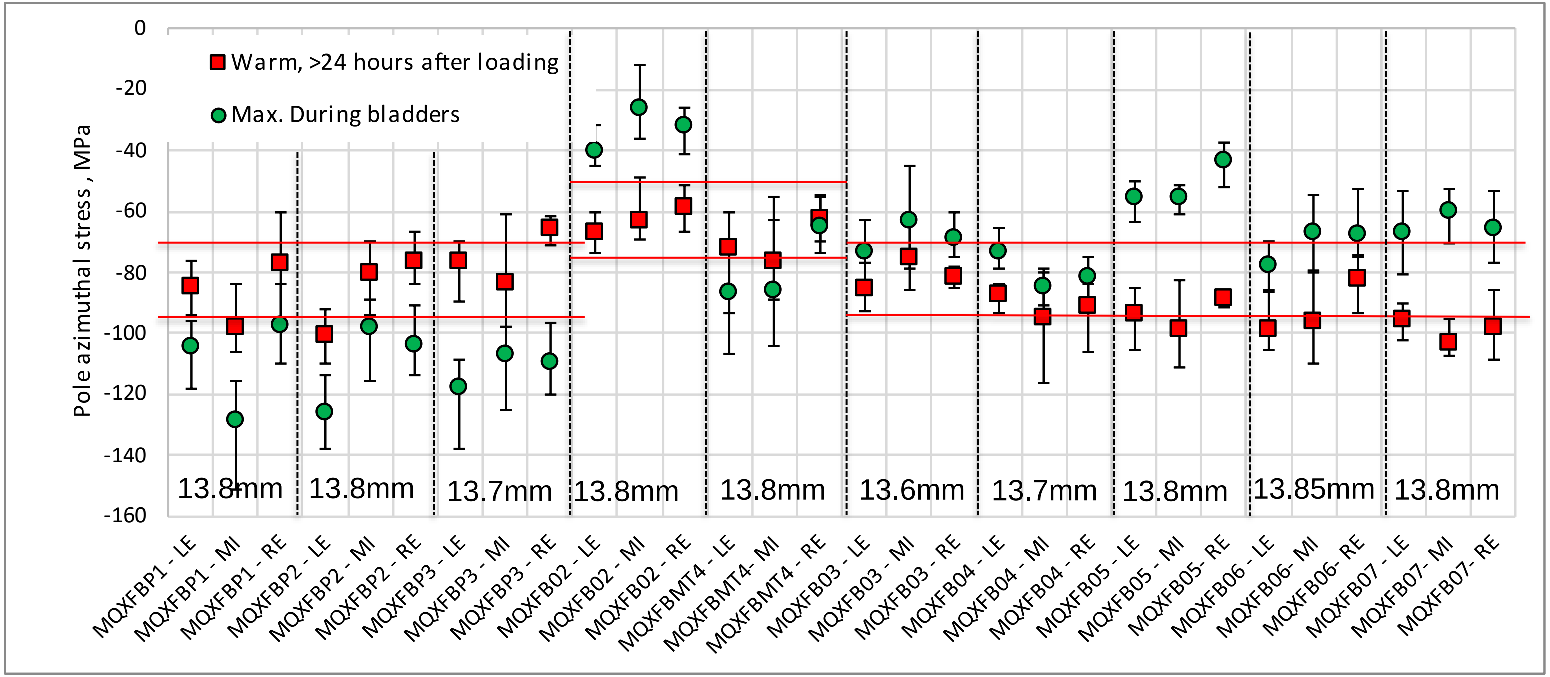
- Average **shell** stress: **58 ± 6 MPa**
- Average **pole** coil stress: **-80 ± 10 MPa**
- **Rod** strain: **650 με**
- Allowable **peak stress** in the coil during loading is **-110 MPa**, achievable thanks to the new loading procedure with auxiliary bladders (AUP has -135 MPa as maximum allowable stress)
- In case the maximum allowable peak stress in the conductor (110 MPa) is reached, the average pre-load will be lowered accordingly to fulfill the peak stress requirement

With the new welding procedure (applied from MQXFBP3), we expect no increase on the azimuthal stress of the coils during welding



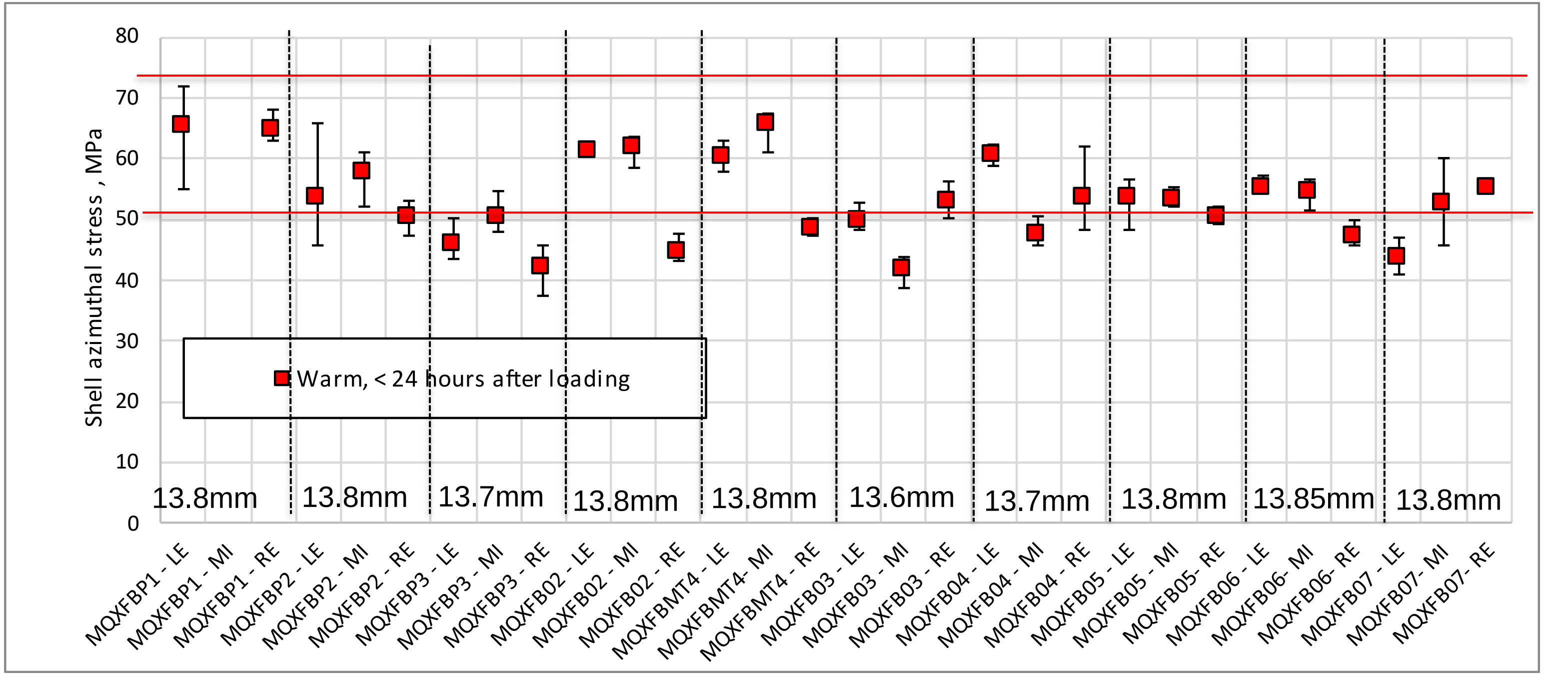
RT: Targets vs achieved

- From MQXFB02, auxiliary bladders in the yoke were used to reduce the peak stress in the coil and from MQXFB03 the new generation coil geometry is used



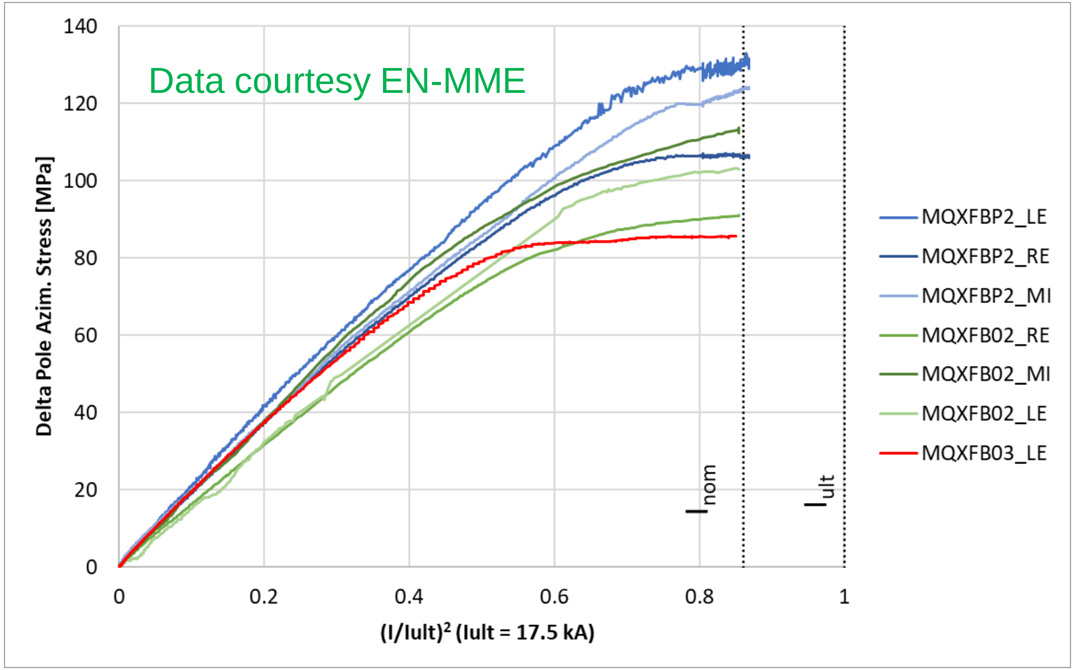
RT: Targets vs achieved

- The shell has similar behaviour in all the magnets



Cold: Targets vs achieved

- At cold, MQXFB02 had 90-110 MPa pole azimuthal compression, corresponding to a pole un-loading around nominal current
- For MQXFB03, we only have ‘clean’ measurements from the LE end, 85 MPa (Remember, B03 has keys 13.6 mm, the smallest used so far).
- From MQXFB04, there are no stress measures at cold



Rods, axial pre-load

- From BP2, all magnets loaded so far with the same axial pre-load (at RT), 650 ± 50 µstrain **after loading**
- **During cooldown** the delta strain is in between 450 µstrain and 550 µstrain for all the magnet
- **During powering** the delta strain is in between 75 µstrain and 85 µstrain from magnet BP3.
- MQXFB03 has similar behaviour to the previous magnets, although now the magnet is mostly quenching in the ends