Pre-load experience in MQXFS magnets

Susana Izquierdo Bermudez on behalf of MQXF team

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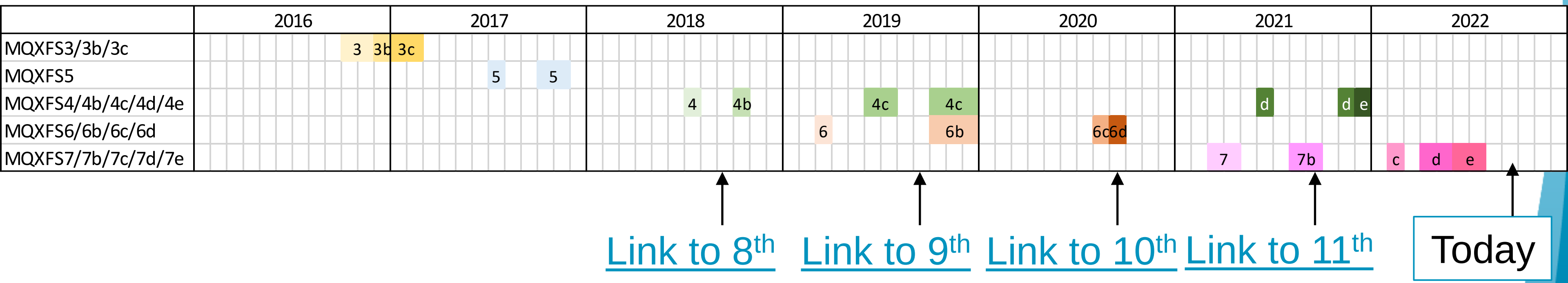
Preamble

- The tests of MQXFS models at CERN started end of 2016, validating the different aspects of the design (protection, field quality, performance…)
- **Focus** of **today**'s talk: summarize the azimuthal pre-load levels reached in MQXFS magnets and the impact on magnet performance

MQXFS test history at CERN



Outline

- Introduction to magnet design and target pre-load
- Pre-load levels explored with MQXFS magnets
  - Nominal pre-load
  - The ‘low preload’ range: MQXFS6
  - The ‘high preload’ range: MQXFS7 and MQXFS4
- Conclusions

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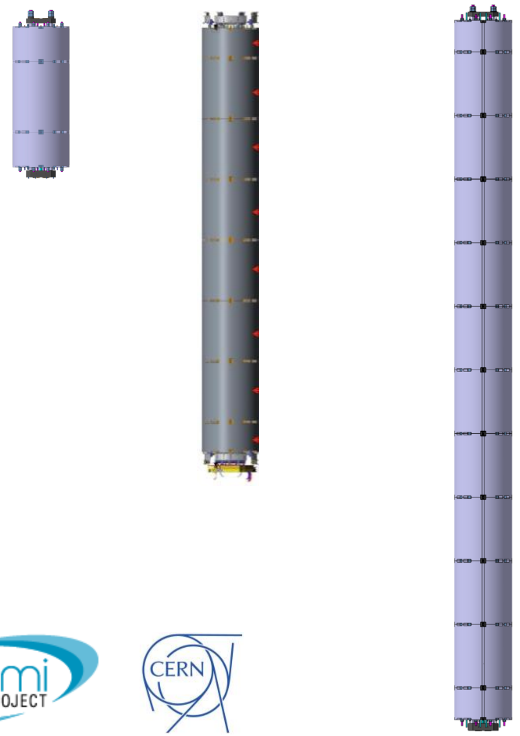
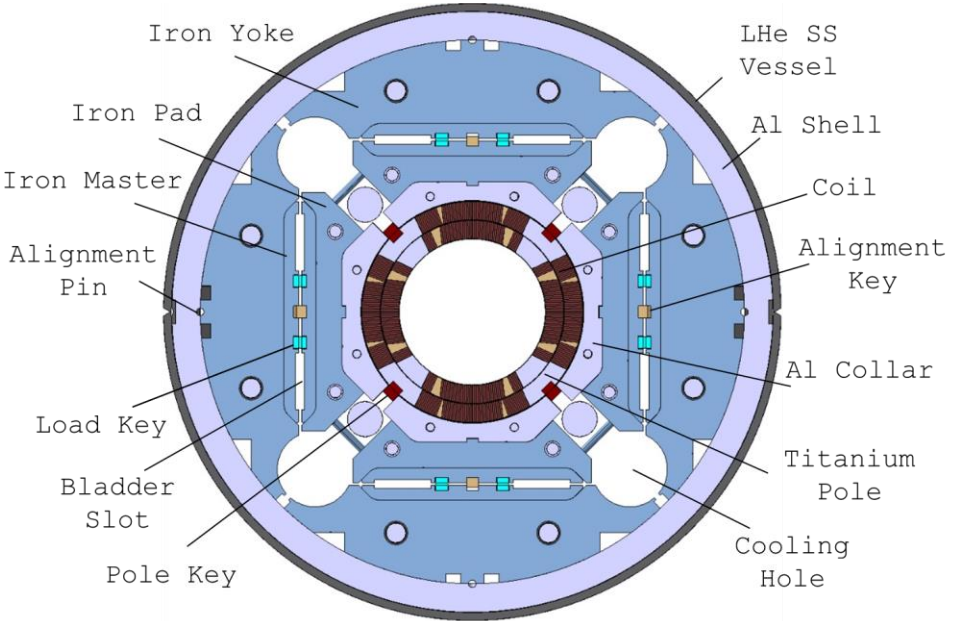
Magnet design

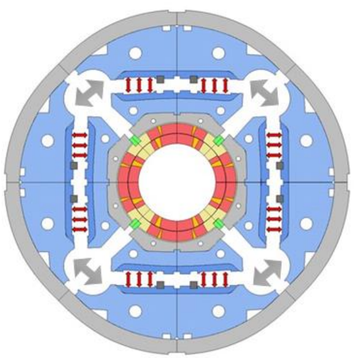
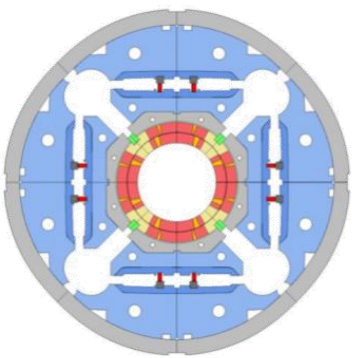
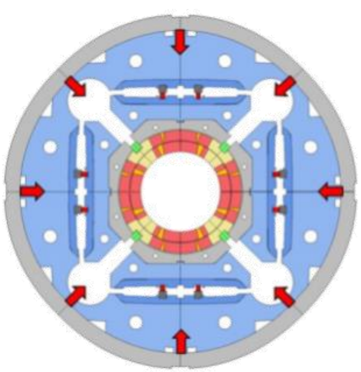
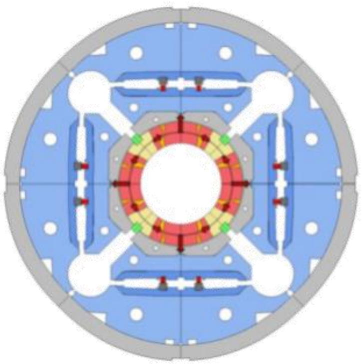
- Target: 132.2 T/m; 150 mm coil aperture, **11.3 T B_{peak}**
- Q1/Q3 (by US-AUP Project), 2 magnets **MQXFA** with 4.2 m L_m
- Q2a/Q2b (by CERN), 1 magnet **MQXFB** with 7.15 m L_m
- Joint short model development program **(MQXFS)** to validate the design
- Different lengths, same design, very similar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

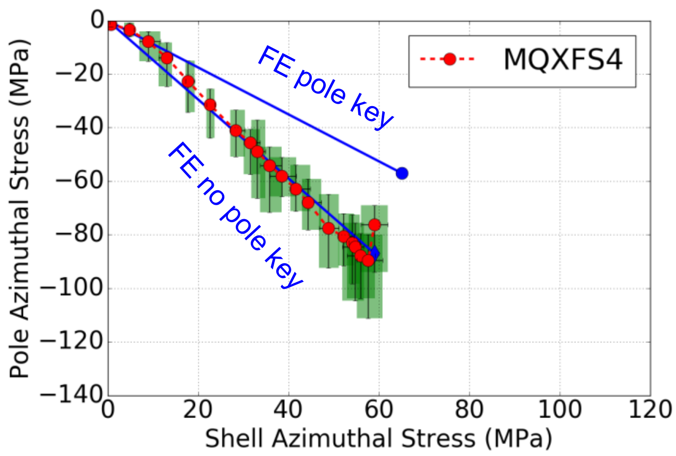
	Bladder pressurization*	Key insertion	Cool down	Powering
	Open enough clearance to insert the keys (key size + ≈ 0.2-0.3 mm clearance)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic forces
F_{θ}/F_{em} shell	--	40 %	87 %	93 %
F_{θ}/F_{em} pole	--	40 %	87 %	10 %
				

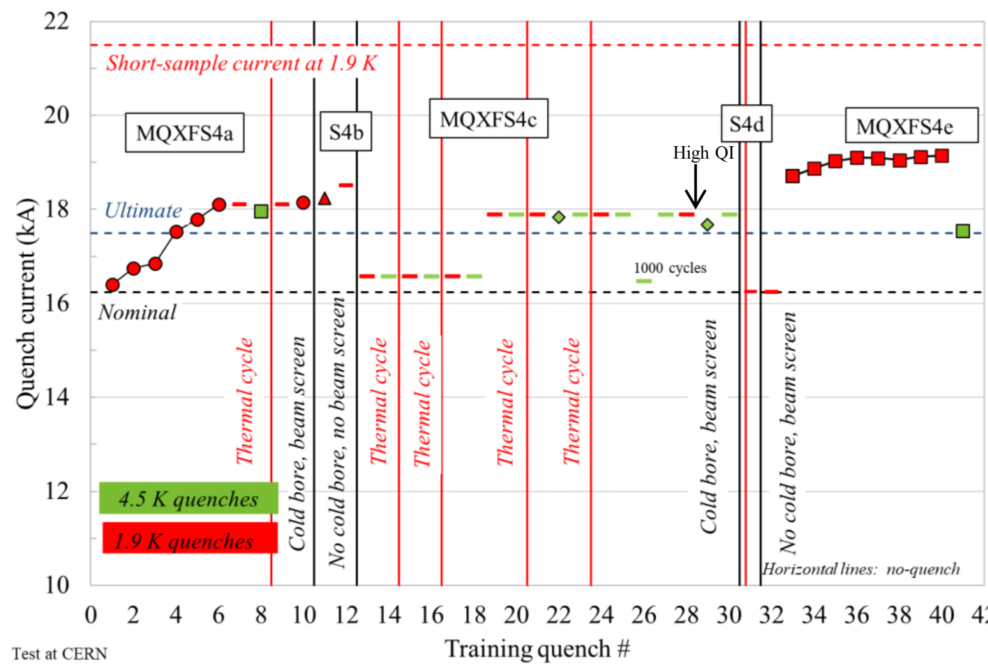
*Depends on the bladder procedure, numbers reported here correspond to the new MQXFB baseline procedure (all bladders at the time including auxiliary bladders in the cooling holes)

Target pre-load

- **MQXFS4** as a reference
  - Only MQXFS magnet built with final conductor (RRP 108/127, ‘old’ heat treatment, i.e., dwell3 plateau duration 75 hours instead of 50 hours)
  - No sign of degradation to I_{ult} after 1000 current cycles to Inom, 11 thermal cycles and high QI test reaching a $T_{hot} \approx 400$ K
  - Average coil stress (> 24 hours after loading): -80 ± 8 MPa
  - Average shell stress (> 24 hours after loading): 58 ± 6 MPa

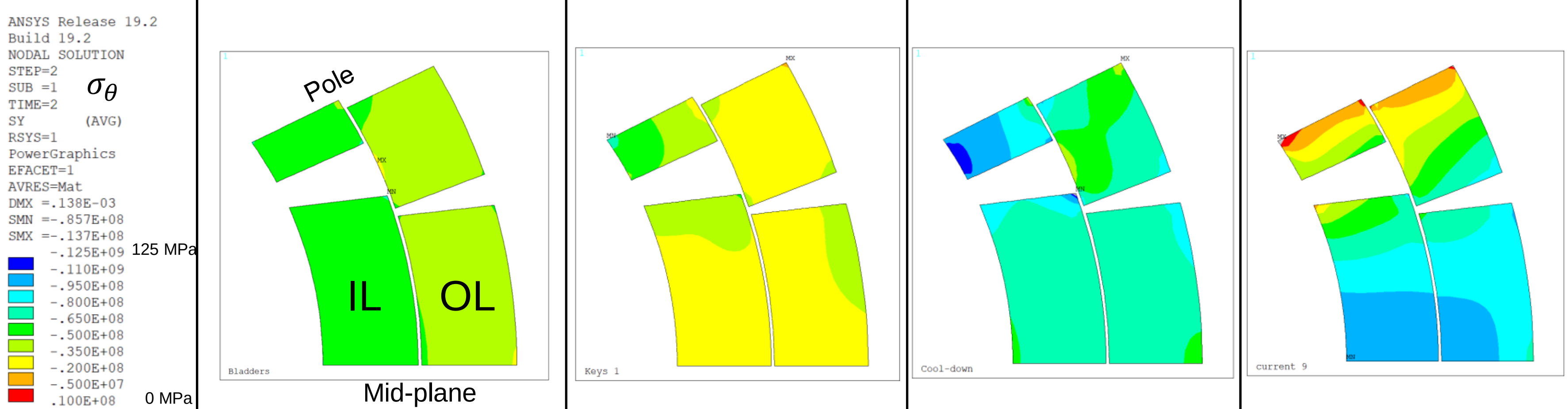
Measured pole and shell azimuthal stress during loading in MQXFS4 magnet





Coil stress for target pre-load

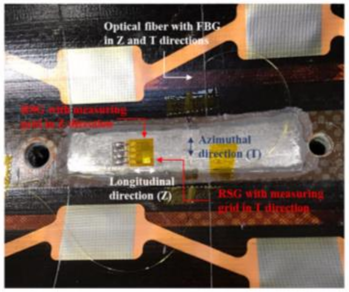
		Bladder pressurization	Key insertion	Cool down	Powering (16.23/17.5 kA)
		Open enough clearance to be insert the keys (key size + 0.2-0.3 mm)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic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



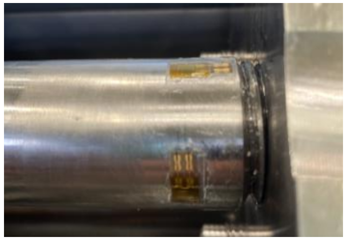
Stress map and stress values for the new procedure, loading with auxiliary bladders in the cooling holes.
Nominal assembly with 80 MPa pole compression at warm, 110 MPa at cold
Uncertainty due to material properties and assembly tolerances ± 15-20 MPa

Mechanical instrumentation

Coils instrumented with strain gauges and FBGs



Rods instrumented with strain gauges



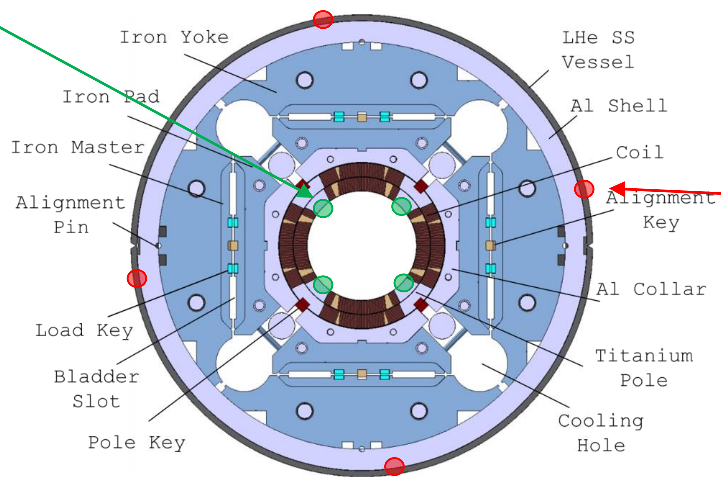
$$\sigma_\theta = \frac{E}{(1-v^2)}(\varepsilon_\theta + v\varepsilon_z)$$

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

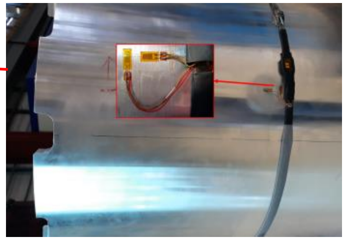
Mechanical behavior monitored. **Strain** is **measured** in:

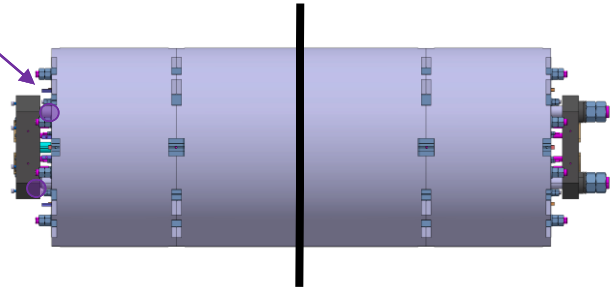
1. Rods
2. Aluminum shell
3. Coil titanium pole

Measurements are performed in the middle of the magnet



Al-shells instrumented with strain gauges





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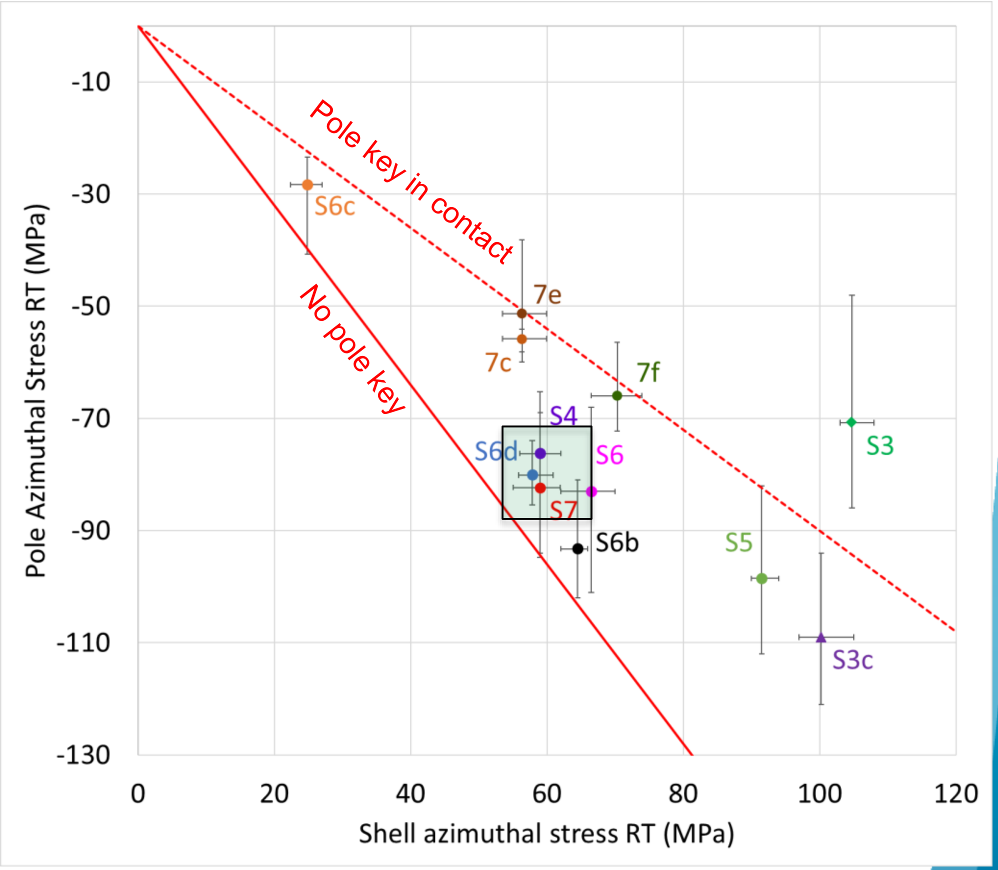
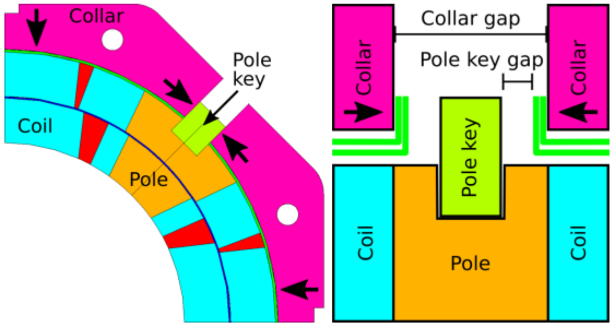
Nominal pre-load

- Starting from MQXFS4, the first assembly iteration of the short model magnets have been done targeting nominal pre-load level:
  - Average coil stress (> 24 hours after loading): -80 ± 8 MPa
  - Average shell stress (> 24 hours after loading): 58 ± 6 MPa
  - The pole key is not in contact with the collars during assembly
- The typical spread among coils is 20-30 MPa

Measured azimuthal pole stress and azimuthal shell stress > 24 hours after loading. Error bars indicate the spread among the 4 measuring points in coils and Al-shells

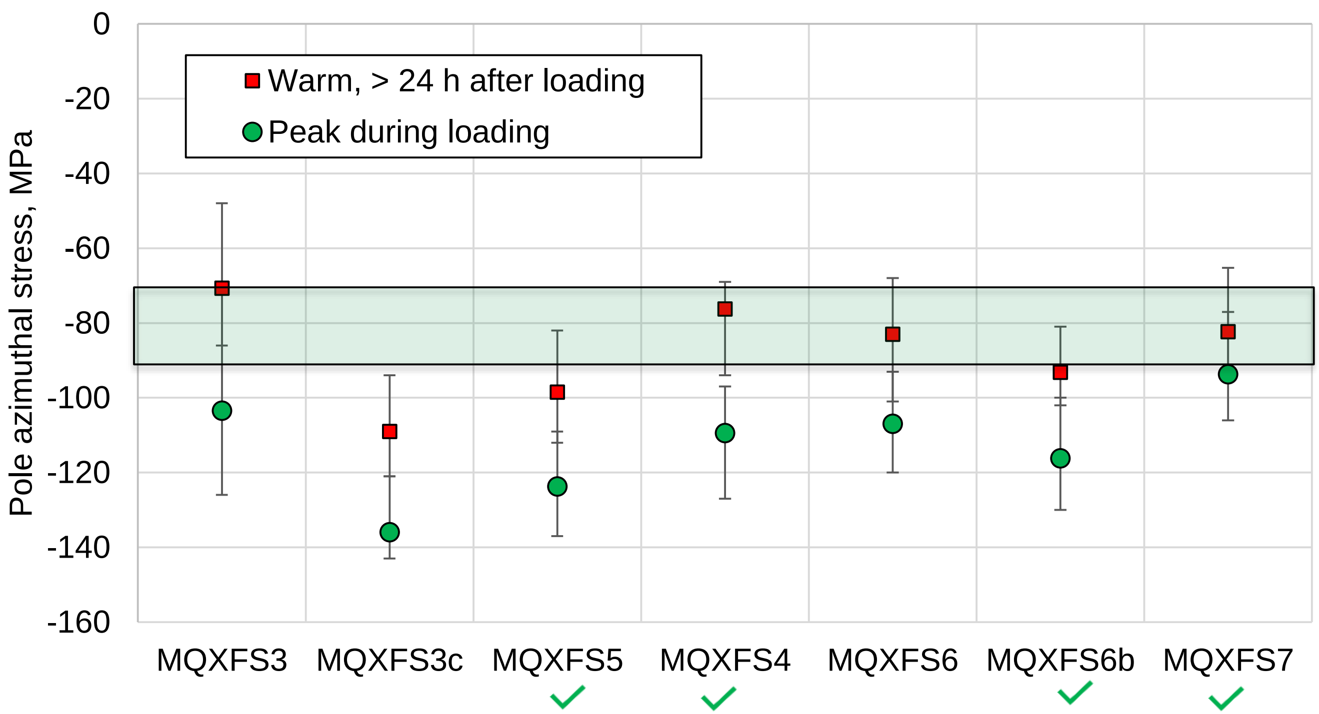




MQXFS azimuthal RT preload levels

- During bladder operations, 20-40 MPa overshoot needed to insert the keys, with a peak of 140 MPa in one coil in MQXFS5.
  - The overshoot was removed thanks to the implementation of a new loading procedure starting from MQXFS7e (see talk from Jose Ferradas Troitino)

Measured azimuthal stress during RT loading for MQXFS magnets assembled with nominal pre-load target. Error bars represent the spread among the 4 coils in the same longitudinal location



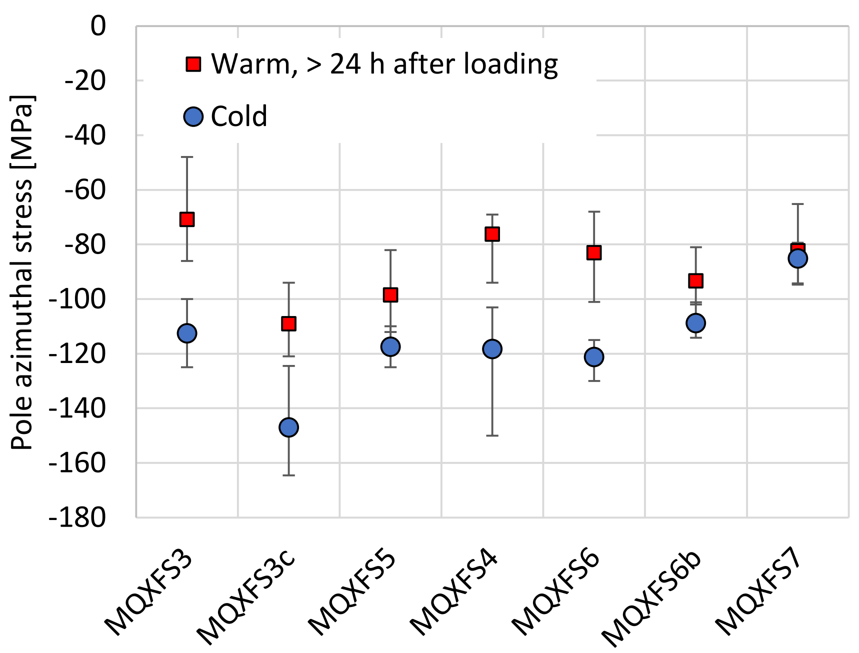
	MQXFS5	MQXFS4	MQXFS6b	MQXFS7
I_{max} (1.9 K), kA	18.5	19.2	19.1	18.5
I_{max} (4.5 K) , kA	17.9	18.0	18.2	18.2

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

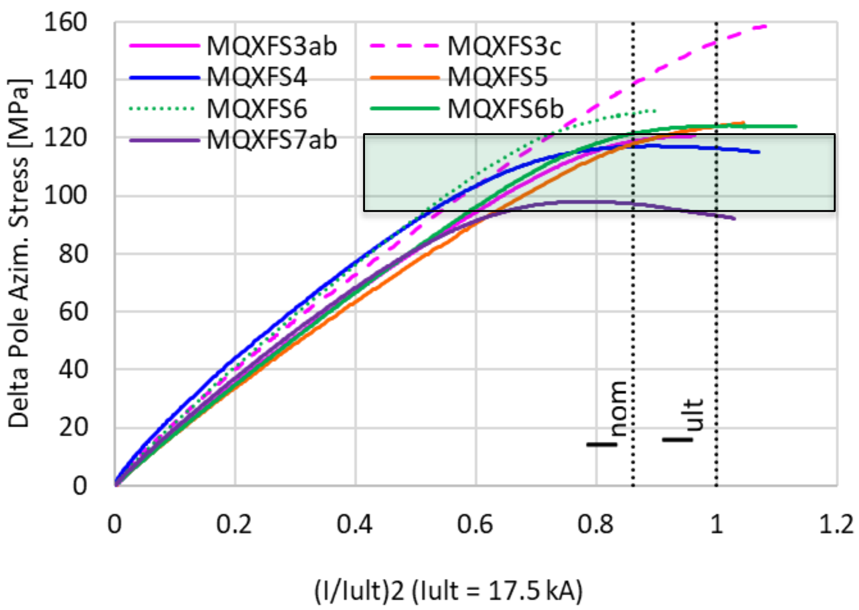
MQXFS azimuthal preload at 1.9 K

- The increase of pole azimuthal stress during cool down is 20-40 MPa (except for MQXFS7), with a resulting pole azimuthal stress at cold of 100-110 MPa for the nominal pre-load target
  - MQXFS7 was a magnet assembled with very different coils (different conductor (RRP/PIT), different QH layout (external/impregnated), very different azimuthal size (max-min arc length excess (L+R) = 0.55 mm)

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.



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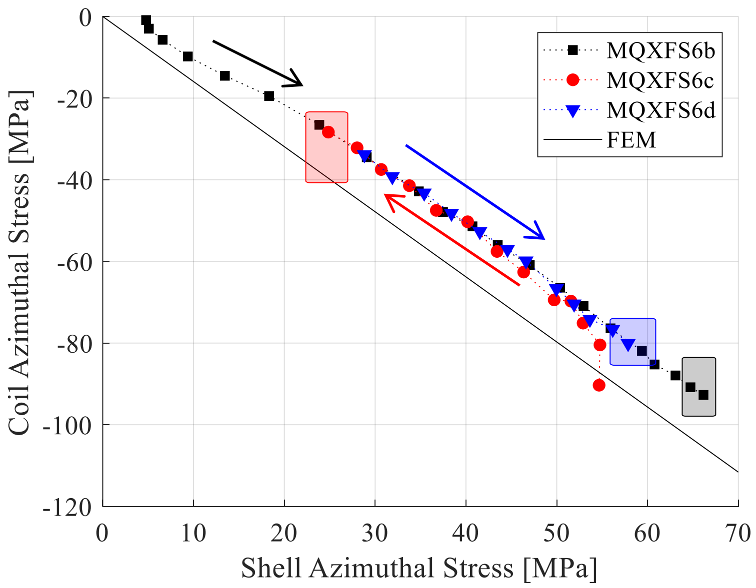
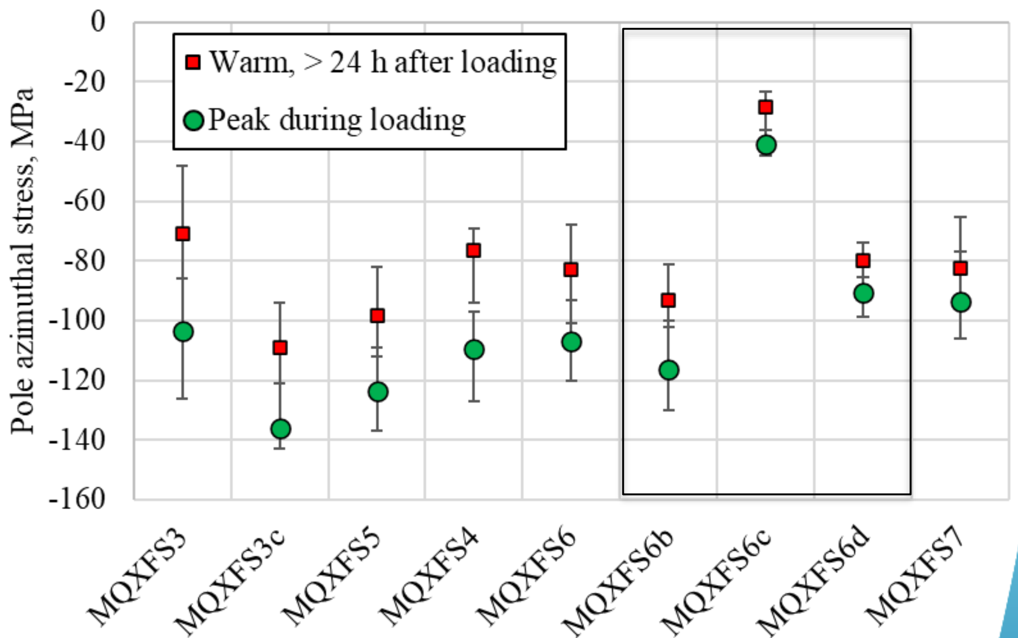
Low pre-load: MQXFS6b/c/d experiment

- MQXFS6 limited at nominal current. Low RRR coils (208 and 209, PIT 192 bundle) were replaced with coils already tested in MQXFS5 (203 and 204, PIT 192 no bundle) → MQXFS6b
- After the good training performance of MQXFS6b, MQXFS6c was reassembled with 40 MPa lower preload
  - The coil pole pre-stress at warm after loading in MQXFS6c was 25-40 MPa



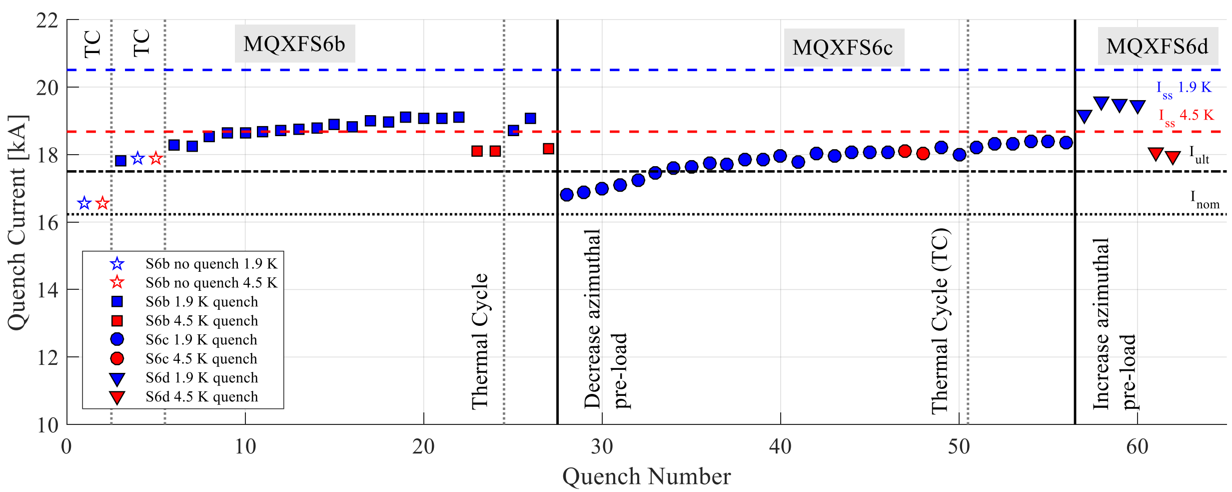
Measured shell azimuthal stress versus measured coil azimuthal stress during coil loading; squares indicates the final status after assembly of the four coils; FEM is the finite element model result



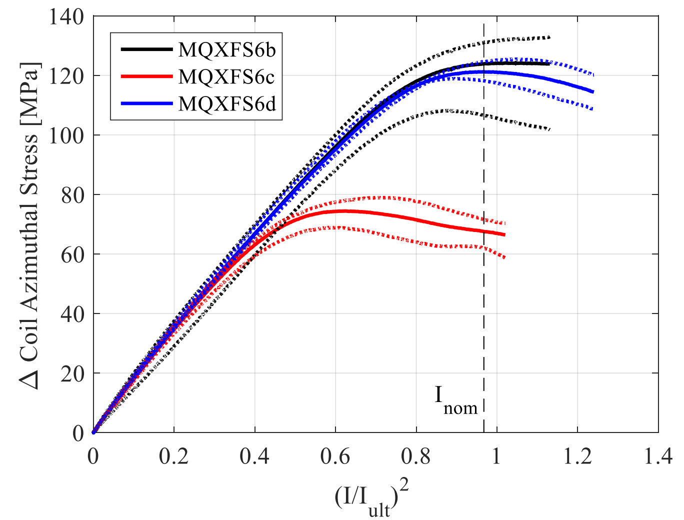
Measured coil azimuthal stress during coil loading and peak during loading. The error bars represent the spread among the four coils;

Low pre-load: MQXFS6b/c/d experiment

- As expected, pole unloading 40 MPa earlier (pole unloading at ≈ 12 kA vs 16 kA in nominal pre-load conditions)
- MQXFS6c reached nominal without training, ultimate reached after retraining, and kept after thermal cycle
- Very good indication of wide preload window to reach ultimate current
- Apparent plateau above ultimate may indicate that larger preload is beneficial to reach 90% of short sample
- Impact of temperature and current cycling in the low preload range (MQXFS6c) was not verified



Training
(F. Mangiarotti, et al)



Measured unloading during powering
(M. Guinchard, et al)

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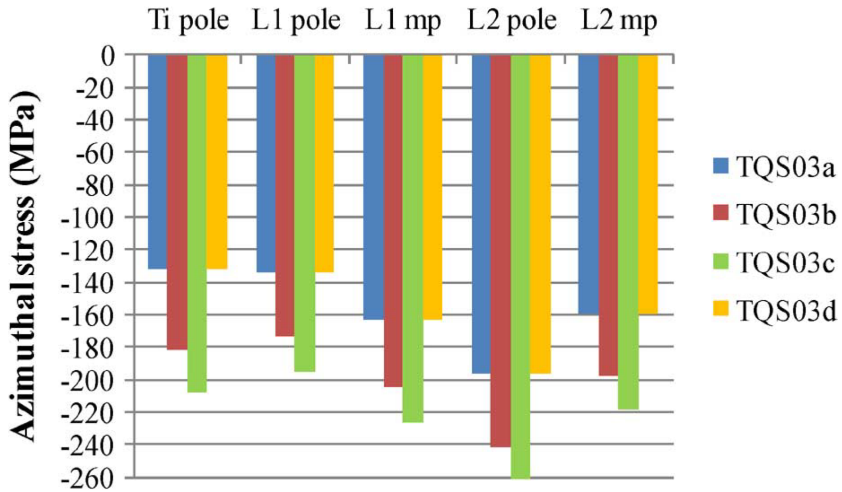
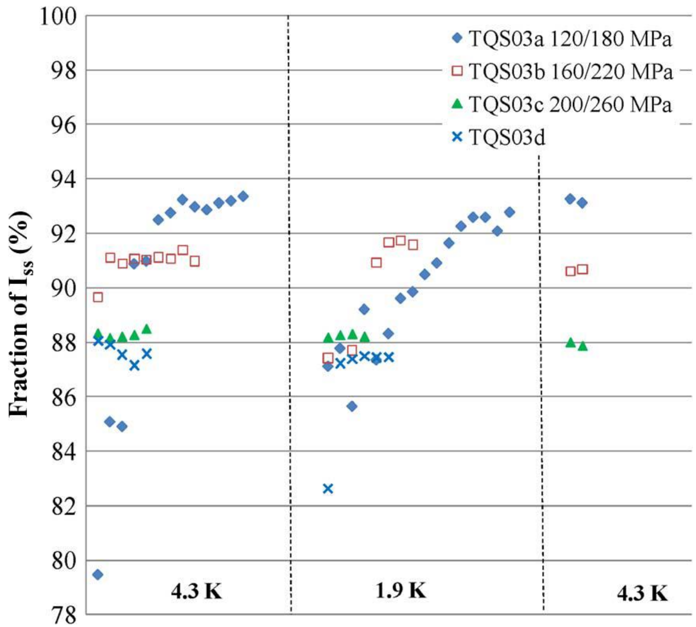
High preload: Previous experience (TQS03)

- TQS03 main characteristics:
  - Strand: 0.7 mm, OST RRP 108/127; Cable geometry: 27 strands, 10.06 x 1.26 mm
  - 1 m long 90 mm aperture quadrupole, 0.5 m outer diameter
- Main findings
  - **5 %** degradation for **260 MPa** peak stress in the conductor **after cool down**, which corresponds to **125 MPa pole stress at RT after loading**.
  - The **degradation** was **permanent**, since TQS03d, pre-loaded to the same level as TQS03a showed similar quench performance
  - **1000 current** cycles were performed in TQS03d showing **no degradation** of the quench current.

Coil azimuthal stress after cool down



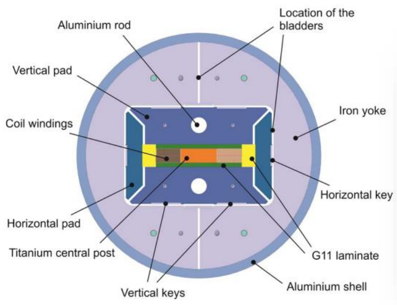
Training performance



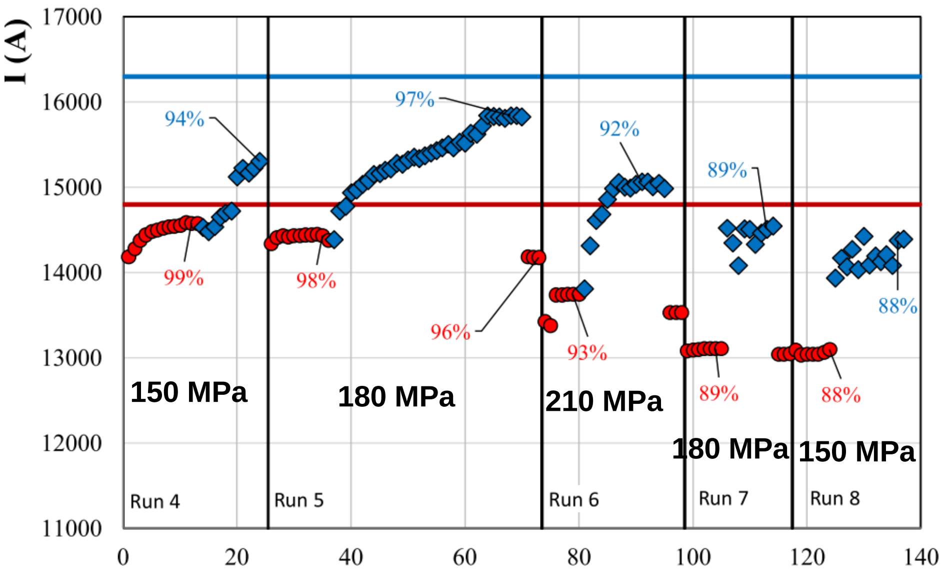
H. Felice et al., "Performance of a Nb_3Sn Quadrupole Under High Stress," in IEEE Transactions on Applied Superconductivity, vol. 21, no. 3, pp. 1849-1853, June 2011, doi: 10.1109/TASC.2010.2090116.

High preload: Previous experience SMC11T-3

- SMC11T-3 main characteristics:
  - Strand: 0.7 mm, OST RRP 132/169
  - Cable geometry: 11 T (40 strands, 14.7 x 1.25 mm)
  - Cable insulation: S2 glass + mica
  - 0.5 m length flat racetrack, 0.54 mm outer diameter
- Main findings:
  - **No degradation** of the conductor **up to 180 MPa** pre-load level at cold (120 MPa at RT)
  - ≈ 5 % degradation both at 1.9 K and 4.5 K for 210 MPa peak stress in the conductor
  - The magnet pre-load was decreased to 180 MPa, with a further decrease of the quench current of ≈ 0.5 kA both at 1.9 K and 4.5 K
  - The **degradation was permanent**. A last run with 150 MPa coil pre-load was performed, showing no further degradation of the quench current.



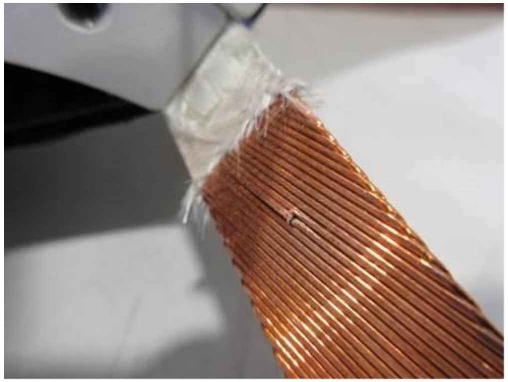
J.C. Perez, H. Bajas et al



H. Bajas et al., "Advanced Nb_3Sn Conductors Tested in Racetrack Coil Configuration for the 11T Dipole Project," in IEEE Transactions on Applied Superconductivity, vol. 28, no. 4, pp. 1-5, June 2018, Art no. 4008605, doi: 10.1109/TASC.2018.2824338.

High preload: 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



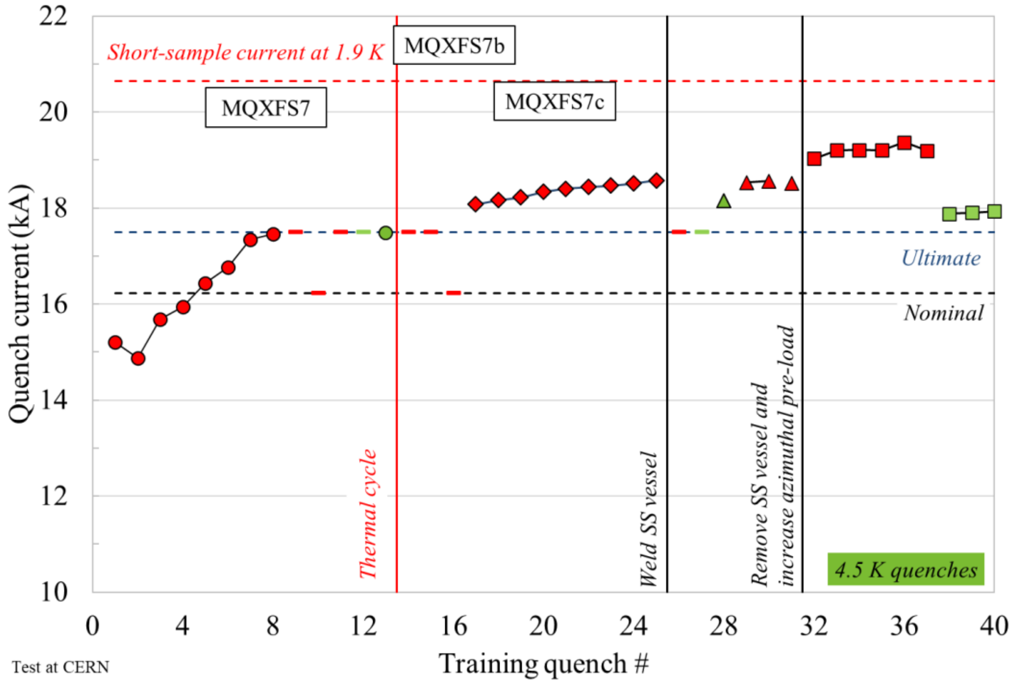
The broken strand in 211 coil

  - 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 (see talk from Jose Ferradas) to limit the peak stress during loading
- The goal of MQXFS7f/g/h is to determine what is the maximum level of preload before impacting magnet performance

MQXFS7/7b/7c

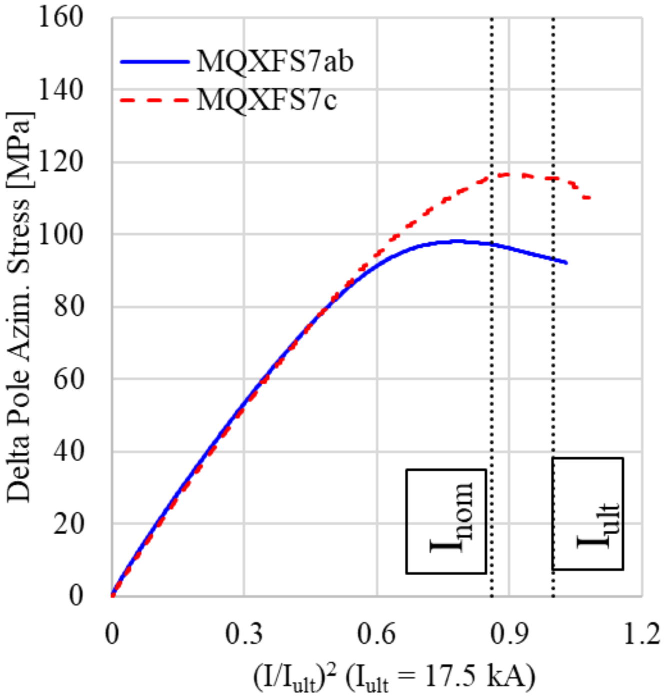
- MQXFS7 reached nominal and ultimate current at 4.5 K. Good memory after thermal cycle
- The welding of the SS vessel in MQXFS7b did not impact the magnet performance
- MQXFS7c, assembled with 15-20 MPa higher coil pre-load, reached higher current at 1.9 K with a similar performance at 4.5 K. The behavior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

Data: Salvador Ferradas Troitino, Franco Mangiarotti



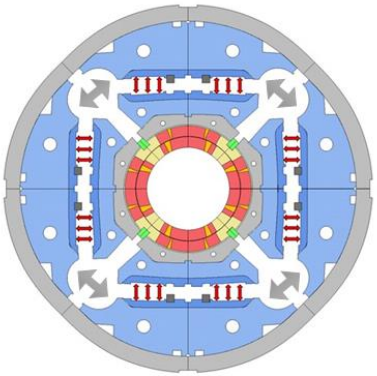
Test at CERN

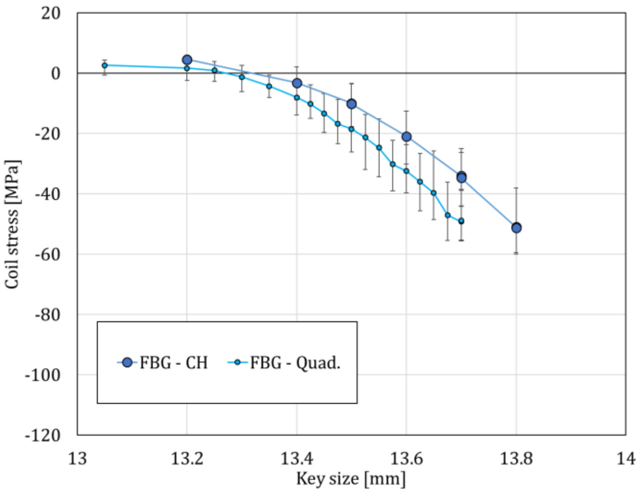
Pole unloading S7 vs S7c

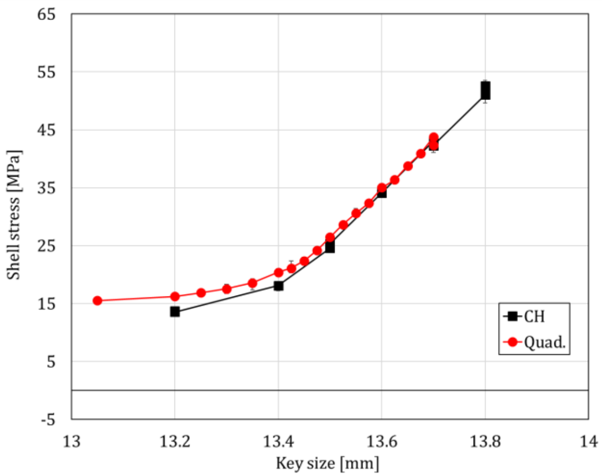


MQXFS7e

- 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 (see talk Jose Ferradas Troitino).
- 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')







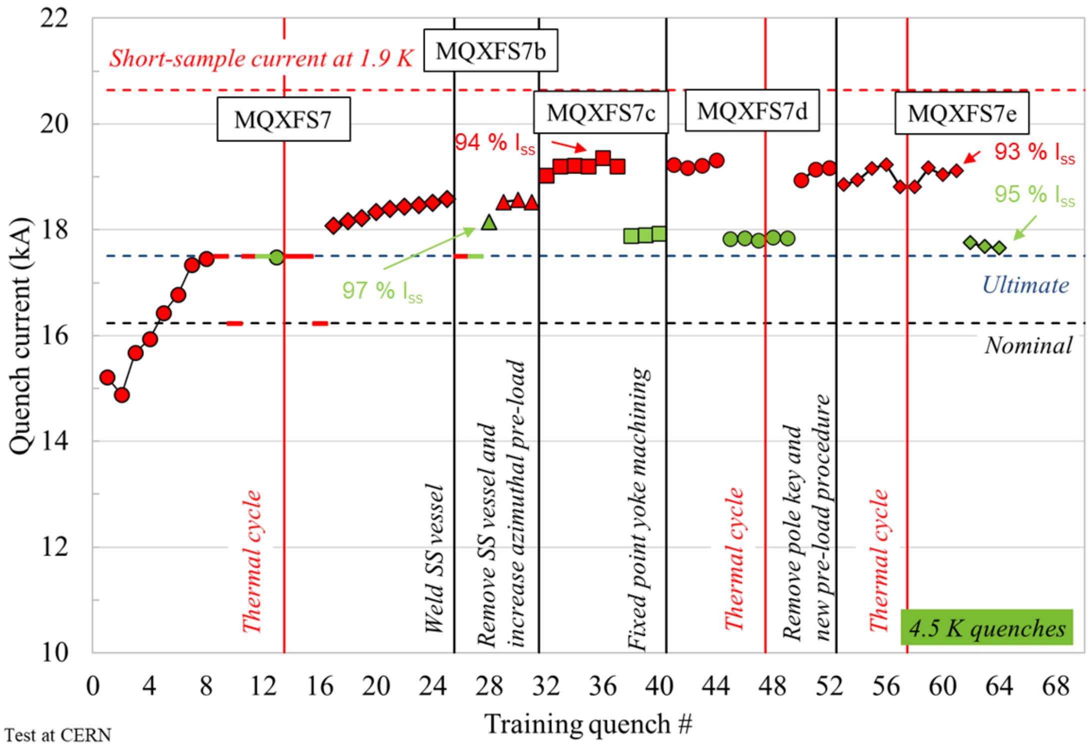
Data: Michael Guinchard, Keziban Kandemir Sylvain Mugnier

Analysis: Jose Ferradas Troitino

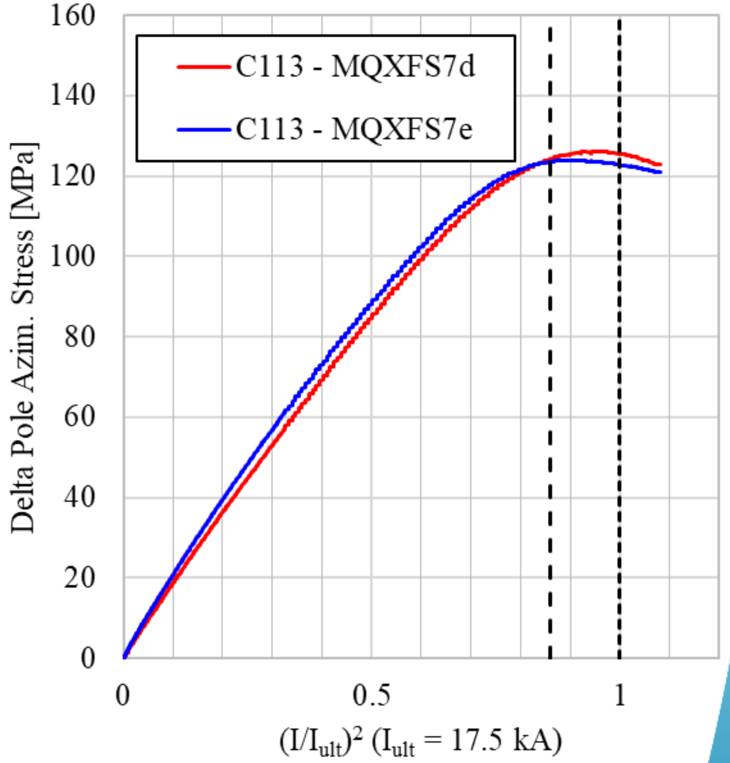
MQXFS7e

- 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

Outline

- Introduction to magnet design and target pre-load
- Pre-load levels explored with MQXFS magnets
- Exploring higher pre-load
- **Conclusions**

Conclusions

- MQXF short model magnets show that a we have a wide preload window to reach performance requirement, 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
- Target pre-load was defined taking MQXFS4 as reference, where we also demonstrated the long-term behaviour: no degradation after 11 thermal cycles and 1000 current cycles
- The low preload window was explored with MQXFS6b/c/d:
  - Apparent plateau above ultimate in MQXFS6c may indicate that larger preload is beneficial to reach 90% of short sample
  - Effect of thermal and current cycling never explored in the low preload regime
- MQXFS7 and MQXFS4 will be used to explore the high pre-load region:
  - Thanks to the implementation of the new pre-load procedure, the peak stress in the coils is not during bladder operations but after key insertion
  - The pole key is removed in the high preload experiments to avoid any potential force interception when going to high preload
  - So far, two pre-load levels have been tested at cold (100 MPa and 120 MPa). MQXFS7f, with 15 MPa higher stress will be tested in September.
  - We plan to proceed in 0.1 mm shim step, which correspond to 15 MPa increase of coil stress, up to the degradation limit.
  - After competition of MQXFS7 experiment we will proceed with MQXFS4

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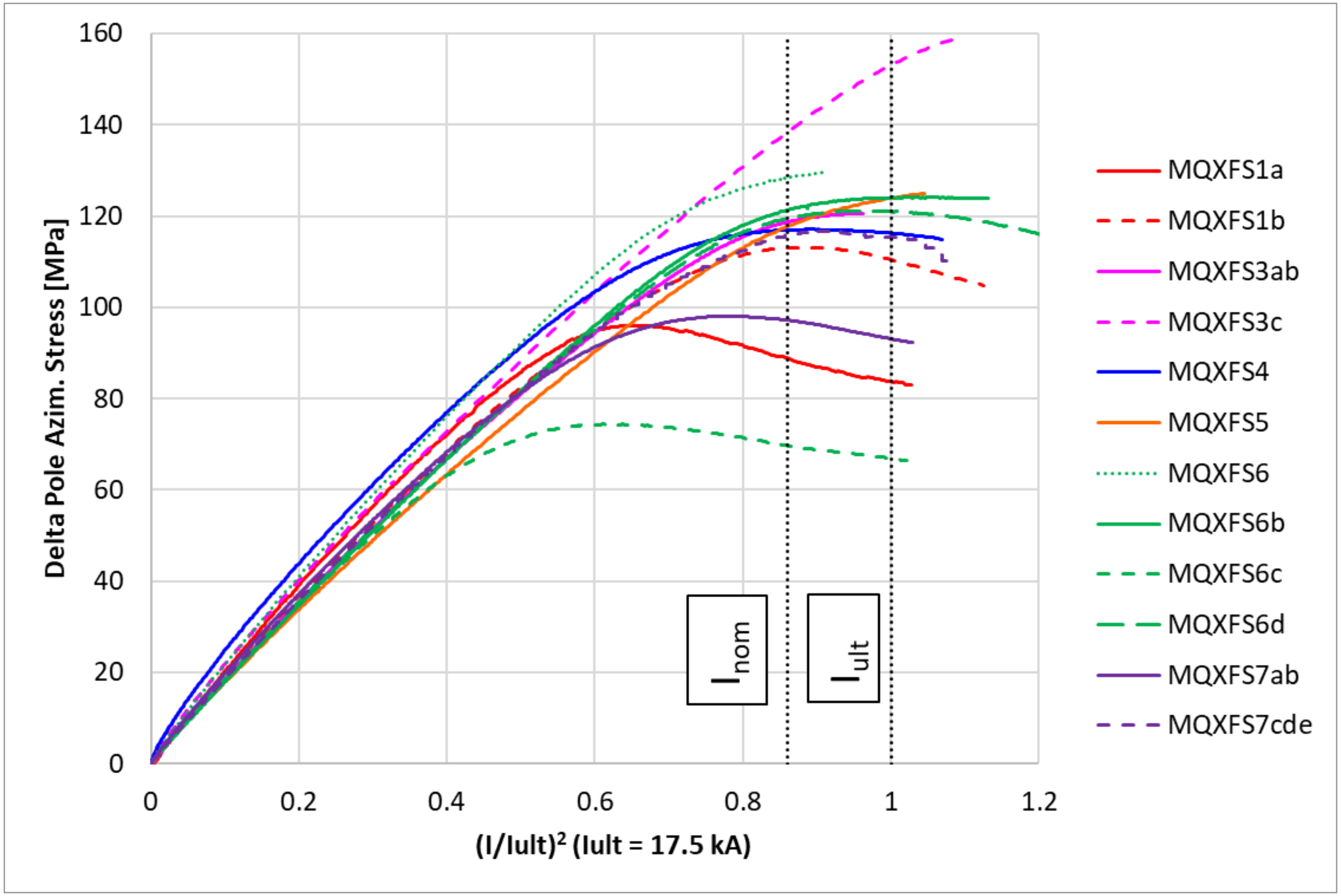
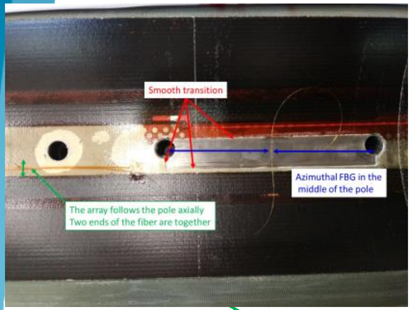
Delta pole stress during powering

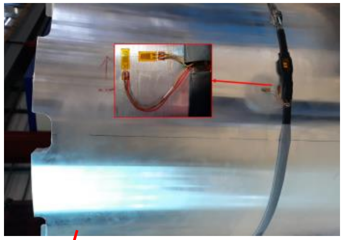


Mechanical instrumentation

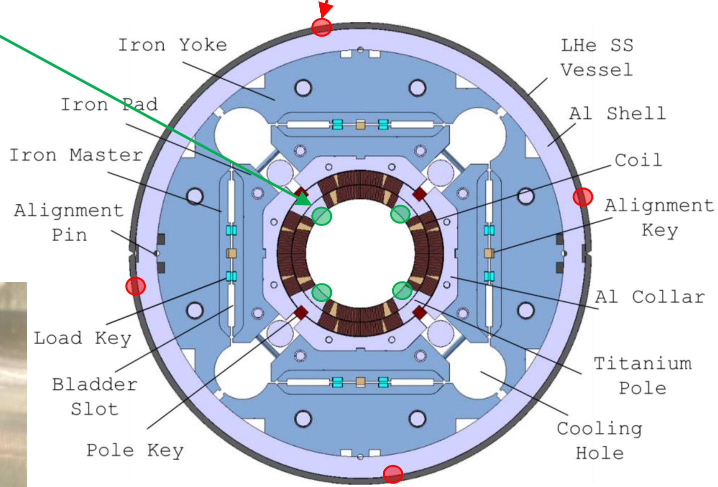
Coils instrumented with strain gauges and of FBGs



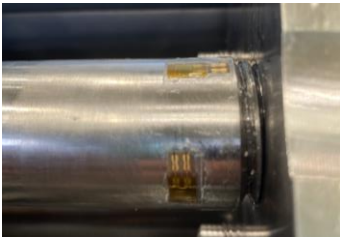
Al-shells instrumented with strain gauges

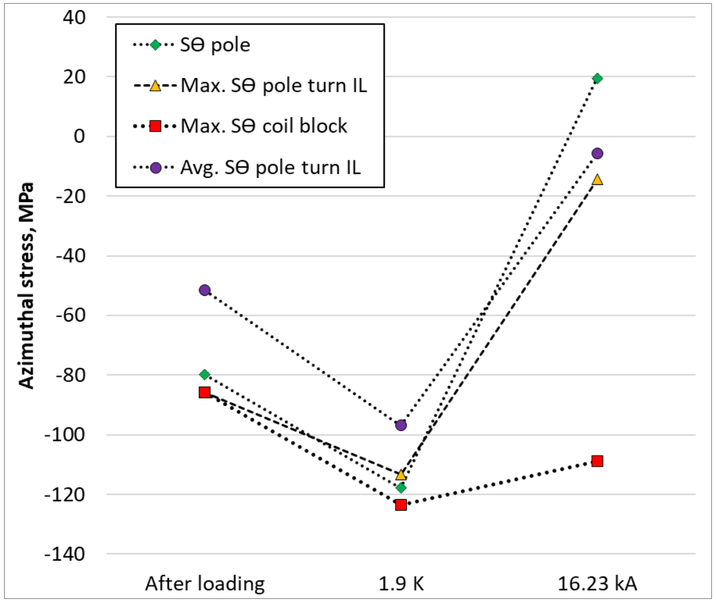


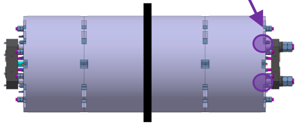
The strain is measured in the coil titanium pole. The peak stress in the coil during loading and cool down is in the IL pole turn, very close to the stress in the Ti pole (measuring location)



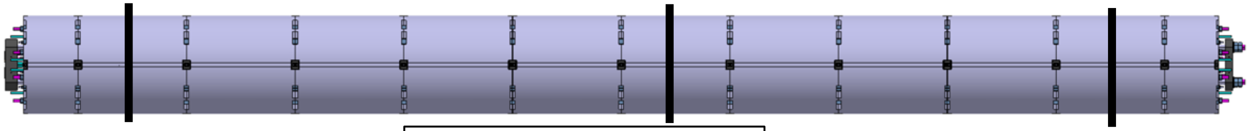
Rods instrumented with strain gauges







MQXFS, one longitudinal measuring location



MQXFB, three longitudinal measuring locations

FE Model

Aluminum

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

Iron

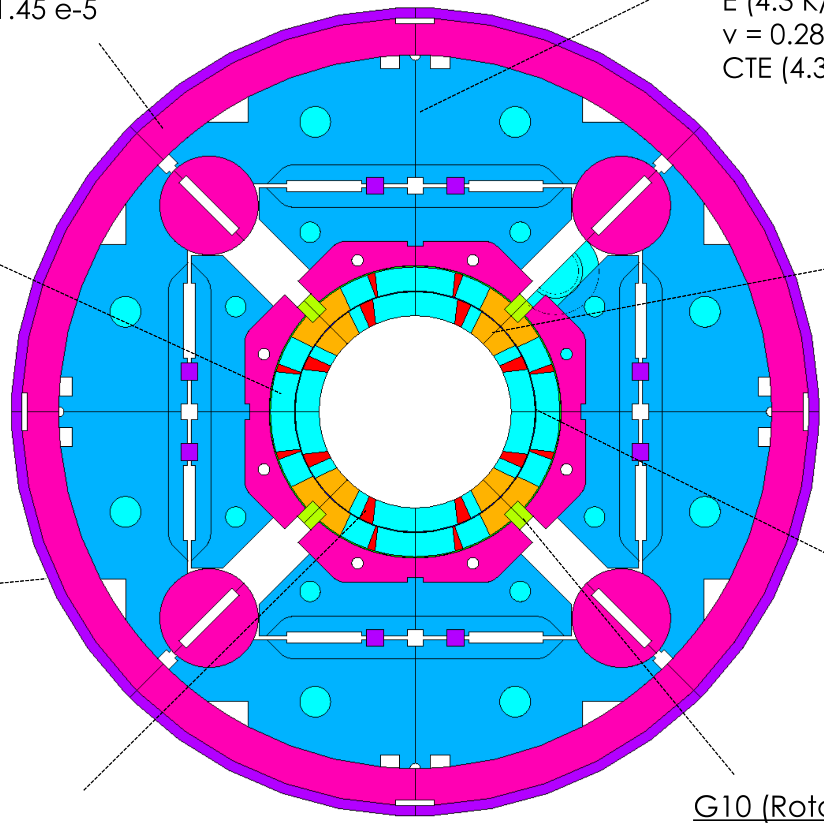
E (4.3 K/ 293 K) = 224 / 213 [GPA]
v = 0.28
CTE (4.3 K – 293 K) = 6.82 e-6

Coil equivalent

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

Titanium

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



Stainless steel

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

G10

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

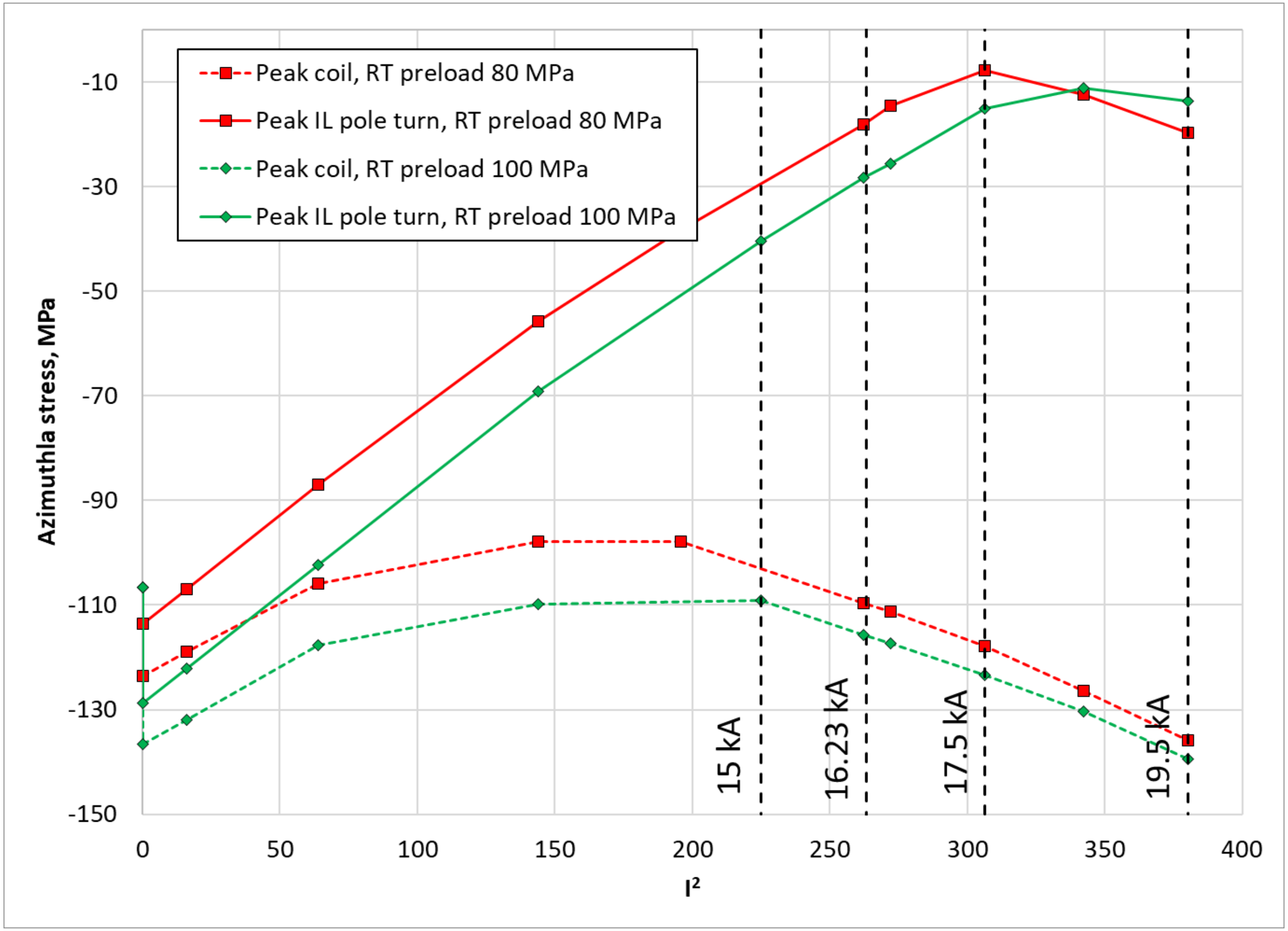
Aluminum bronze

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

G10 (Rotated)

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