MQXFB: Improvements in magnet assembly

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Acknowledgements: Jose Ferradas Troitino, Attilio Milanese, Ezio Todesco
https://indico.cern.ch/event/1150724/

CERN: April 29th, 2022

Outline

- Introduction to the magnet design
- MQXFS, MQXFA and MQXFB pre-load levels
- Improvements in MQXFB assembly process
- Conclusions

The focus of the presentation is on the analysis of the magnet straight section, since MQXFBP1 and MQXFBP2 were limited in middle of the magnet

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- **Introduction to the magnet design**
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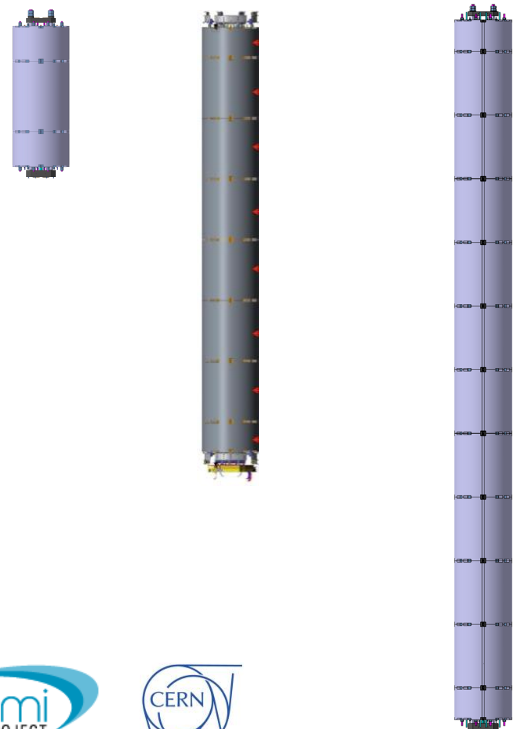
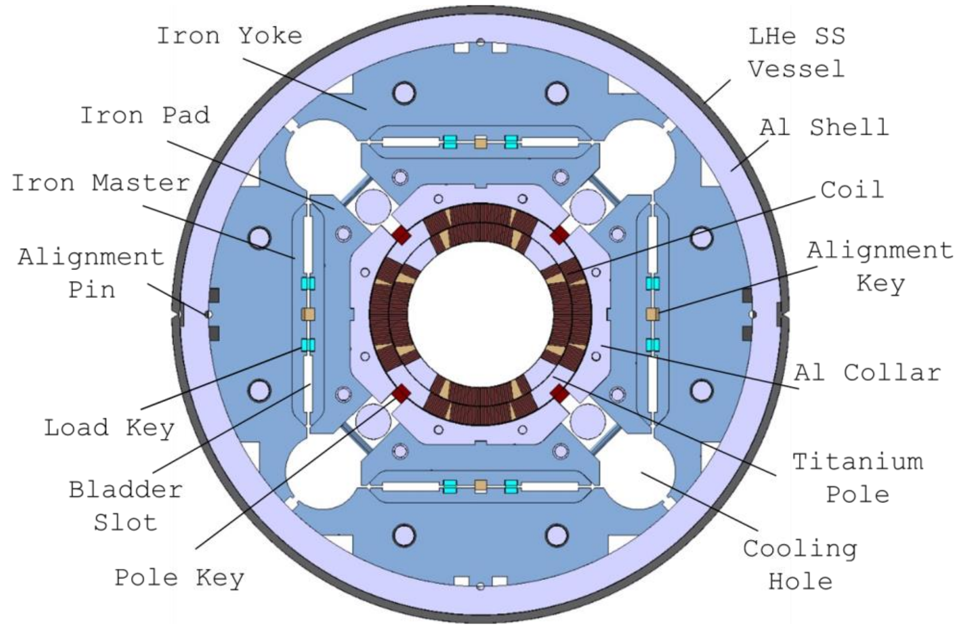
Magnet design

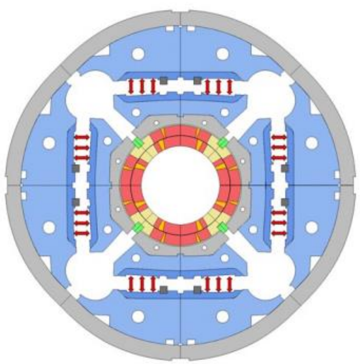
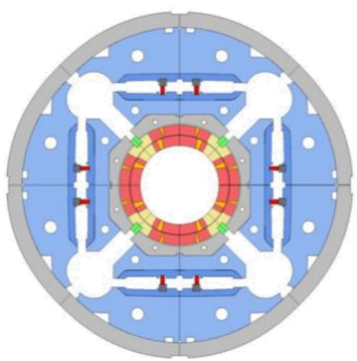
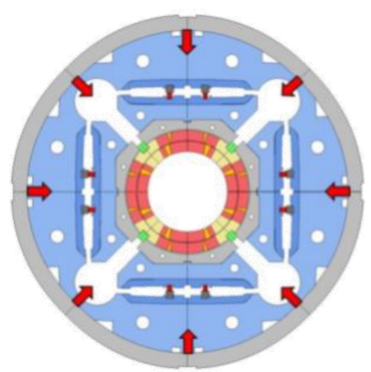
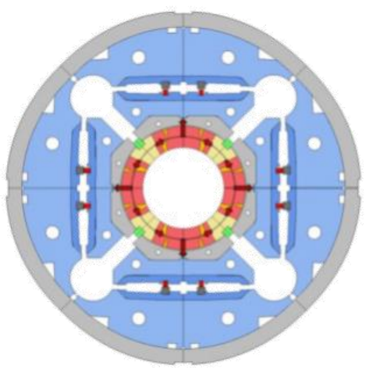
- Target: 132.2 T/m; 150 mm coil aperture, **11.3 T B_{peak}**
- Q1/Q3 (by US-AUP Project), 2 magnets **MQXFA** with 4.2 m L_m
- Q2a/Q2b (by CERN), 1 magnet **MQXFB** with 7.15 m L_m
- Joint short model development program **(MQXFS)** to validate the design
- Different lengths, same design, very similar assembly procedure and loading target

MQXFS (1.2 m) *MQXFA (4.2 m)* *MQXFB (7.15 m)*

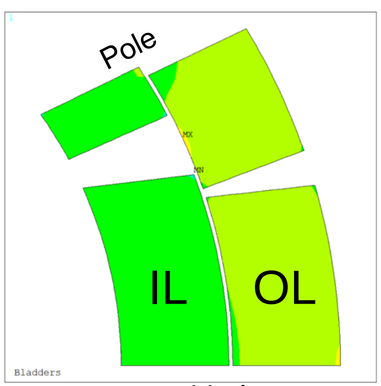
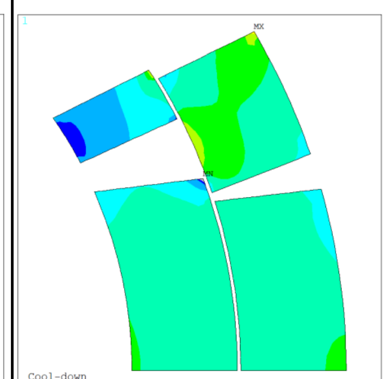
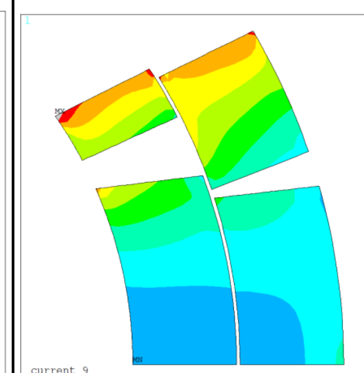




Magnet assembly

	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. of 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 %
				

Magnet assembly

		Bladder pressurization	Key insertion	Cool down	Powering (16.23/17.5 kA)
		Open enough clearance to be insert the keys (key size + 0.2-0.3 mm)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic forces
σ_θ coil, Mpa	Ave Pole turn IL	-58	-52	-97	-6/-2
	Peak Pole turn IL	-72	-86	-113	-14/-8
	Peak Coil	-72	-86	-124	-109/-120
ANSYS Release 19.2 Build 19.2 NODAL SOLUTION STEP=2 SUB =1 TIME=2 SY (AVG) RSYS=1 PowerGraphics EFACET=1 AVRES=Mat DMX =.138E-03 SMN =-.857E+08 SMX =-.137E+08 -.125E+09 125 MPa -.110E+09 -.950E+08 -.800E+08 -.650E+08 -.500E+08 -.350E+08 -.200E+08 -.500E+07 .100E+08 0 MPa		 Mid-plane			

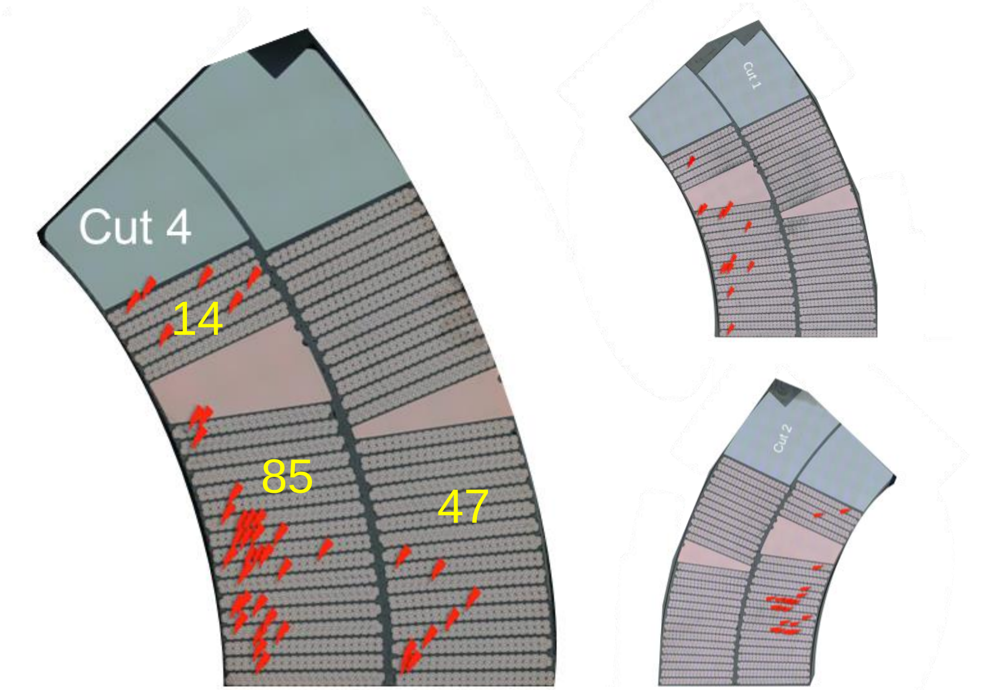
Stress map and stress values for the new procedure, loading with auxiliary bladders in the cooling holes.
Nominal assembly with 80 MPa pole compression at warm, 110 MPa at cold
Uncertainty due to material properties and assembly tolerances ± 15-20 MPa

Radial cracks and stress map

- The higher concentration of micro-cracks in the analyzed sections of coil 108 straight section is in IL the mid- plane block (see talk from S. Sgobba)

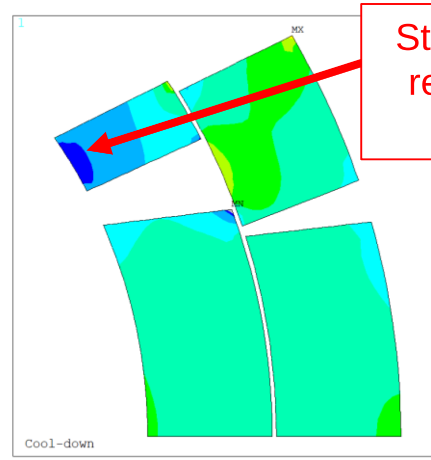
Coil 108, coil straight section

Conductor exhibiting micro-cracks (several sub-elements can be impacted for an indicated location)



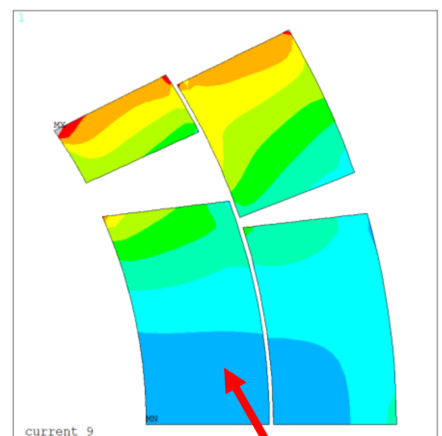
Remark: In the case of BP1, with a maximum coil stress of 100 MPa at warm after loading, we expect 135 MPa in the pole block after cool down and a maximum of 110 MPa in the mid-plane at 15 kA

After cool down

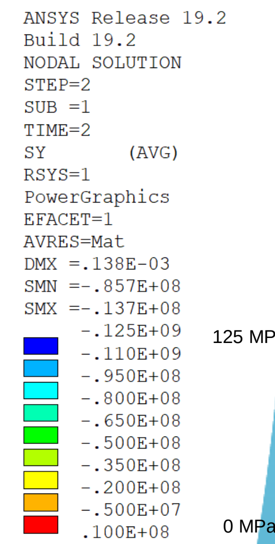


Stress concentration region, 125 MPa at 1.9 K

Powering (16.23 kA)



Stress concentration region, 110 MPa at I_{nom} (120 MPa at I_{ult})



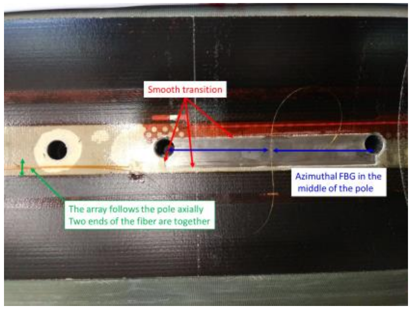
Mechanical instrumentation

Strain is measured in:

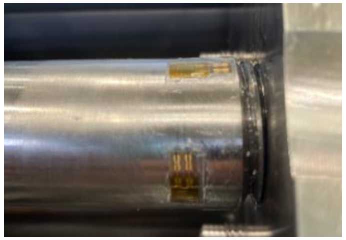
1. Rods
2. Aluminum shell
3. Coil Titanium pole, providing the peak stress in the coil (pole turn inner layer) during loading and cool down.

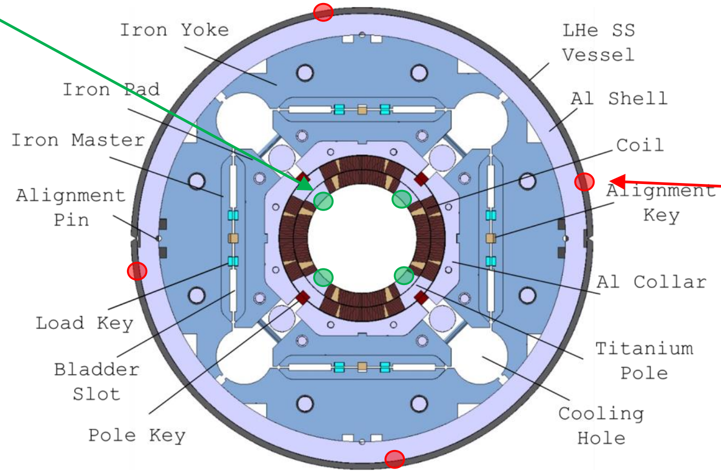
For MQXFS, one longitudinal section is measured. For MQXFB, measurements are performed in 3 longitudinal sections

Coils instrumented with strain gauges and of FBGs

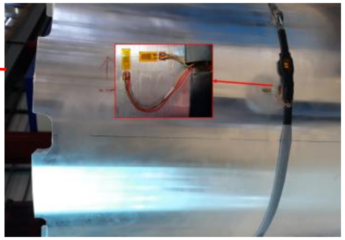


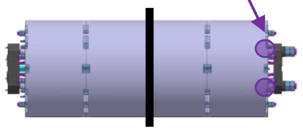
Rods instrumented with strain gauges



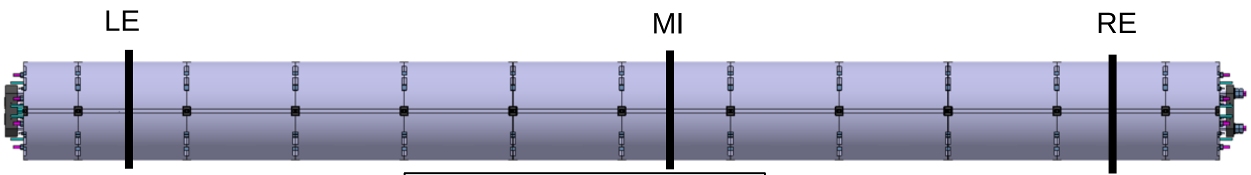


Al-shells instrumented with strain gauges





MQXFS, one longitudinal measuring location



MQXFB, three longitudinal measuring locations

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- Introduction to the magnet design
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- Improvements in MQXFB assembly process
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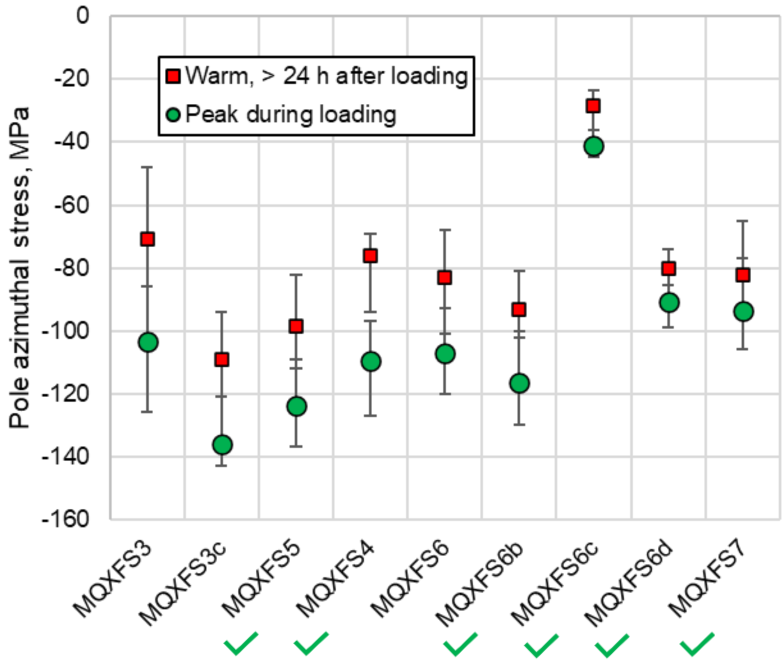
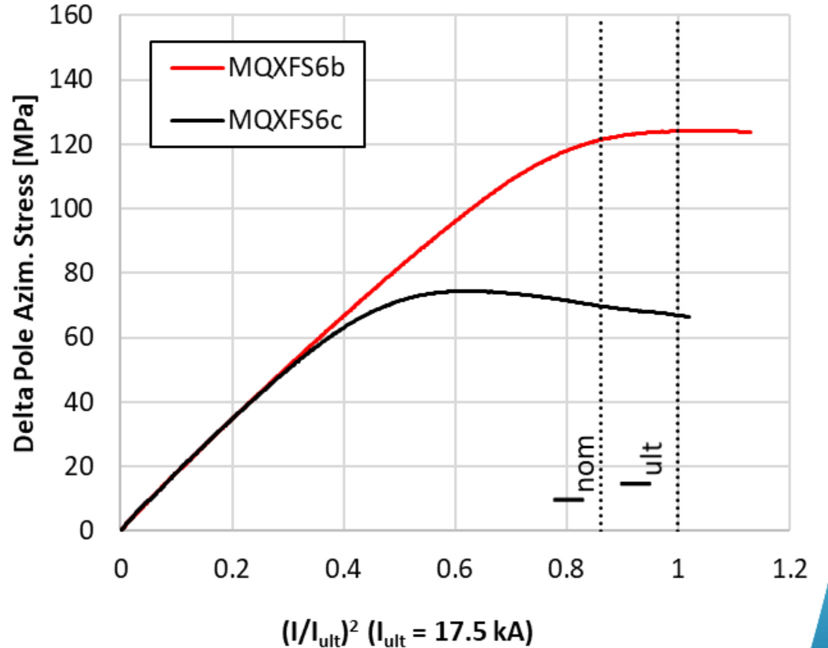
MQXFS

- Azimuthal pre-load level parameter space explored with the short model program, with magnets reaching > 90 % of the short sample limit, with a pole coil compression ranging from:
  - 25 MPa – 115 MPa after RT loading
  - 65 MPa – 120 MPa after cool down
- During bladder operations, 20-40 MPa overshoot needed to insert the keys, with a peak of 140 MPa in one coil in MQXFS5.
- The measured unloading of the pole during powering is consistent with the expected pre-stress lever from the RT assembly: lower pre-load at room temperature, sooner unloading during powering

Measured azimuthal stress during RT loading. Error bars represent the spread among the 4 coils in the same longitudinal location



Change of azimuthal pole pre-stress during powering, as a function of the square of the current. Average among the 4 coils in the magnet.



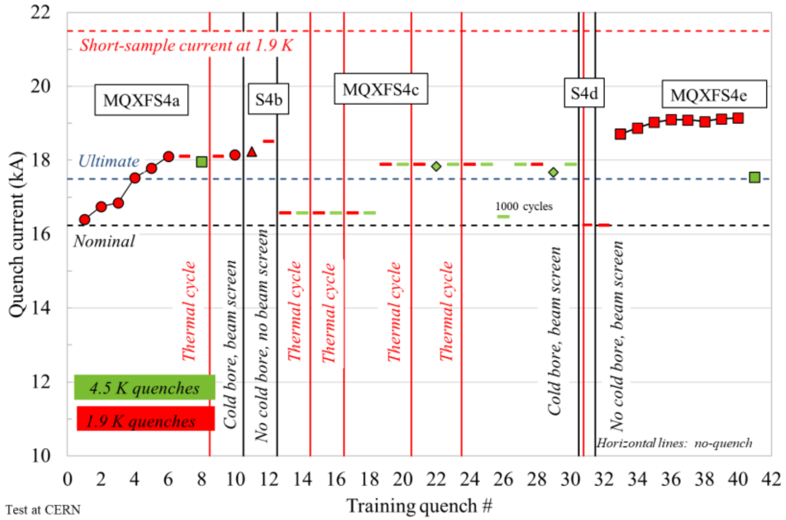
I_{max} (1.9 K), kA	18.5	19.2	19.1	19.1	19.6	18.5
I_{max} (4.5 K) , kA	17.9	18.0	18.2	18.1	18.1	18.2

I_{nom} = 16.23 kA
I_{ult} = 17.5 kA

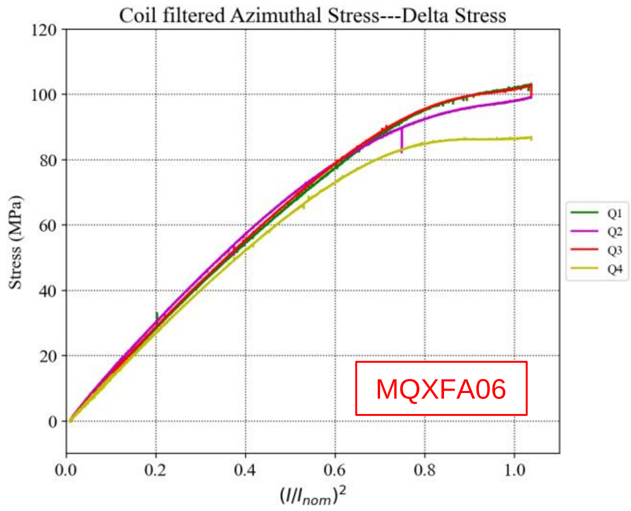
MQXFA

- AUP defined the pre-load targets as reference MQXFS4 (see MQXFA Series Magnet Production Specification, US-HiLumi-doc-4009)
- The target **average** measured stress on coils and shells at the end of the loading (after at least 24 h) shall be
  - **Shell** average azimuthal stress: **+58 ± 6 MPa**
  - **Coil** (winding pole) average azimuthal stress: **-80 ± 8 MPa**
- For the **maximum stress** reached during the pre-load operations, the maximum compression measured on each **coil** shall never exceed **-110 MPa**
- After cool down, the pole pre-stress is 100 – 110 MPa → coils remain in contact with the winding pole up to 80-90 % of the nominal current. Good magnet to magnet reproducibility

Training performance MQXFS4

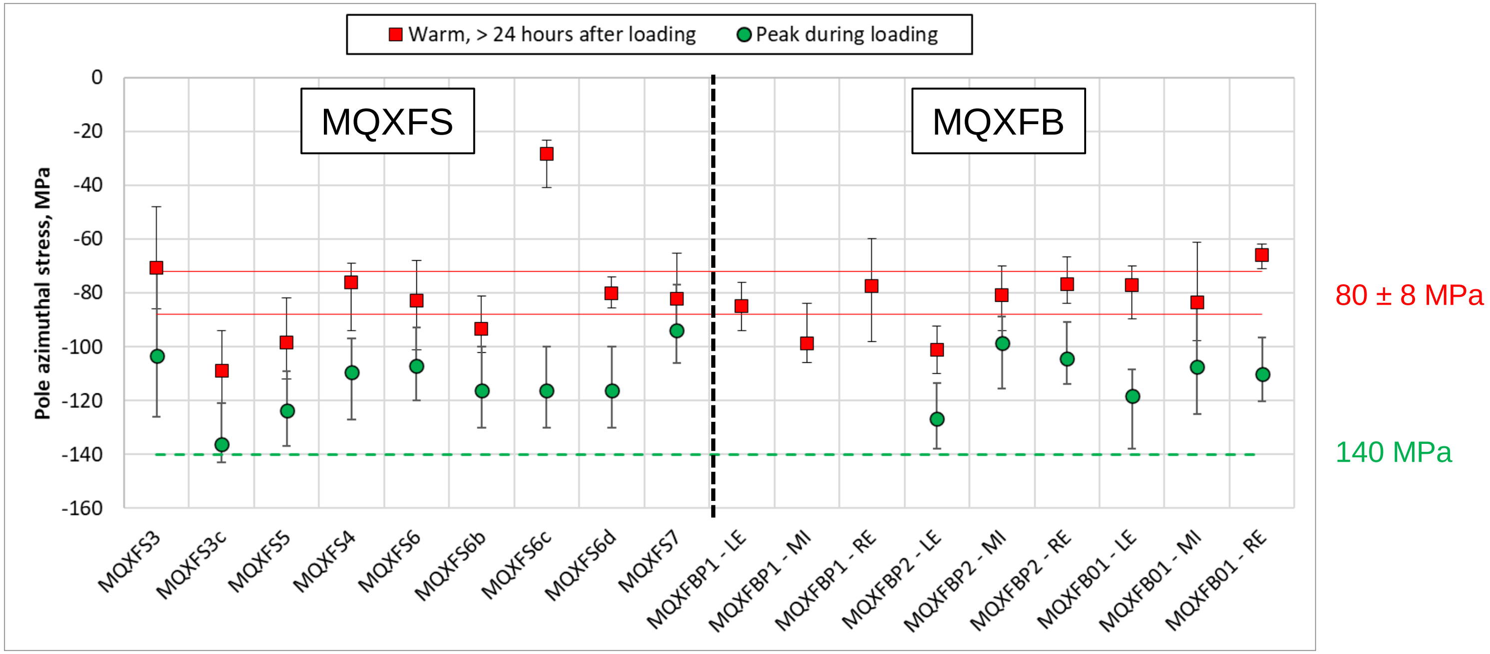


Change of azimuthal pole pre-stress during powering, as a function of the square of the current.



MQXFB – RT loading

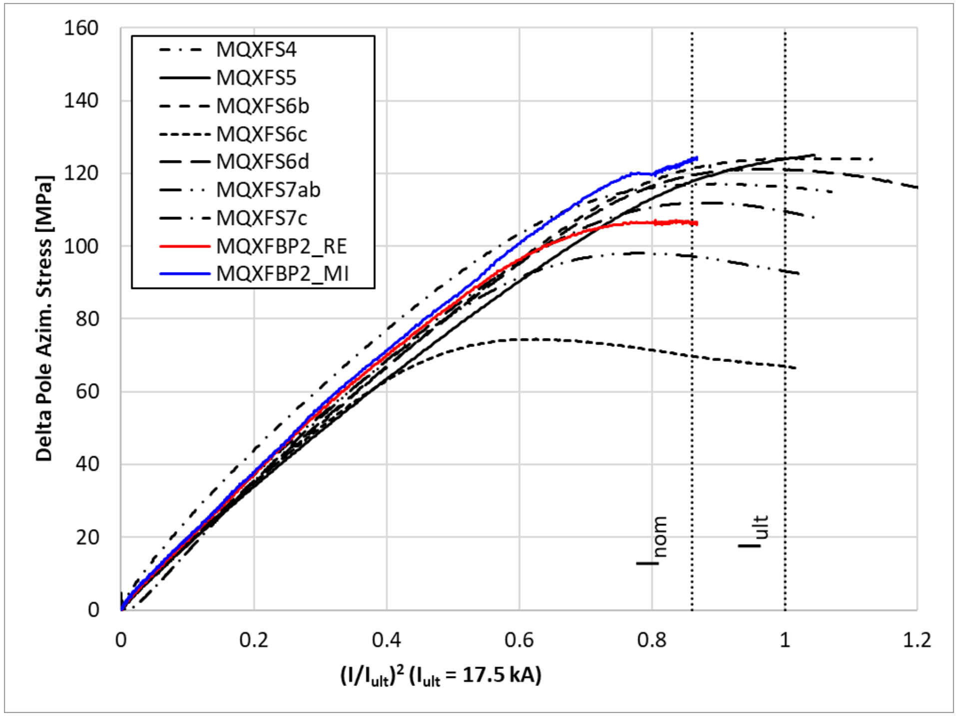
- MQXFB and MQXFA have identical **target** preload, i.e., **average shell** stress **+58** ± 6 MPa, **average coil stress** (winding pole): **-80** ± 8 MPa
- In terms of **peak** stress during loading, the maximum measured in MQXFBP2&P3 magnets was **-140 MPa**, higher than the -110 MPa set as limit for MQXFA, but reached in MQXFS5
- The increase of coil azimuthal stress during welding is lower than the overshoot during loading



MQXFB – Cold

- At cold, only MQXFBP2 measurements in the return and middle magnet sections are available
  - In MQXFBP2, the increase of the coil stress during welding was 30 MPa (vs 8 ± 8 MPa specified at the time), so the final stress of the coil at cold is 15-20 MPa higher than the initial target
  - Un-loading of the pole turn measured with the mechanical instrumentation when approaching the nominal current, as expected from the RT pre-load levels when including the additional stress form the welding

Change of azimuthal pole pre-stress during powering, as a function of the square of the current. Average among the 4 coils in the magnet.



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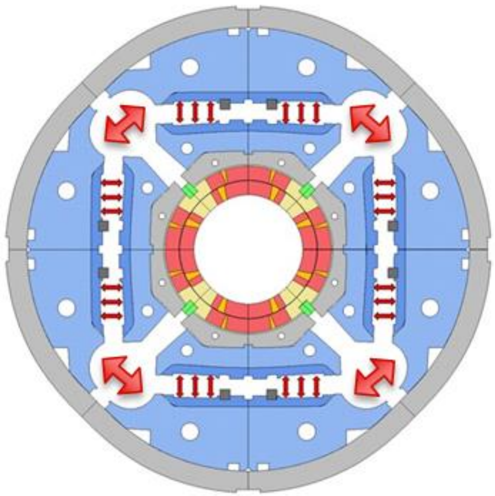
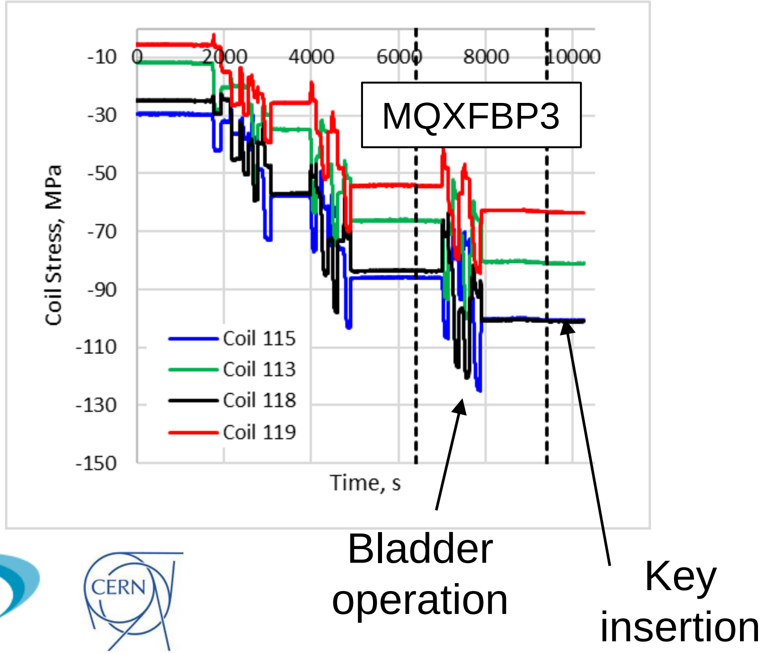
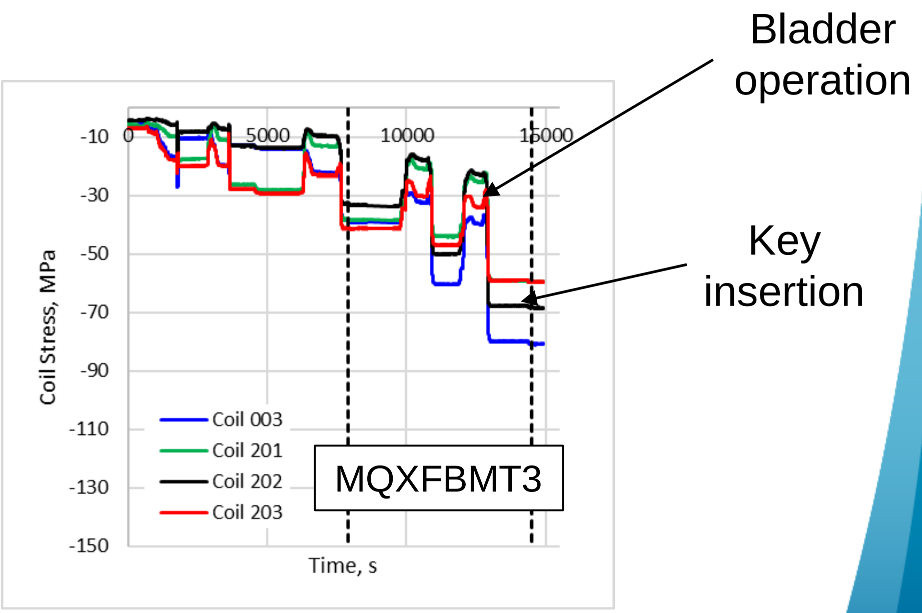
- Introduction to the magnet design
- MQXFS, MQXFA and MQXFB pre-load levels
- **Improvements in MQXFB assembly process**
  - **New procedure for loading**
  - **Alignment**
  - **Bladders and axial pre-load**
- Conclusions

Improved procedure: Loading

- During bladder operations, 20 - 40 MPa overshoot needed to insert the keys
- New loading procedure developed in MQXBMT3, using auxiliary bladders in the cooling holes, allows to completely remove the 20 - 40 MPa overshoot of coil stress during loading



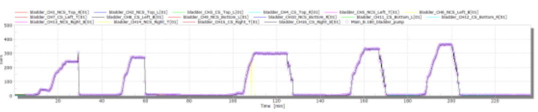




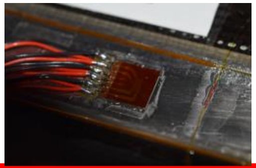
MQXFBMT3: the assembly validation experiment

Heavily instrumented experiment, for a full characterization of the mechanical behavior of the magnet

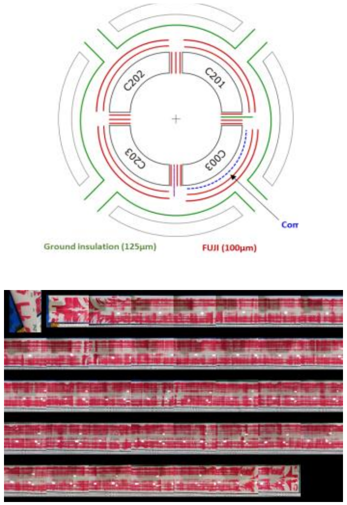
Pressure sensors in each bladder circuit



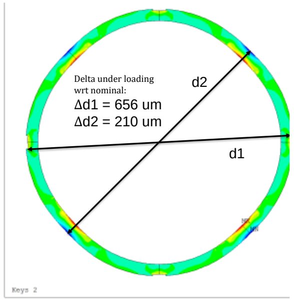
Rosette SG in the pole, confirmed a biaxial longitudinal and azimuthal strain state



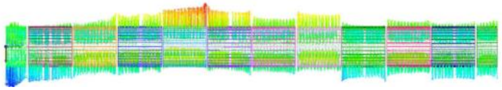
Fuji pressure sensitive film



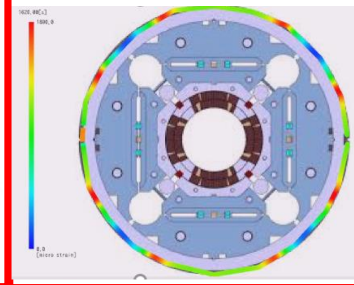
Displacement sensors on the OD to monitor deformation during loading



Geometrical measurements (alignment + pre-stress estimation)



Distributed FBGs measurements around Al-shells

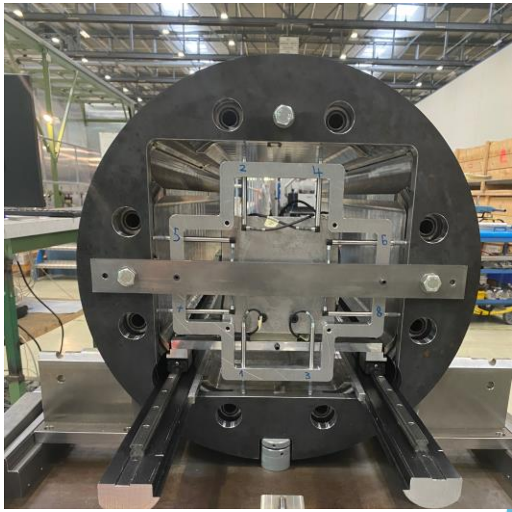


For more details, see https://indico.cern.ch/event/1138192/

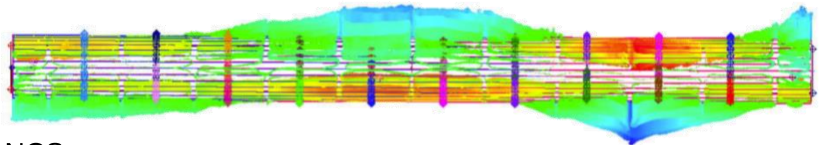
Improved procedure: Alignment (yoke-shell)

- In MQXFBP3, mis-alignment in the horizontal axis between yoke-shell subassembly modules observed, resulting on a magnet 'snaky' shape (max-min = 1.4 mm), see EDMS 2477740.
  - After cold mass completion, same shape as after magnet loading

- In MQXFBMT3, the external faces of the yoke modules were machined after shell-yoke subassembly, and the procedure & measurement system for the horizontal yoke shell subassembly was optimized, keeping the alignment of the outer surface of the Al shell is within ± 0.3mm

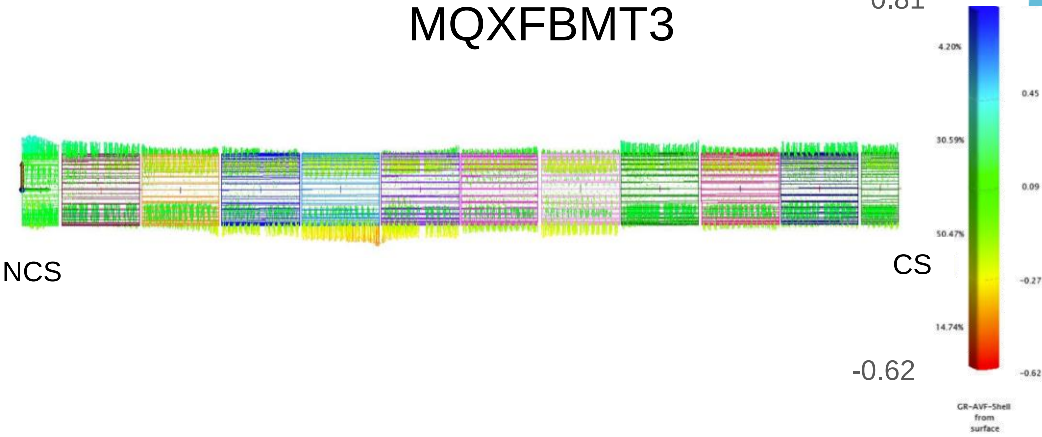


MQXFBP3



NCS CS

MQXFBMT3



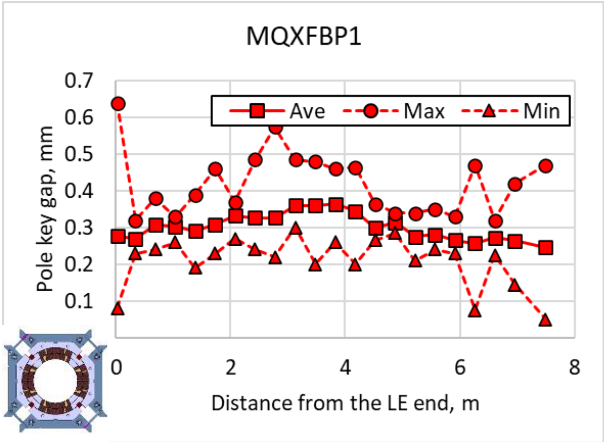
NCS CS

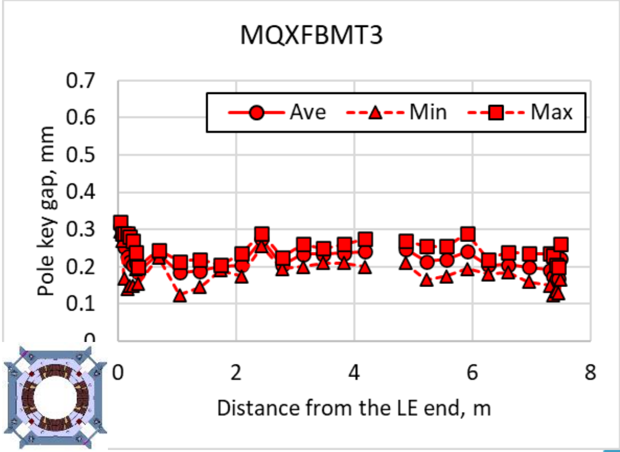
Improved procedure: Bladders, axial pre-load and coil pack

- During the loading of MQXFBP1, 8 bladders broke. One case resulted in an unbalance stress situation for the coils (see EDMS 2276044)
  - New bladder technology (**tubular bladders** instead of welded plates) implemented in MQXFBP2. No bladder failure in BP2, BP3 and MT3.
- For MQXFBP2, improved **axial loading system** (4 pistons instead of 1) for an easier force balance among rods, including in-situ measurements of rods elongation during loading → Very good balance of force among the four rods
- **Coil pack bolting** process optimized in MQXFBP3, reducing the spread of the average pole key gap per quadrant from 0.5 mm to 0.1 mm

Axial system with 4 rods

Coil pack squareness





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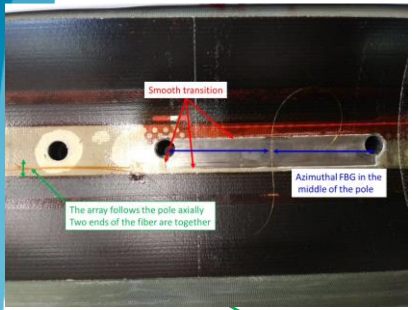
Conclusions

- A **new loading procedure**, with auxiliary bladders in the cooling holes, has been developed and demonstrated in MQXFBMT3. The new loading method allows to **eliminate the 20-40 MPa overshoot** of coil stress during bladder operations.
- **MQXFBMT3** was heavily instrumented, it **validated** all parameters relevant for **magnet assembly.**
- In addition to the new loading procedure, the most **relevant improvements in magnet assembly** are:
  - New bladder tubular technology (MQXFBP2), allows loading without bladder failure
  - New axial loading system (MQXFBP2), for a more balanced axial preload
  - New coil bolting procedure (MQXFBP3), for a better alignment of the coil pack
  - New yoke-shell subassembly procedure (MQXFBMT3), for a better alignment of the structure
- Coils for the assembly of the next magnet, **MQXFB02**, are available, see here (Technical meeting to review and select the coils). Timeline for the assembly:
  - Yoke-shell & coil pack subassembly: May 2022
  - Magnet assembly and loading: June-July 2022

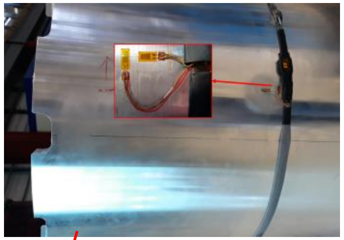
Additional slides

Mechanical instrumentation

Coils instrumented with strain gauges and of FBGs

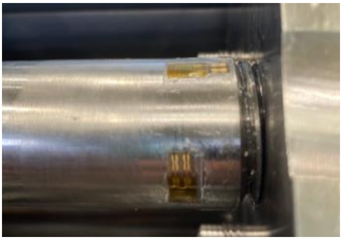


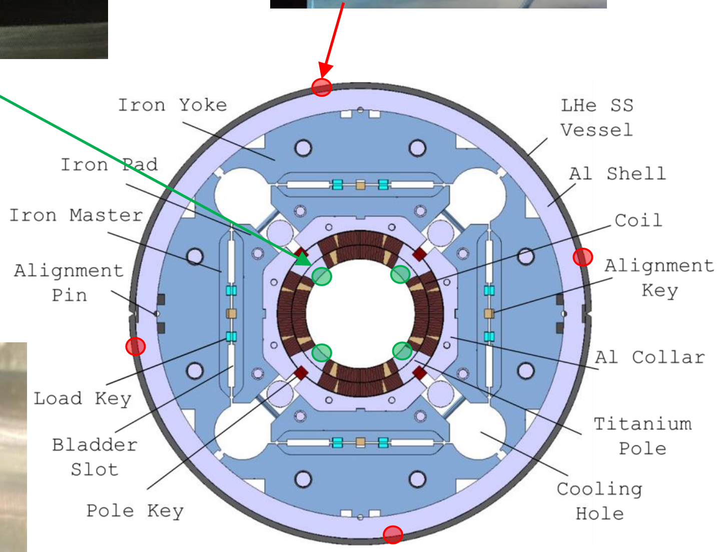
Al-shells instrumented with strain gauges

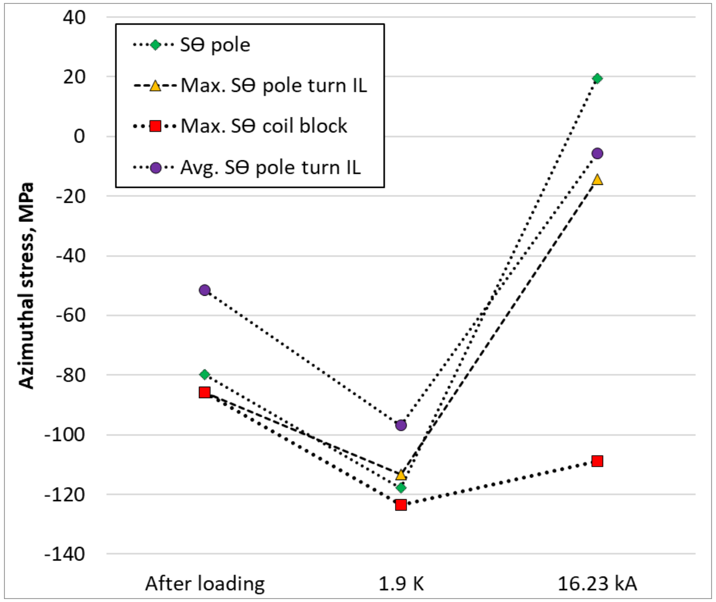


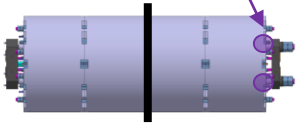
The strain is measured in the coil titanium pole. The peak stress in the coil during loading and cool down is in the IL pole turn, very close to the stress in the Ti pole (measuring location)

Rods instrumented with strain gauges

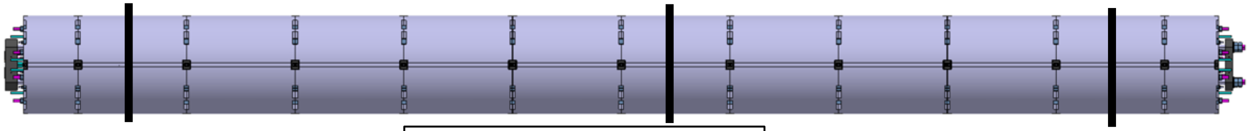






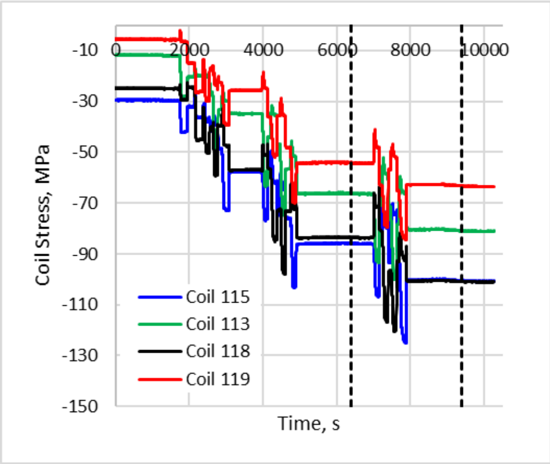


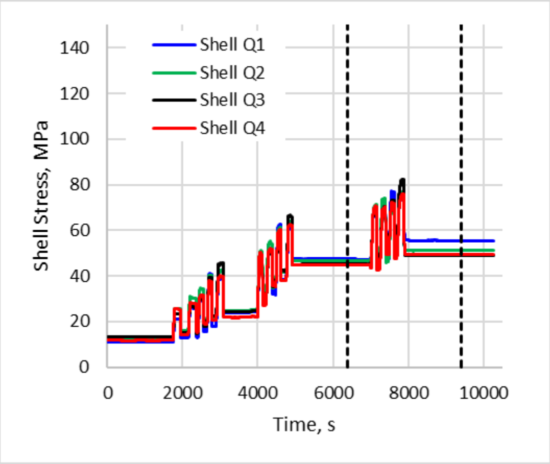
MQXFS, one longitudinal measuring location

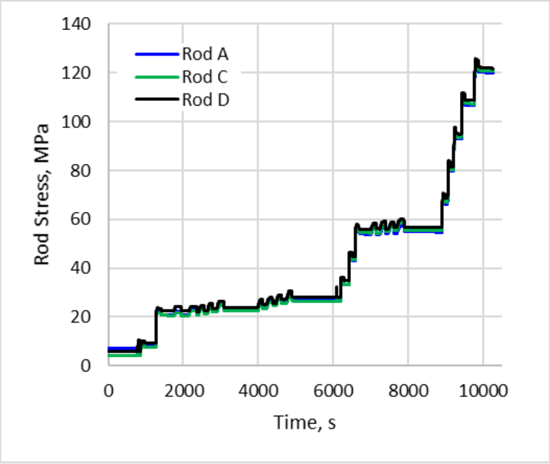


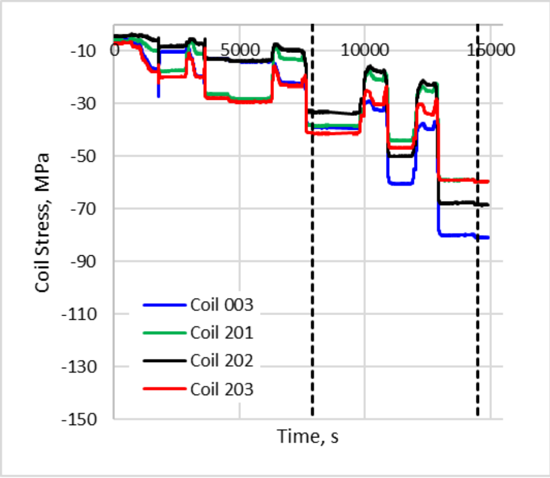
MQXFB, three longitudinal measuring locations

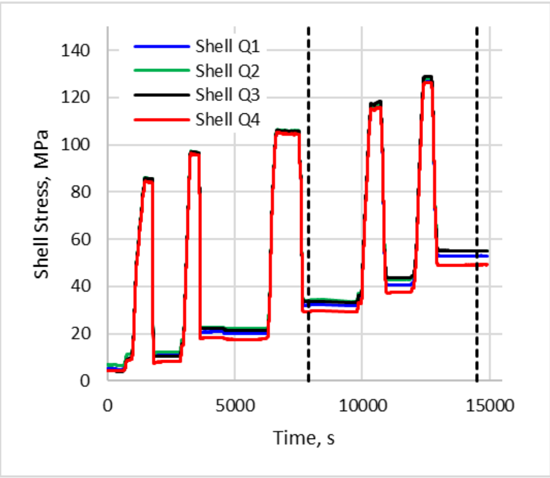
BP3 vs MT3 loading

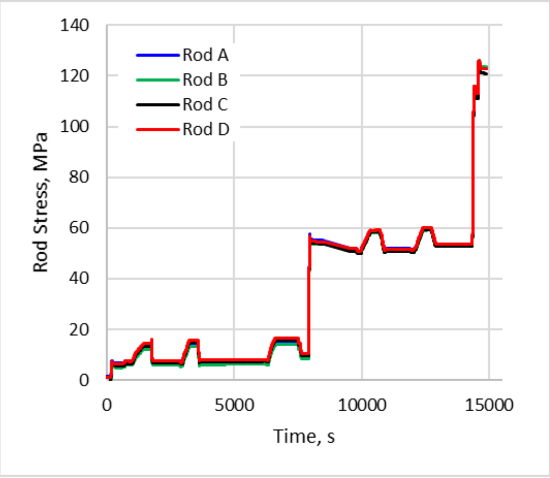






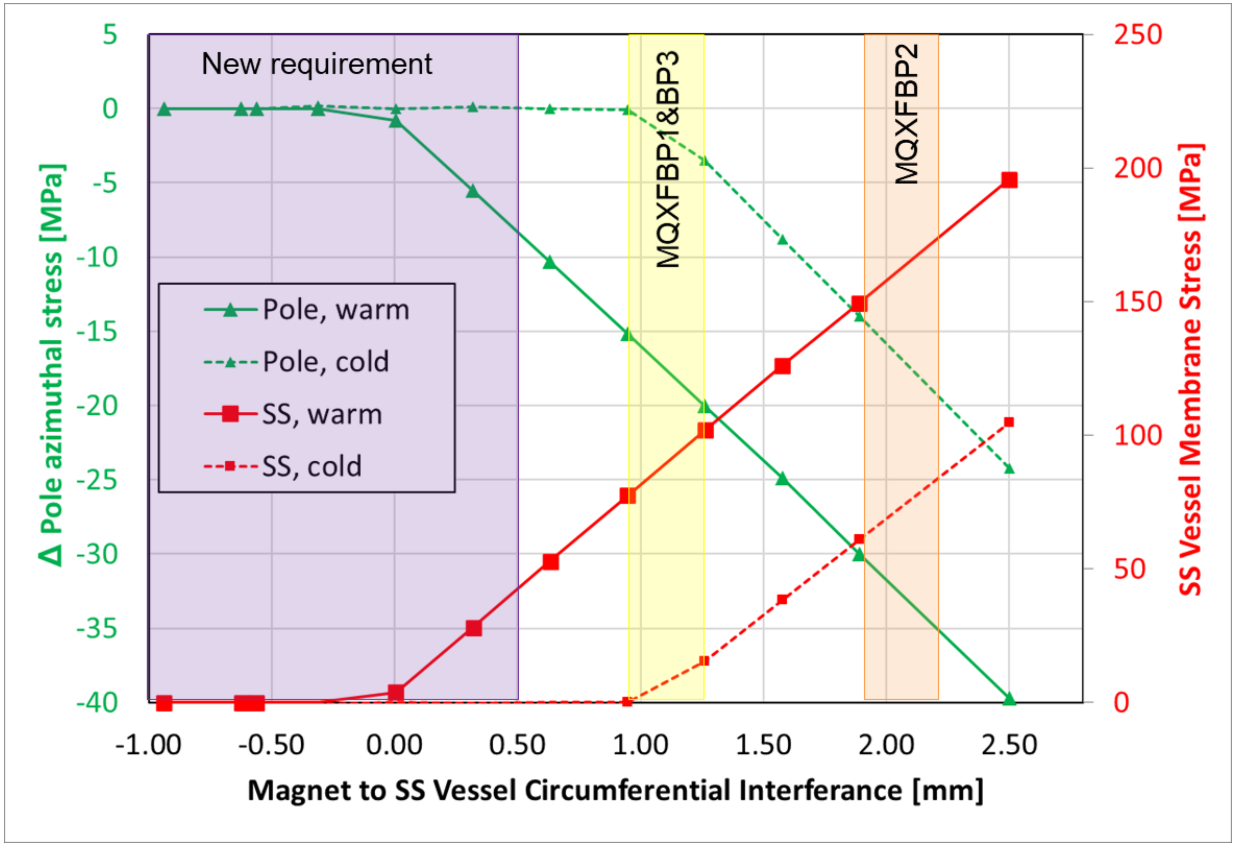




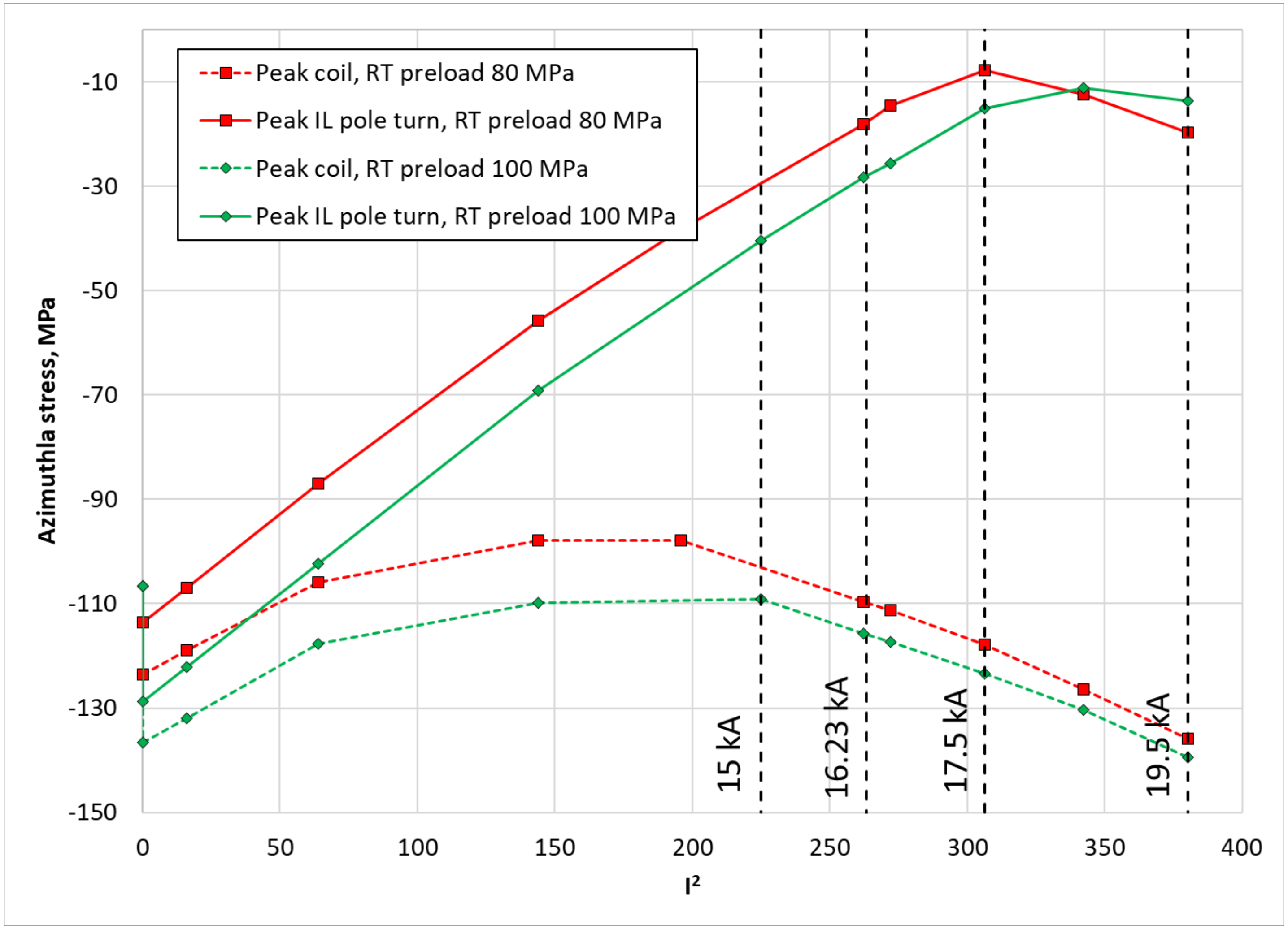


Welding

- Welding requirements were modified, to assure no coupling of the SS vessel to the magnet (**Same** requirements for **AUP** and **CERN**)
  - **Previous target**: 8 ± 8 MPa ΔCoil stress from welding
  - **New target**: 0 + 8 MPa ΔCoil stress from welding



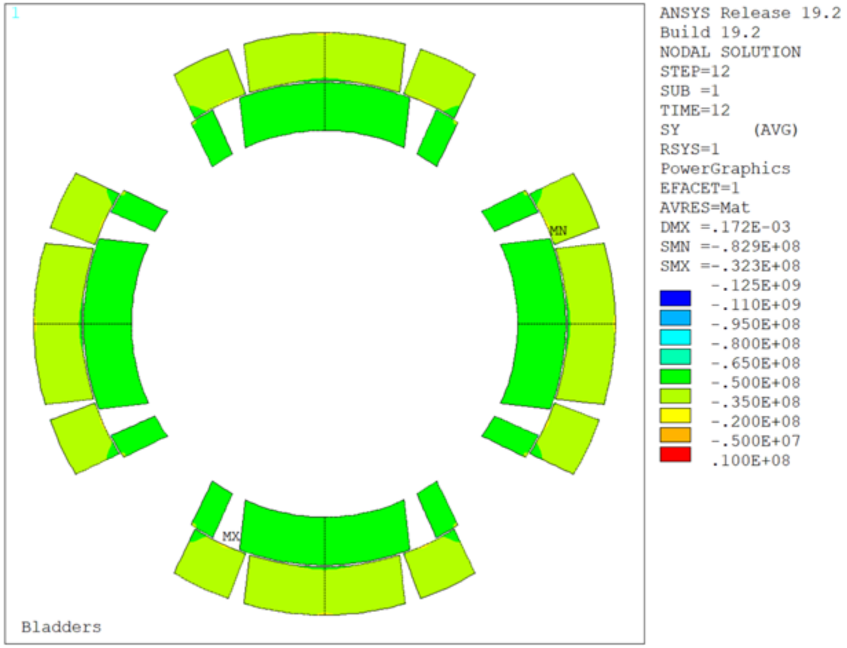
Coil stress



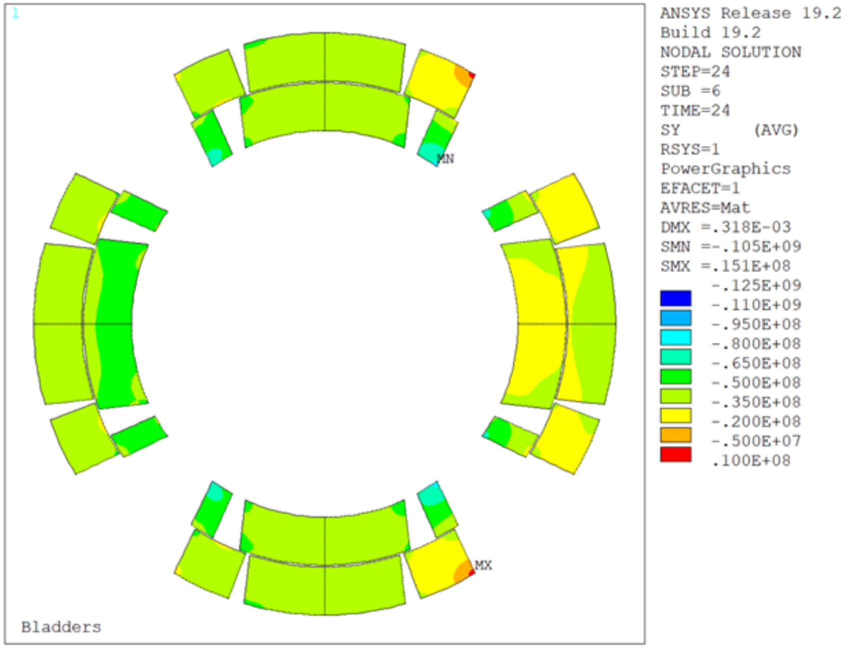
Peak coil, RT preload 80 MPa
Peak IL pole turn, RT preload 80 MPa
Peak coil, RT preload 100 MPa
Peak IL pole turn, RT preload 100 MPa
Azimuthla stress, MPa
-10
-30
-50
-70
-90
-110
-130
-150
0
50
100
150
200
250
300
350
400
I²
15 kA
16.23 kA
17.5 kA
19.5 kA

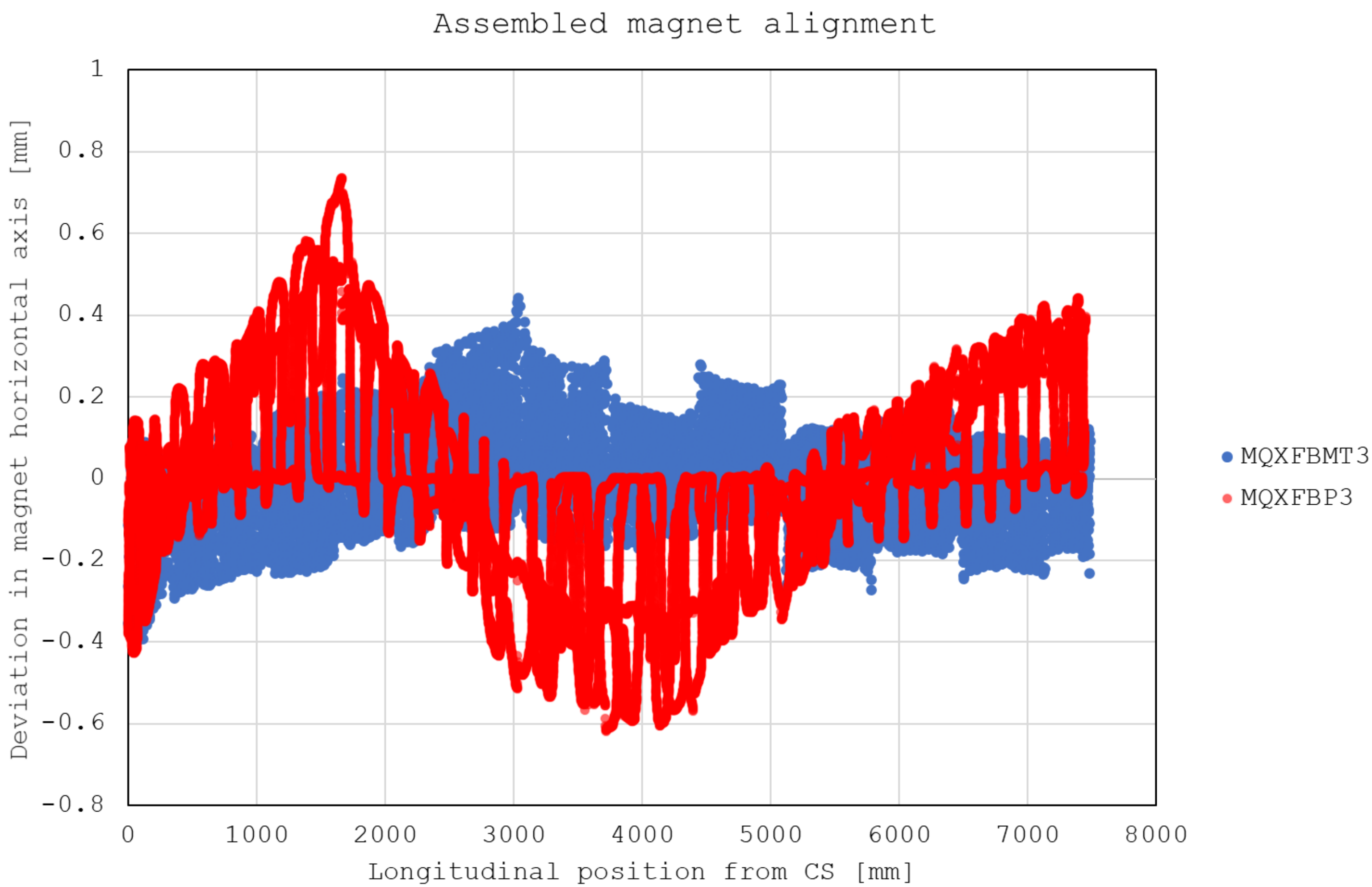
Stress during bladders operation

All quadrants, with cooling channels



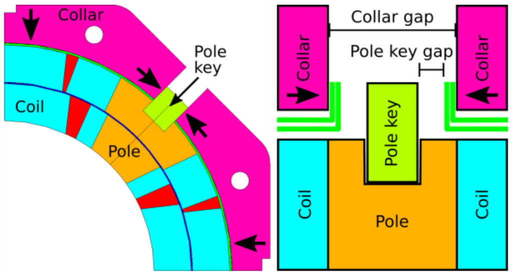
Quadrant by quadrant

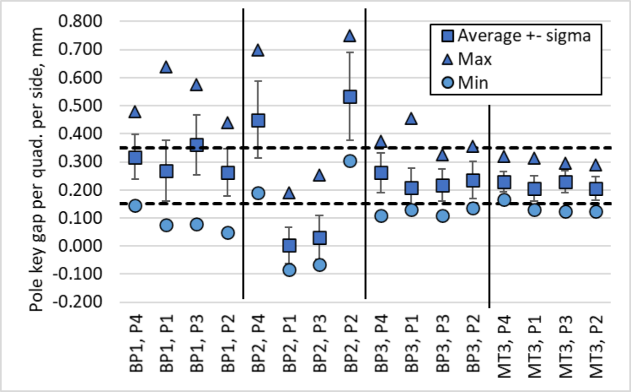



Assembled magnet alignment
Deviation in magnet horizontal axis [mm]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
1000
2000
3000
4000
5000
6000
7000
8000
Longitudinal position from CS [mm]
MQXFBMT3
MQXFBP3

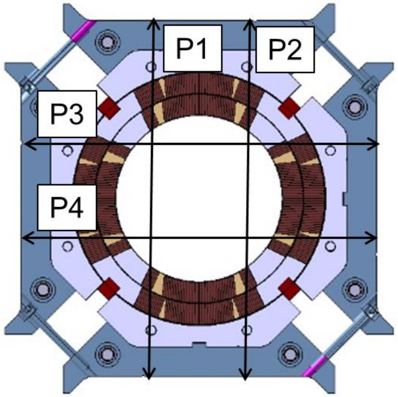
Improved procedure: Alignment (coil pack)

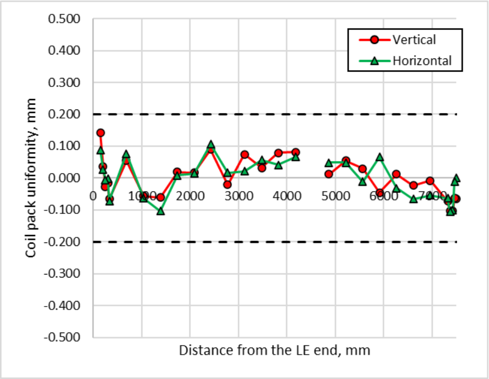
- By design, 0.25 mm gap between the pole key collar at room temperature
- Coil pack bolting process optimized in MQXFBP3, reducing the spread of the average pole key gap per quadrant from 0.5 mm to 0.05 mm

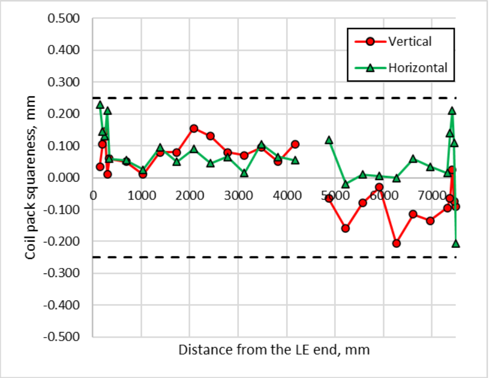




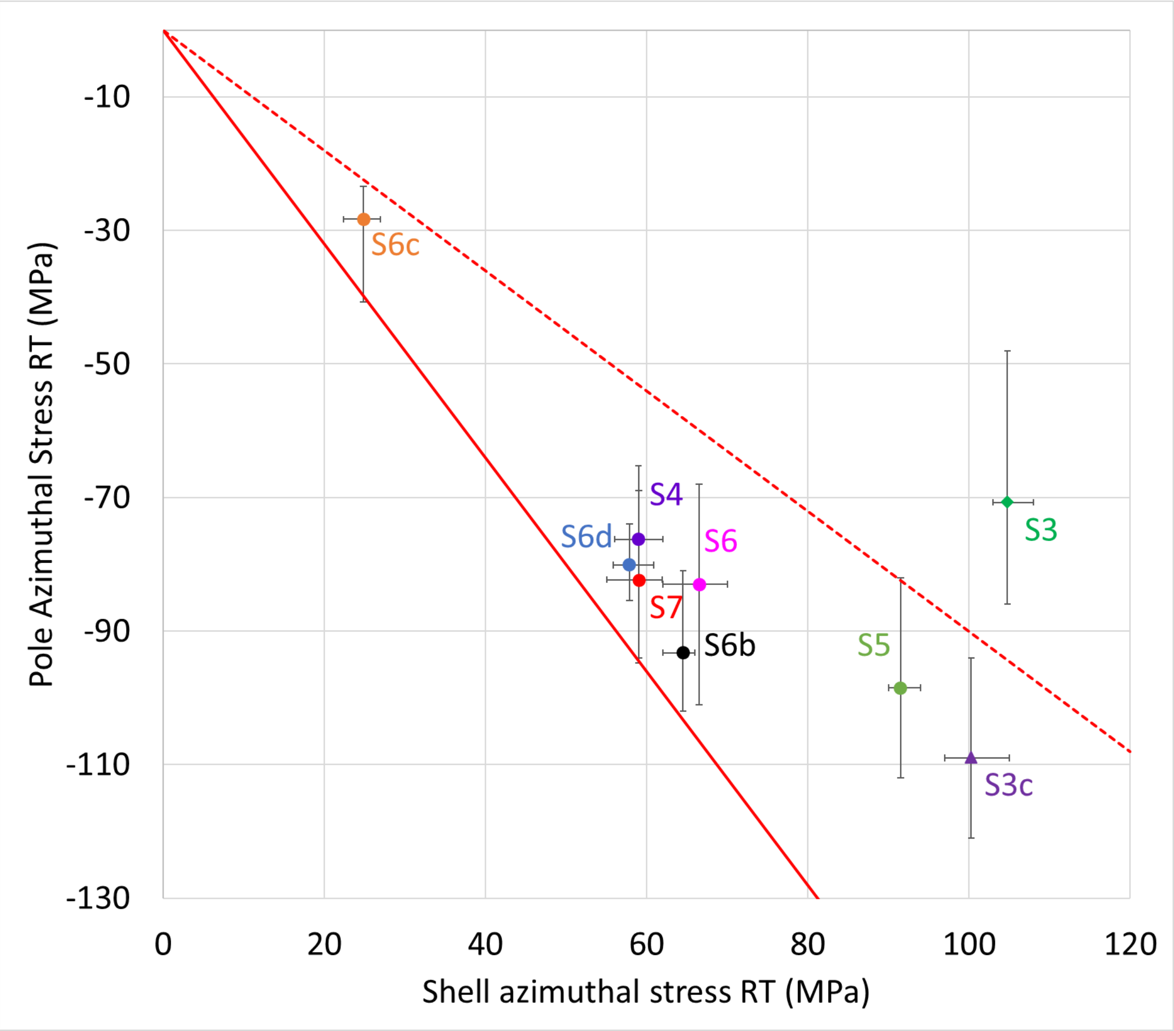
- Improved methodology and measuring system in MQXFBMT3, reaching a uniformity and squareness the coil pack of ± 0.1 mm and ± 0.2 mm respectively



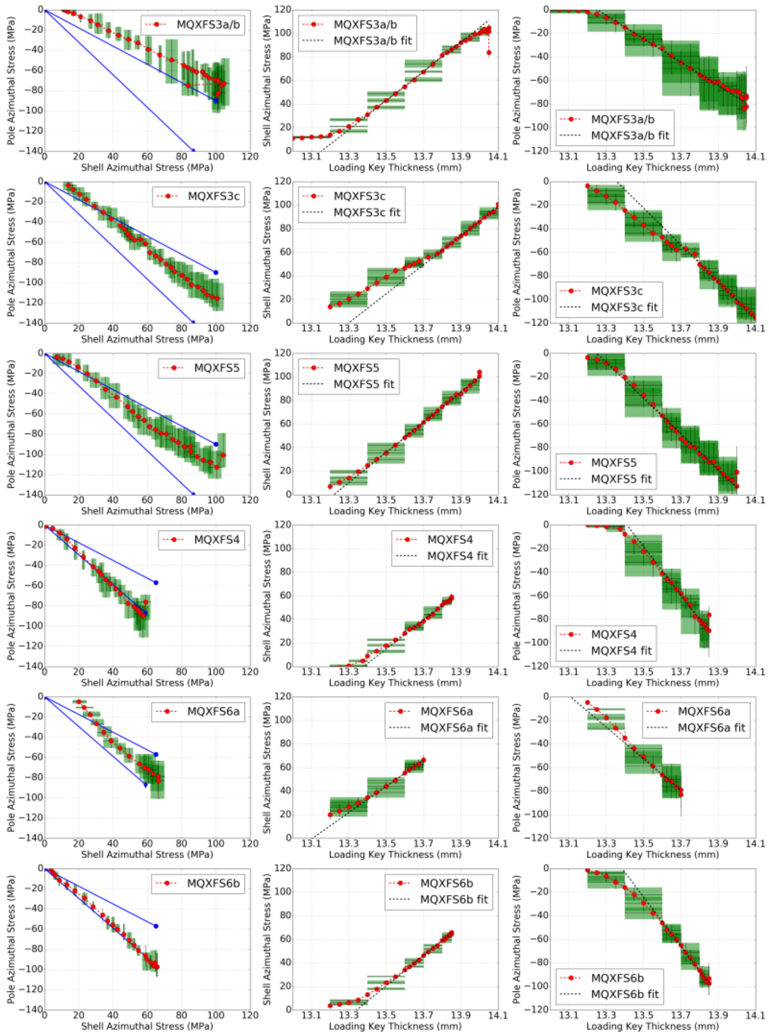




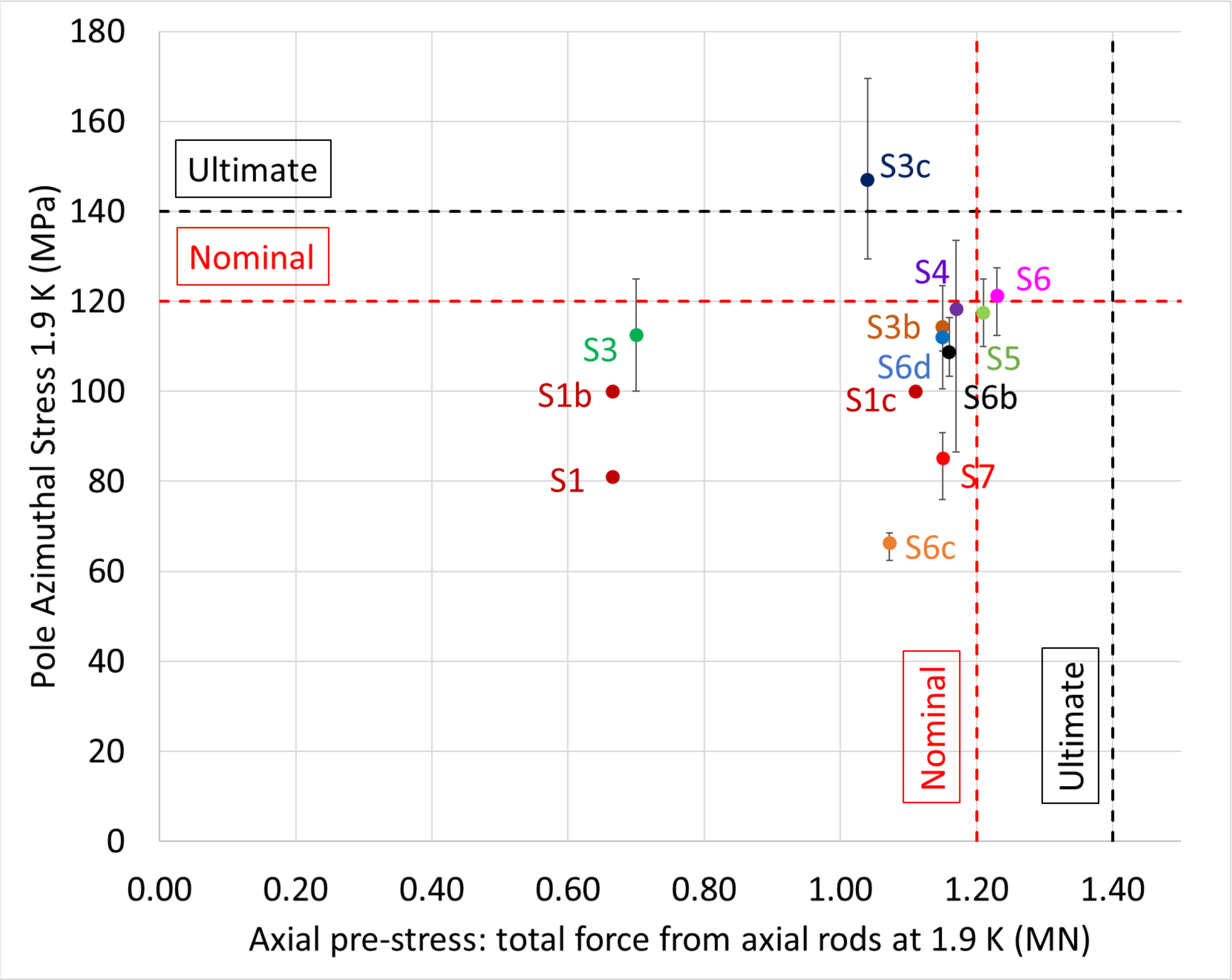
RT loading MQXFS



RT transfer functions



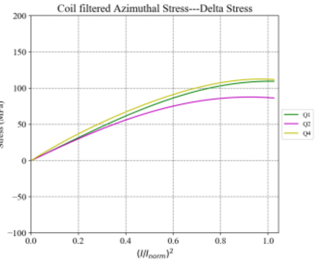
1.9 K MQXFS



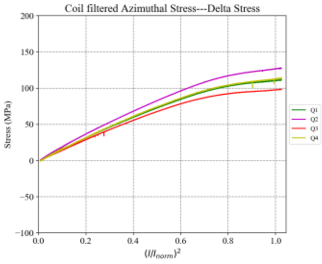
Ultimate
Nominal
S3c
S4
S6
S3b
S3
S6d
S5
S1b
S1c
S6b
S1
S7
S6c
Nominal
Ultimate
Pole Azimuthal Stress 1.9 K (MPa)
Axial pre-stress: total force from axial rods at 1.9 K (MN)
0
20
40
60
80
100
120
140
160
180
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40

MQXFA

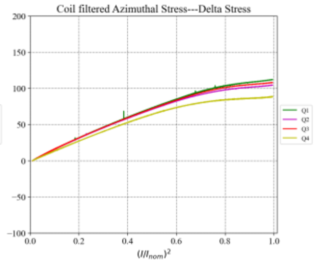
MQXFA03



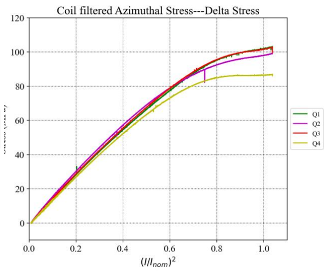
MQXFA04



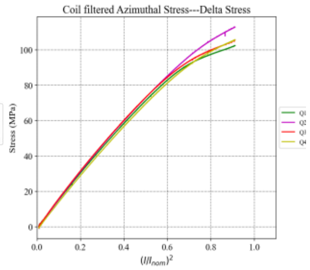
MQXFA05



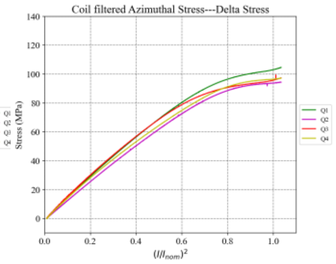
MQXFA06

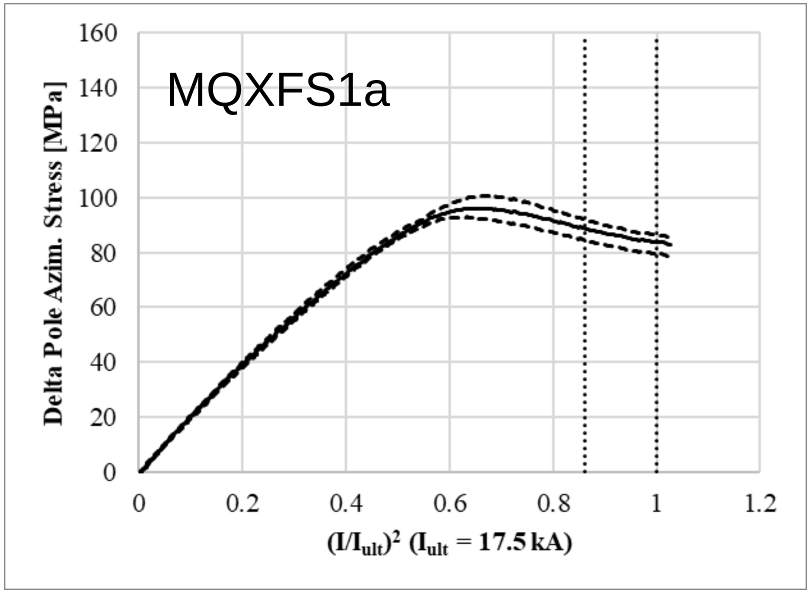


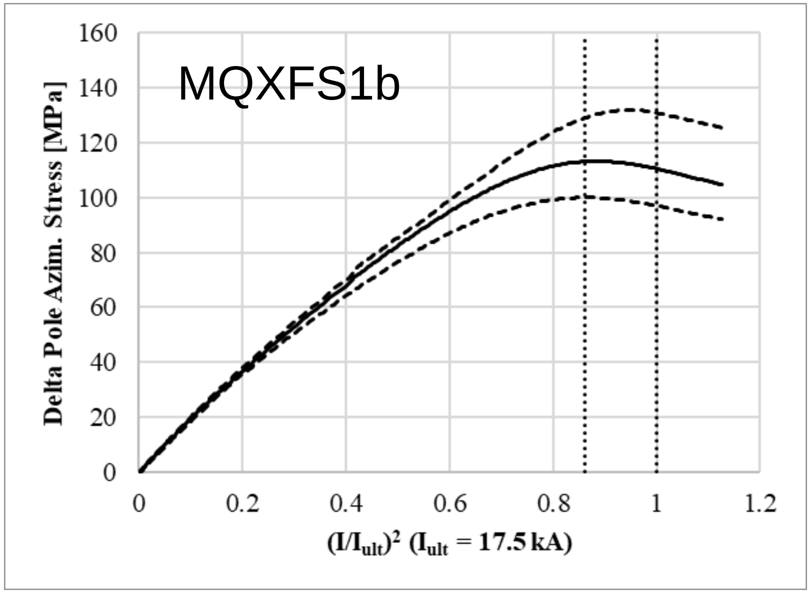
MQXFA07

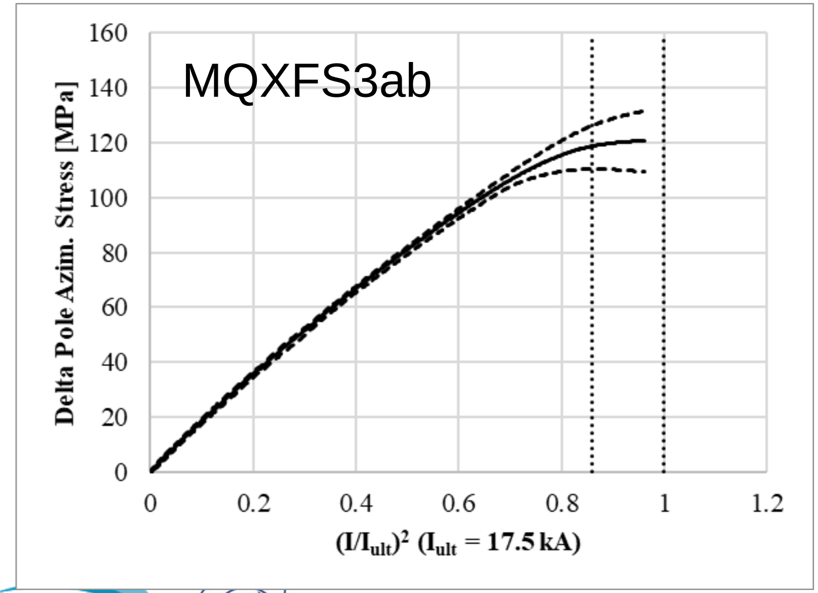


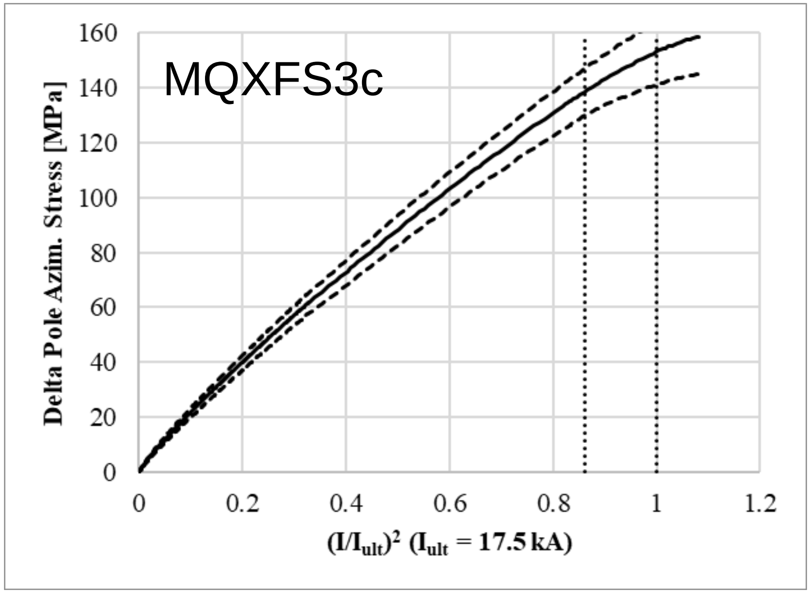
MQXFA08

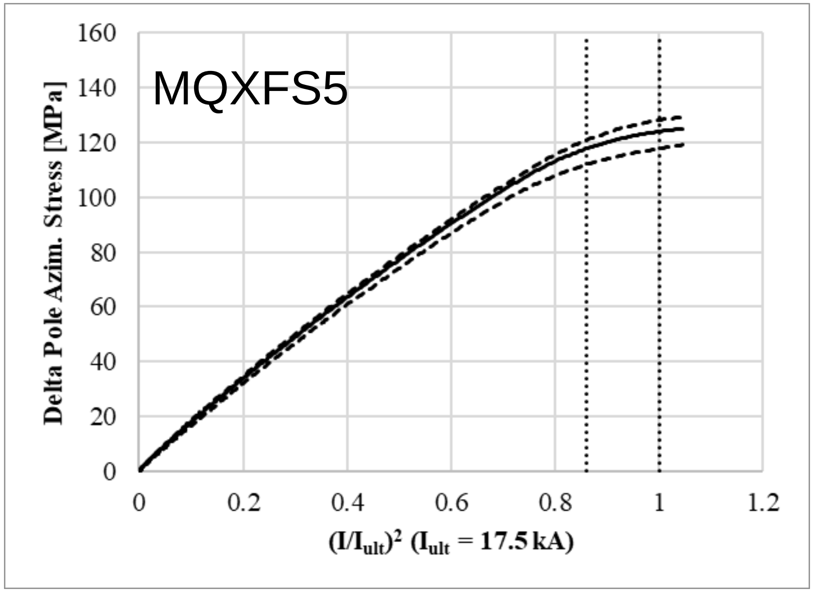


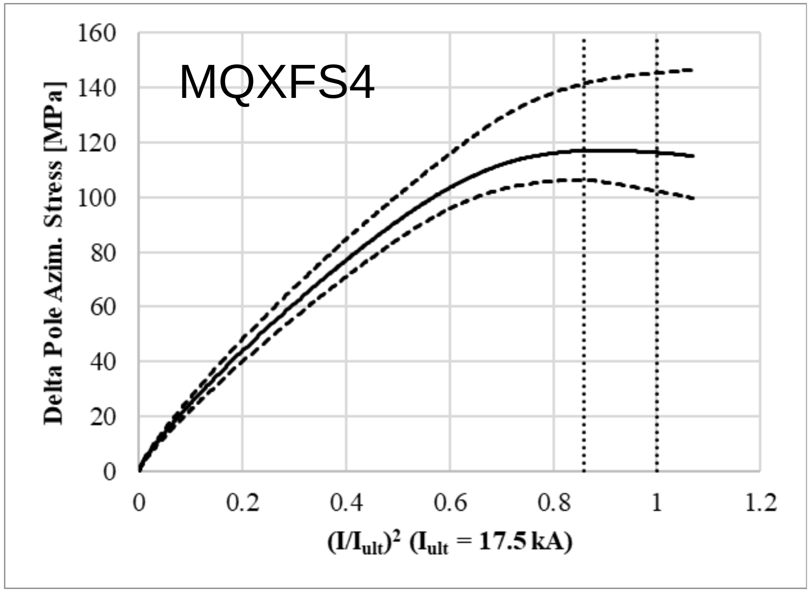

MQXFS1a
Delta Pole Azim. Stress [MPa]
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

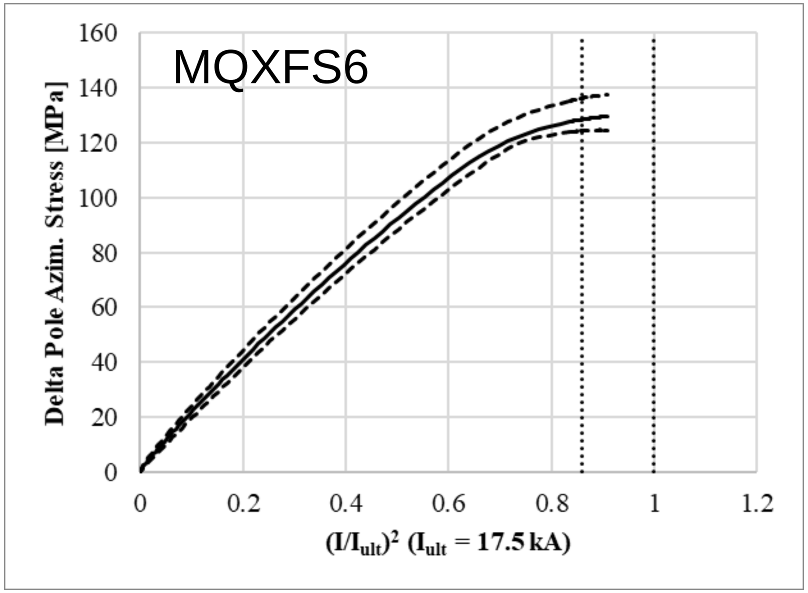

MQXFS1b
Delta Pole Azim. Stress [MPa]
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

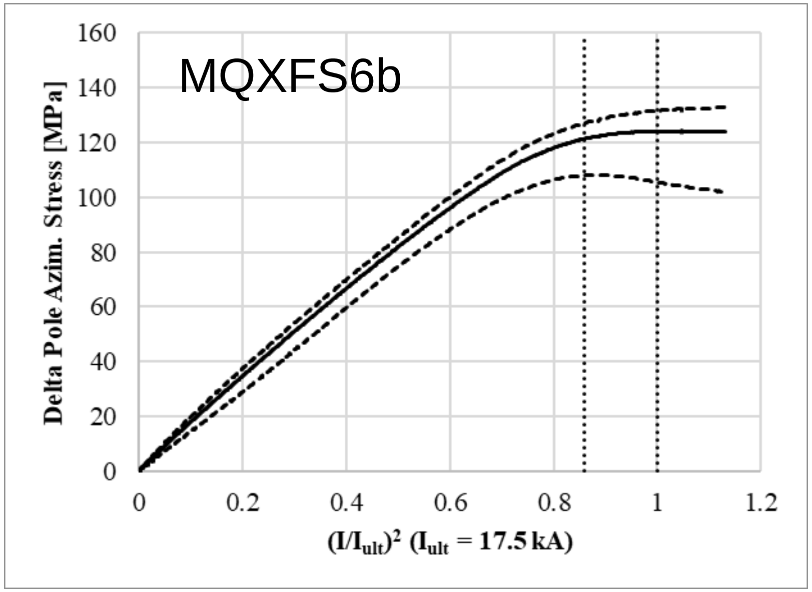

MQXFS3ab
Delta Pole Azim. Stress [MPa]
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

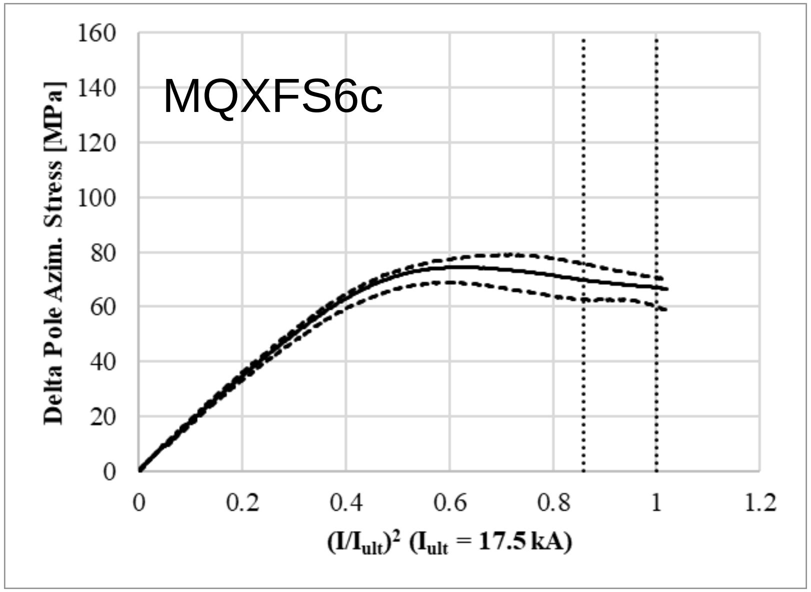

MQXFS3c
Delta Pole Azim. Stress [MPa]
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

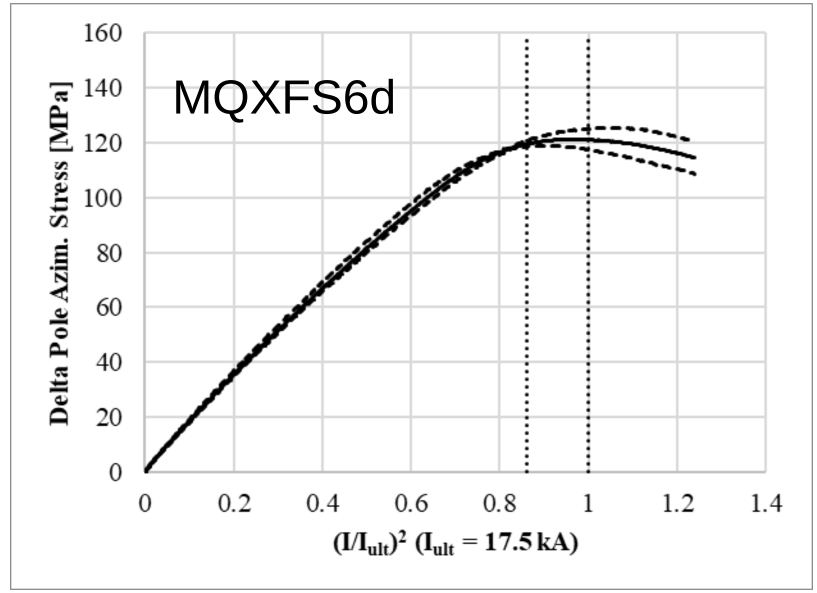

MQXFS5
Delta Pole Azim. Stress [MPa]
0
20
40
60
80
100
120
140
160
0
0.2
0.4
0.6
0.8
1
1.2
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

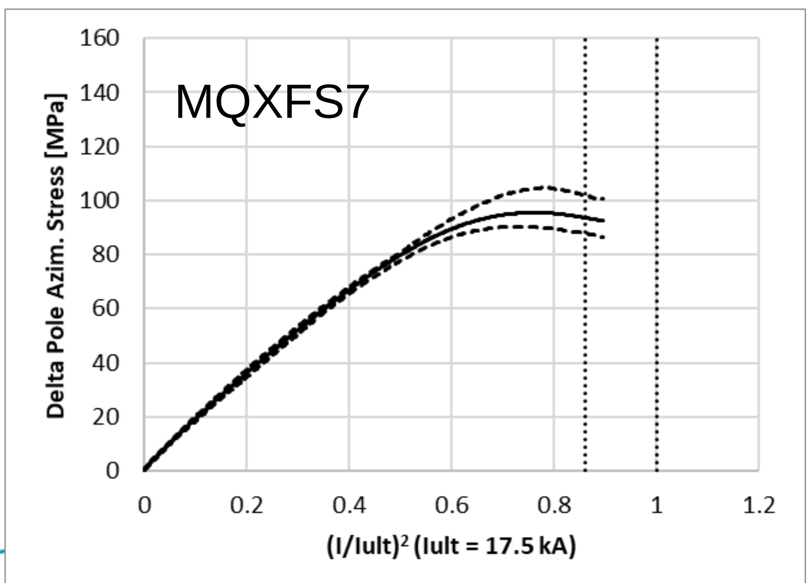

MQXFS4
Delta Pole Azim. Stress [MPa]
0
20
40
60
80
100
120
140
160
0
0.2
0.4
0.6
0.8
1
1.2
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

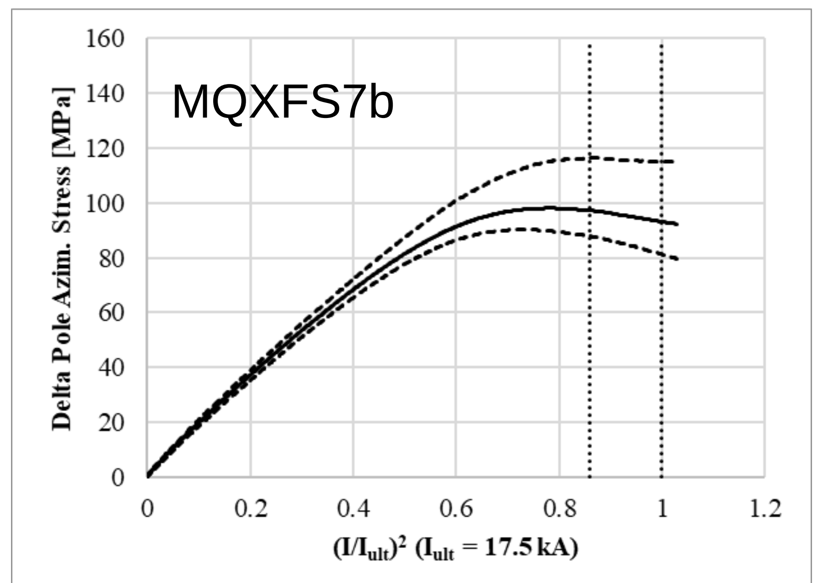

MQXFS6
Delta Pole Azim. Stress [MPa]
0
20
40
60
80
100
120
140
160
0
0.2
0.4
0.6
0.8
1
1.2
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

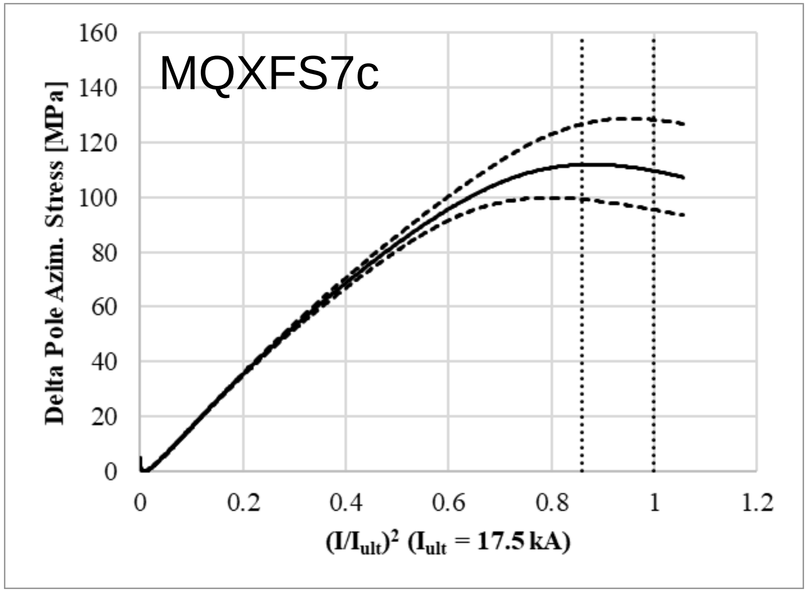

MQXFS6b
Delta Pole Azim. Stress [MPa]
0
20
40
60
80
100
120
140
160
0
0.2
0.4
0.6
0.8
1
1.2
$(I/I_{ult})^2$ (I_{ult} = 17.5 kA)

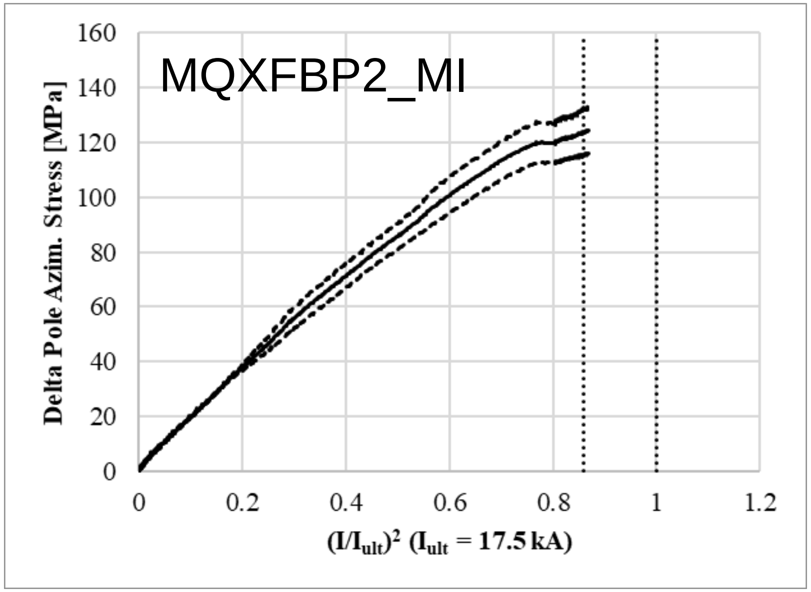

MQXFS6c
Delta Pole Azim. Stress [MPa]
0 20 40 60 80 100 120 140 160
0 0.2 0.4 0.6 0.8 1 1.2
(I/Iult)² (Iult = 17.5 kA)

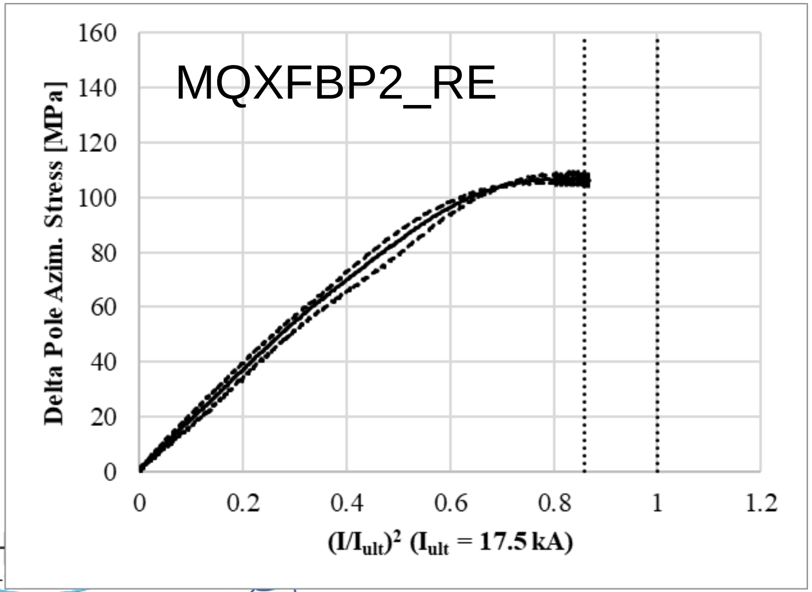

MQXFS6d
Delta Pole Azim. Stress [MPa]
0 20 40 60 80 100 120 140 160
0 0.2 0.4 0.6 0.8 1 1.2 1.4
(I/Iult)² (Iult = 17.5 kA)


MQXFS7
Delta Pole Azim. Stress [MPa]
0 20 40 60 80 100 120 140 160
0 0.2 0.4 0.6 0.8 1 1.2
(I/Iult)² (Iult = 17.5 kA)

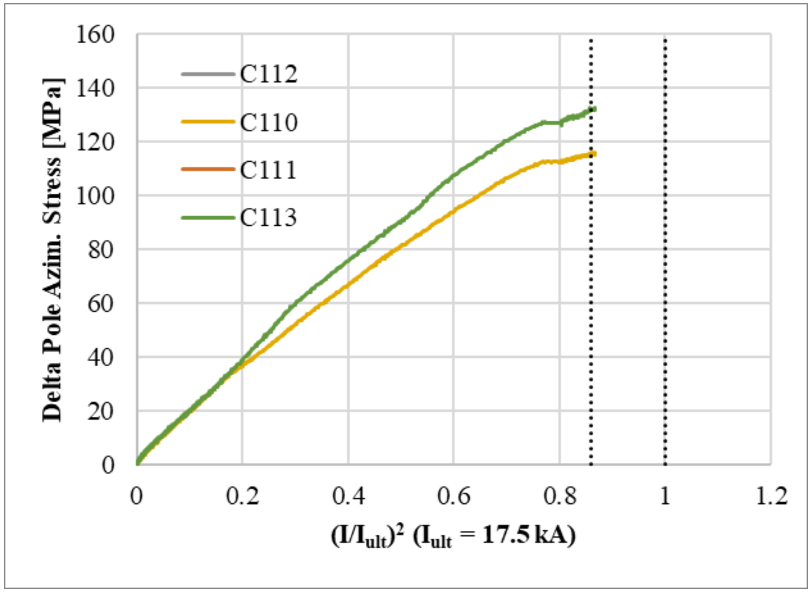

MQXFS7b
Delta Pole Azim. Stress [MPa]
0 20 40 60 80 100 120 140 160
0 0.2 0.4 0.6 0.8 1 1.2
(I/Iult)² (Iult = 17.5 kA)


MQXFS7c
Delta Pole Azim. Stress [MPa]
(I/Iult)2 (Iult = 17.5 kA)


MQXFBP2_MI
Delta Pole Azim. Stress [MPa]
(I/Iult)2 (Iult = 17.5 kA)


MQXFBP2_RE
Delta Pole Azim. Stress [MPa]
(I/Iult)2 (Iult = 17.5 kA)

MQXFBP2_MI



MQXFBP2_RE