MQXFA magnet assembly and preload

P. Ferracin

on behalf of the MQXF collaboration

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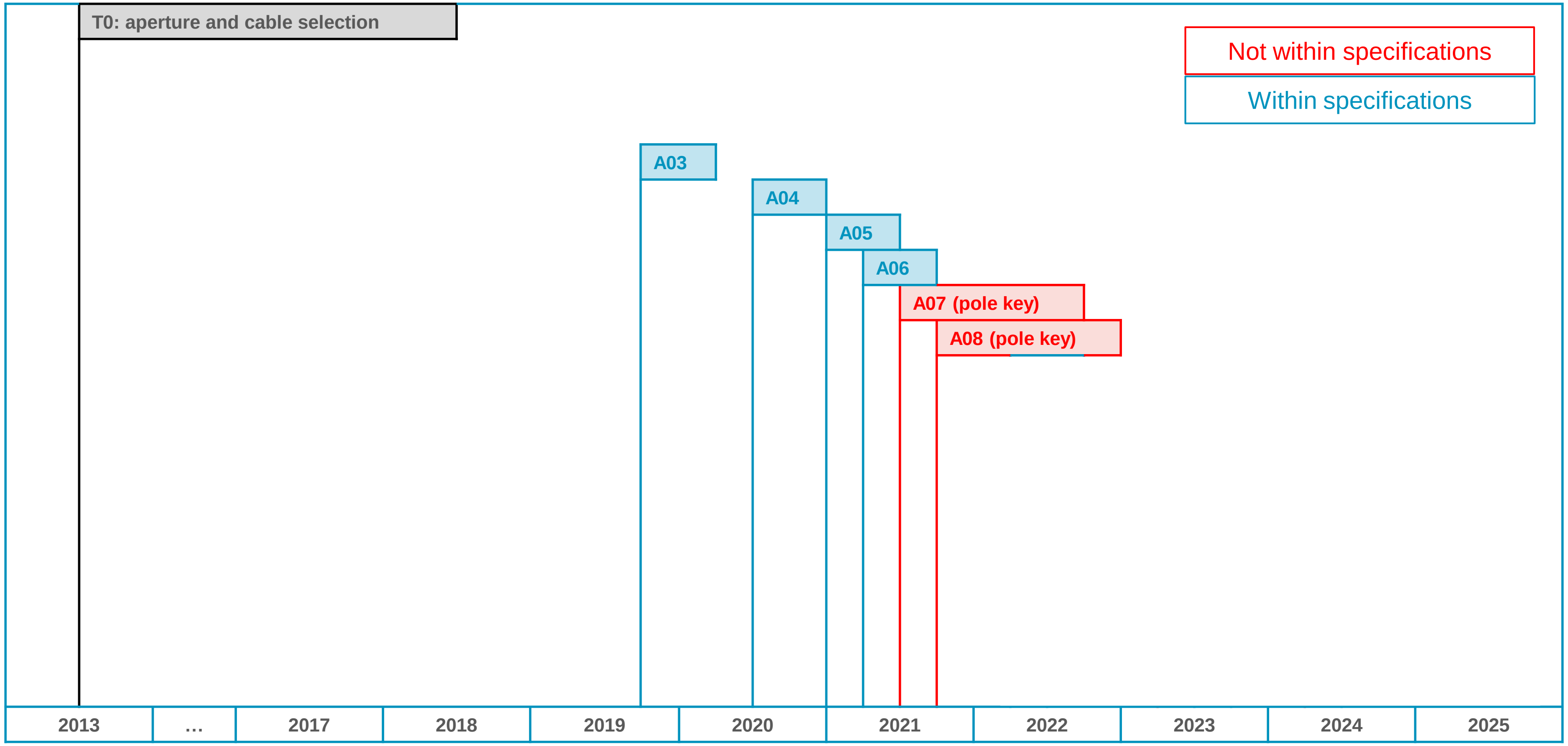
Outline

- Quick recall of “pole key issue” in A07-A08
  - Longitudinal vs lateral pre-load
- The A13-A17 case
- Update of assembly - loading specs
- Conclusions

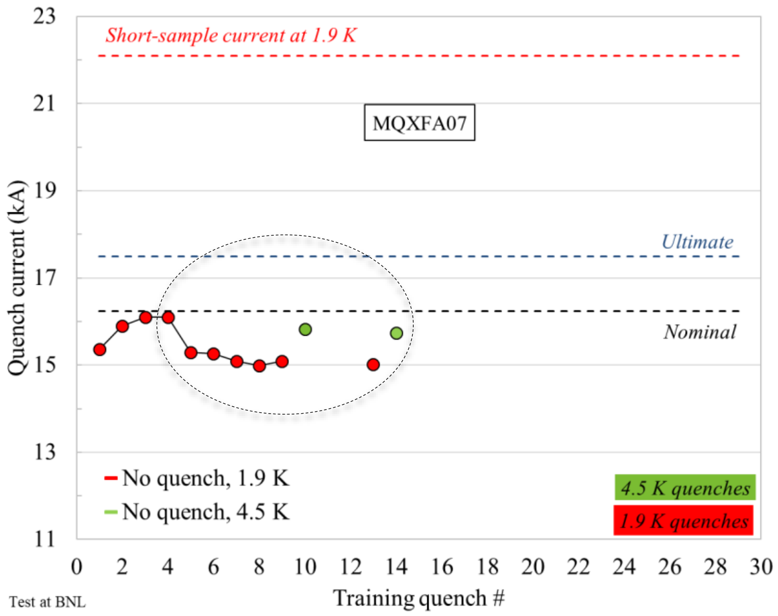
MQXFA series magnet timeline and test status

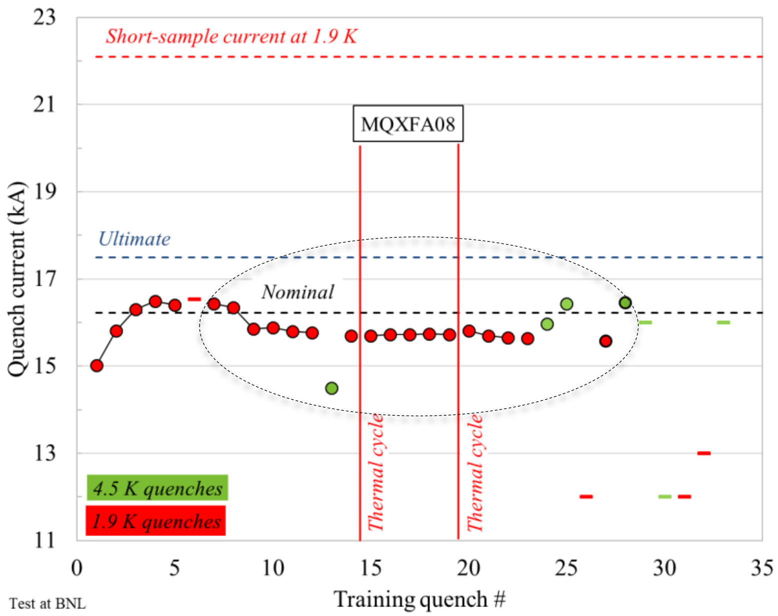
- After 4 series magnets in spec (A03-A06), two consecutive magnets (A07, A08) did not meet requirements



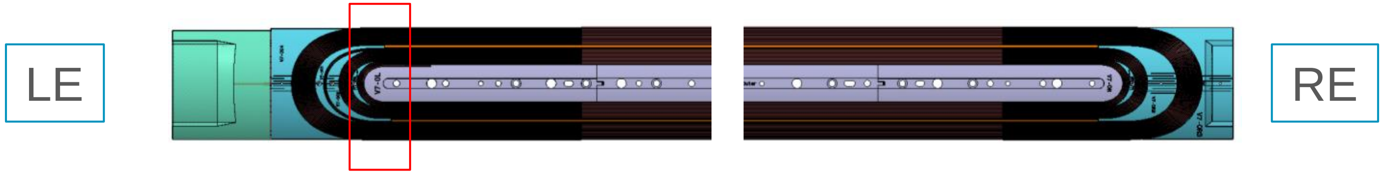
A07 and A08 test results

- Both magnets with detraining after few quenches



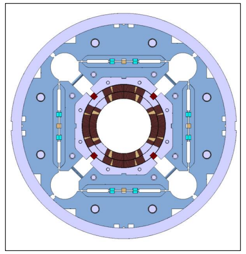


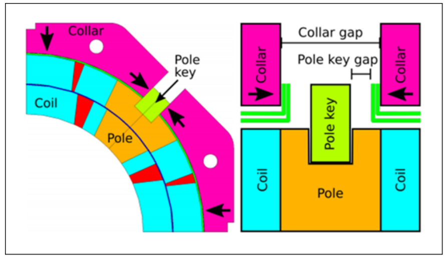
- Both magnets limited by one coil in same segment a3-a4
  - Based on quench antenna signals: LE, where pole block turns go around the pole tip

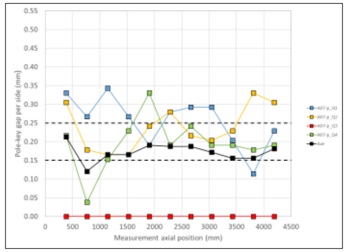


A07 and A08 investigation / analysis

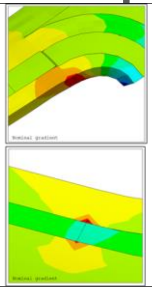
- Assembly data inspection: pole key locked in limiting quadrant

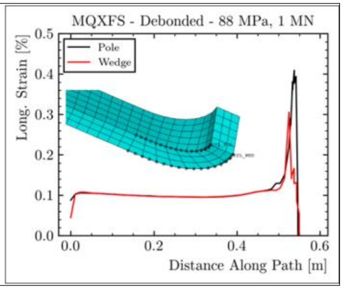




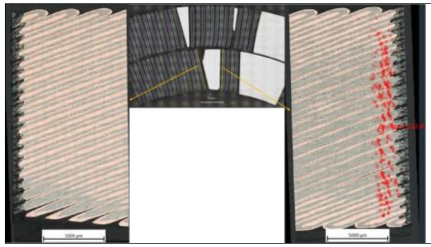


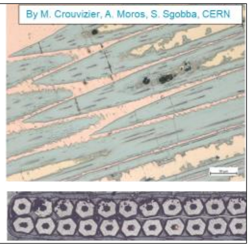
- FE analysis: lack of azimuthal pre-stress → high strain in the LE





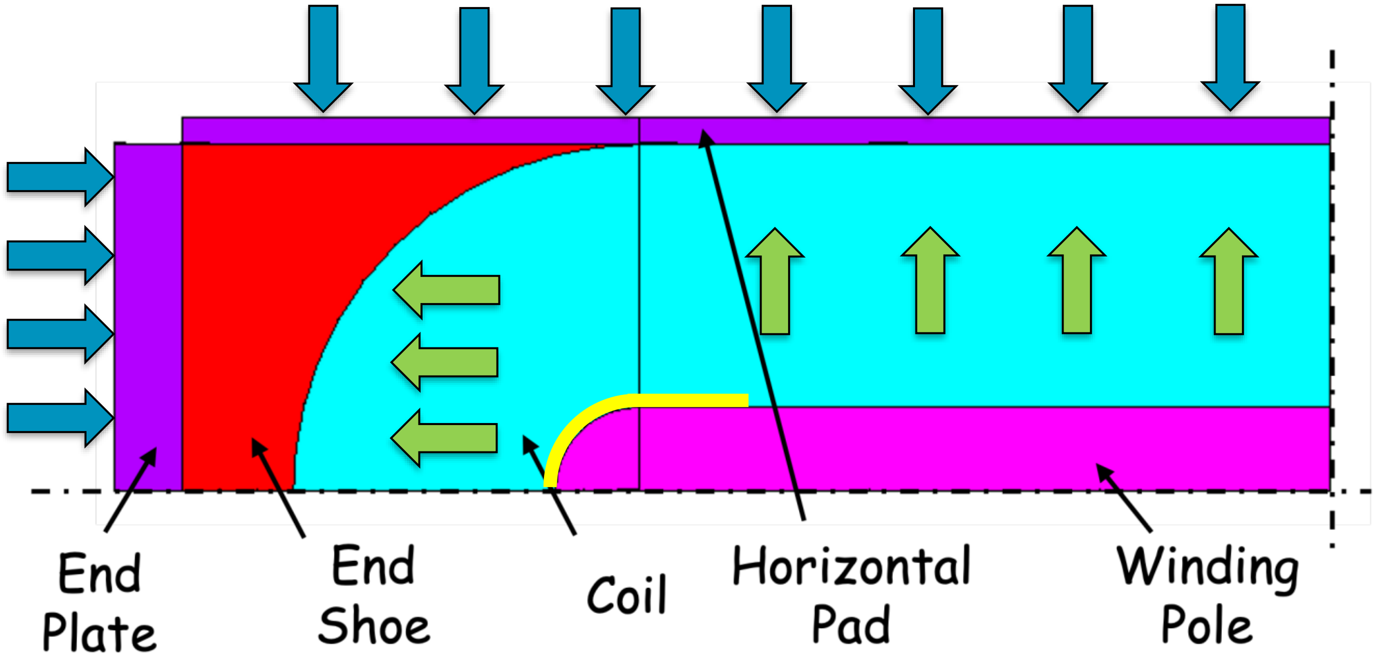
- Metallurgical inspection: cracks close to wedge – end-spacer





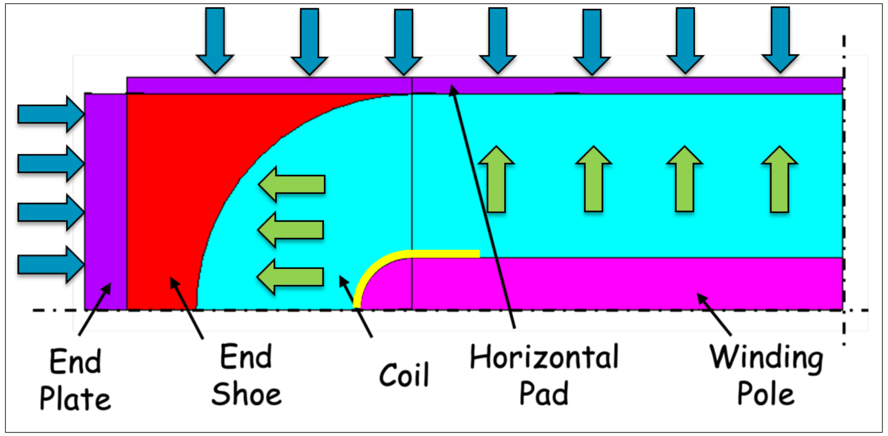
Longitudinal vs "lateral" pre-load

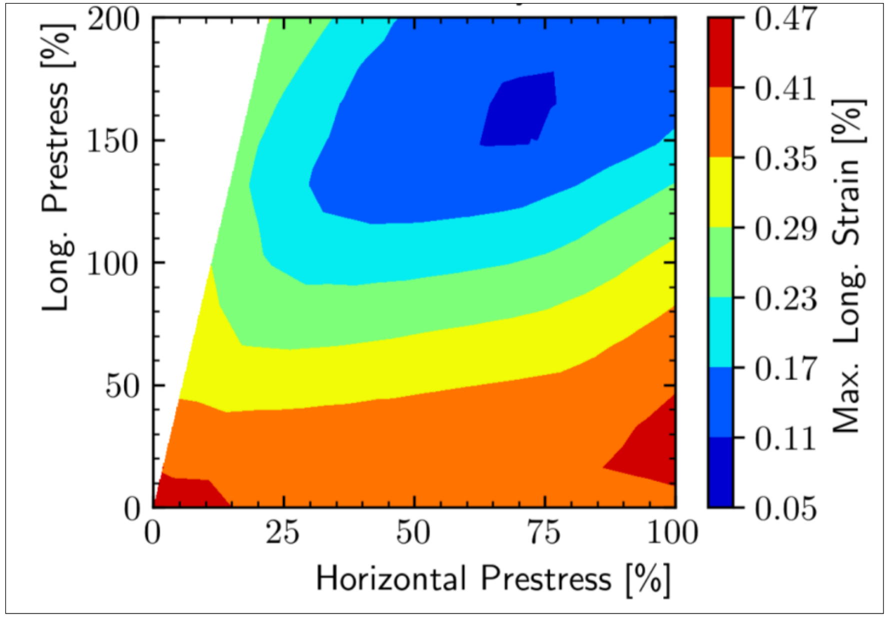
- Simplified model:
  - Racetrack coil with e.m. axial + lateral forces + axial + lateral pre-load
  - Output: pole turn axial strain



Longitudinal vs "lateral" pre-load

- Low (blue area) axial strain with high pre-load both azimuthally and axially
- Axial pre-load cannot minimize the axial strain without the "help" of azimuthal pre-load
- …and vice versa





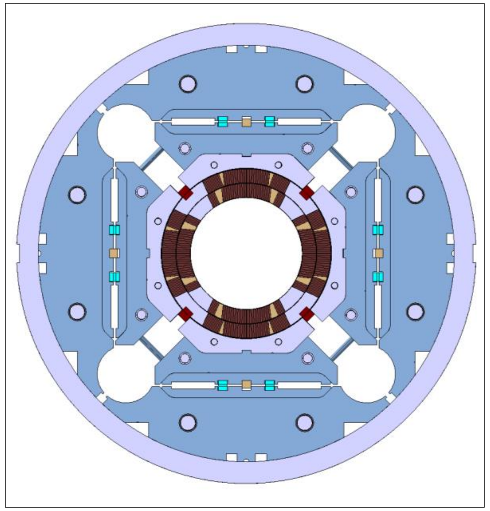
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY 1

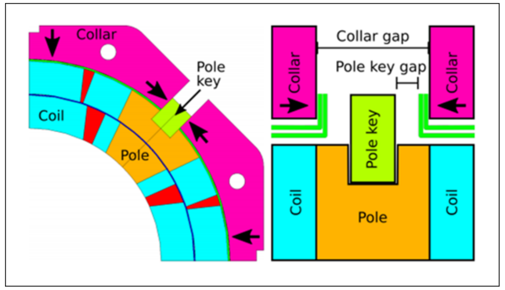
The Role of Azimuthal Prestress in Longitudinal Degradation of Nb_3Sn Superconducting Magnets

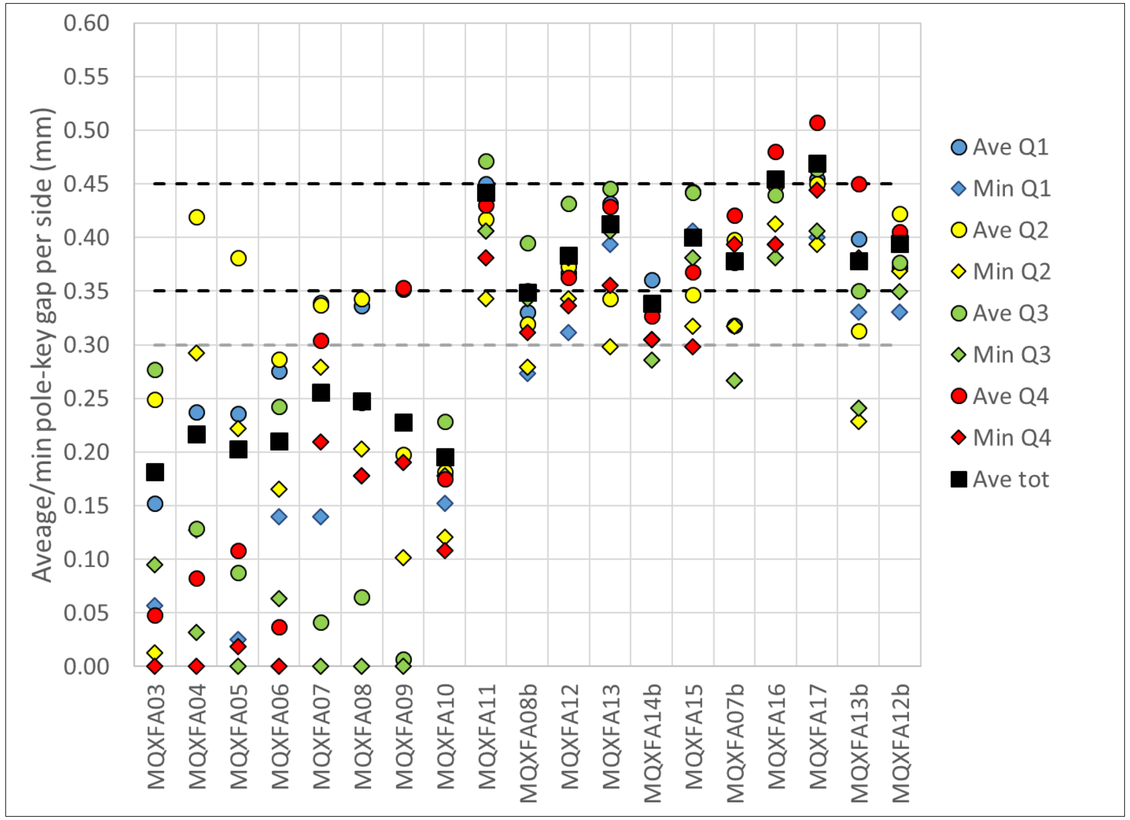
G. Vallone, G. Ambrosio, E. Anderssen, P. Ferracin

Corrective strategy post A07 and A08

- New pole key gap spec defined → larger gap

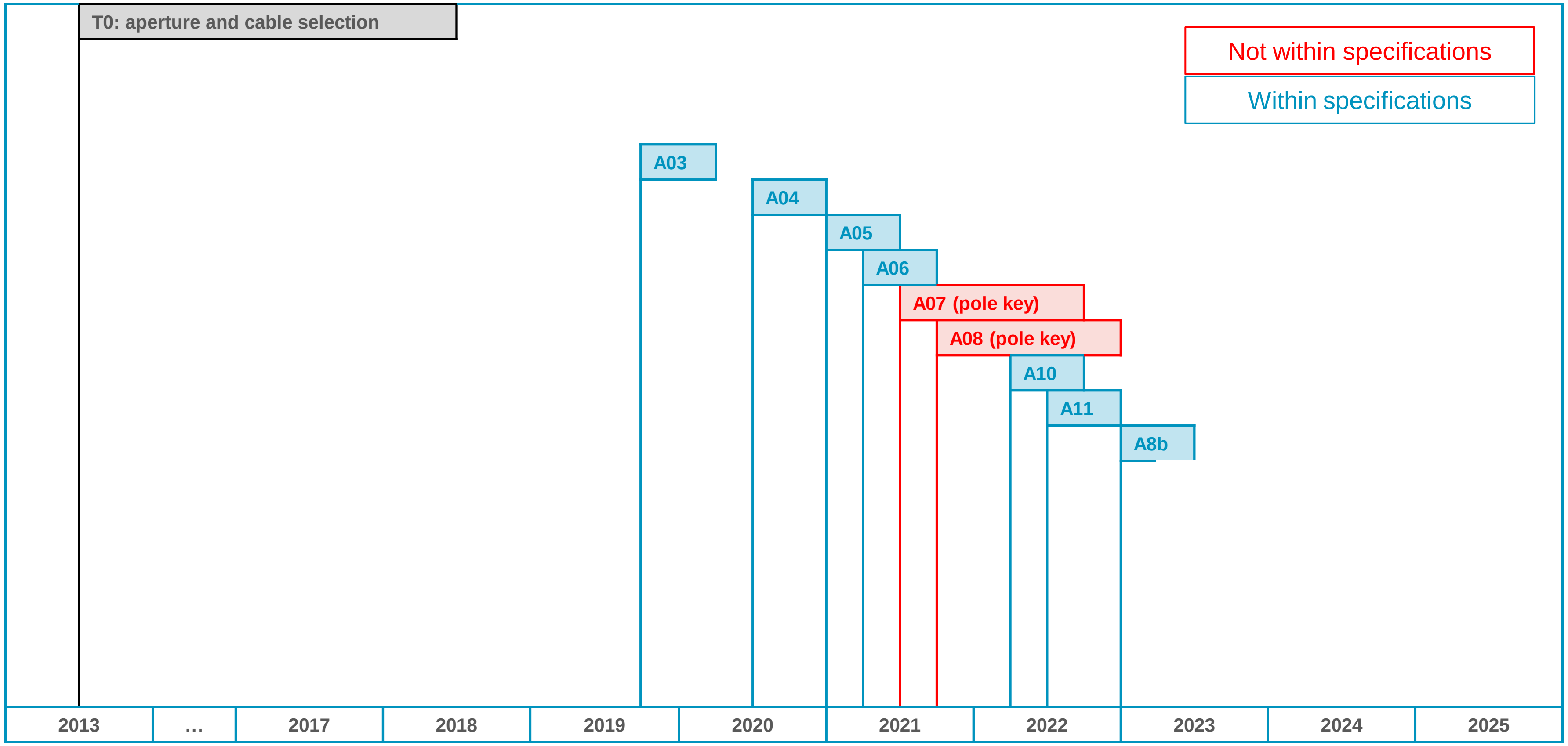






MQXFA series magnet timeline and test status

- After A07, A08, three magnet within specs

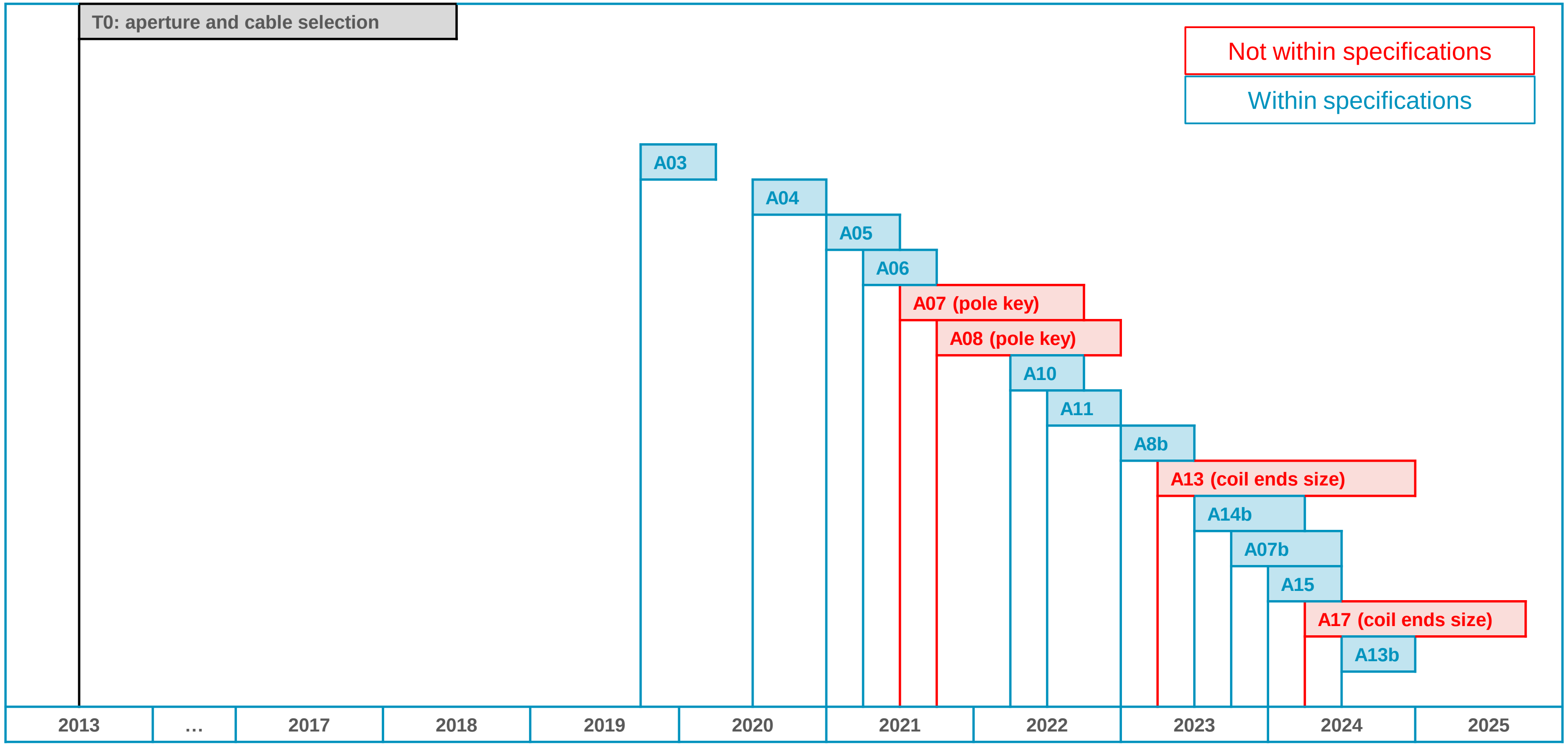


Outline

- Quick recall of “pole key issue” in A07-A08
  - Longitudinal vs lateral pre-load
- The A13-A17 case
- Update of assembly - loading specs
- Conclusion

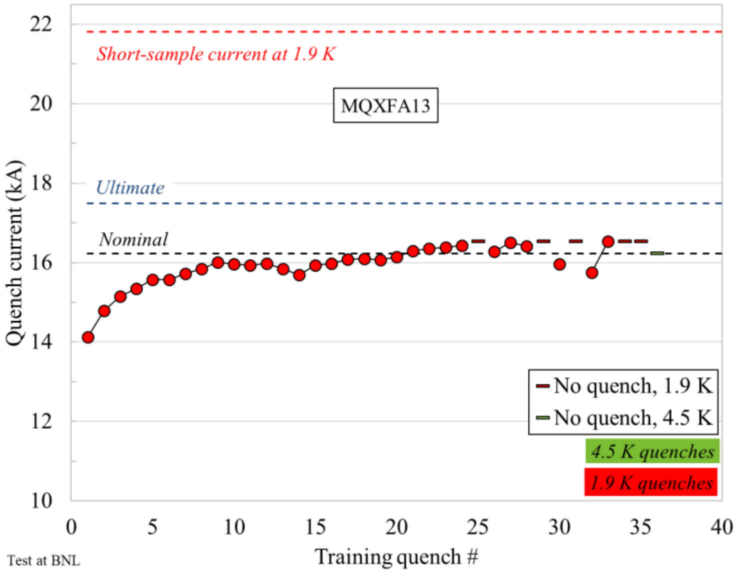
MQXFA series magnet timeline and test status

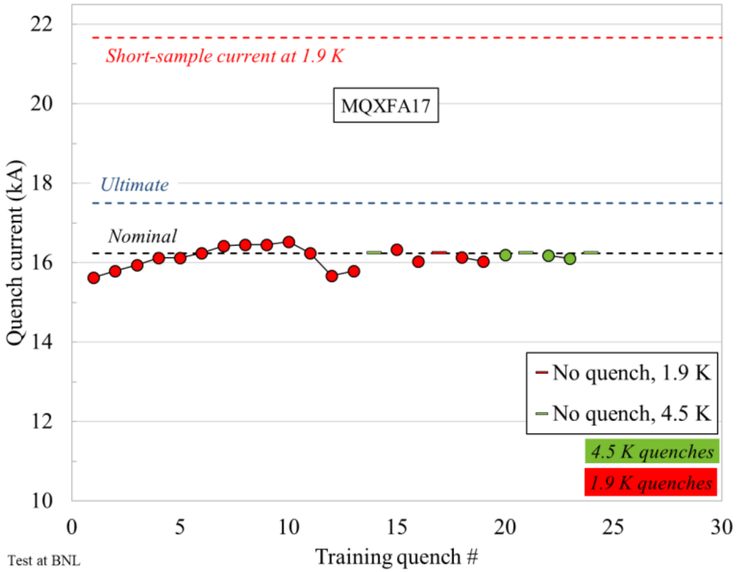
- Two additional magnets, A13 and A17, did not meet specs



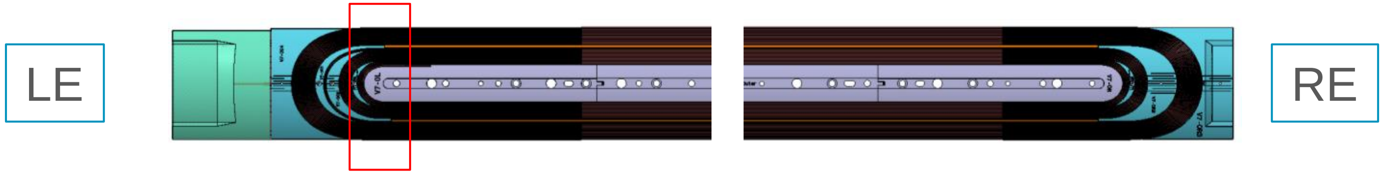
A13 and A17 test results

- Both magnets with detraining
  - Although, not as much as in A07-A08



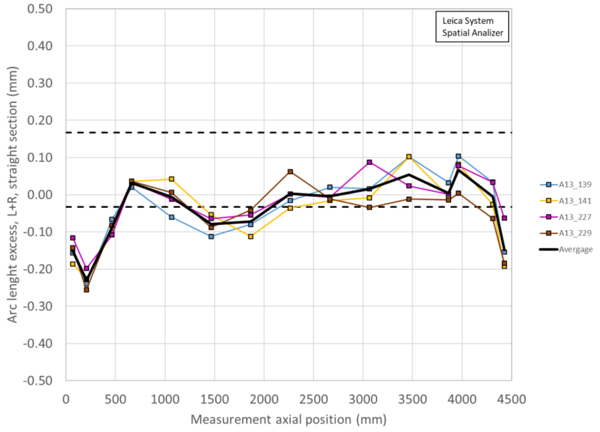


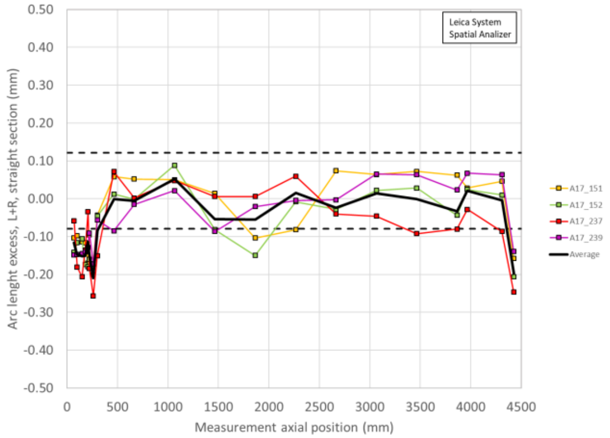
- Both magnets limited by the LE in the usual longitudinal location
  - Cracks observed in coil 227 (A13), although not as many as in A07-A08



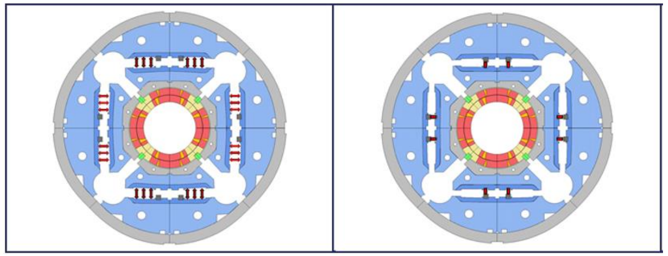
A13 and A17 investigation / analysis

- Focus of the investigation: smaller coil size in the ends
  - Observed in most of the coils



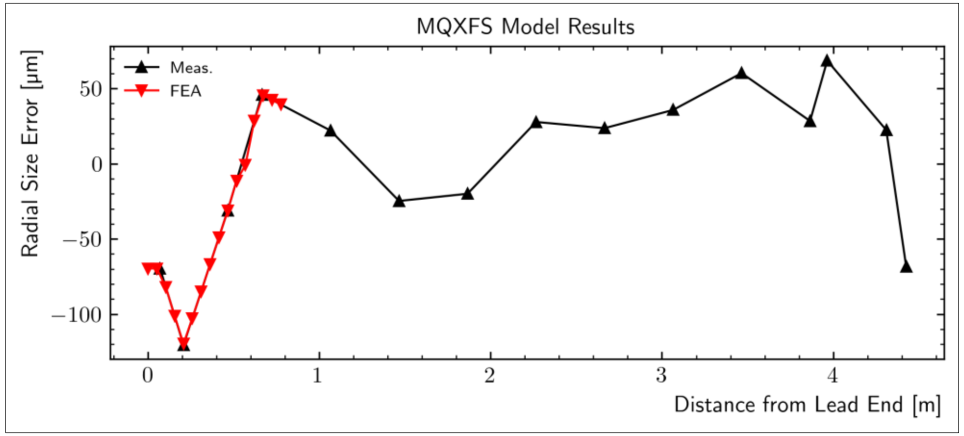


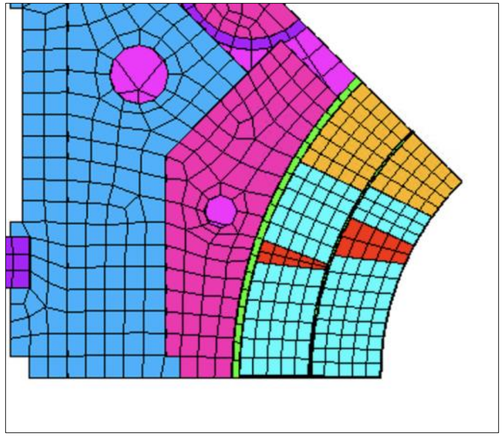
- Azimuthal pre-load depends on loading key size + coil size → low azimuthal pre-load in the ends → low end support

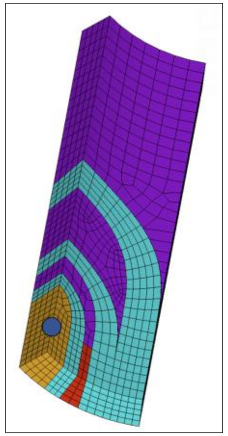


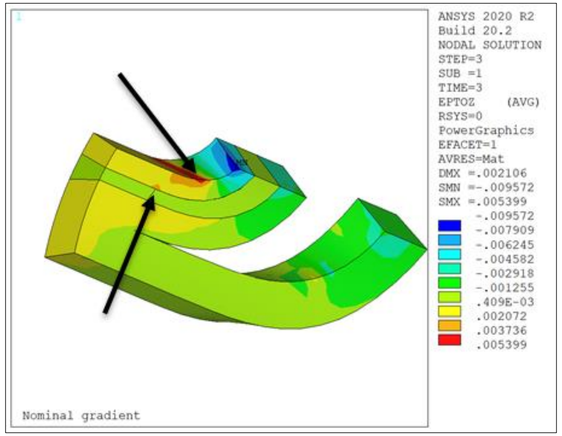
A13 and A17 investigation / analysis

- FE analysis of the A13 case: real coil size implemented

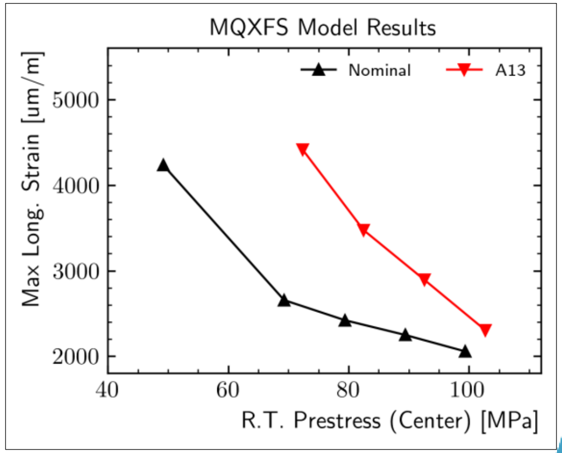






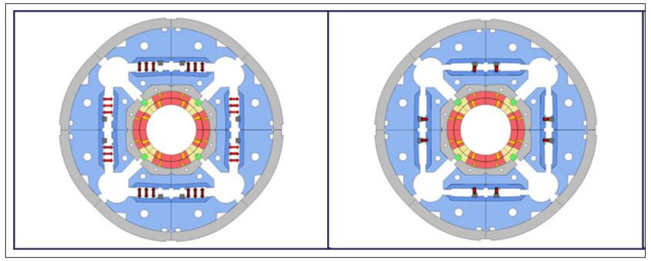


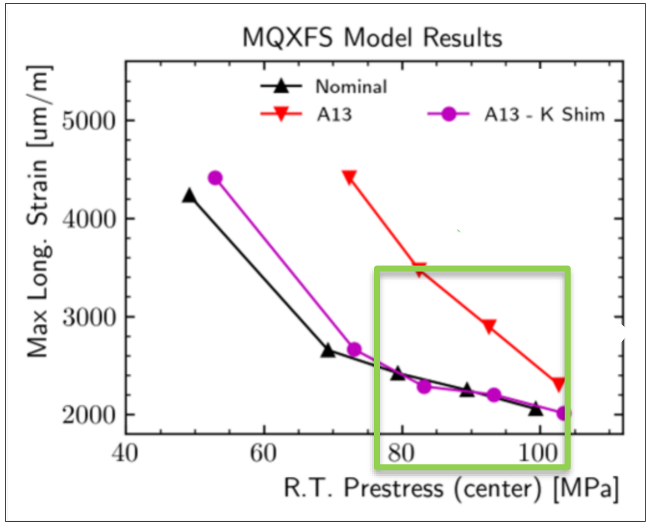
- For the same pre-stress in the straight section
  - A smaller coil in the ends causes high strain in the end
- Possible solutions
  - 1) Increase the pre-stress everywhere (“brute force”)
  - 2) Increase the pre-stress only where is needed (LE)
  - 3) **all of the above**

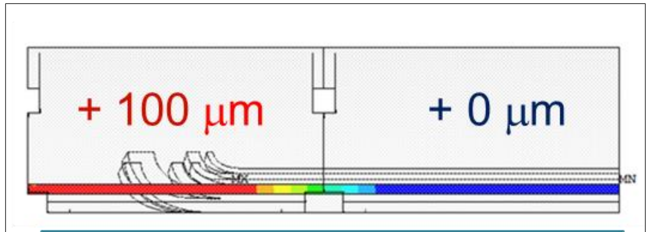


Corrective strategy post A13 and A17

- Target an higher overall pre-load
  - Same loading key size as best performing magnets (A14b and A05)
    - Loading key of 13.80-13.85 mm
- Insertion of tapered load shim (TLS)
  - 100 mm tapered after the critical zone







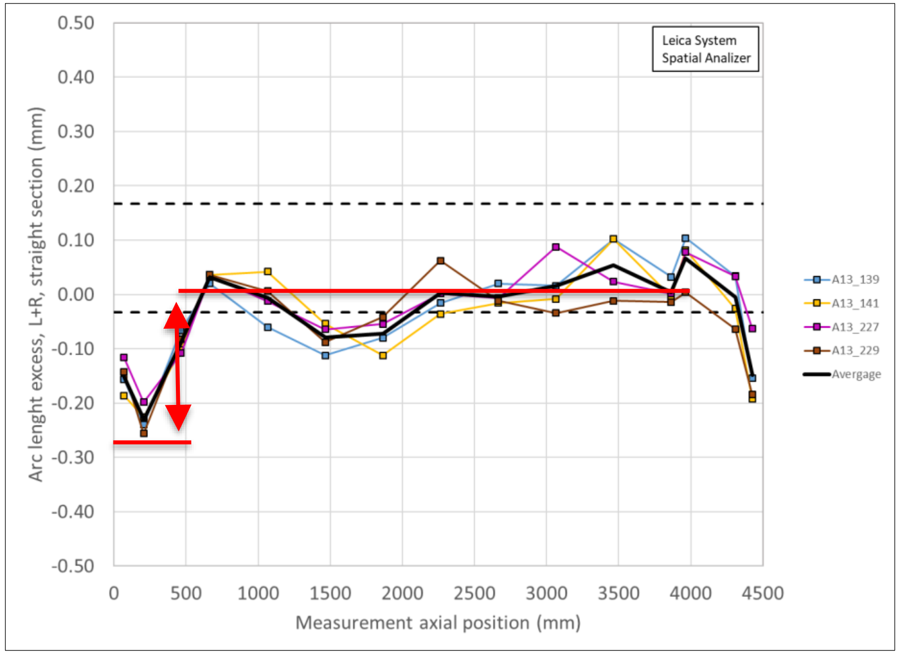
Tapered load shims in Lead End

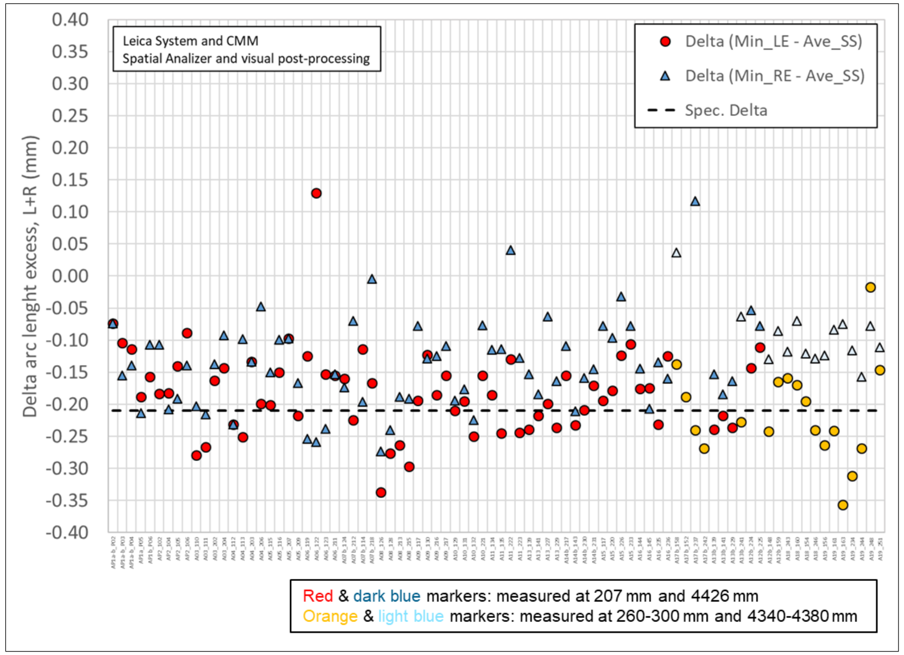
Outline

- Quick recall of “pole key issue” in A07-A08
  - Longitudinal vs lateral pre-load
- The A13-A17 case
- Update of assembly - loading specs
- Conclusion

1: Coil selection

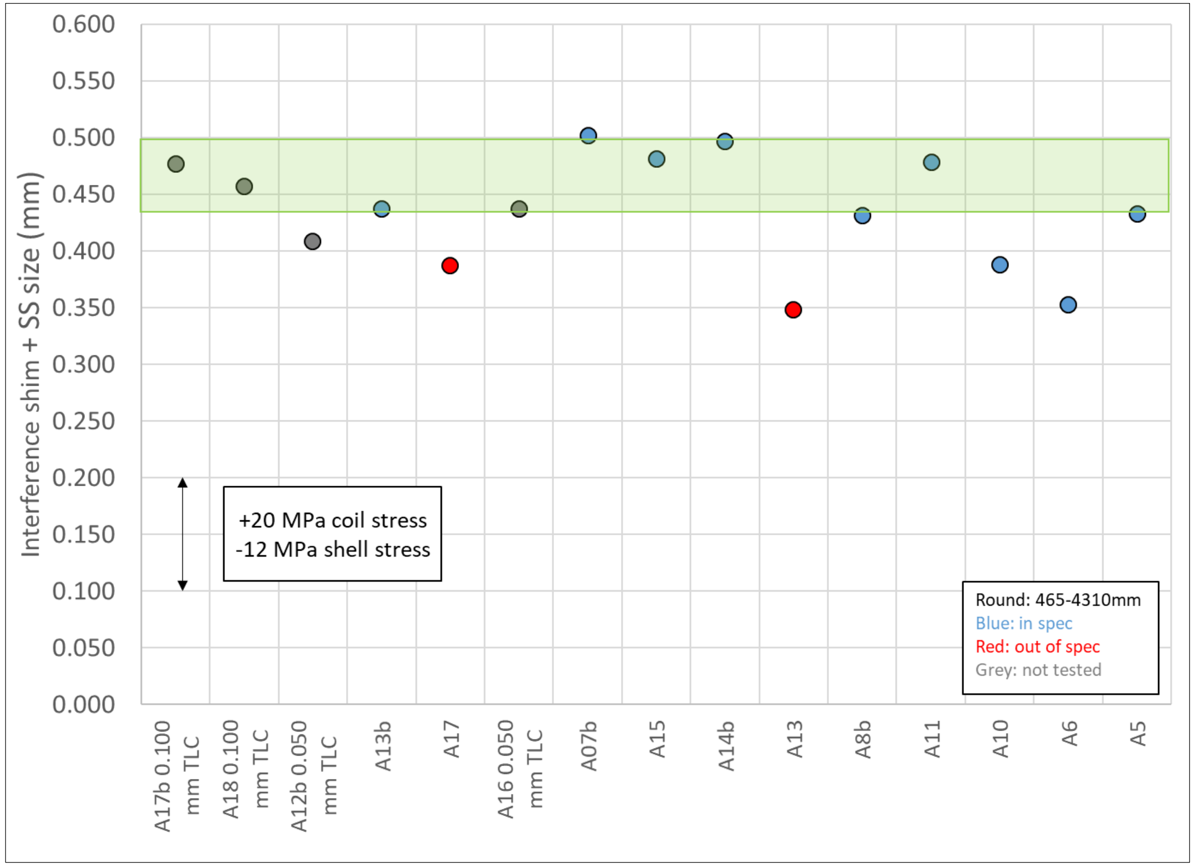
- We measure and monitor coil size in the ends, in particular
  - Δ (arc-length$_{\text{straight section}}$ - arc-length$_{\text{LE}}$)
- We try to select coils without excessive Δ
  - We will do FE analysis for using these coils with larger TLS





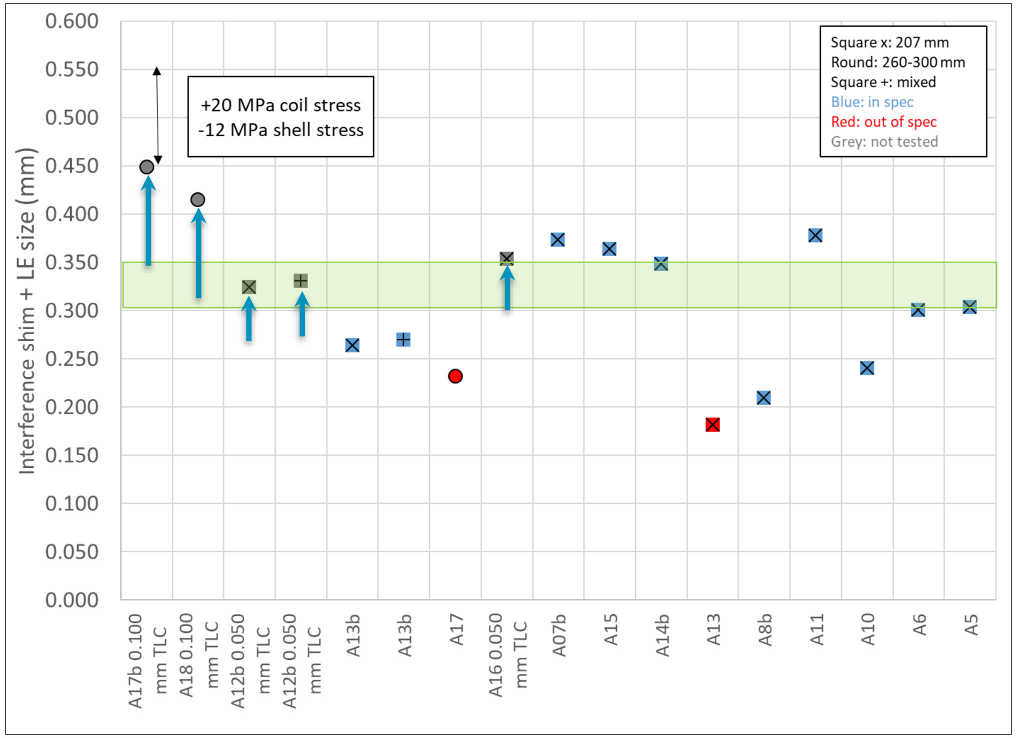
2: Overall pre-load

- We increased the target coil pre-load (measured with strain gauges)
  - from 80±8 MPa → 90±10 MPa
- At the same time we target a loading shim size similar to A05 and A14b
  - 18.0-18.5 mm load key thickness
- So pre-load not only based on strain gauges but also on loading key and coil sizes



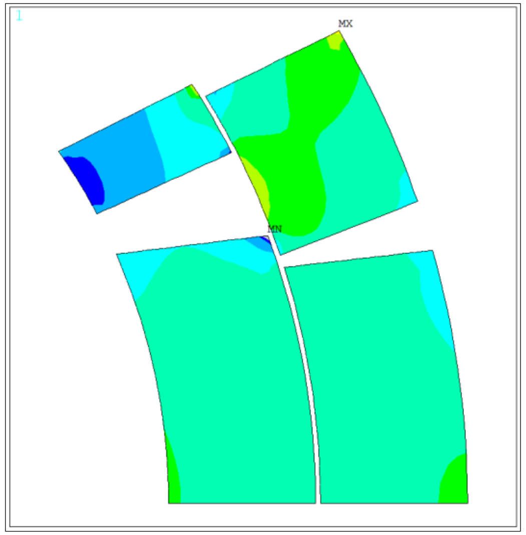
3: Pre-load of the LE

- If average Δ(arc-length$_{straight\ section}$ - arc-length$_{LE}$) is more than 0.150 mm (basically always)
  - Insertion of 0.100 mm thick Tapered Load Shims (TLS) in the LE
  - After checking with FE and real coil geometry that stress of coil and structure are within limits (see next slide)

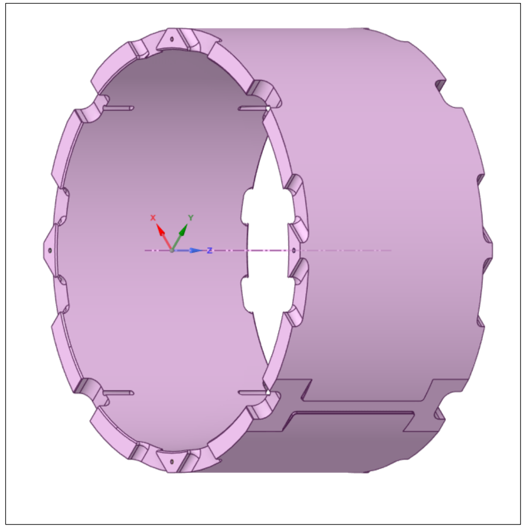


4: Stress limits

- Measured stress limit in coil
  - from ≤110 MPa → ≤ 120 MPa → ≤ 135 MPa
    - Following the results from short model MQXFS07



- Measured stress limit in shell 1 (TLS location): <80 MPa



Outline

- Quick recall of “pole key issue” in A07-A08
  - Longitudinal vs lateral pre-load
- The A13-A17 case
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- Conclusions

Conclusions

- So far 11 magnet met performance spec. and 4 magnets (A07-A08 and A13-A17) showed performance limitation
- Investigation of possible design/fabrication/assembly weaknesses on going
- Assembly-loading focus: uniform and sufficient azimuthal pre-load of the coil, including the ends
  - Essential, together with the axial pre-load, to minimize strain in the ends
- Two main issues identified: pole-key gap size, and coil size in the ends
- Corrective strategies
  - Increase of pole-key gap size
  - Increase of overall pre-load levels, and use of additional tapered shims to compensate for coil size variations
- Implemented in A18, A12b, and A16
  - Test results coming soon…..

Appendix

Longitudinal vs "lateral" pre-load

- Impact (importance) of azimuthal pre-load on axial elongation of the coil
  - Extensively studied in 3D with FE models

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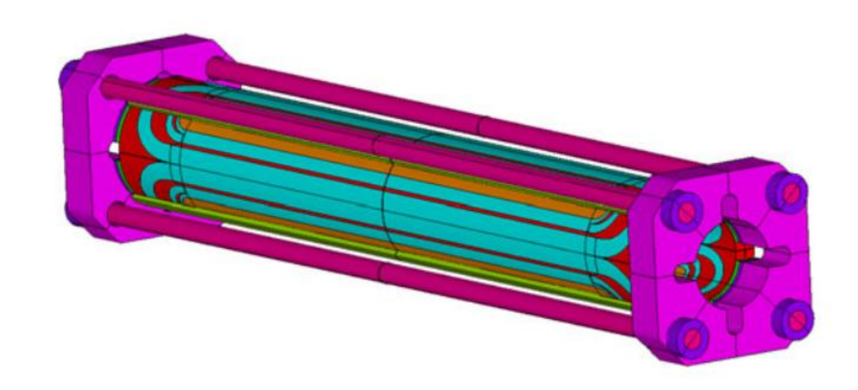
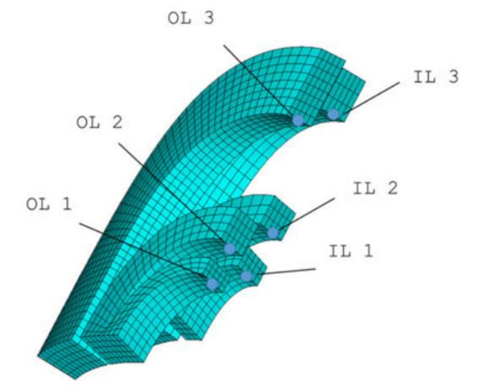
Mechanical Design Analysis of MQXFB, the 7.2-m-Long Low-β Quadrupole for the High-Luminosity LHC Upgrade

Giorgio Vallone, Giorgio Ambrosio, Nicolas Bourcey, E. Anderssen, Daniel W. Cheng, Paolo Ferracin, Philippe Grosclaude, Michael Guinchard, Susana Izquierdo Bermudez, Mariusz Juchno, Friedrich Lackner, Heng Pan, Juan Carlos Perez, and Soren Prestemon

TABLE I
MAIN PARAMETERS GOVERNING THE LONGITUDINAL MOTIONS

Parameter	Unit	MQXFS	MQXFB
Coil Elongation:			
No friction, no rods	mm	1.09	7.04
No friction, Al. rods	mm	0.91	5.63
No friction, SS. rods	mm	0.73	4.22
Friction, Al. rods	mm	0.10	0.28
Friction, SS. rods	mm	0.06	0.28





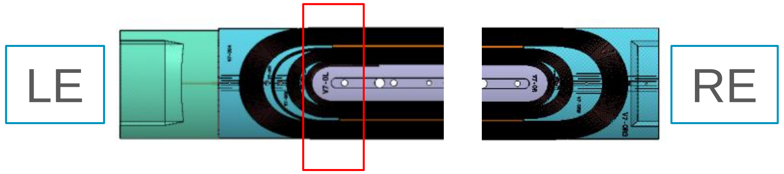
MQXFA “disease”: coil issue vs. pre-load issue

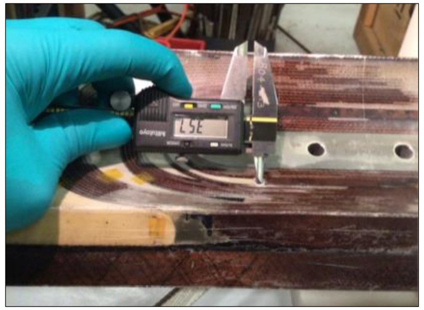
- All the out-of-spec magnets limited by lead ends of 200 series coils
- Investigation of possible “weaknesses”

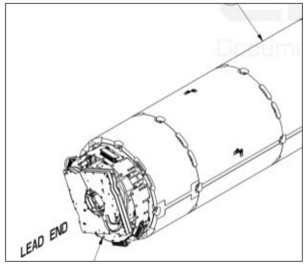
- Design
  - Large gaps wedge to end spacer
    - to accommodate Al-Br wedge expansion during HT
      - Unlike Ti pole wedge, they remain open, and filled with fiber glass
  - End shoe extension → less effective axial loading
  - Different end-spacers geometry in LE vs RE
  - Al shell segmentation aligned with wedge to end spacer transition → lower pre-load

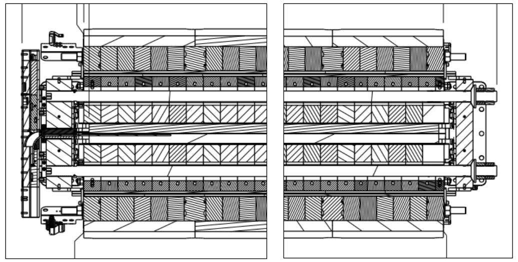
- Coil fabrication
  - Differences/variation in wedge to end-spacer bonding strength (under investigation)
    - Different impregnation process: vertical vs. tilted
  - Difference in wedge to end-spacer gaps (under investigation)
  - Coil size in the ends (*being addressed with tapered shim*)

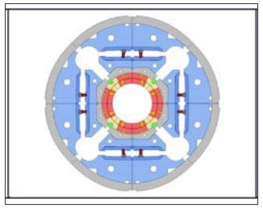
- Assembly
  - Pole keys (*addressed with new spec*)

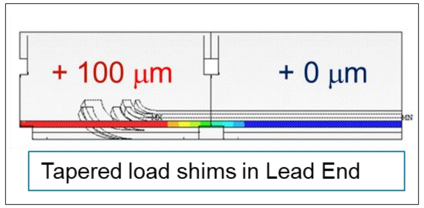


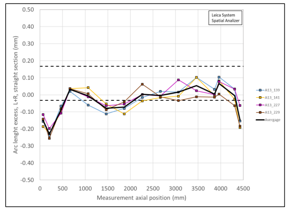






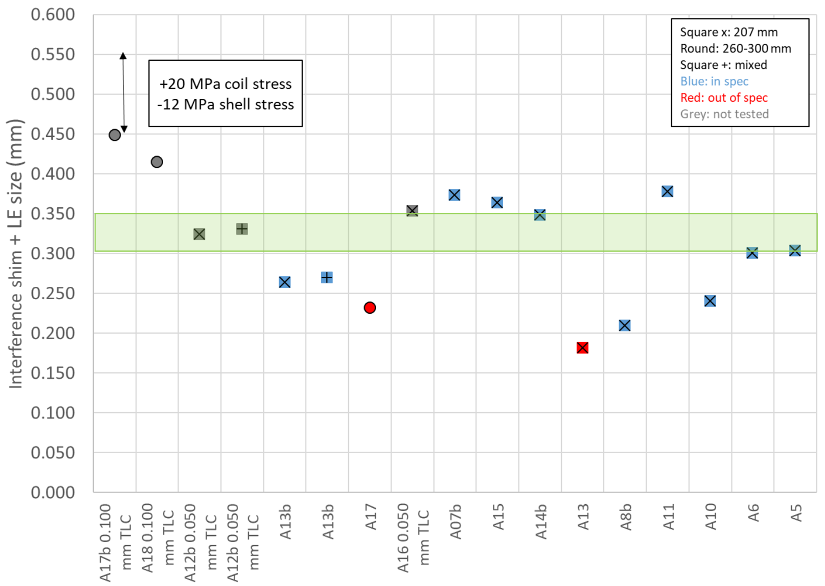






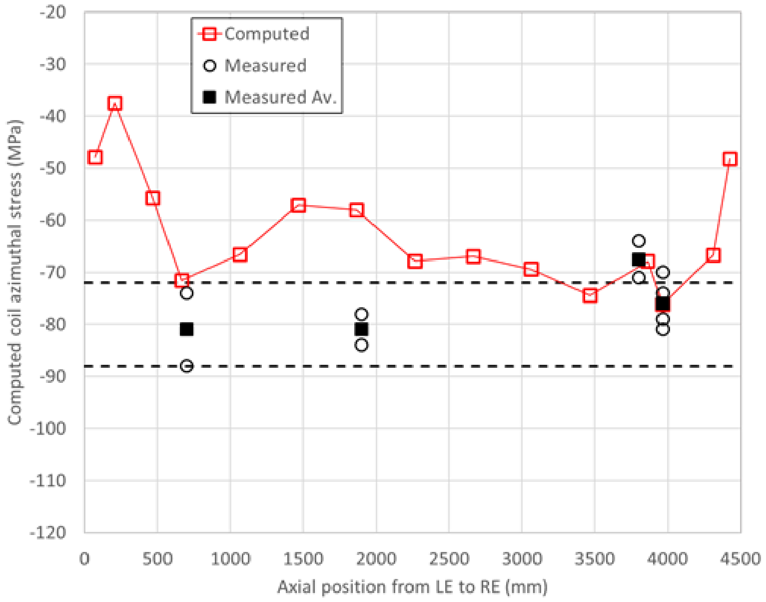
Corrective strategy post MQXFA13 and A17

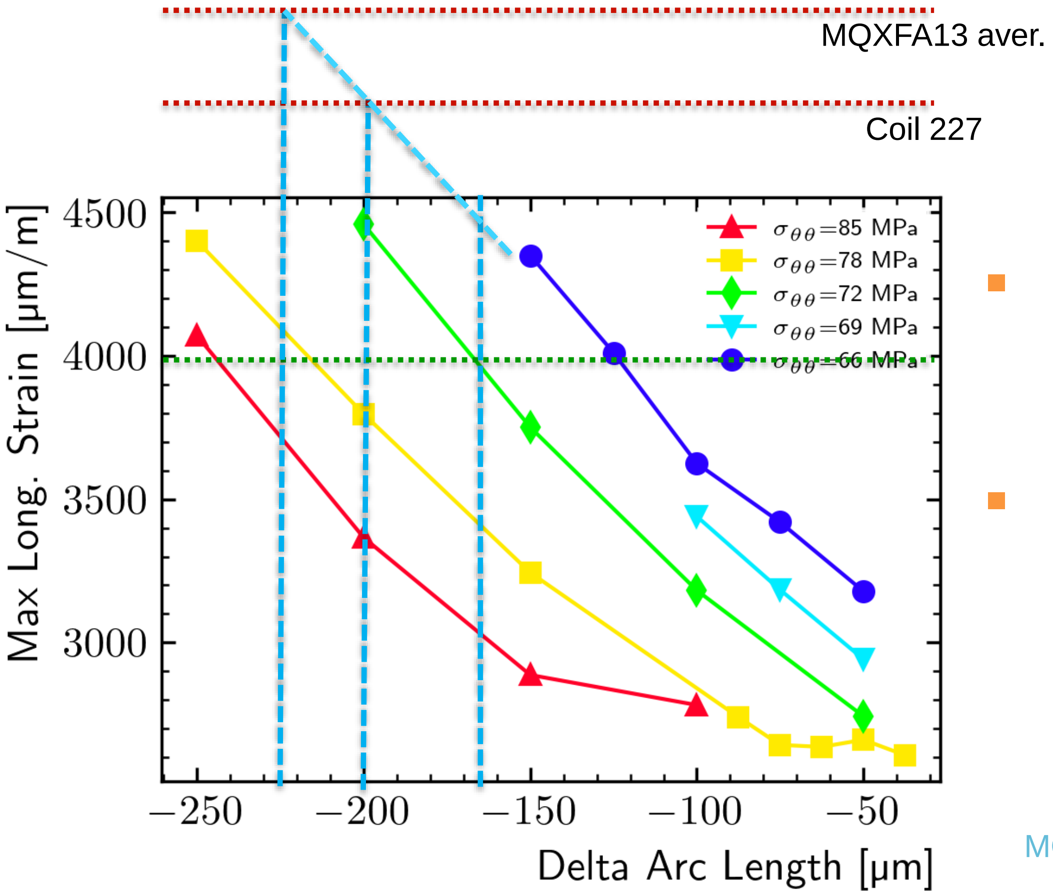
- Important caveat
  - The “green zone” of loading shim + TLS is based on magnet which had an excellent training performance
  - Not all the magnets below the green zone where out of spec → only A17, A13
  - So, not a clear correlation but rather setting a minimum pre-load level below which we face a “risky” zone



Critical / Safe Strain (for this kind of simulations)

- Assuming MQXFA13 had **67 MPa** average preload at RT in the straight section
  - Based on coil CMM, 4 SGs, 3 FBGs
  - Consistent with small key size: 13.72 mm





- MQXFA13 failure strain (for this kind of simulations) was:

  ~ 4800-5100 microstrain

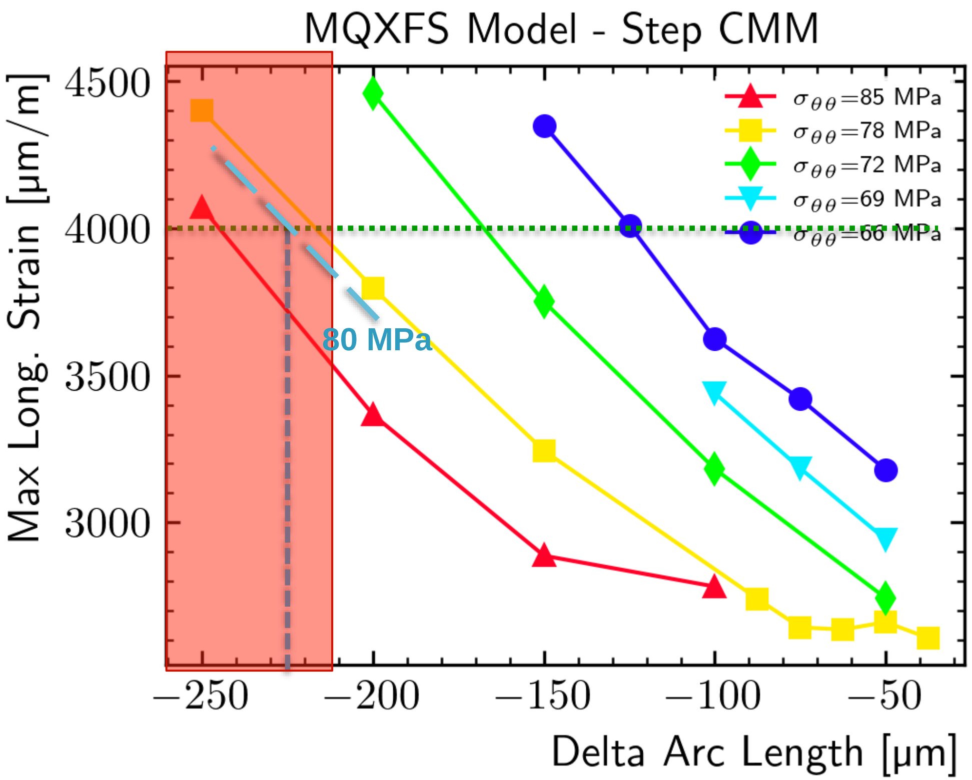
- MQXFA05 had **72 MPa** average prestress in SS and **167 um** Delta LE-SS:

  4000 microstrain

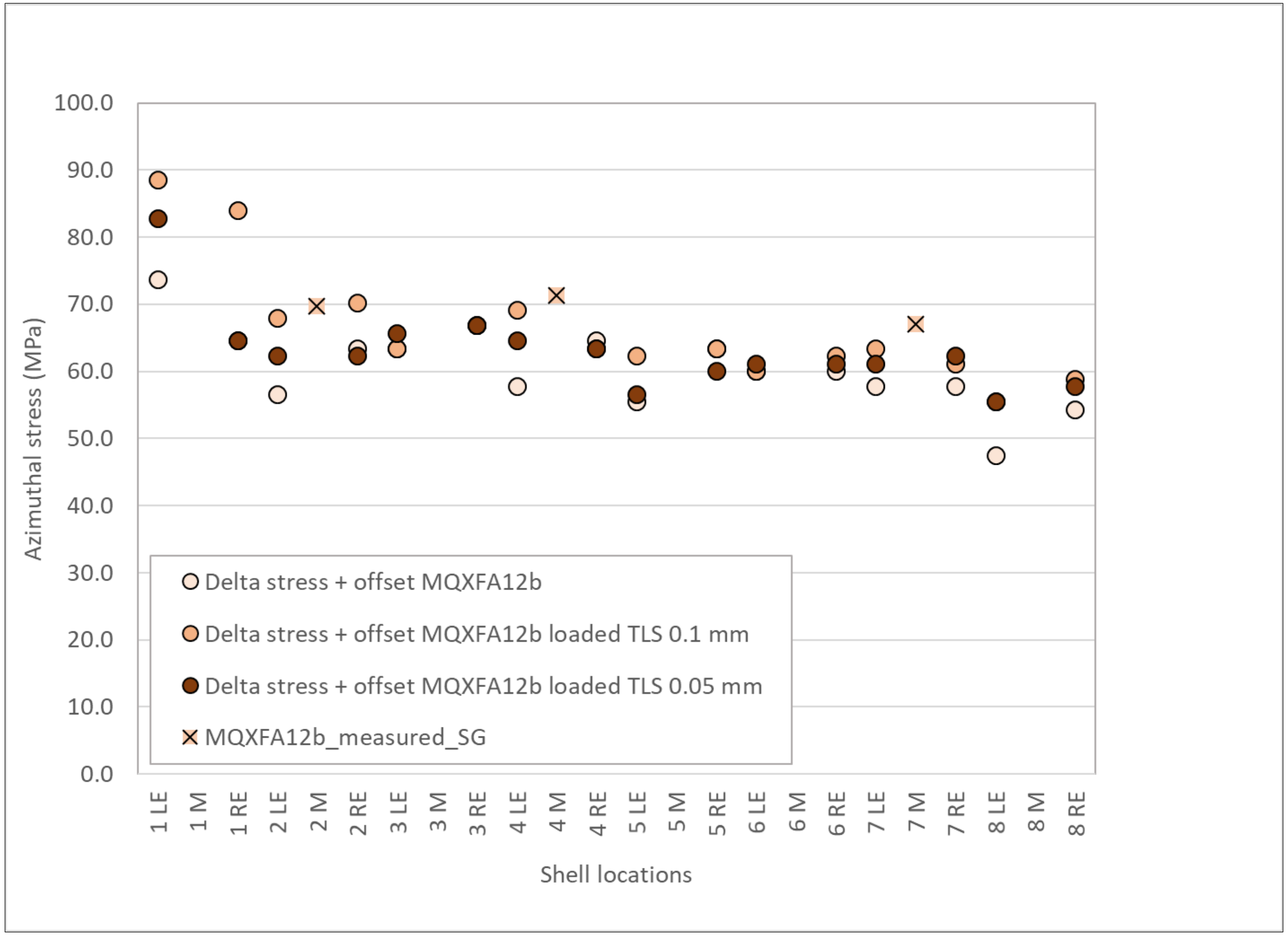
  (max Delta = 218 um)

Threshold Delta Arc Length

- Assuming we can always preload magnet with average preload at RT in the straight section > **80 MPa**
  - Because we are computing min key-size shims for each magnet



- The threshold for Critical DR: Delta Arc-Length is: **210 um** for RT prestress > 80 MPa



100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Azimuthal stress (MPa)
Delta stress + offset MQXFA12b
Delta stress + offset MQXFA12b loaded TLS 0.1 mm
Delta stress + offset MQXFA12b loaded TLS 0.05 mm
MQXFA12b_measured_SG
1 LE
1 M
1 RE
2 LE
2 M
2 RE
3 LE
3 M
3 RE
4 LE
4 M
4 RE
5 LE
5 M
5 RE
6 LE
6 M
6 RE
7 LE
7 M
7 RE
8 LE
8 M
8 RE
Shell locations

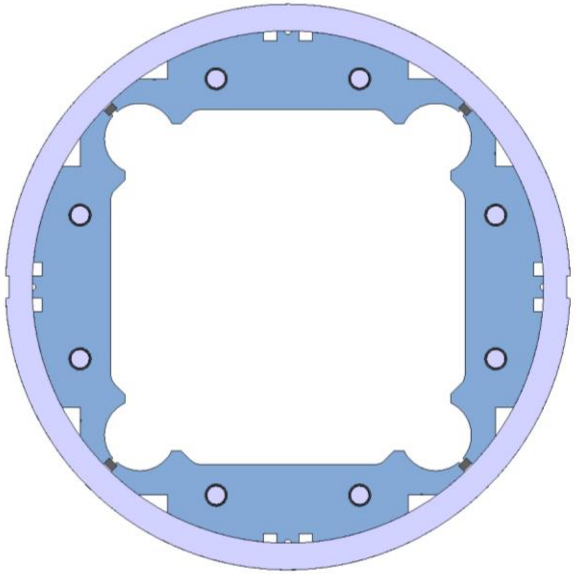
Plans for Coils with Critical DR

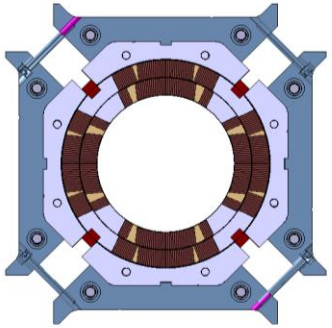
- If Delta arc-length is slightly above 210 um, disposition may be to **set minimum magnet preload > 80+ MPa**

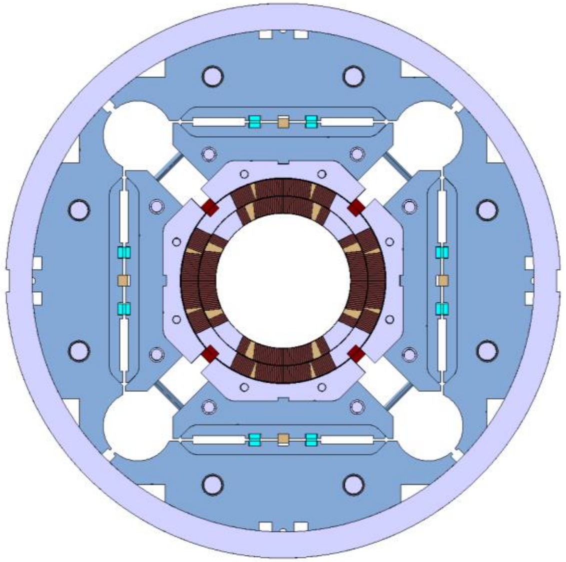
- If Delta arc-length is significantly above 210 um, disposition may be to **use shims for loading keys in the ends**

Introduction

- List of specifications in "chronological" order
  - From shell-yoke to coil-pack to magnet pre-load
- Definition based on dimensional, magnetic, electrical, and strain measurements
  - Some specs defined by "design and analysis" (example: peak stress)
  - Some defined by experience from previous successful magnet (example: coil pack uniformity/squareness)

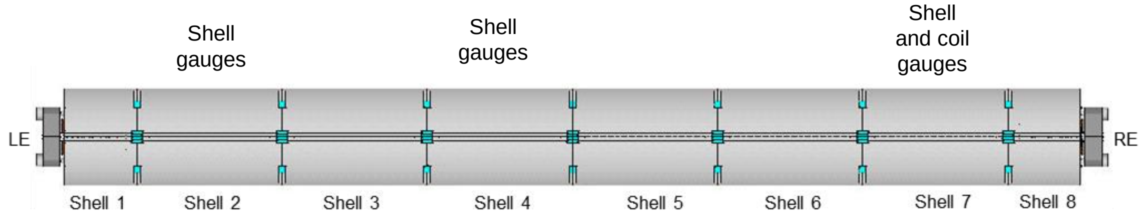


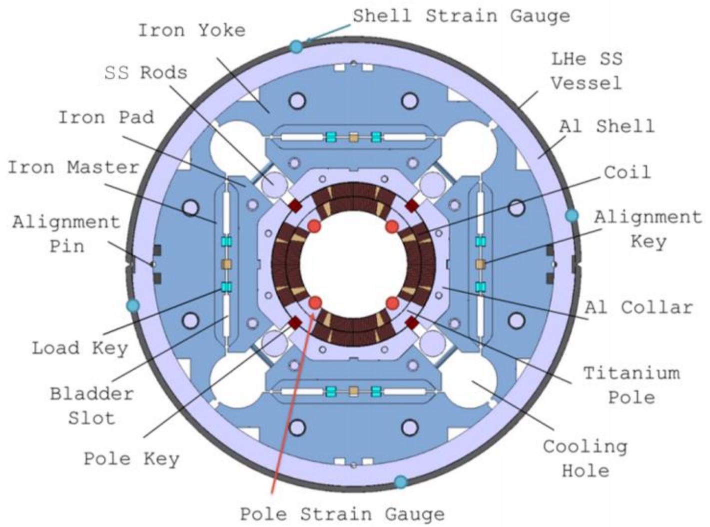


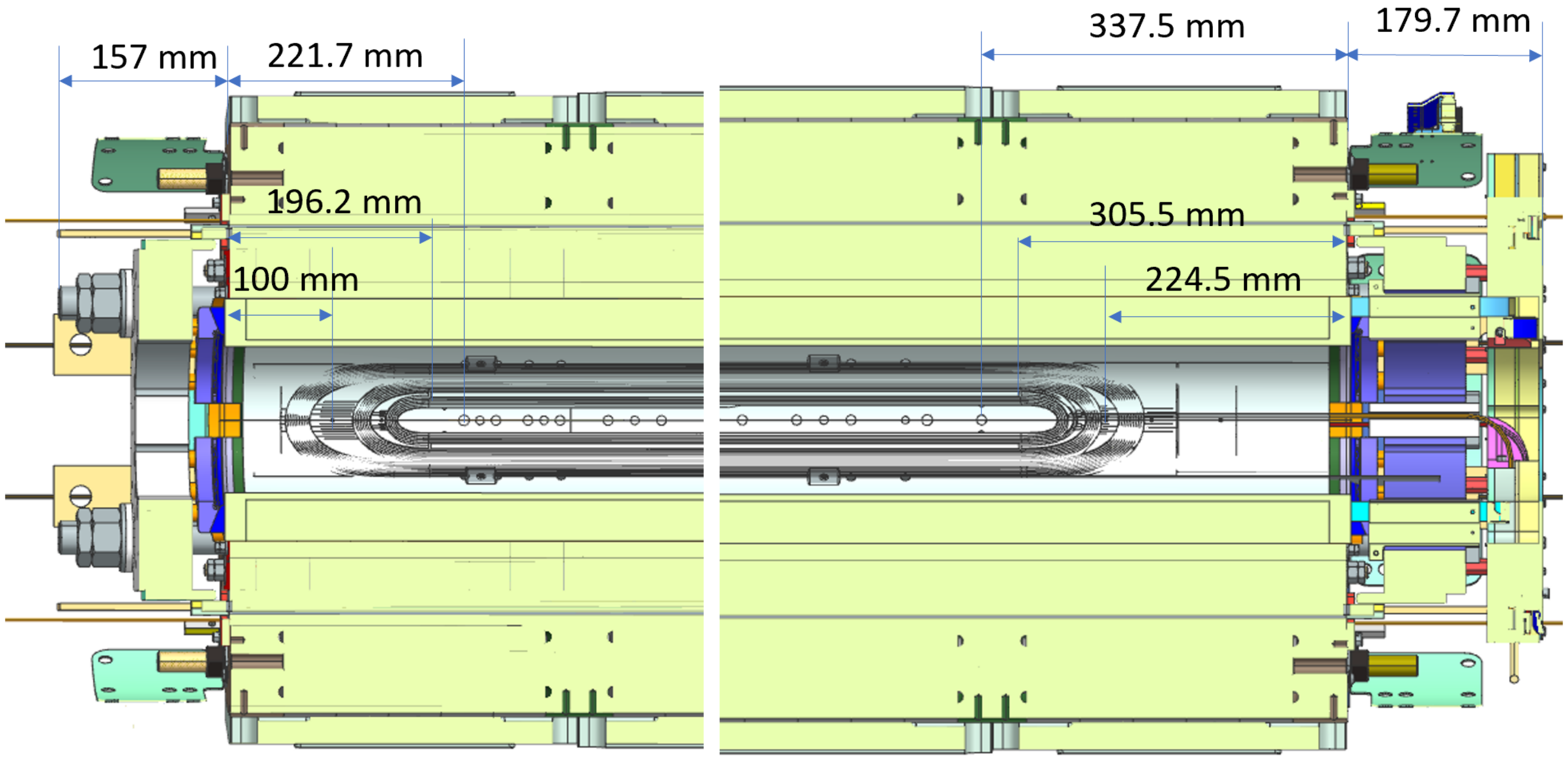


Introduction

- On strain measurements….
  - Strain gauge locations
    - Shell: 3 axial location, 4 quadrants, azimuthal and axial
      - Shell 2, shell 4, shell, 7
    - Coil: 1 axial location, 4 coils (pole), azimuthal and axial
      - Center of shell 7
    - Axial rods: 1 axial location, 4 rods, axial






157 mm
221.7 mm
196.2 mm
100 mm
337.5 mm
179.7 mm
305.5 mm
224.5 mm