MQXFS Test Results

Susana Izquierdo Bermudez and Franco Mangiarotti on behalf of MQXF team

28/09/2022

13th HL-LHC Collaboration Meeting

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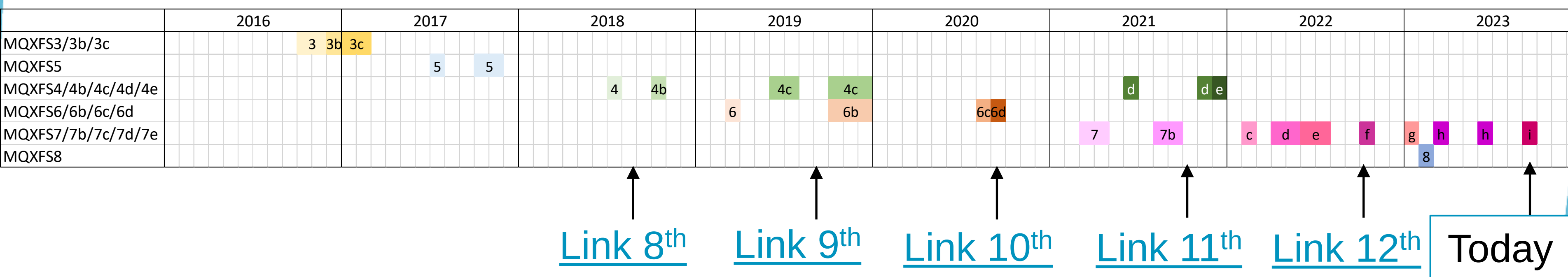
Preamble

What is new with respect the 12th HL-LHC collaboration meeting ([link here](#))?

- *Pre-load experiment in MQXFS7*
- *Mini-swap quench heater validation in MQXFS8*



Outline

- MQXFS7 pre-load experiment
- MQXFS8
- Conclusions

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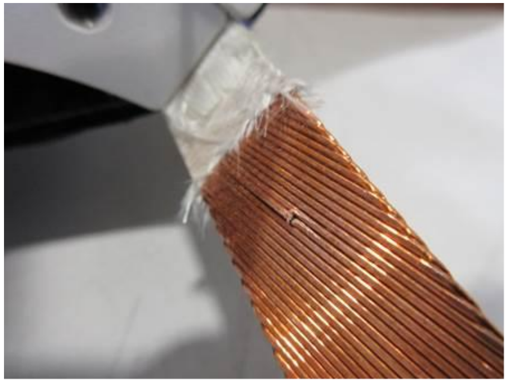
- **MQXFS7 pre-load experiment**
- MQXFS8
- Conclusions

High preload experiment: MQXFS7

- MQXFS7 history:
  - Short model built with 4 virgin coils:
    - Two coils with final series conductor (RRP 108/127) and external quench heaters (113&114).
    - One coil (211) PIT 192 with bundle, and a broken strand in the splice region
    - One coil (207) PIT 192



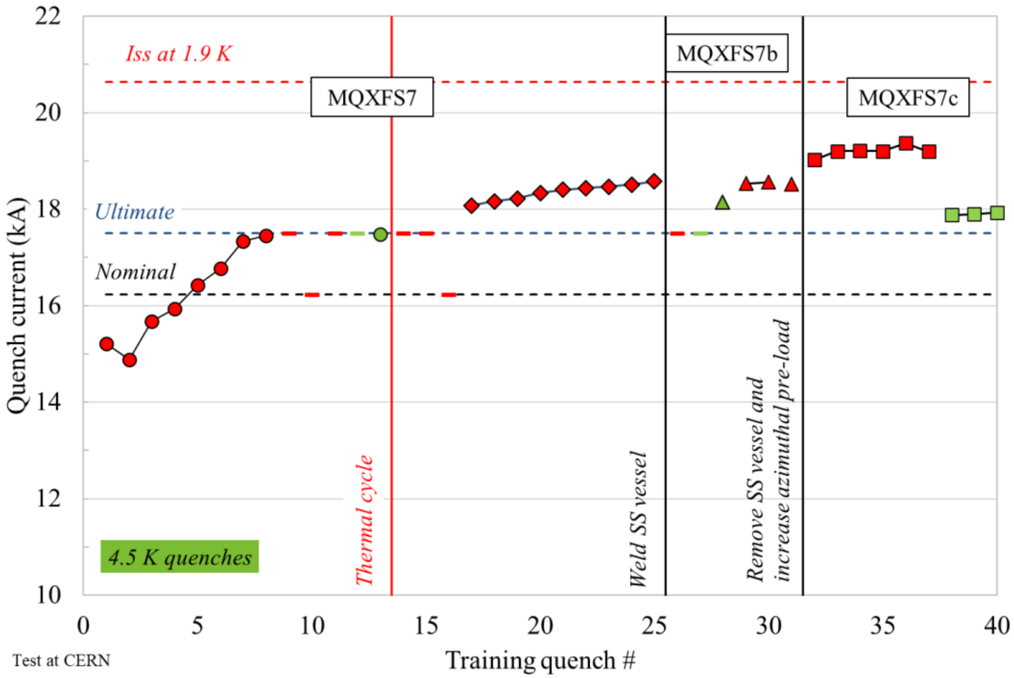
The broken strand in 211 coil

- MQXFS7 reached performance (2021).
- MQXFS7b validated the new welding procedure for MQXFB cold masses (no coupling of the SS vessel to the magnet after cool down)
- In MQXFS7c, the SS vessel was removed, and the azimuthal pre-load was increased by 15-20 MPa
- MQXFS7d demonstrated that the machining of a hole in the yoke for the implementation of MQXFB fixed point does not impact magnet performance.
- In MQXFS7e, validated the new pre-load procedure for MQXFB magnets to limit the peak stress during loading
- The goal of MQXFS7f/g/h/i is to determine what is the maximum level of preload before impacting magnet performance

MQXFS7/7b/7c

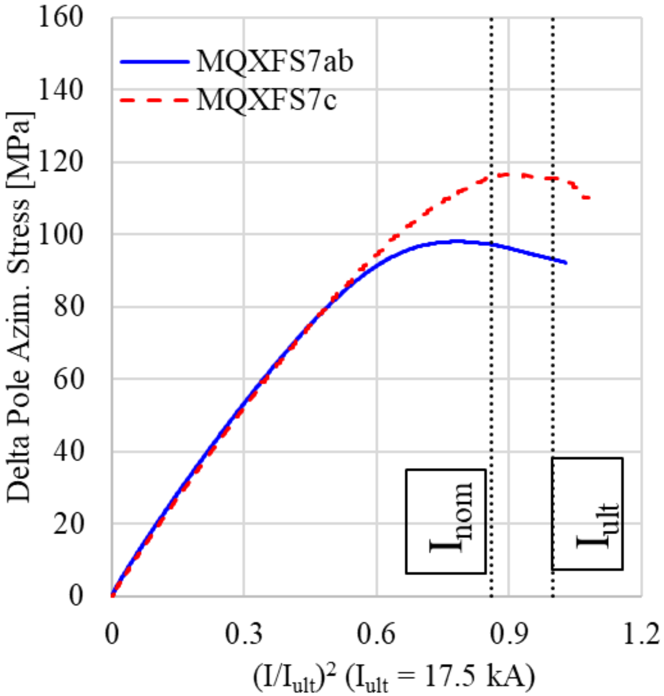
- MQXFS7 reached nominal and ultimate current at 4.5 K. Good memory after thermal cycle
- The welding of the SS vessel in MQXFS7b did not impact the magnet performance
- MQXFS7c, assembled with 15-20 MPa higher coil pre-load, reached higher current at 1.9 K with a similar performance at 4.5 K. The behavior is consistent with MQXFS6 experience: larger preload is beneficial to reach 90% of short sample at 1.9 K. We reached 97 % of the short sample limit at 4.5 K.

Data: Salvador Ferradas Troitino, Franco Mangiarotti



Test at CERN

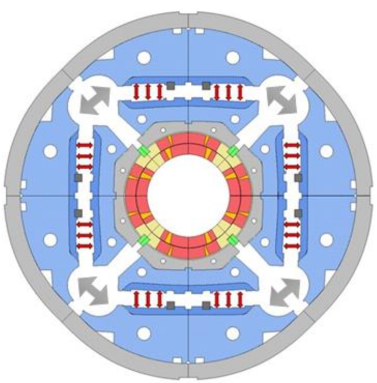
Pole unloading S7 vs S7c

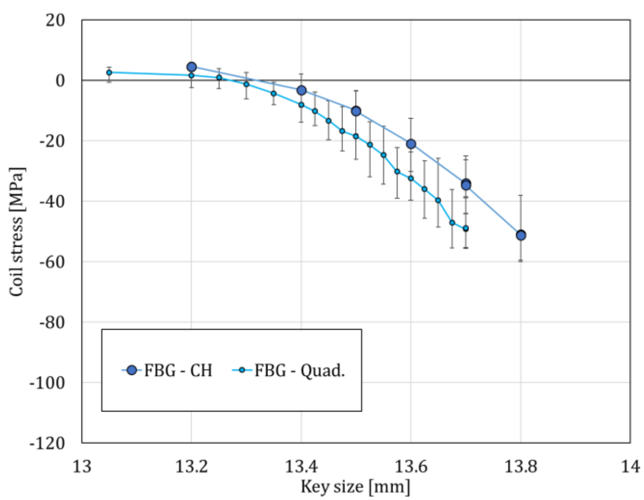


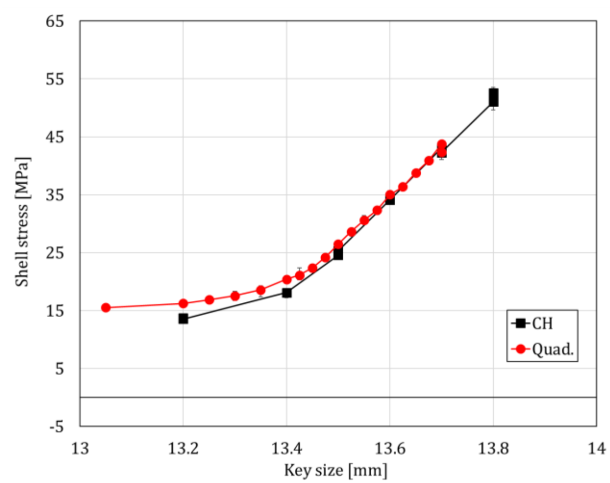
MQXFS7e

- A new loading procedure was developed for MQXFB magnets to limit the peak stress in the coil during loading using auxiliary bladders in the cooling hole channels
- Loading quadrant by quadrant or all quadrant at the time using cooling channels (CH) we expect for a given key size:
  - The same Al-shell stress
  - ≈ 10 MPa lower pole stress
- This is a frictional effect that was predicted by the FE model. According to the FE model, the stress state at cold is independent of the loading process (friction effect during loading ‘resets’)

For MQXFB magnets, starting from MQXFB02 we modified the target RT per-load target to 70 ± 10 MPa (it was 80 ± 8 MPa) to account for this effect.







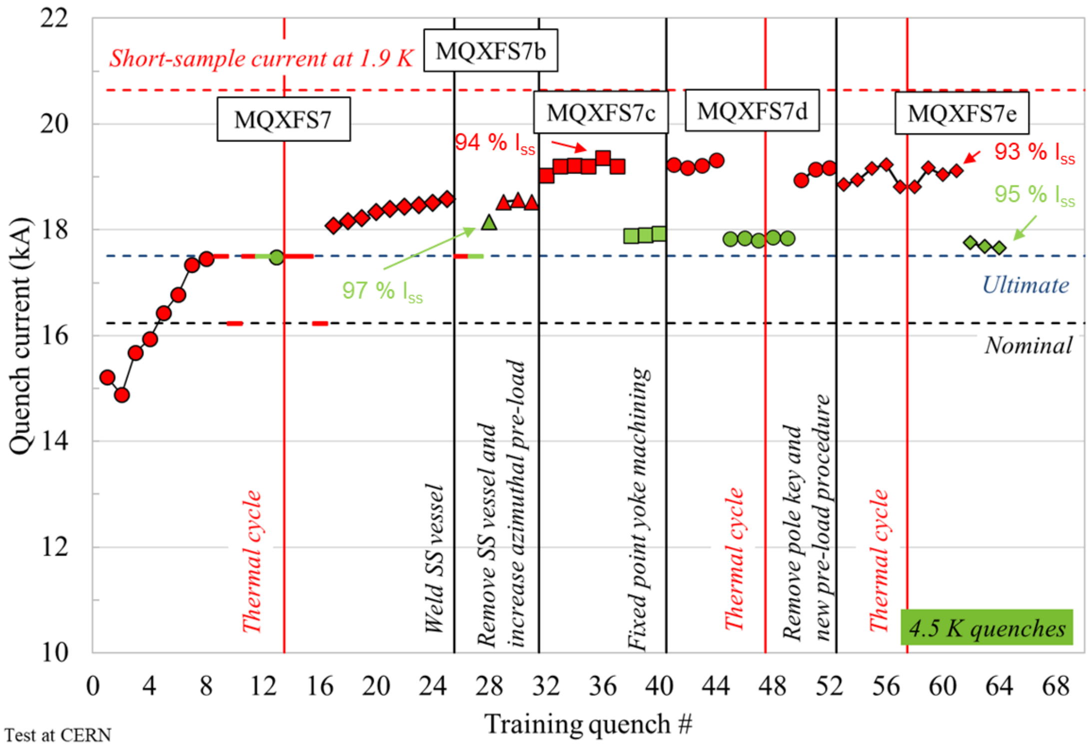
Data: Michael Guinchard, Keziban Kandemir Sylvain Mugnier

Analysis: Jose Ferradas Troitino

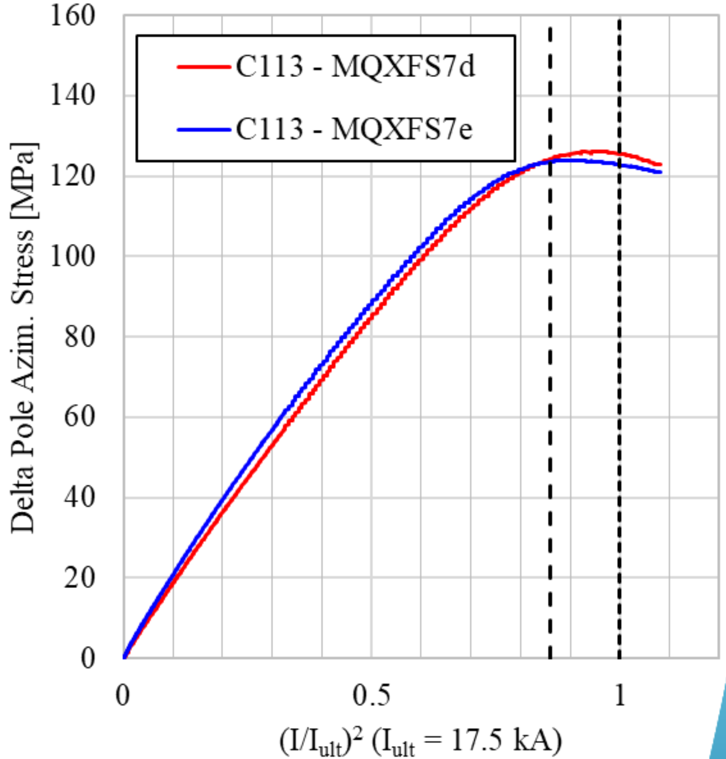
MQXFS7e

- The quench performance of MQXFS7e is similar to MQXFS7d: the new loading procedure does not have a detrimental effect in the magnet performance
- As expected from the FE model, the coil stress at cold is independent of the loading process (friction effect during loading 'resets') → MQXFS7d and MQXFS7e have identical pole unloading behavior

Data: Salvador Ferradas Troitino, Franco Mangiarotti



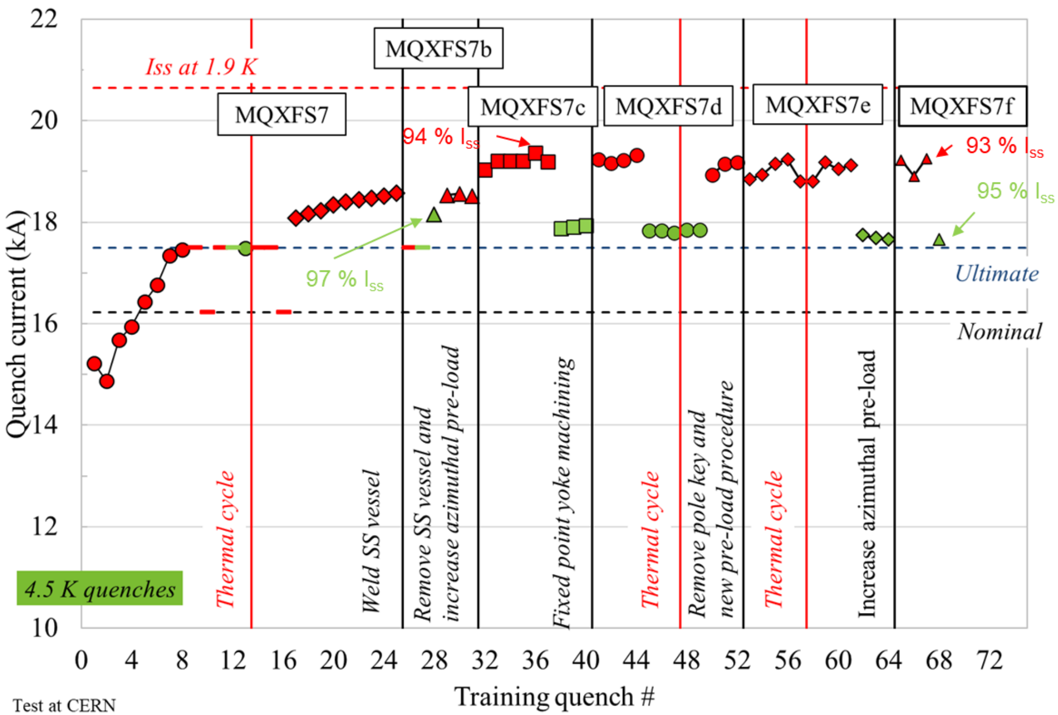
Pole unloading in coil 113 S7d vs S7e

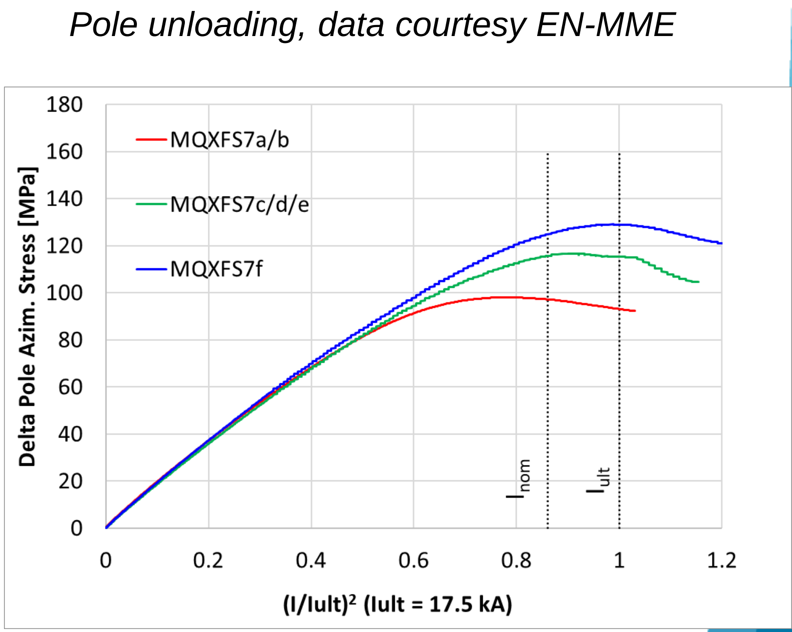


- Next steps: Gradual increase (Δ 15-10 MPa) of the coil pre-load up to performance degradation limit

MQXFS7f

- In MQXFS7f, key thickness was increased from 13.8 to 13.9 mm (required bladder pressure 350 bars)
- RT pre-load went smoothly. At cold:
  - Similar performance to MQXFS7e, the measured increase of azimuthal pole stress is in line with expectations (pole azimuthal stress at cold 130 MPa)

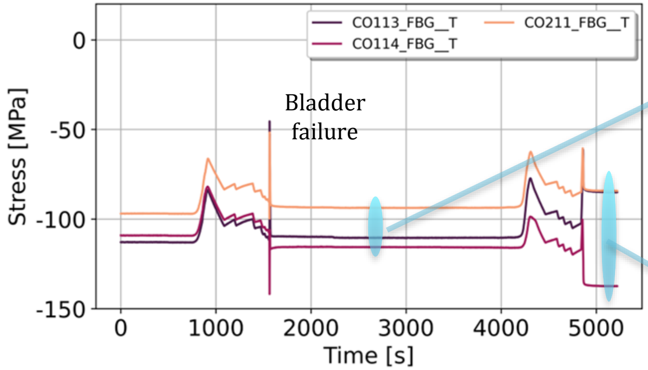


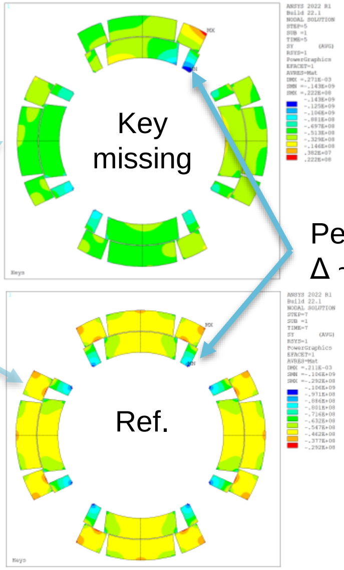


Data: Salvador Ferradas Troitino, Franco Mangiarotti

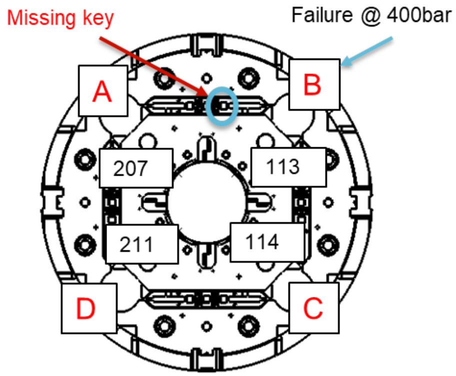
MQXFS7g

- In MQXFS7g, key thickness was increased from 13.9 to 14.0 mm
- Bladder failure at 400 bars when inserting the last 14 mm key
  - Root cause: Tubular bladders re-used from MQXFS8 (flattened) → from MQXFS7g assembly, we don't re-use bladders
  - One key missing after bladder failure→ measured peak az. stress ~ 145 MPa. Large coil imbalance upon completion of the pre-load.





2D FE simulations for the failure case

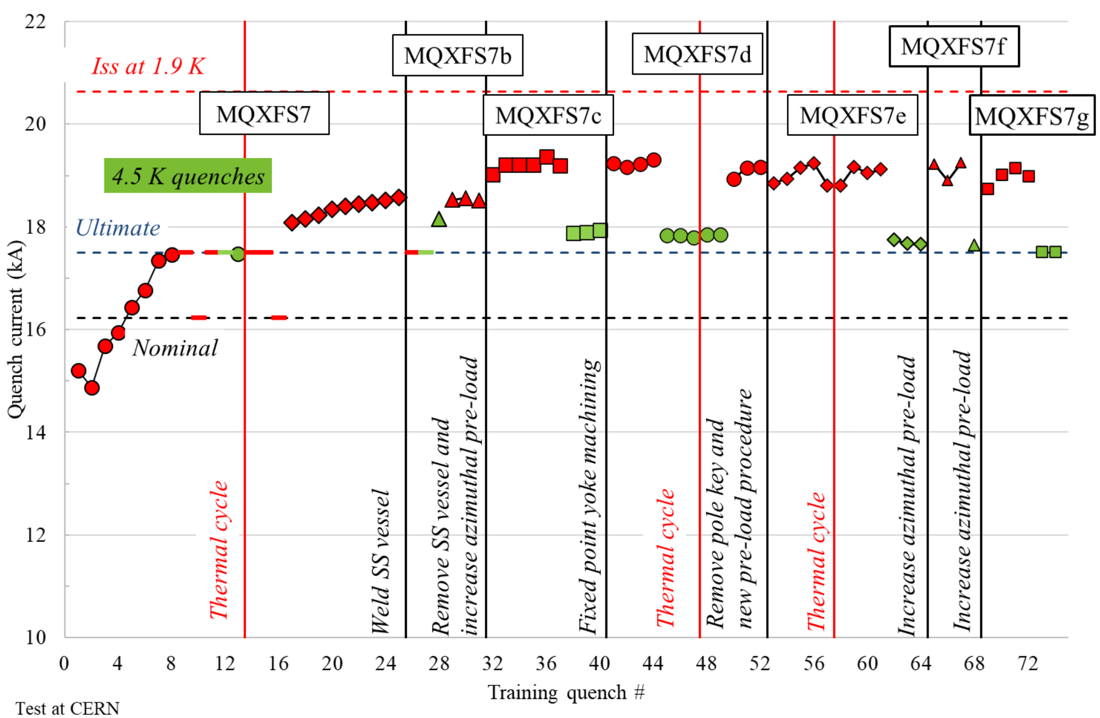


Position of the damaged bladder and the coils in the assembly (LE view).

(P. M. Quassolo)

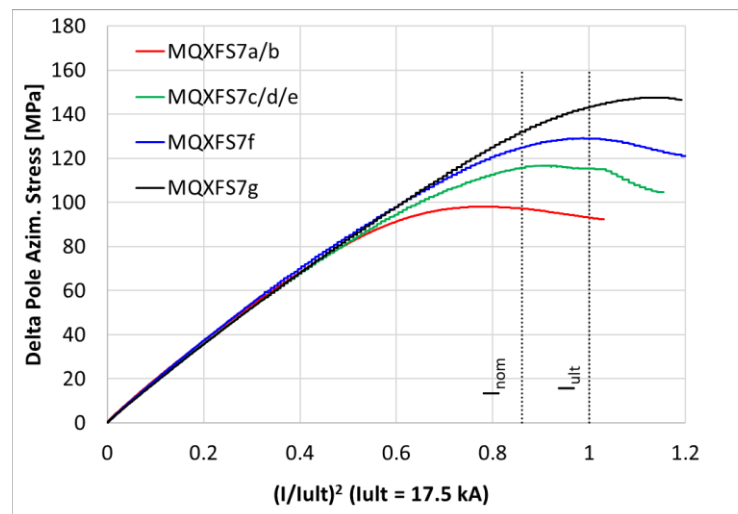
MQXFS7g

- In spite of the bladder failure, MQXFS7g reached similar level of current both at 1.9 K and 4.5 K.
- The measured increase of azimuthal pole stress is in line with expectations (pole azimuthal stress at cold 150 MPa)



Test at CERN

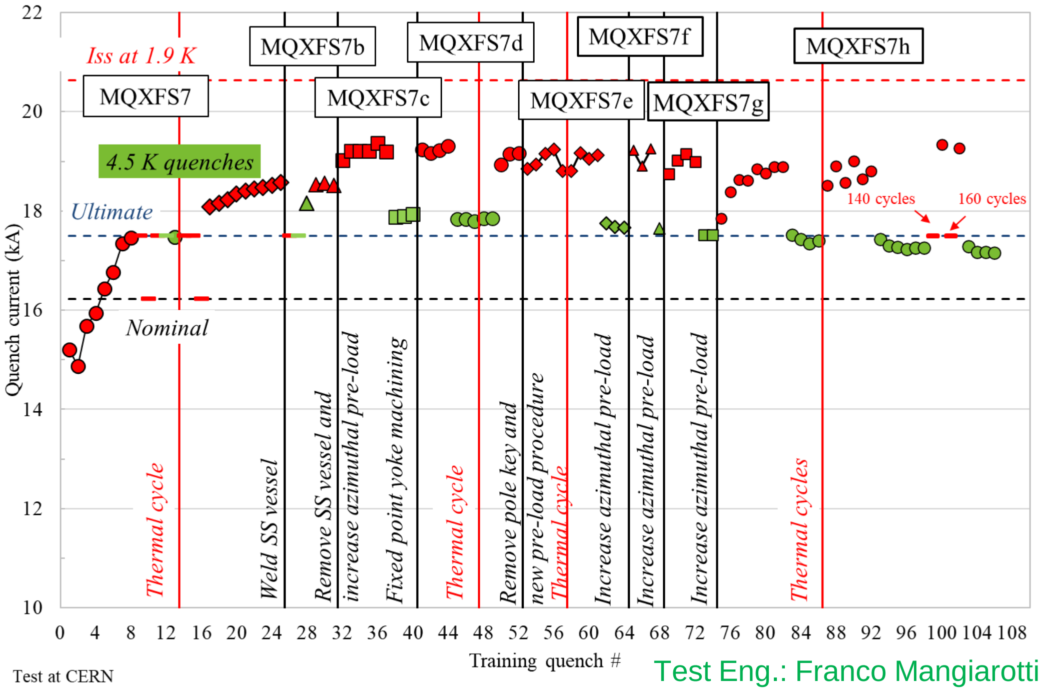
Pole unloading, data courtesy EN-MME



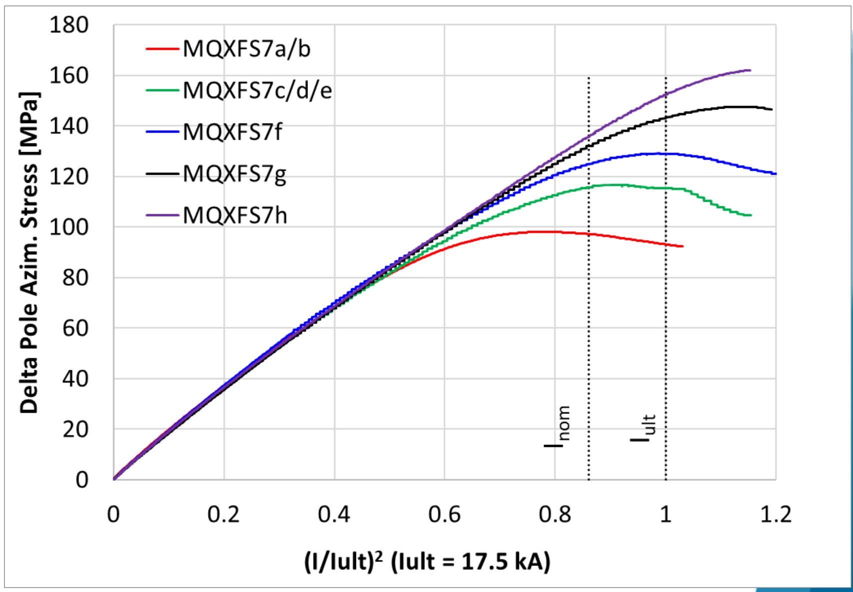
Test Eng.: Franco Mangiarotti

MQXFS7h

- In MQXFS7h, key thickness was increased from 14.0 to 14.1 mm (required bladder pressure 440 bars)
- RT pre-load went smoothly. At cold (pole azimuthal stress ≈ 190 MPa) :
  - 1st Thermal Cycle:
    - Loose about 1 kA of memory, but re-training at 1.9 K to similar current levels
    - Small drop on the quench current at 4.5 K
  - 2nd thermal cycle (mainly to verify memory): a bit more erratic behavior at 1.9 K and slight decrease on the quench current at 4.5 K. After 300 cycles to ultimate current, 19.4 kA at 1.9 K (94 % I_{ss})



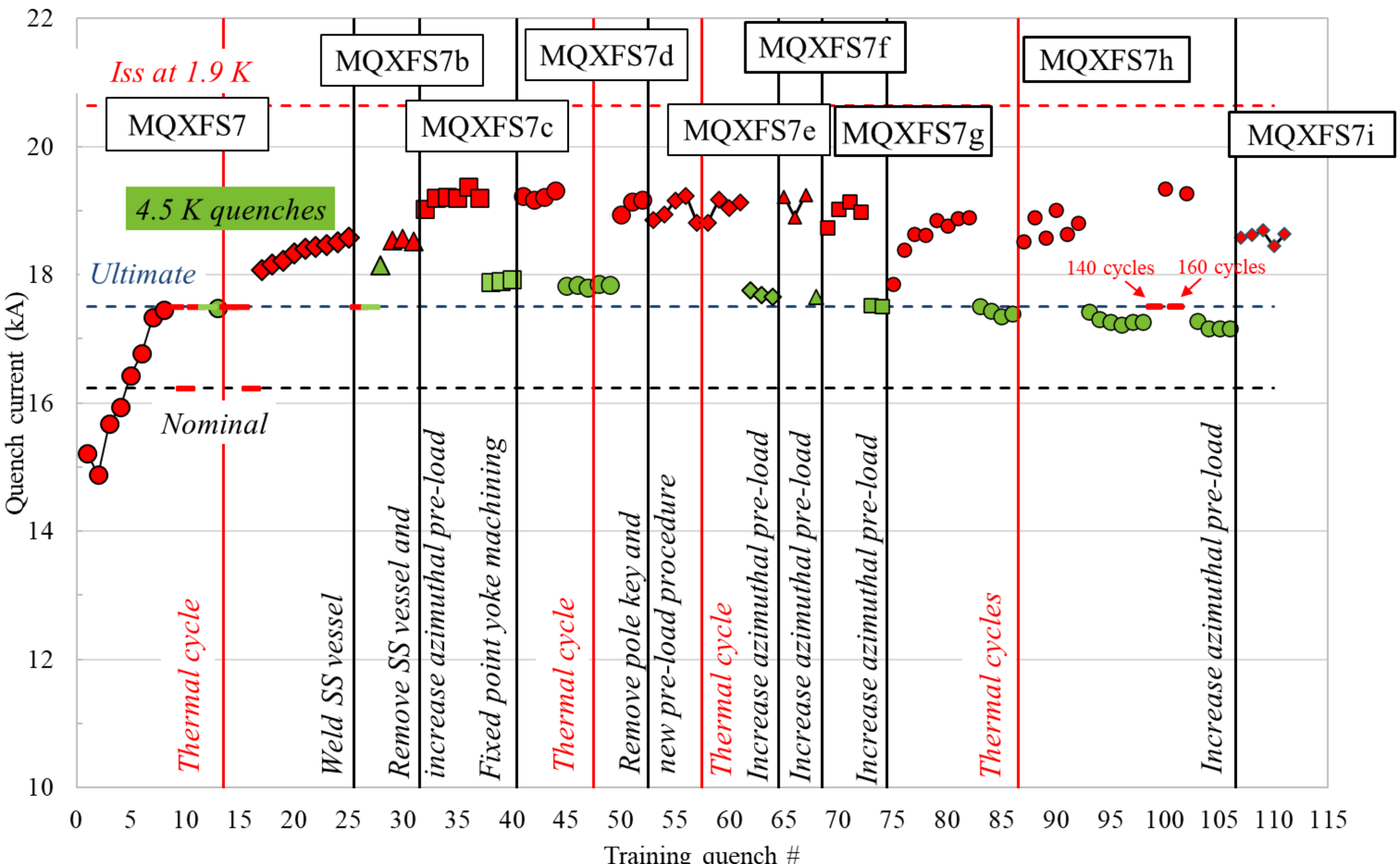
Pole unloading, data courtesy EN-MME



Test Eng.: Franco Mangiarotti

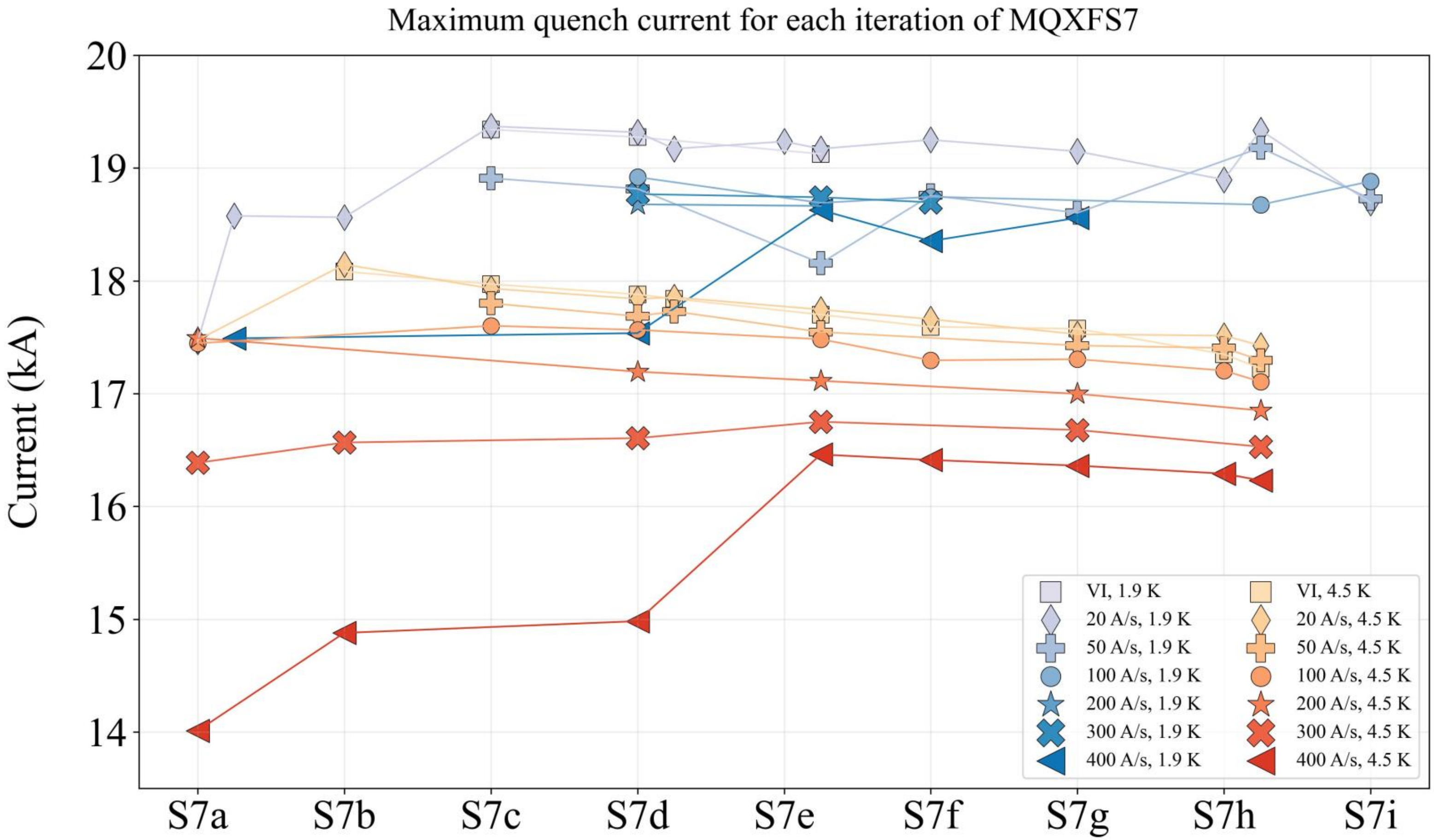
MQXFS7i

- In MQXFS7i, key thickness was increased from 14.1 to 14.2 mm (required bladder pressure 550 bars). RT pre-load went smoothly.
- Cold powering test just started. Maximum reached current at 1.9 K 450 A below the maximum reached the previous cycle, but the magnet is still training. 4.5 K test in the coming days



Test at CERN

MQXFS7 maximum quench level



S7a/b: 95 MPa
S7c/d/e: 115 MPa
S7f: 130 MPa; S7g: 150 MPa; S7h: 170 MPa ; S7i: 190 MPa

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Outline

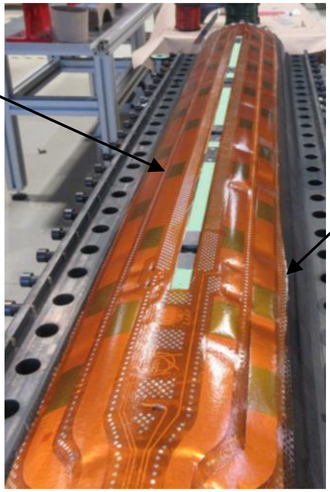
- MQXFS7 pre-load experiment
- **MQXFS8**
- Conclusions

MQXFS8 – Magnet features

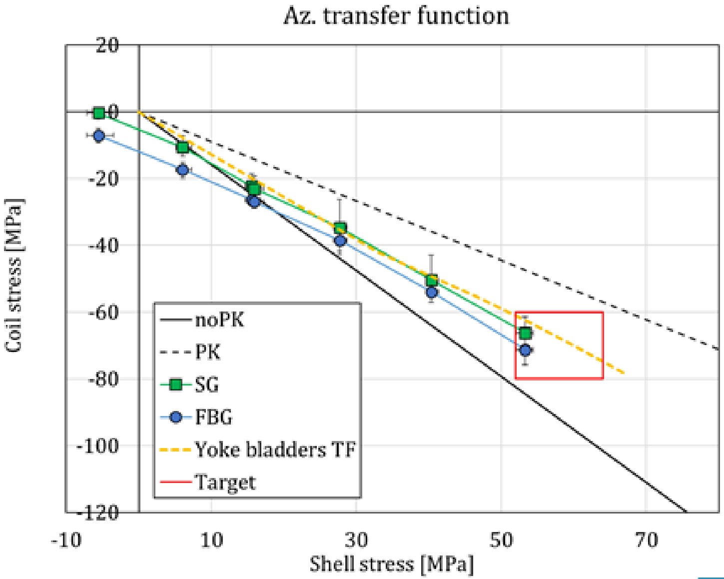
- MQXFS8 features
  - Short model built with 2 virgin coils; 2 coils already tested:
    - Two virgin coils with final series conductor (RRP 108/127) and mini-swap quench heaters (115&116).
    - Two coils PIT 192 with bundle already tested in MQXFS6b-d

- The goal main goal of MQXFS8 is to qualify the mini-swap quench heaters (see EDMS 2646046)
  - As a secondary goal, we want to prove our capability to mix virgin and already tested coils
- 'New' loading target and procedure, as MQXFB02, with bladders in the cooling hole channels

'Encapsulated' quench heaters, qualified to 8 kV before installation in the coil instead of 3.7 kV

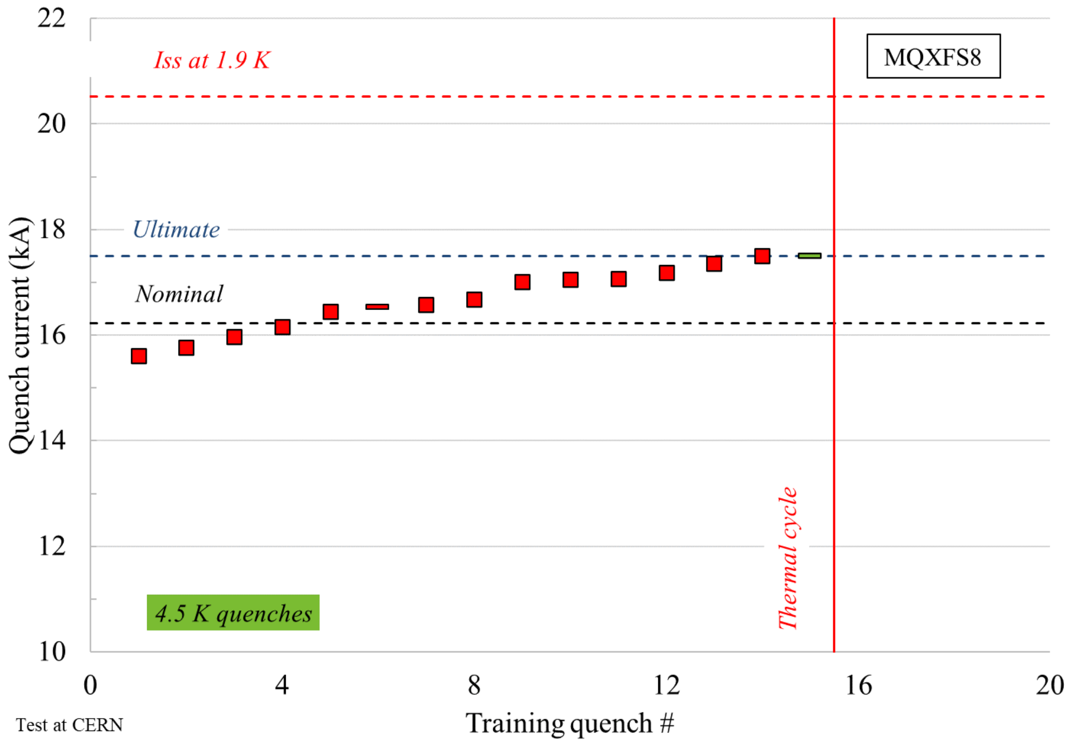


Additional 0.055 mm glass between heater and coil



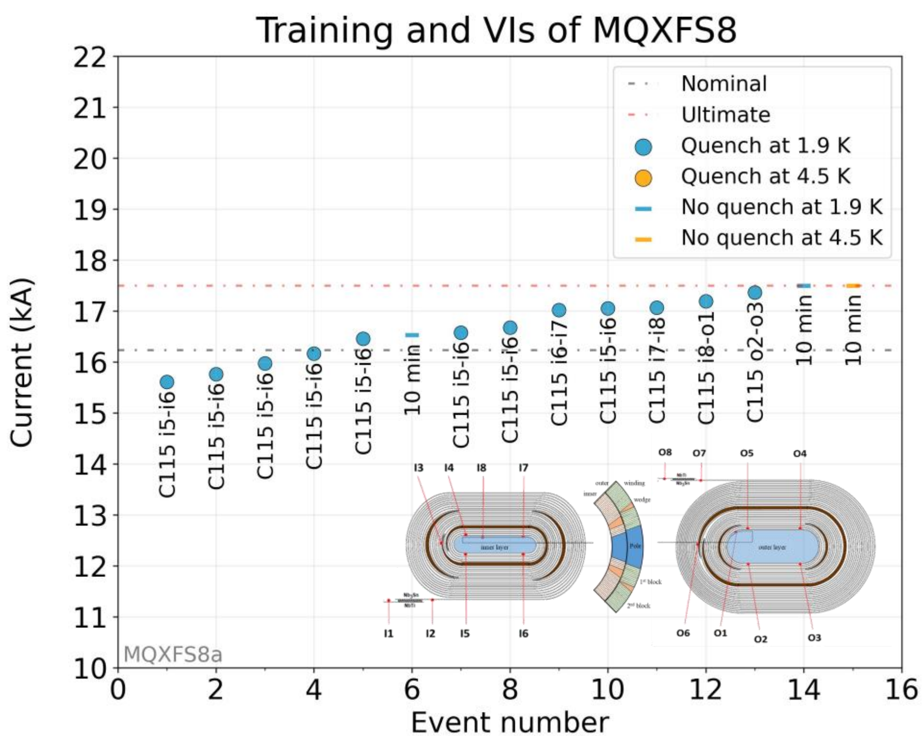
MQXFS8 – Quench performance

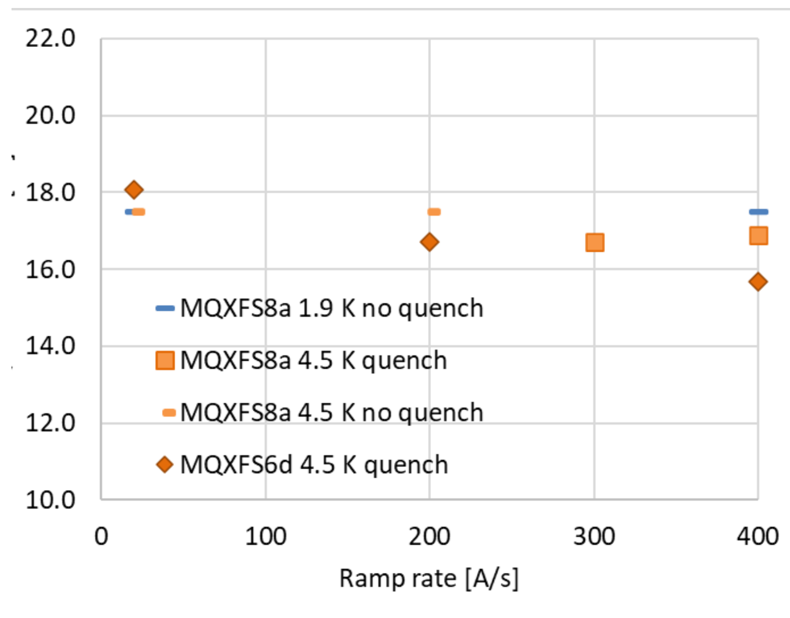
- Target current (I_{nom} + 300 A) reached after 5 quenches
- 14 quenches to reach ultimate current (17.5 kA).
  - Stable operation at I_{ult} and 4.5 K
- The magnet will be pushed to its maximum current in the next thermal cycle



MQXFS8 – Quench performance

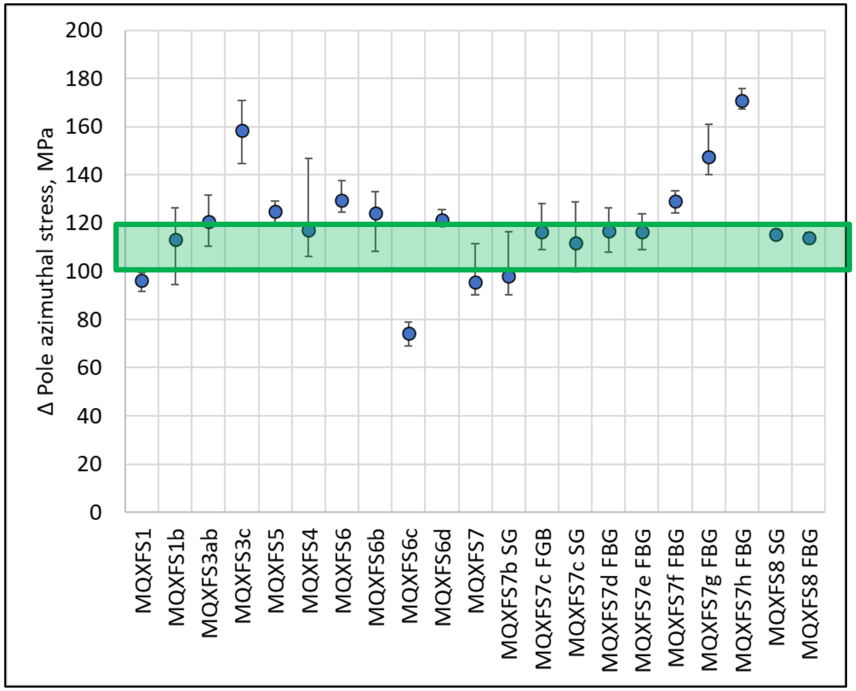
- All quenches in coil 115 (virgin coil), mostly pole turn inner layer
- We are able to reach ultimate current at 200 A/s at 4.5 K
  - Quench current at 400 A/s higher than in MQXFS6d (two shared coils)

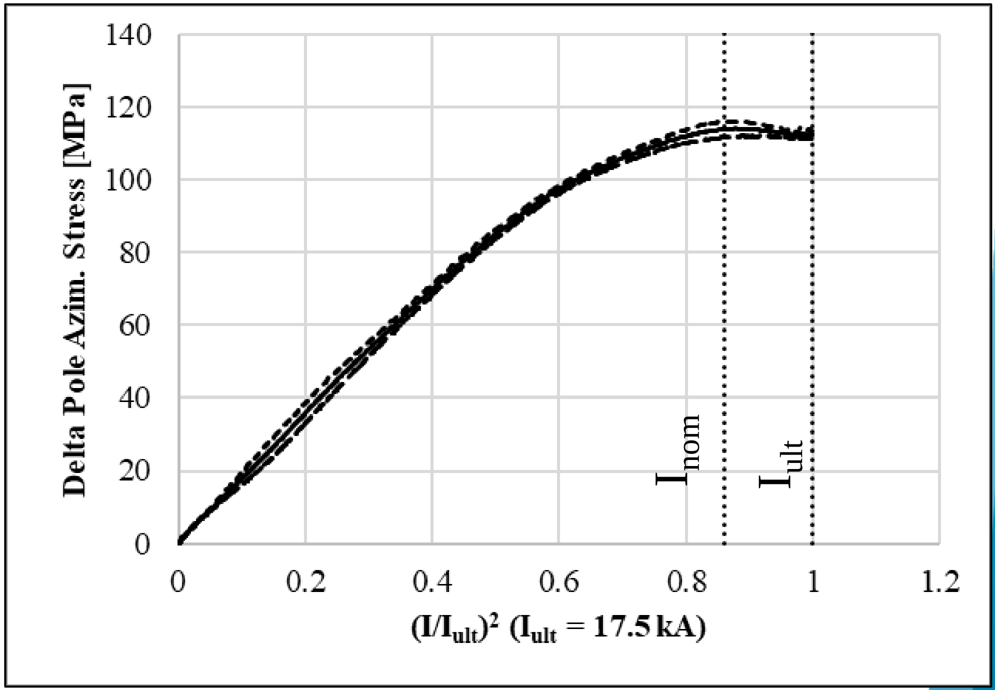




MQXFS8 - Mechanics

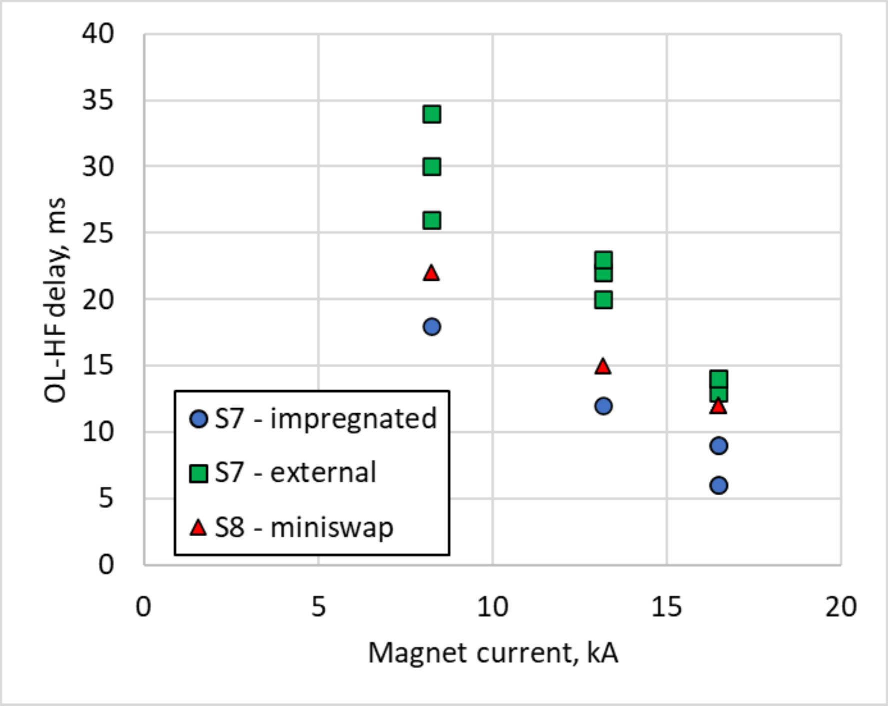
- Rather ‘nominal’ magnet from the mechanical point of view

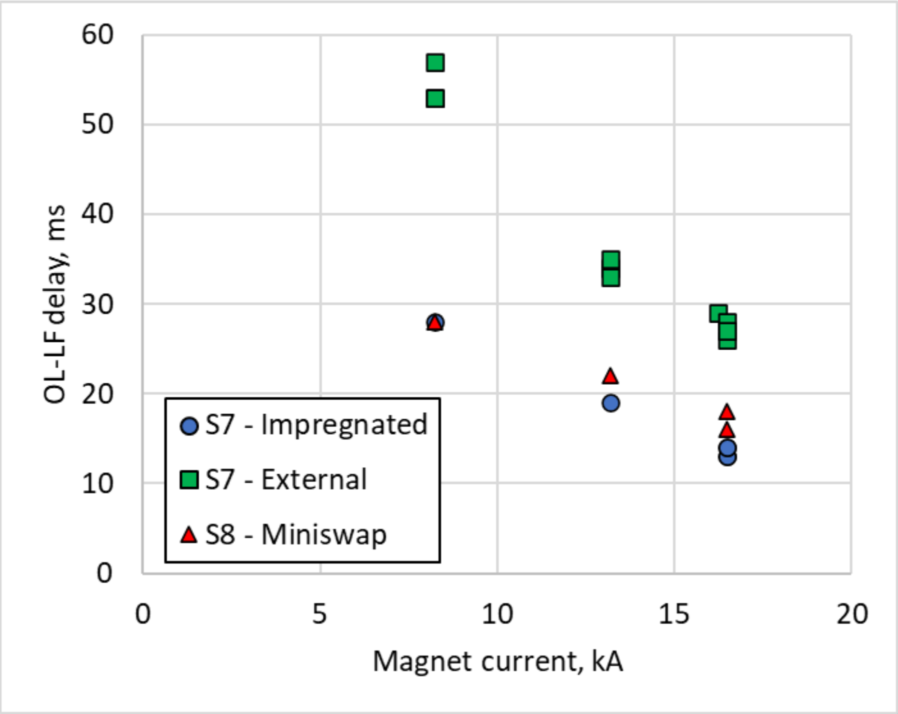




QH performance - delay

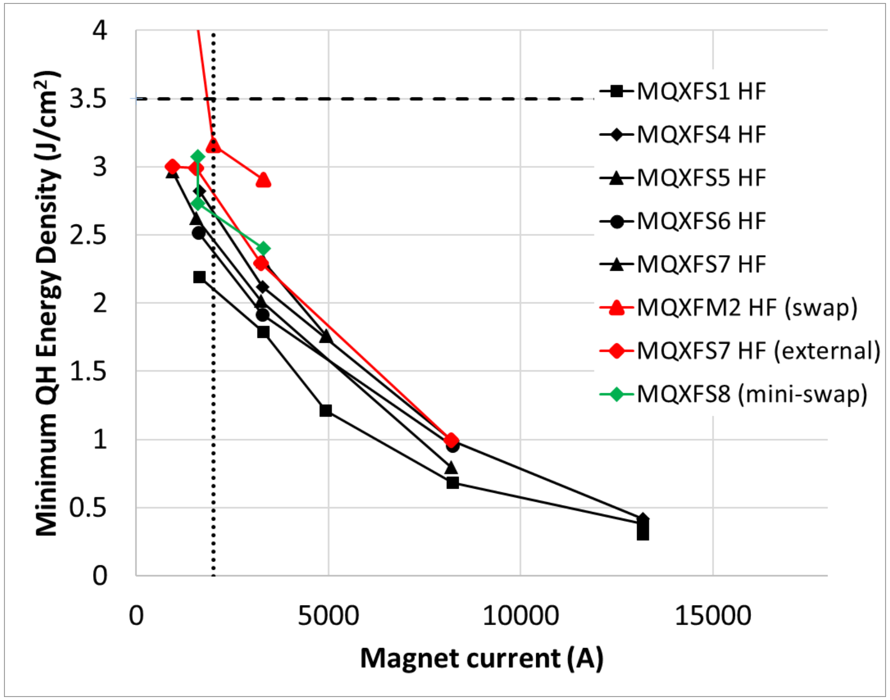
- 14 quenches done, ~50 more do to in the next cool down
- First results: QH delay with the mini-swap close to expectations. At Inom:
  - High Field expected 14 ms, measured 12 ms
  - Low Field expected 19 ms, measured 18 ms

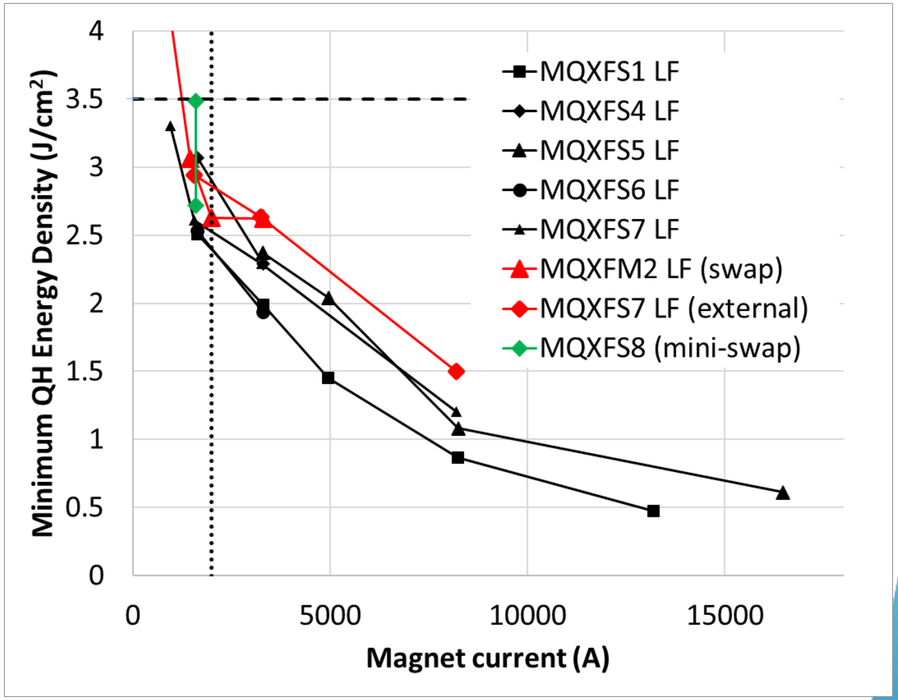




QH performance – min. quench energy

- At 1.6 kA, mini-swap QH effective to provoke a quench
  - Nominal Energy Density = 3.5 J/cm^2
  - Minimum Energy Density = 2.5 – 2.7 J/cm^2 (to initiate a quench at 2 kA)





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Outline

- MQXFS7 pre-load experiment
- MQXFS8
- **Conclusions**

Conclusions

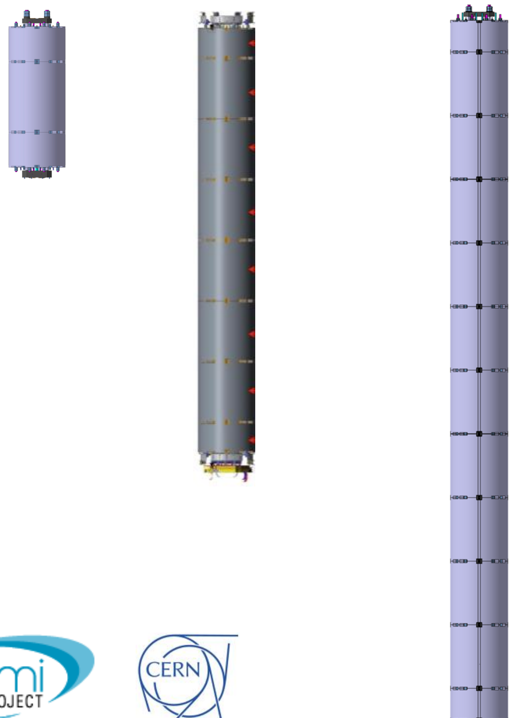
- 7 years after the test of the first MQXFS at CERN, short magnets are still providing very useful feedback
- Based on MQXFS7 pre-load experiment, small impact on performance at 1.9 K up to a level of pole azimuthal stress of 190 MPa (MQXFS7i)
  - Small drop on the maximum current at 4.5 K (3 %), but not clear if it is only related to the increase of azimuthal preload. Tests at 4.5 K in MQXFS7i expected in the coming days.
- After competition of MQXFS7 experiment we will proceed with MQXFS4 (final conductor, RRP 108/127) implementing lessons learnt from MQXFS7.
- MQXFS8 reached ultimate current at 4.5 K, the magnet will be pushed to its maximum current in the next thermal cycle.
- Protection studies in MQXFS8 coils with mini-swap quench heater layout are in line with expectations.

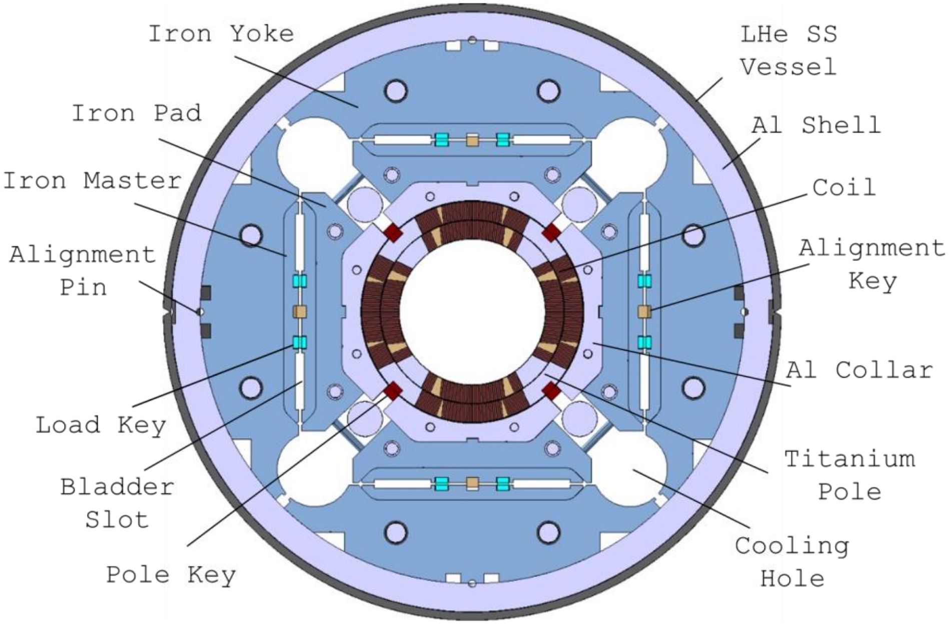
Additional slides

Magnet design

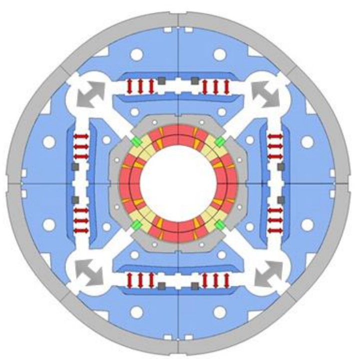
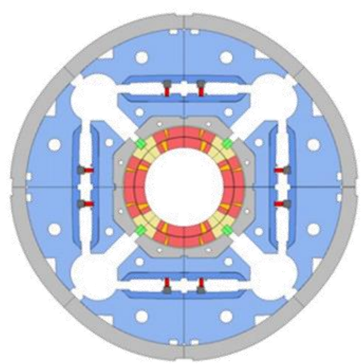
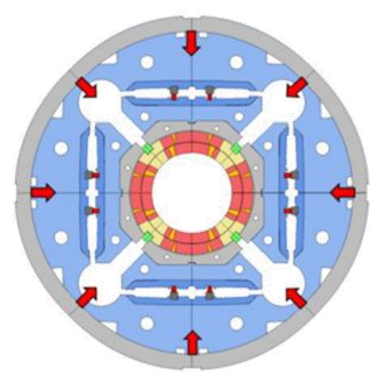
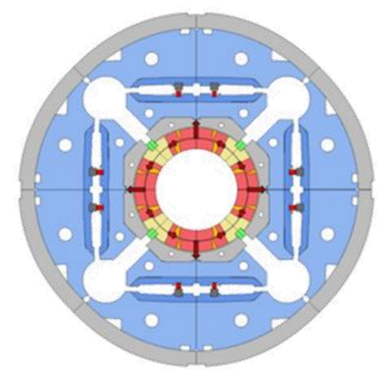
- Target: 132.2 T/m; 150 mm coil aperture, **11.3 T B_{peak}**
- Q1/Q3 (by US-AUP Project), 2 magnets **MQXFA** with 4.2 m L_m
- Q2a/Q2b (by CERN), 1 magnet **MQXFB** with 7.15 m L_m
- Joint short model development program **(MQXFS)** to validate the design
- Different lengths, same design, very similar assembly procedure and loading target
- SS vessel mechanically decoupled from the magnet → results discussed here are mainly without the contribution of the SS Shell

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





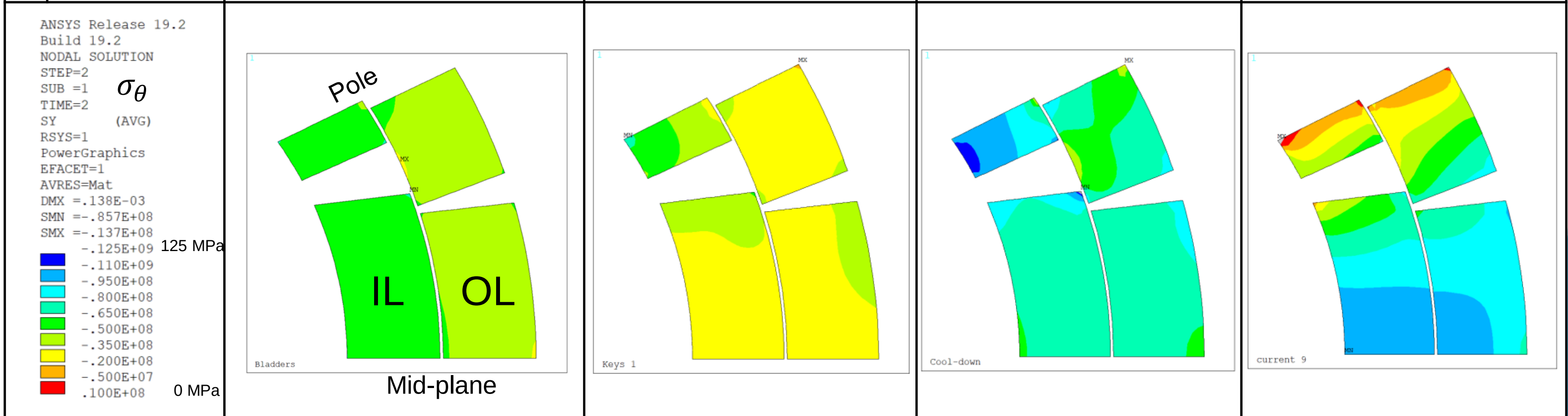
Magnet assembly

	Bladder pressurization*	Key insertion	Cool down	Powering
	Open enough clearance to insert the keys (key size + ≈ 0.2-0.3 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	--	40 %	87 %	93 %
F_θ/F_{em} pole	--	40 %	87 %	10 %
				

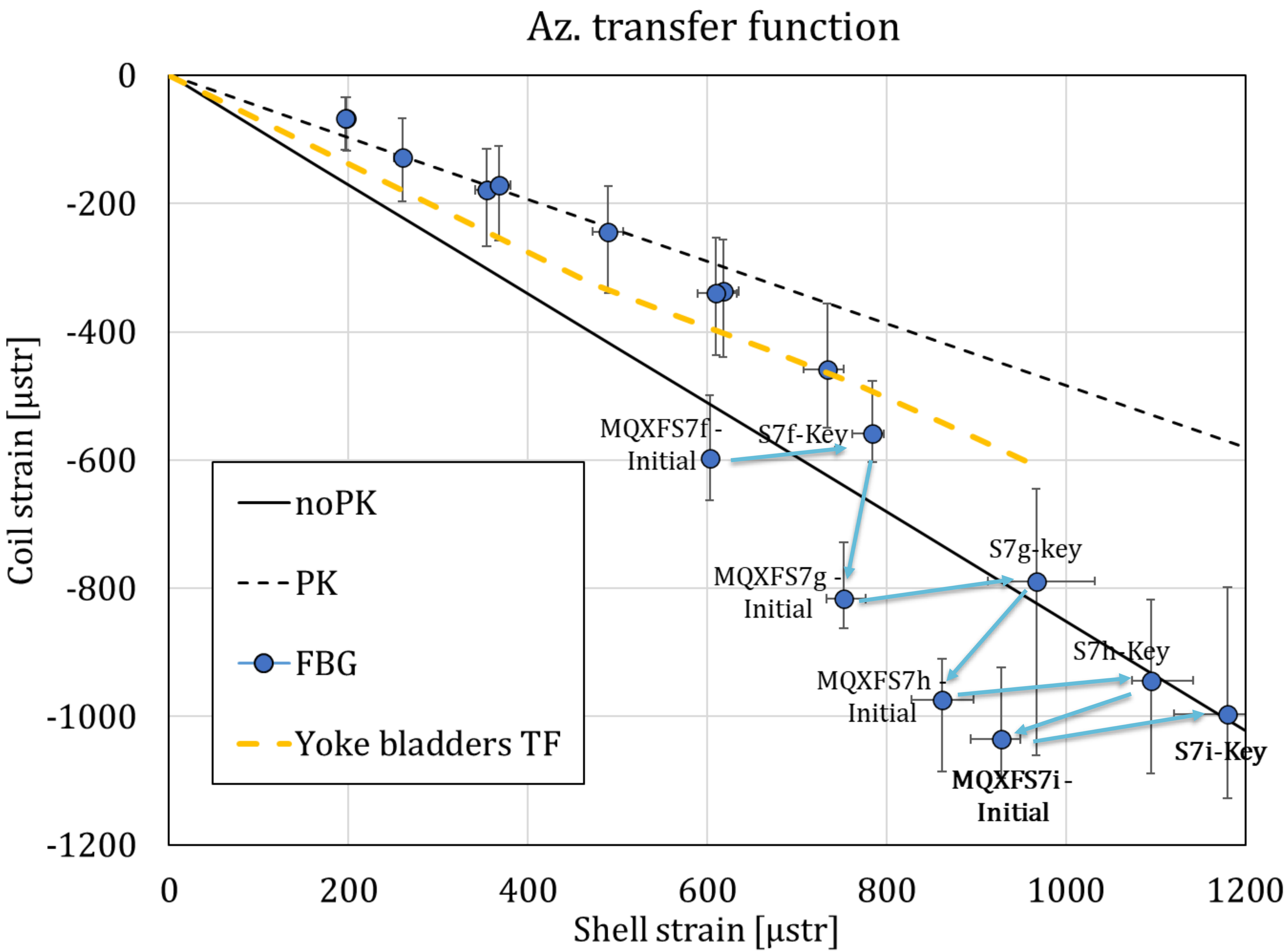
*Depends on the bladder procedure, numbers reported here correspond to the new MQXFB baseline procedure (all bladders at the time including auxiliary bladders in the cooling holes)

Coil stress for target pre-load

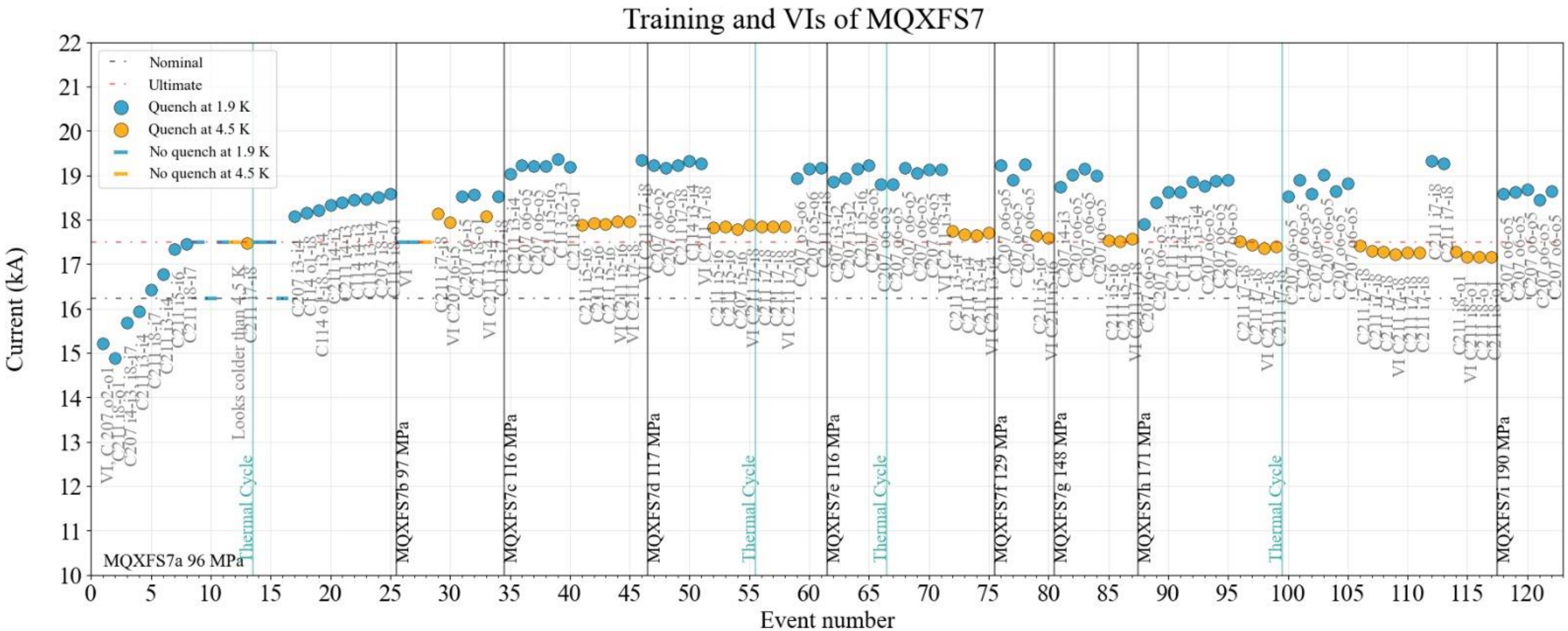
		Bladder pressurization	Key insertion	Cool down	Powering (16.23/17.5 kA)
		Open enough clearance to be insert the keys (key size + 0.2-0.3 mm)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic 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



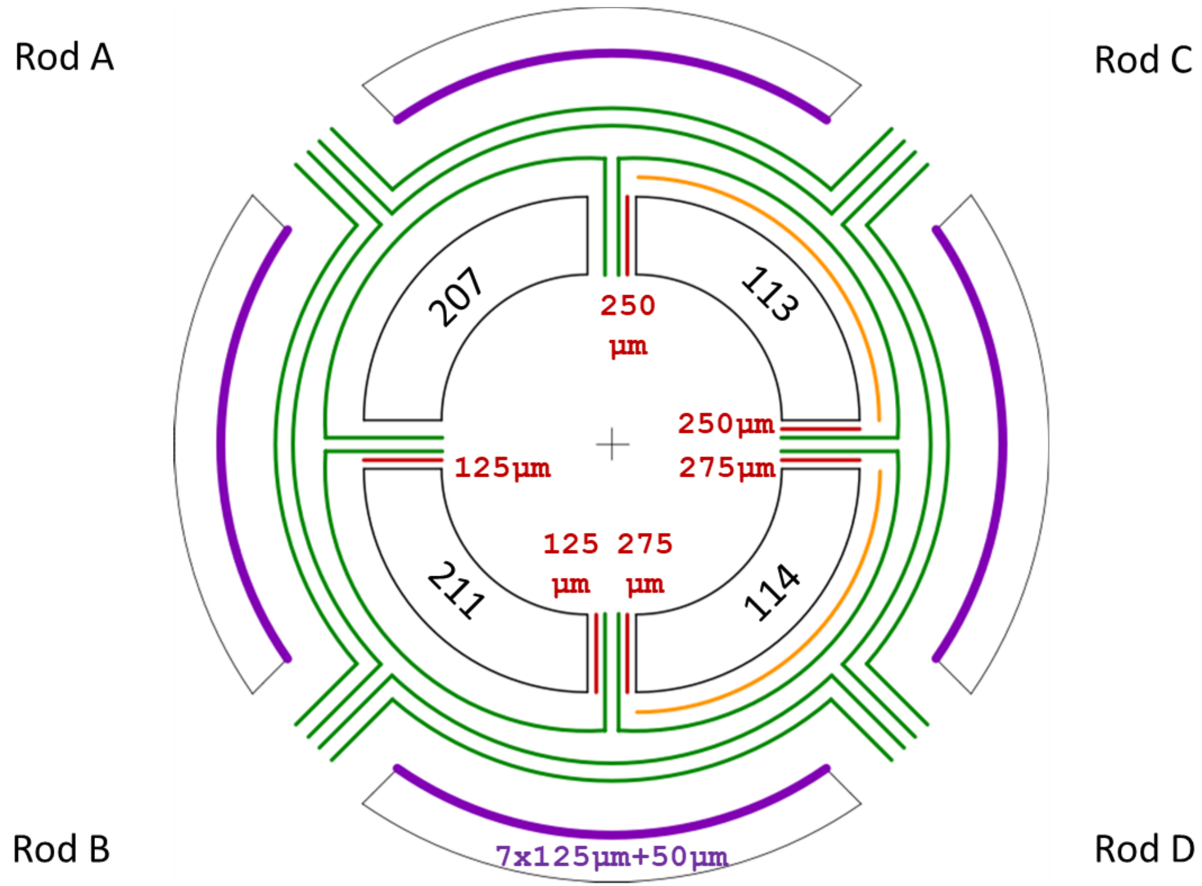
Stress map and stress values for the new procedure, loading with auxiliary bladders in the cooling holes.
Nominal assembly with 80 MPa pole compression at warm, 110 MPa at cold
Uncertainty due to material properties and assembly tolerances ± 15-20 MPa



Az. transfer function
Coil strain [µstr]
Shell strain [µstr]
0
-200
-400
-600
-800
-1000
-1200
0
200
400
600
800
1000
1200
noPK
PK
FBG
Yoke bladders TF
MQXFS7f - Initial
S7f-Key
MQXFS7g - Initial
S7g-key
MQXFS7h - Initial
S7h-Key
MQXFS7i - Initial
S7i-Key


Training and VIs of MQXFS7
Nominal
Ultimate
Quench at 1.9 K
Quench at 4.5 K
No quench at 1.9 K
No quench at 4.5 K
Current (kA)
Event number
MQXFS7a 96 MPa
Thermal Cycle
Looks colder than 4.5 K
MQXFS7b 97 MPa
MQXFS7c 116 MPa
MQXFS7d 117 MPa
MQXFS7e 116 MPa
MQXFS7f 129 MPa
MQXFS7g 148 MPa
MQXFS7h 171 MPa
MQXFS7i 190 MPa

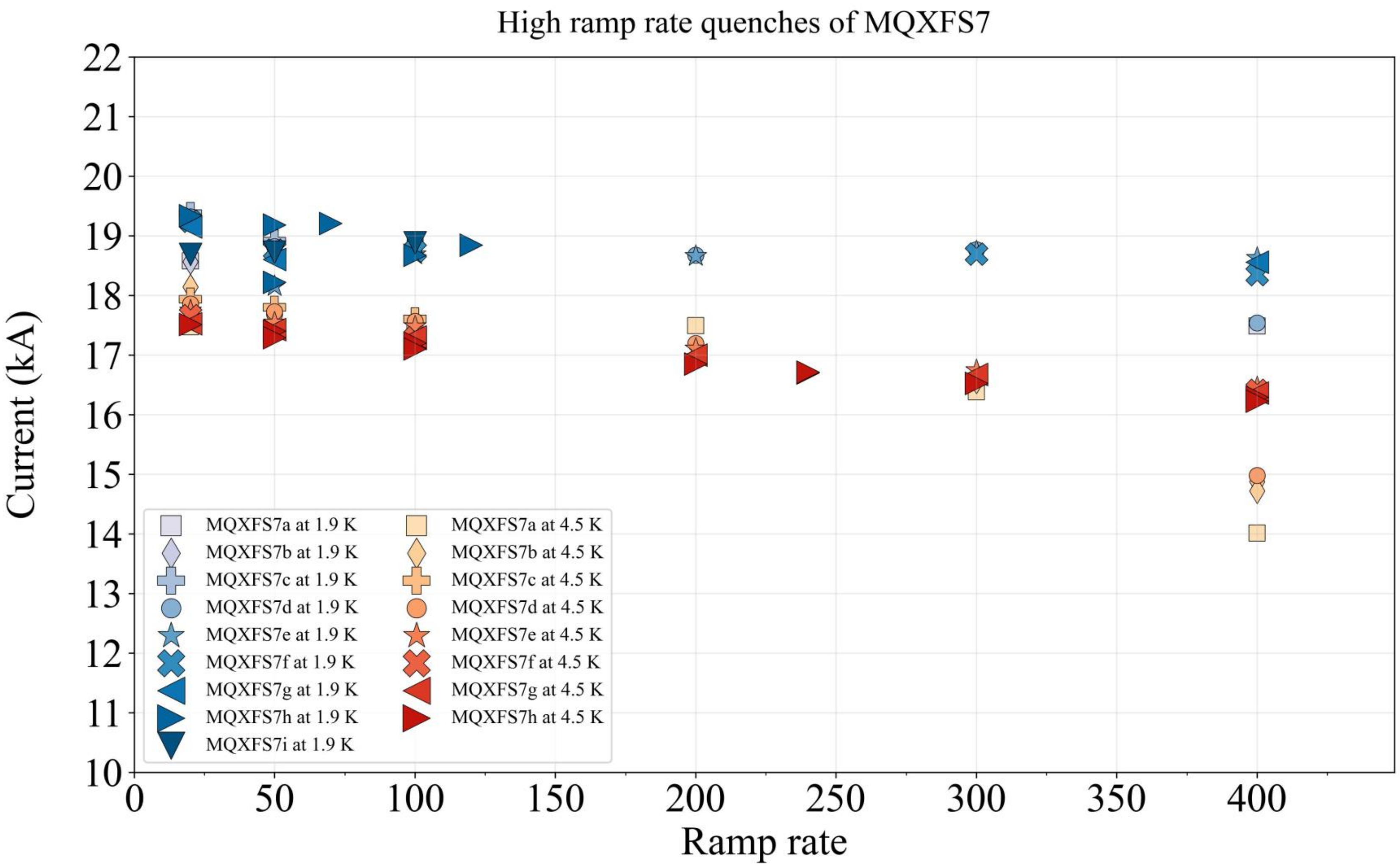
S7 – Frankenstein magnet



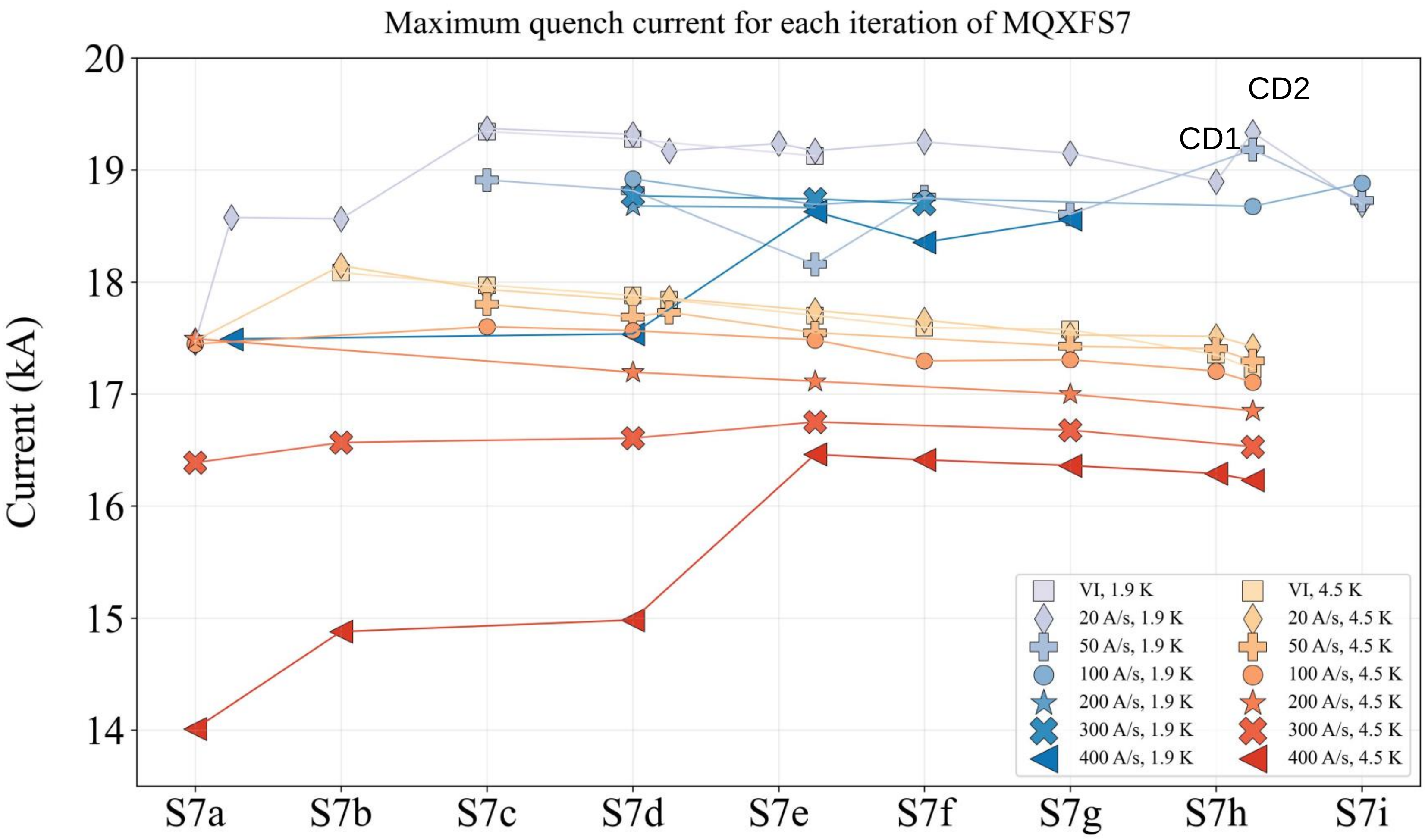
Ground insulation 125µm

Heater 100µm + shims 125µm + 75µm

Outer radius of Coil 113 and 114 is 113.076 mm (-300um)

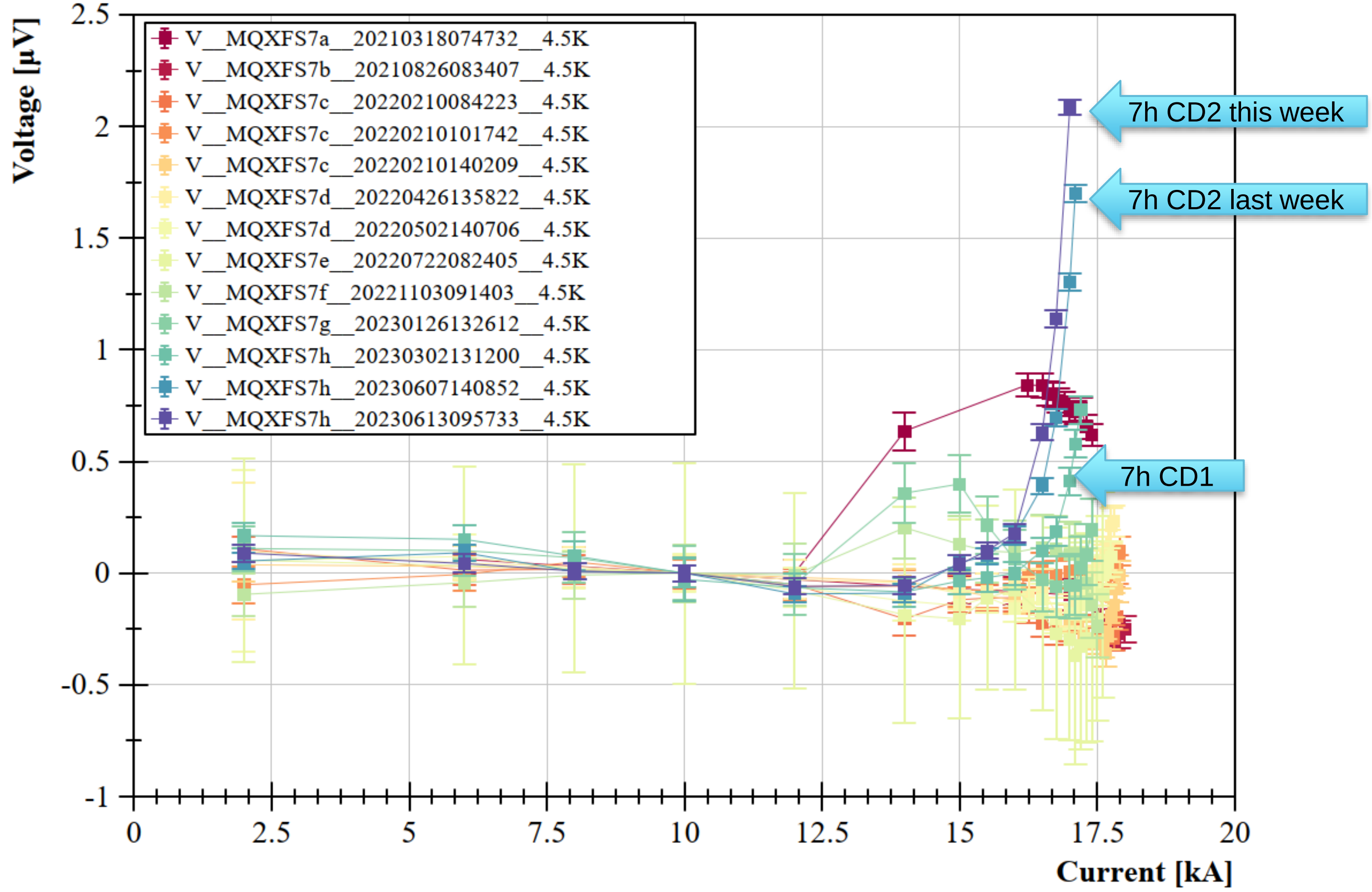


High ramp rate quenches of MQXFS7
Current (kA)
Ramp rate
22
21
20
19
18
17
16
15
14
13
12
11
10
0
50
100
150
200
250
300
350
400
MQXFS7a at 1.9 K
MQXFS7b at 1.9 K
MQXFS7c at 1.9 K
MQXFS7d at 1.9 K
MQXFS7e at 1.9 K
MQXFS7f at 1.9 K
MQXFS7g at 1.9 K
MQXFS7h at 1.9 K
MQXFS7i at 1.9 K
MQXFS7a at 4.5 K
MQXFS7b at 4.5 K
MQXFS7c at 4.5 K
MQXFS7d at 4.5 K
MQXFS7e at 4.5 K
MQXFS7f at 4.5 K
MQXFS7g at 4.5 K
MQXFS7h at 4.5 K



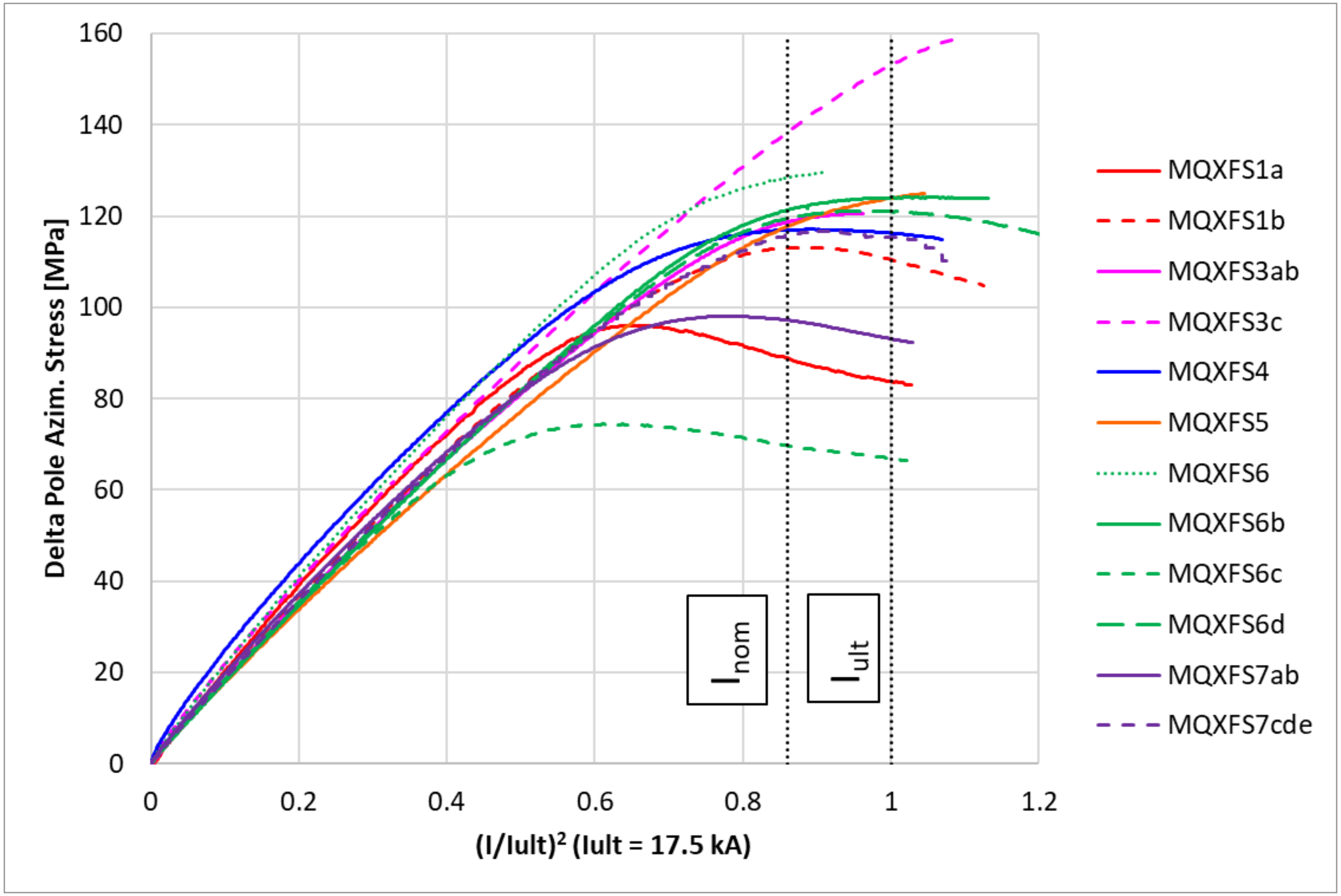
Maximum quench current for each iteration of MQXFS7
Current (kA)
20
19
18
17
16
15
14
S7a
S7b
S7c
S7d
S7e
S7f
S7g
S7h
S7i
CD1
CD2
VI, 1.9 K
20 A/s, 1.9 K
50 A/s, 1.9 K
100 A/s, 1.9 K
200 A/s, 1.9 K
300 A/s, 1.9 K
400 A/s, 1.9 K
VI, 4.5 K
20 A/s, 4.5 K
50 A/s, 4.5 K
100 A/s, 4.5 K
200 A/s, 4.5 K
300 A/s, 4.5 K
400 A/s, 4.5 K

211 I8-O1



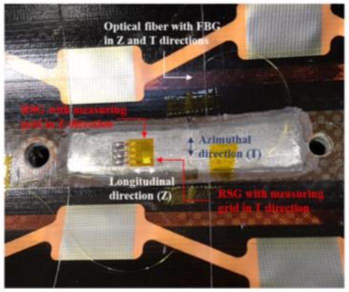
Voltage [µV]
Current [kA]
V__MQXFS7a__20210318074732__4.5K
V__MQXFS7b__20210826083407__4.5K
V__MQXFS7c__20220210084223__4.5K
V__MQXFS7c__20220210101742__4.5K
V__MQXFS7c__20220210140209__4.5K
V__MQXFS7d__20220426135822__4.5K
V__MQXFS7d__20220502140706__4.5K
V__MQXFS7e__20220722082405__4.5K
V__MQXFS7f__20221103091403__4.5K
V__MQXFS7g__20230126132612__4.5K
V__MQXFS7h__20230302131200__4.5K
V__MQXFS7h__20230607140852__4.5K
V__MQXFS7h__20230613095733__4.5K
7h CD2 this week
7h CD2 last week
7h CD1

Delta pole stress during powering

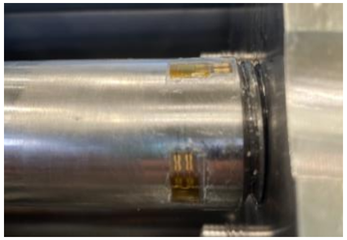


Mechanical instrumentation

Coils instrumented with strain gauges and FBGs



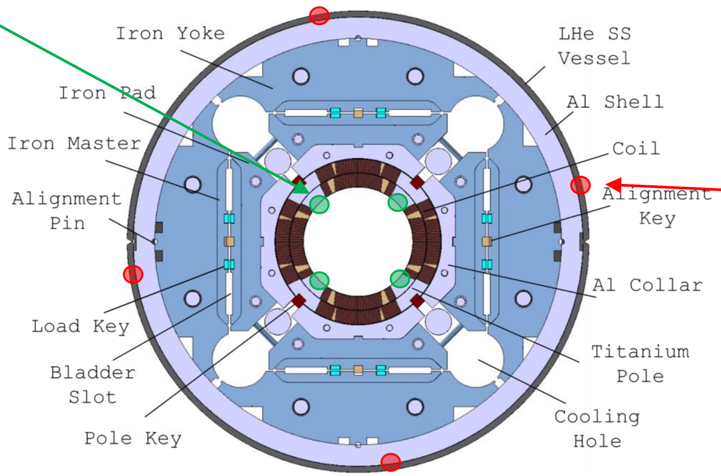
Rods instrumented with strain gauges



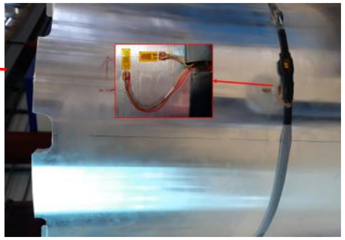
Mechanical behavior monitored. **Strain** is **measured** in:

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

Measurements are performed in the middle of the magnet

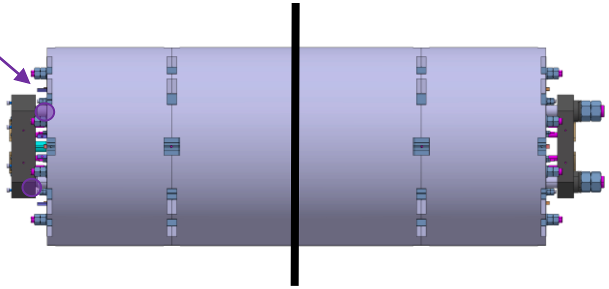


Al-shells instrumented with strain gauges



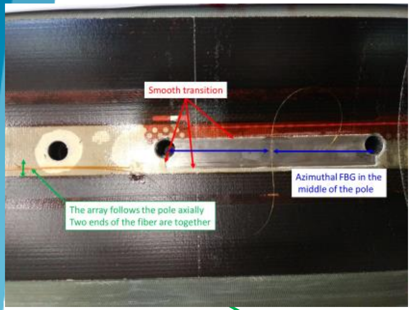
$$\sigma_\theta = \frac{E}{(1-\nu^2)}(\varepsilon_\theta + \nu\varepsilon_z)$$

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

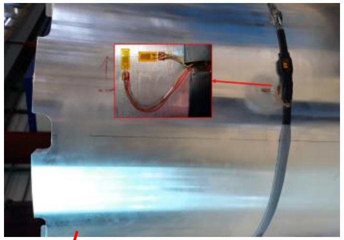


Mechanical instrumentation

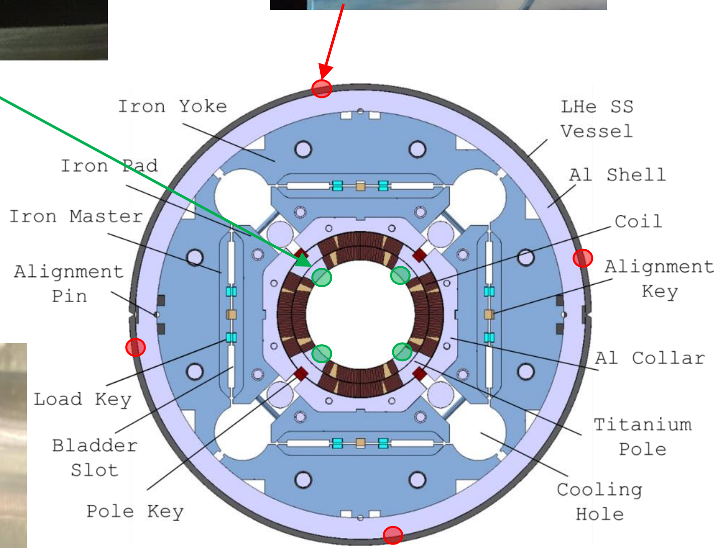
Coils instrumented with strain gauges and of FBGs

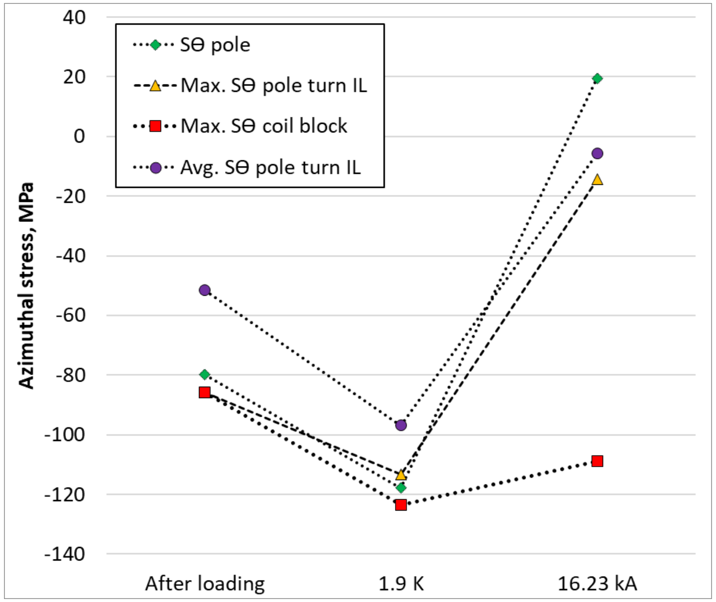


Al-shells instrumented with strain gauges

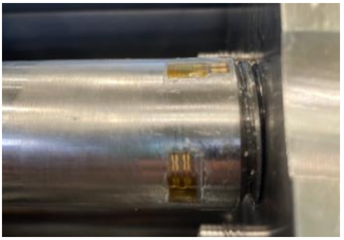


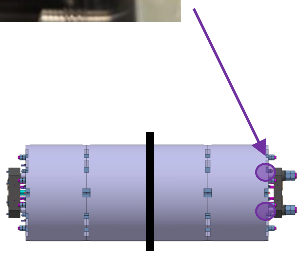
The strain is measured in the coil titanium pole. The peak stress in the coil during loading and cool down is in the IL pole turn, very close to the stress in the Ti pole (measuring location)



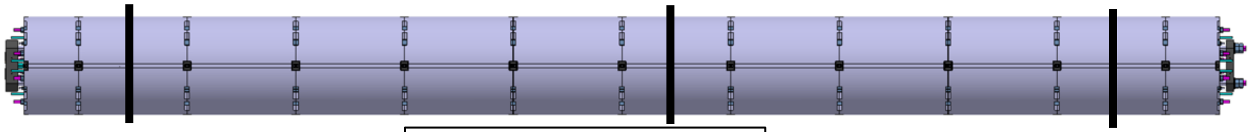


Rods instrumented with strain gauges





MQXFS, one longitudinal measuring location



MQXFB, three longitudinal measuring locations

FE Model

<u>Aluminum</u>

E (4.3 K / 293 K) = 79 / 70 [GPa]
v = 0.34
CTE (4.3 K – 293 K) = 1.45 e-5

<u>Iron</u>

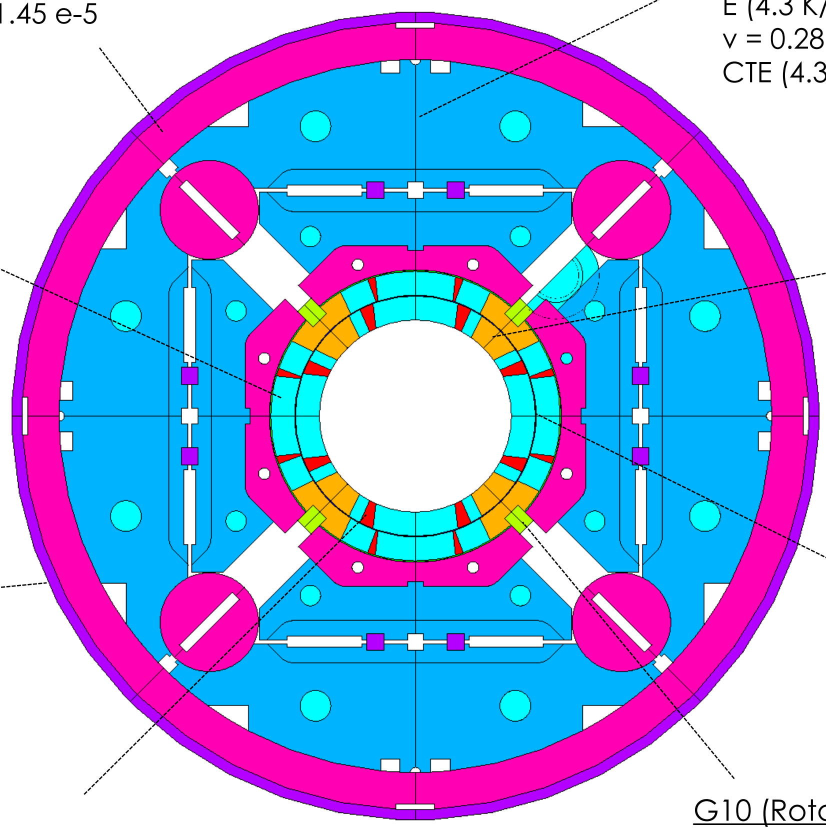
E (4.3 K/ 293 K) = 224 / 213 [GPA]
v = 0.28
CTE (4.3 K – 293 K) = 6.82 e-6

<u>Coil equivalent</u>

E (4.3 K / 293 K) = 20 [GPA]
v = 0.3
CTE (4.3 K – 293 K) = 1.35 e-5

<u>Titanium</u>

E (4.3 K/ 293 K) = 130 [GPA]
v = 0.3
CTE (4.3 K – 293 K) = 6.03 e-6



<u>Stainless steel</u>

E (4.3 K/ 293 K) = 210 / 193 [GPA]
v = 0.28
CTE (4.3 K – 293 K) = 9.83 e-6

<u>G10</u>

E (4.3 K/ 293 K) = 30 [GPA]
v = 0.3
CTE (4.3 K – 293 K) = 2.44 e-5

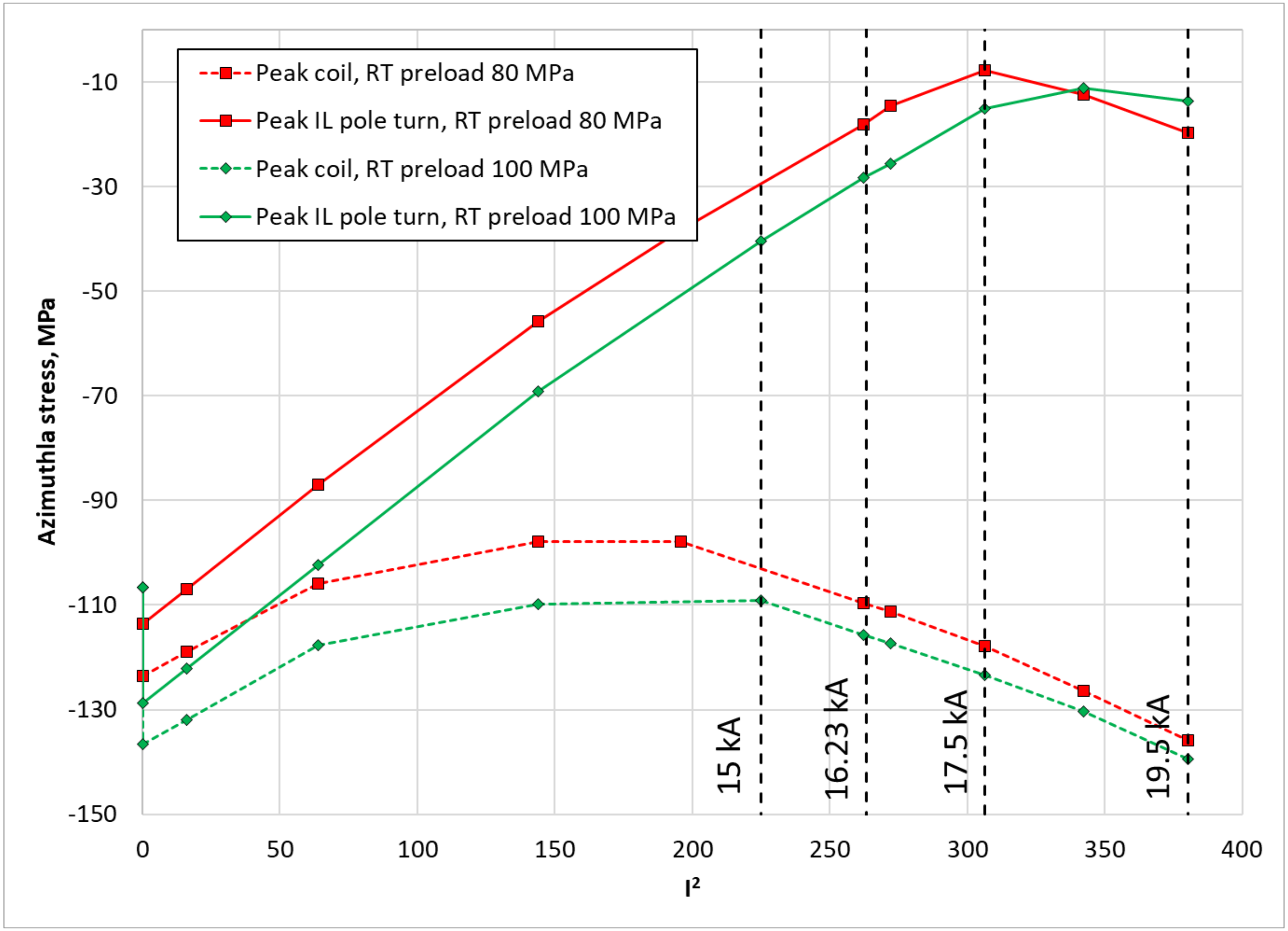
<u>Aluminum bronze</u>

E (4.3 K/ 293 K) = 120 / 110 [GPA]
v = 0.3
CTE (4.3 K – 293 K) = 1.08 e-5

<u>G10 (Rotated)</u>

E (4.3 K/ 293 K) = 30 [GPA]
v = 0.3
CTE (4.3 K – 293 K) = 0.846 e-5

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