MQXFA magnet assembly: lessons learnt from MQXFA07/08

P. Ferracin

on behalf of the MQXF collaboration

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Acknowledgements

- CERN
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    - Bartosz Bulat
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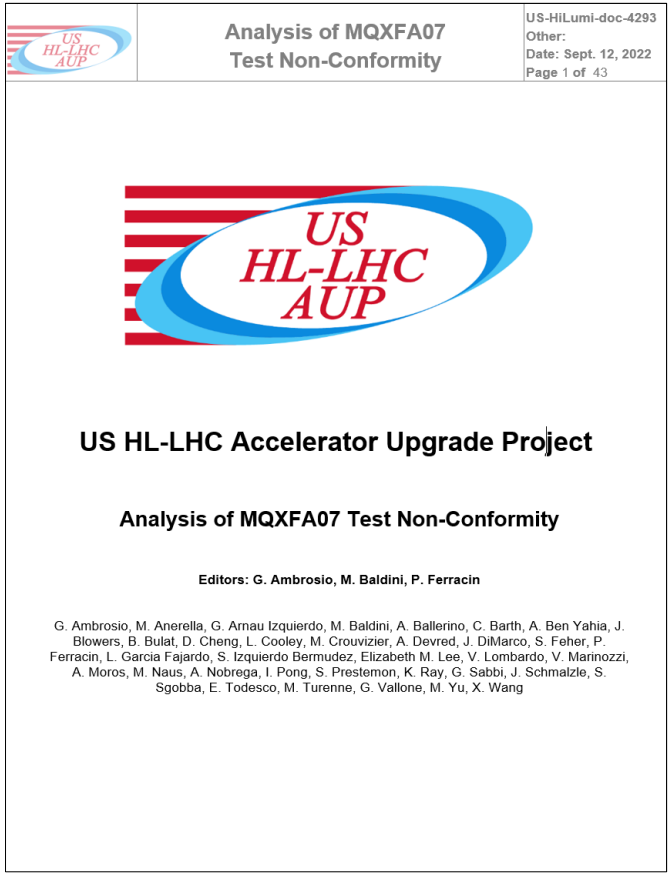
    - M. Crouvizier
    - S. Sgobba
    - A. Moros
      - Talk on Thursday, 8.30 am, “Coil post-mortem inspection”

References

- US-HiLumi-doc-4293
- https://edms.cern.ch/document/2777612/1



US HL-LHC AUP

US HL-LHC Accelerator Upgrade Project

Analysis of MQXFA07 Test Non-Conformity

Editors: G. Ambrosio, M. Baldini, P. Ferracin

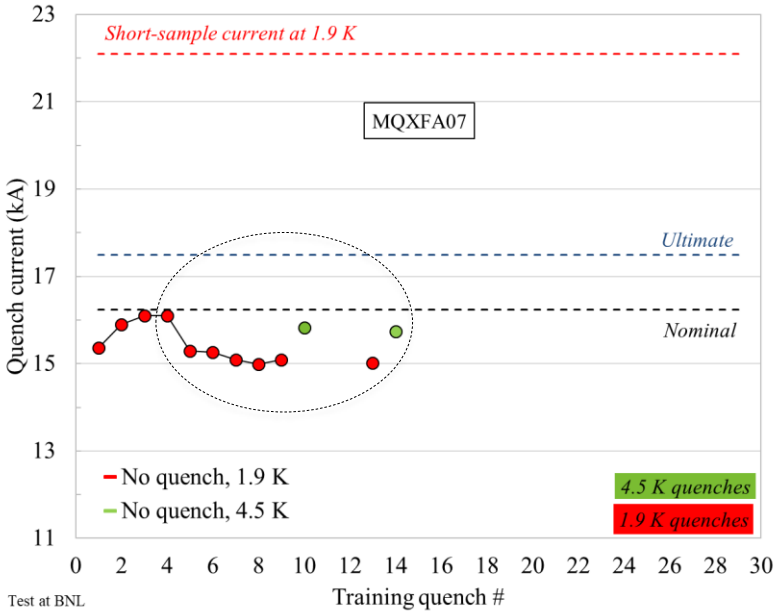
G. Ambrosio, M. Anerella, G. Arnau Izquierdo, M. Baldini, A. Ballerino, C. Barth, A. Ben Yahia, J. Blowers, B. Bulat, D. Cheng, L. Cooley, M. Crouvizier, A. Devred, J. DiMarco, S. Feher, P. Ferracin, L. Garcia Fajardo, S. Izquierdo Bermudez, Elizabeth M. Lee, V. Lombardo, V. Marinozzi, A. Moros, M. Naus, A. Nobrega, I. Pong, S. Prestemon, K. Ray, G. Sabbi, J. Schmalzle, S. Sgobba, E. Todesco, M. Turenne, G. Vallone, M. Yu, X. Wang

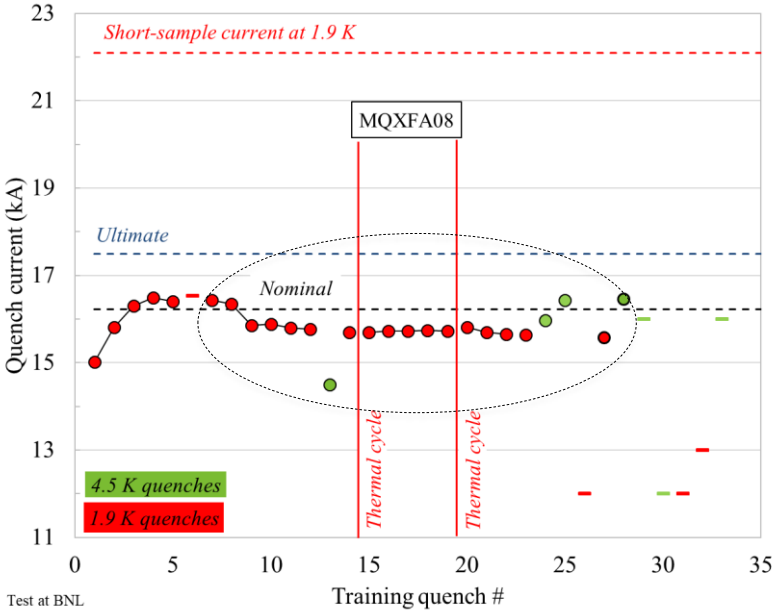
Outline

- MQXFA07/A08 test results
- Magnet disassembly: coil-pack
- Coil visual inspection
- Finite element analysis
- Coil die penetration test, CT scan, metallurgical inspection
- Corrective actions for magnet A10 and beyond
- Conclusions

MQXFA07 and A08 test results

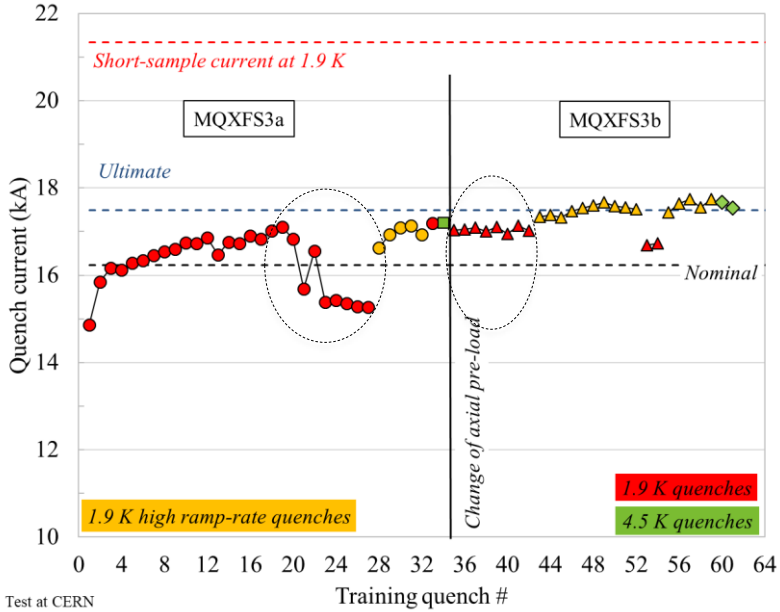
- Both magnets with detraining after few quenches
  - Reverse temperature and ramp-rate dependence
  - Both magnets limited by segment a3-a4
    - Coil 214 in A07 and coil 213 in A08

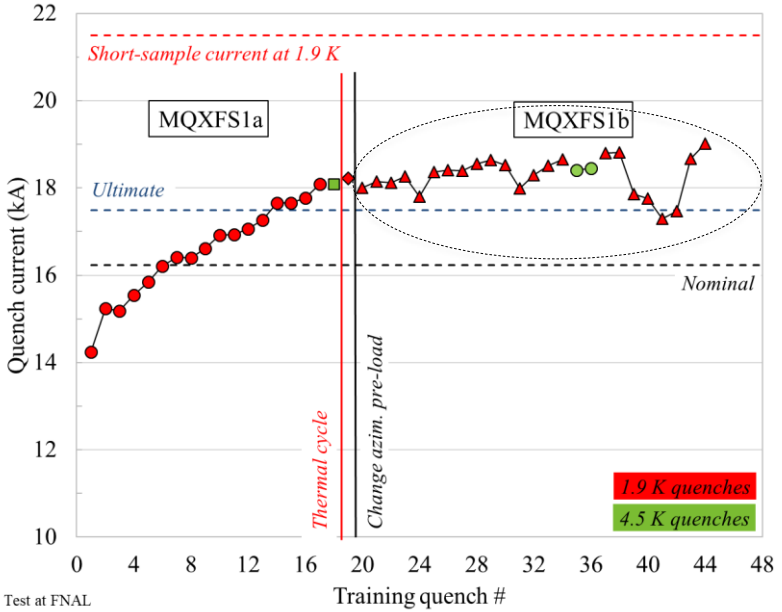




Segment a3a4….an “old friend”

- Also in MQXFS3 (Oct 2016)
  - Detraining…a3a4…increase with ramp-rate,4.5 K….and with axial loading
- MQXFS1b (Oct 2016)
  - a3a4 appeared after increase of azimuthal, with low axial
  - No clear detraining, but more erratic….

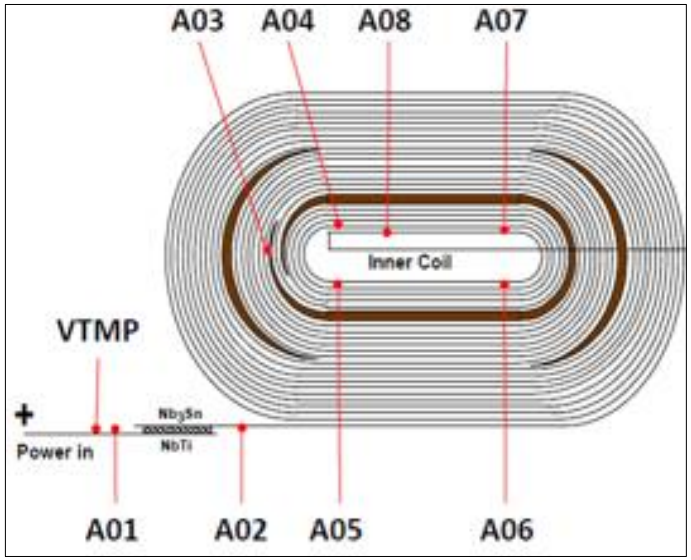


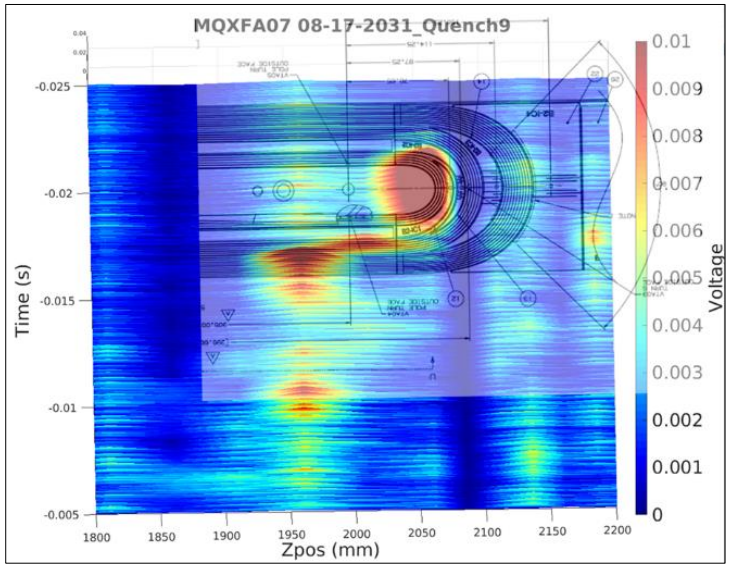


- Interpretation of behavior: self-field instability triggered by a local issue, likely affecting only some strands, that pushes more current in adjacent strand(s)

Back to MQXFA07 and A08 test results

- Quench location
  - a3a4: multi-turn segment including turns 2 to 6
    - Turns 2-5 are included in the pole-block multiturn
    - Turn 6 is the first turn outside the wedge
  - Quench antenna signals (50 mm long circuits) point out LE, where pole block turns go around the pole tip





Again…lead end, pole block….an "old friend"

MQXFS3
By H. Bajas
CERN

MQXFS1b
By Guram Chlachidze
LARP

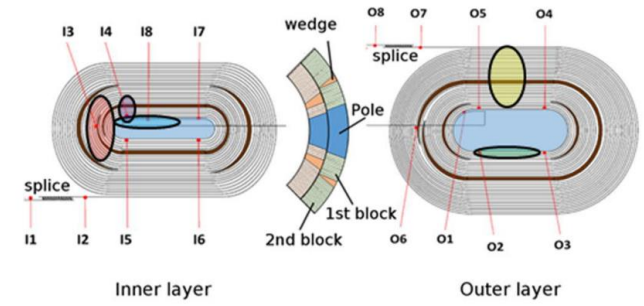


Fig. 38 : Localization of the quench location for the coil 105 pole turn near the layer jump (blue), the coil 7 first block lead ends (red), the coil 107 outer layer pole turn straight part and in the multitrun of the outer layer for the Coil 106..

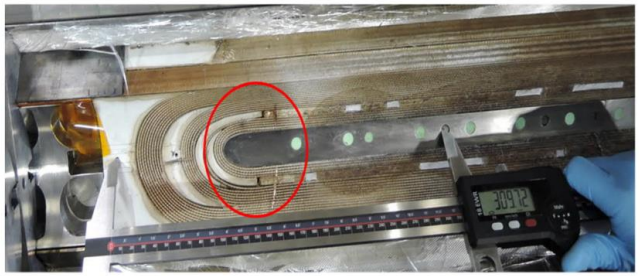
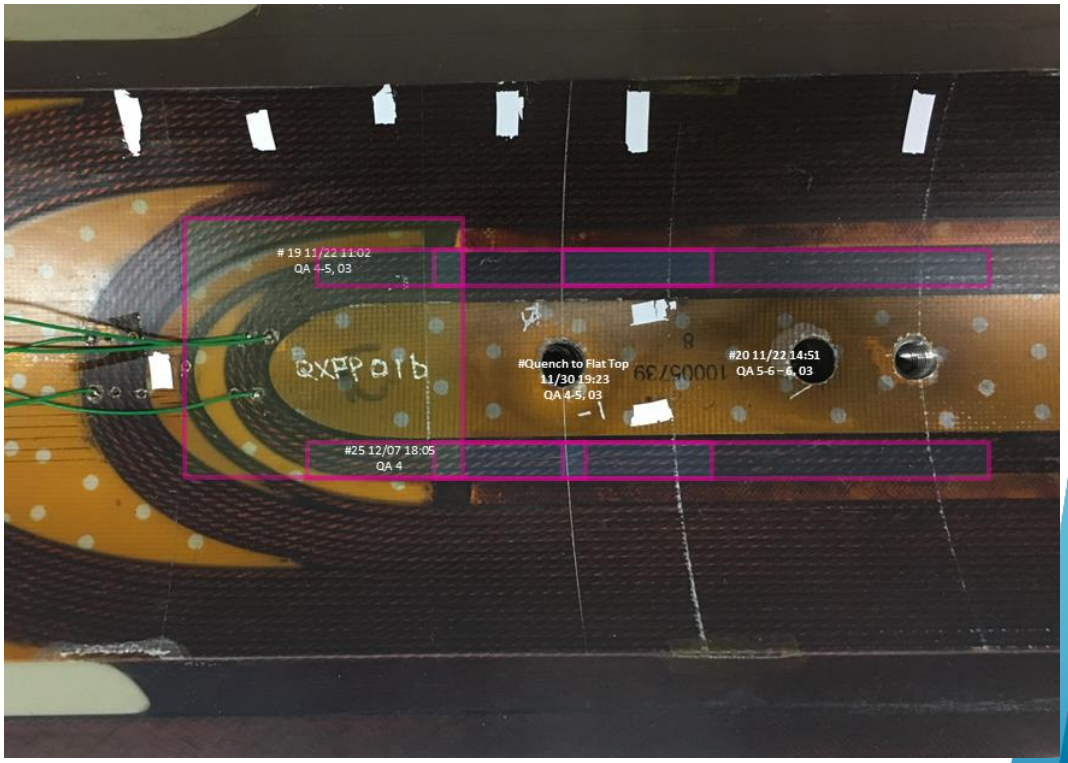


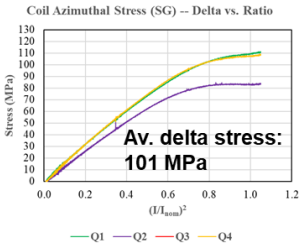
Fig. 39: Coil view of the position of the critical zone at the end spacer of the coil 7.



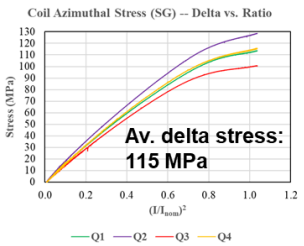
Strain gauges in MQXFA07-A08

- No major anomaly in azimuthal pre-stress of shell and coil
  - Nothing unusual in the coil unloading
    - However, measurements only on the RE (4 m from quenching)

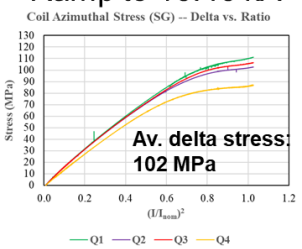
MQXFA03
Ramp to 16.65 kA



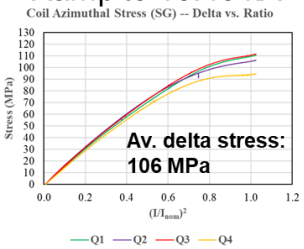
MQXFA04
Ramp to 16.55 kA



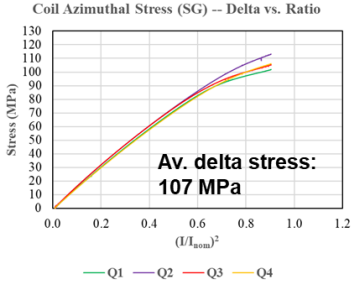
MQXFA05
Ramp to 16.46 kA



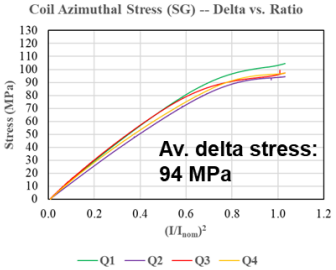
MQXFA06
Ramp to 16.45 kA



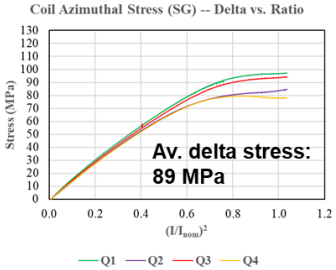
MQXFA07
Ramp to 15.45 kA



MQXFA08
Ramp to 16.50 kA



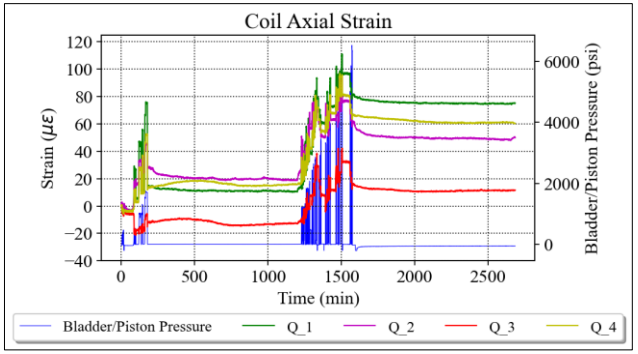
MQXFA10
Ramp to 16.54 kA

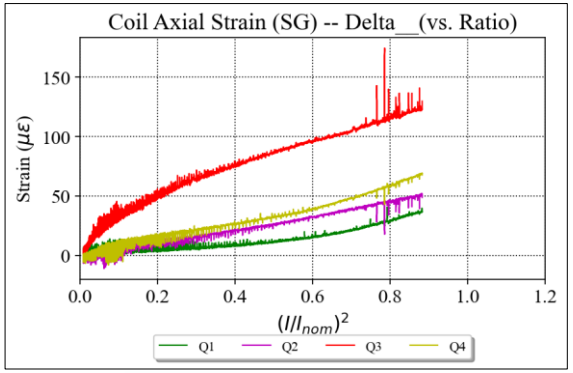


Strain gauges in MQXFA07-A08

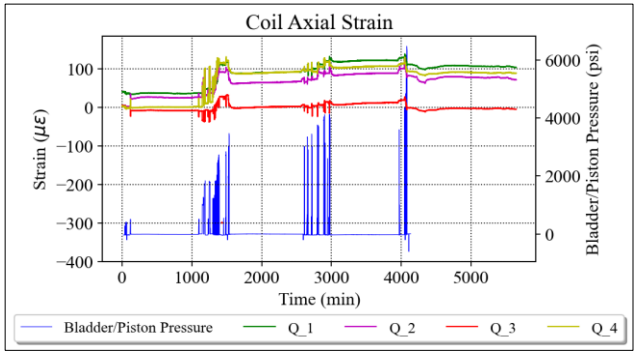
- "Suspicious" coil *z* behavior during loading/excitation, however
  - Visible also in some previous magnets
  - Not reproduced by any of the FE models
  - Again measured far from the quenching zone

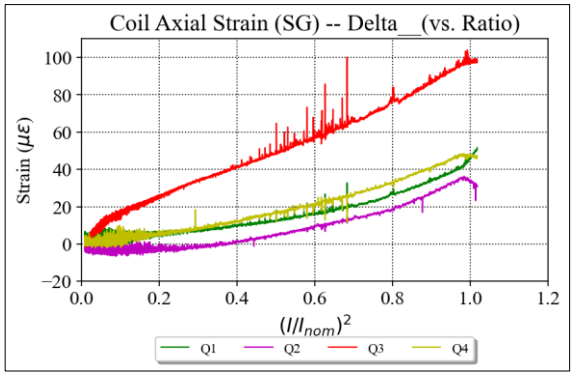
MQXFA07





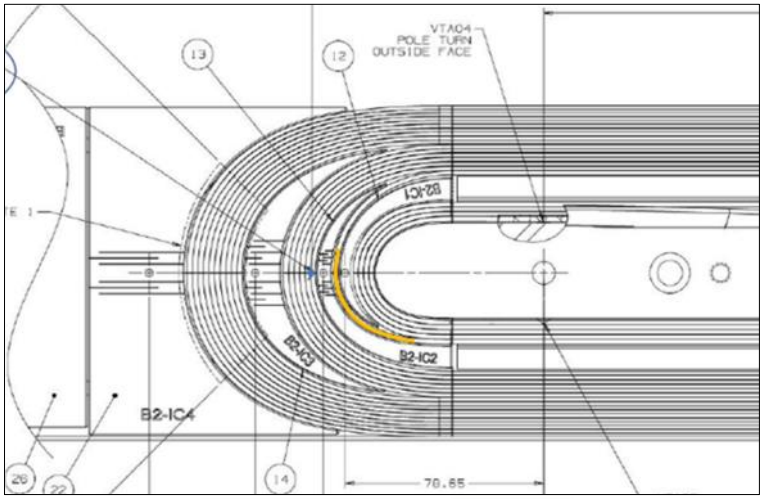
MQXFA08

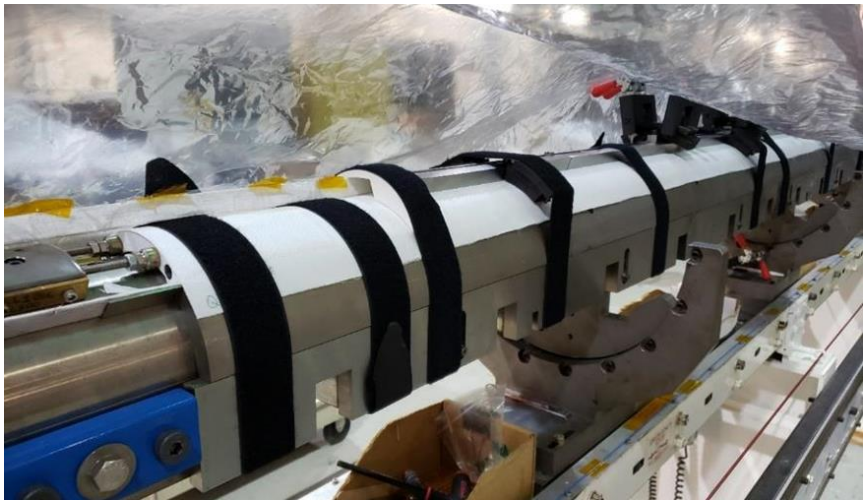




Review of coil fabrication
NCRs or off-normal procedures

- In MQXFA08, splice between the magnet negative lead, connected to inner layer LE Q3, and the test facility had resistance equal to 42 nΩ
  - Thermal analysis from CERN did not show any significant impact on quench zone
- A07 coil 214:
  - Some strands popped out during winding, then fixed, popped out overnight, fixed a second time
    - Occurred in previous coils
  - Affected by COVID lockdown: 14 weeks stop after winding & curing of inner layer
- A08 coil 213
  - Affected by COVID lockdown: 14 weeks stop in the reaction fixture, in the oven.





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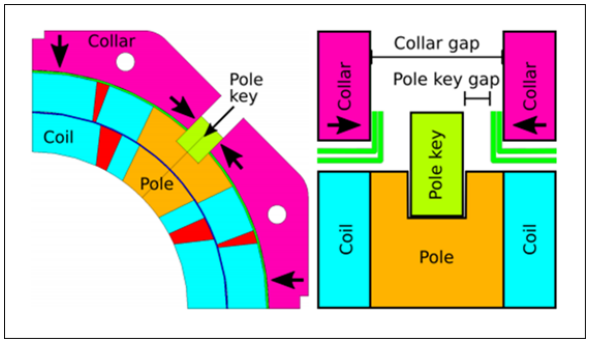
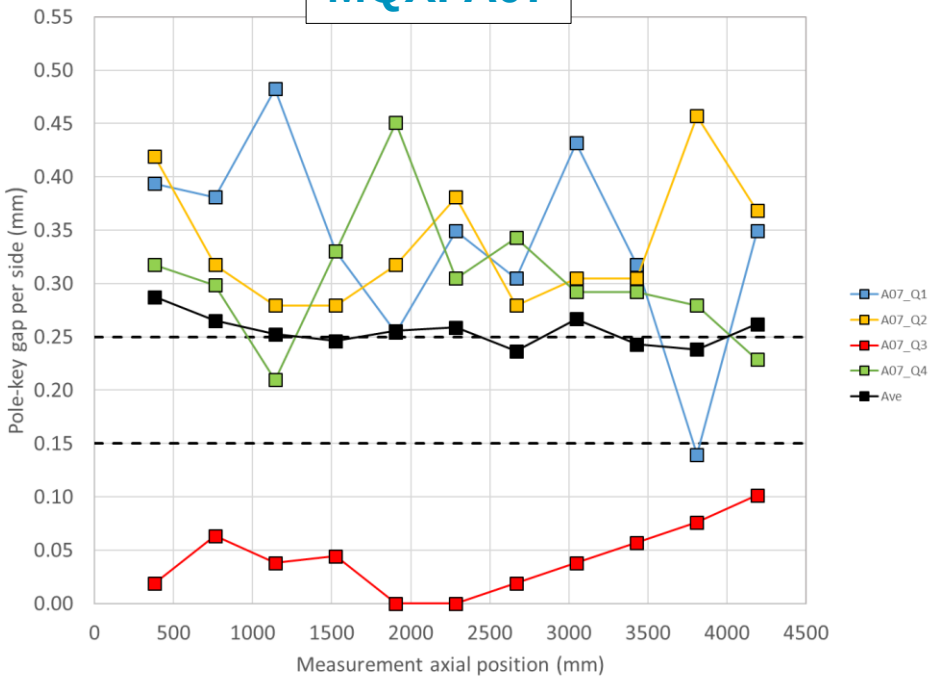
Disassembly: coil pack inspection
Pole key gap

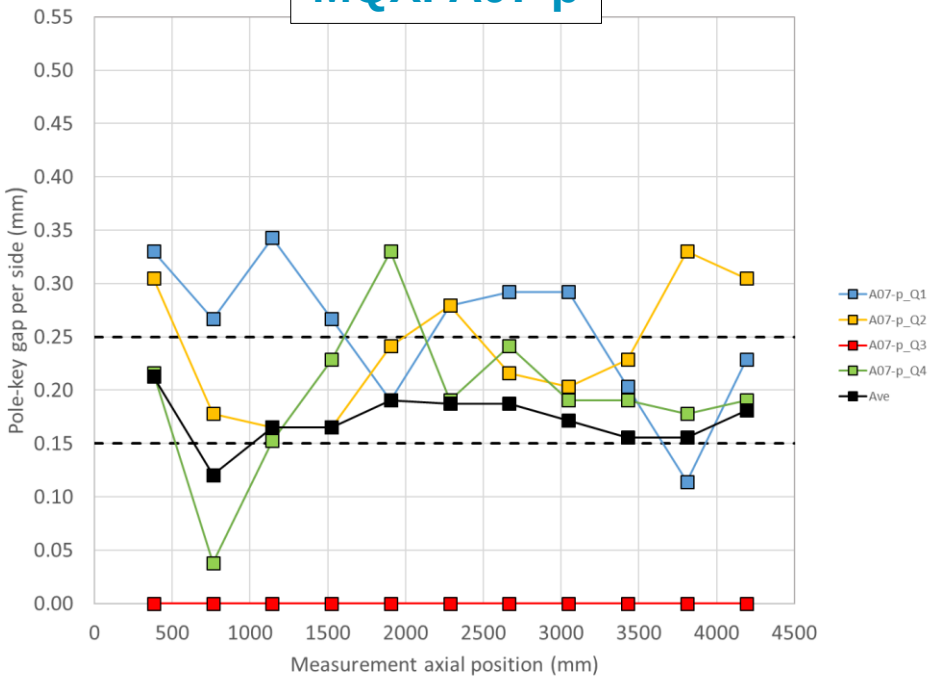
- Spec. pole key gap (local ave. on cross-section)
  - 0.200± 0.050 mm
- Before to after the test
  - Q3 with an very low gap both before and after the test
  - Average decreased by about 0.100 mm
  - Same profiles after pre-load and test



MQXFA07

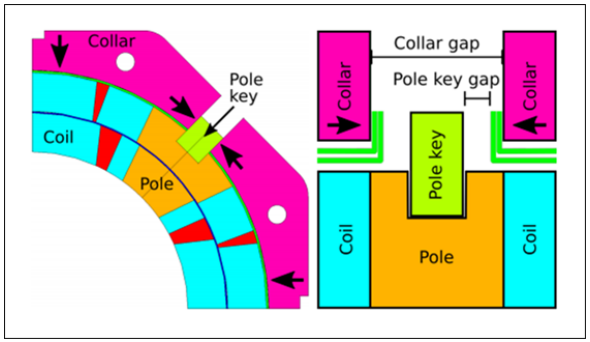


MQXFA07-p

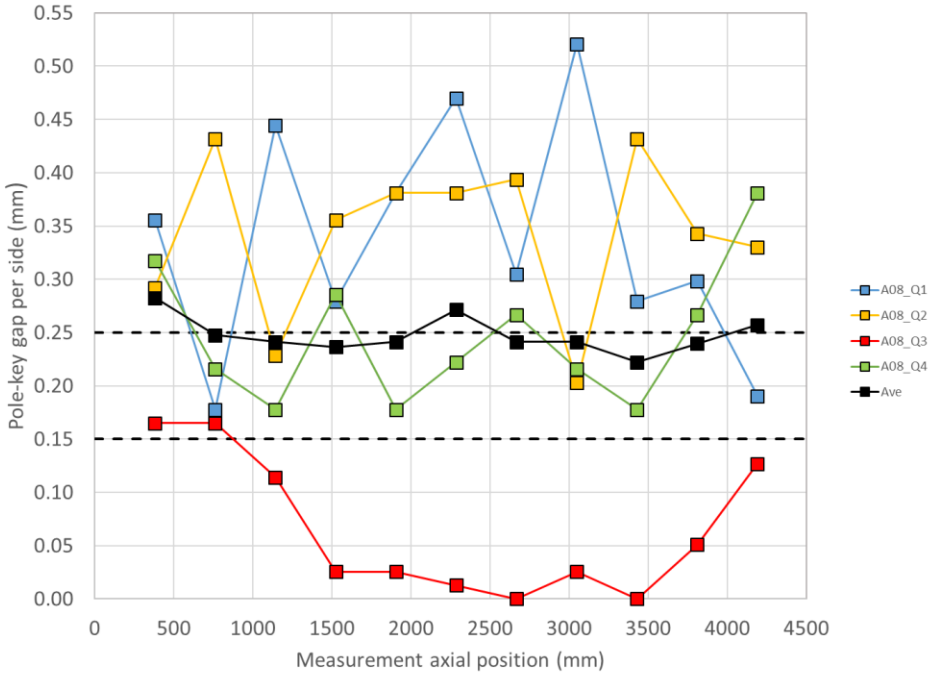


Disassembly: coil pack inspection
Pole key gap

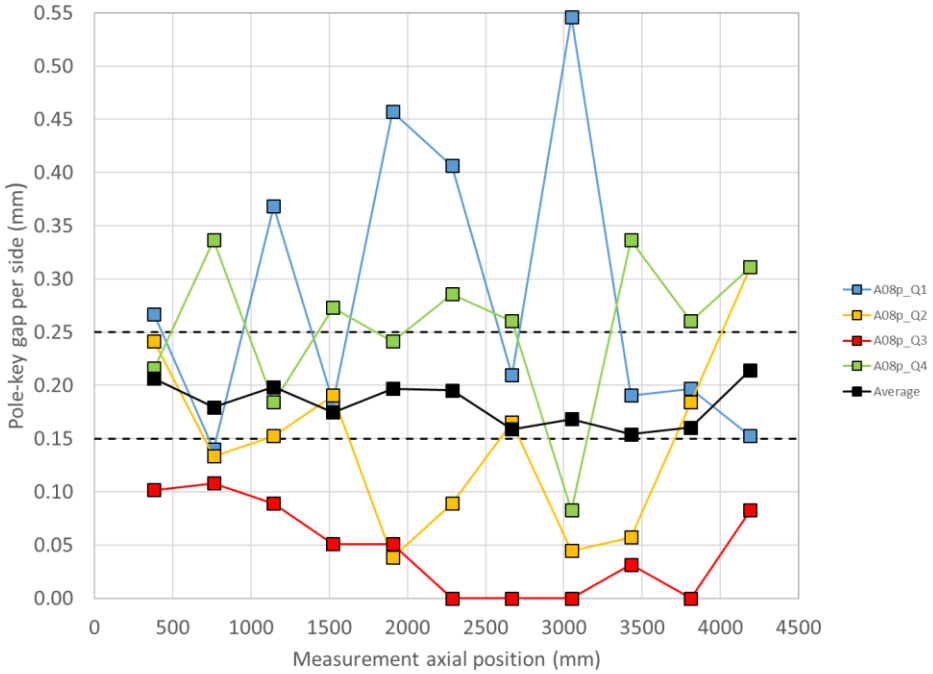
- Similar results on MQXFA08
  - But not as dramatic as in A07-p



MQXFA08

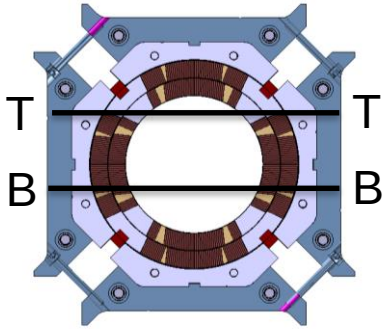


MQXFA08-p

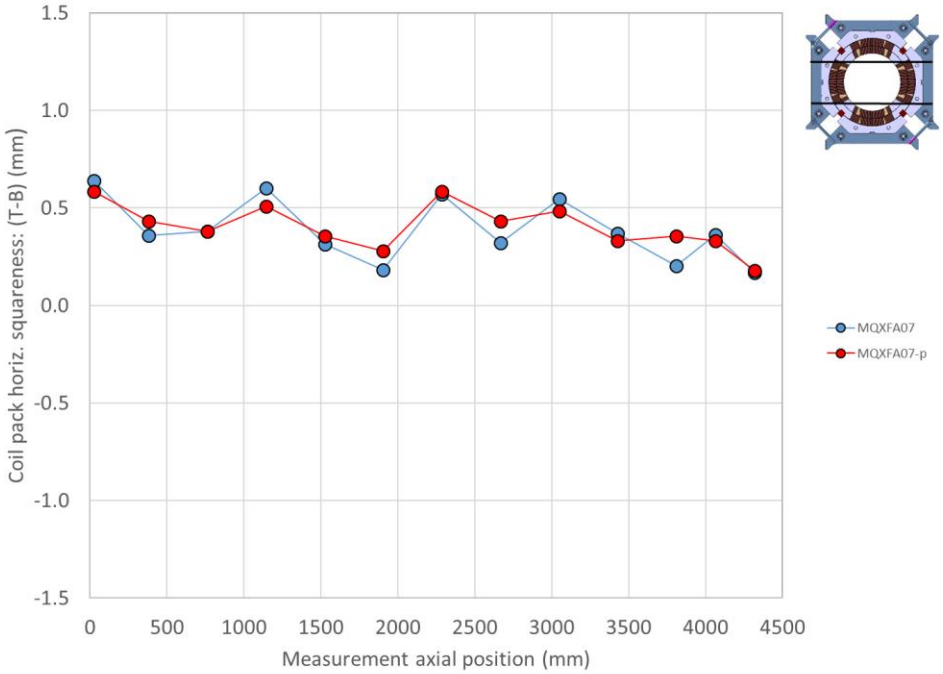


Disassembly: coil pack inspection
Pole key gap

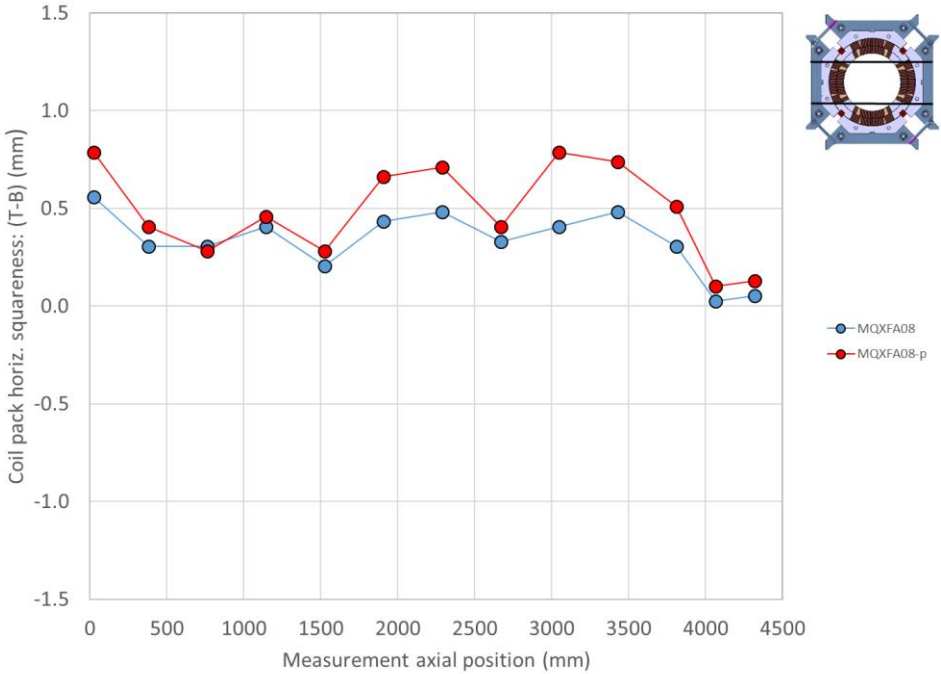
- The same conclusion could be drawn looking at the coil pack dimensions
  - Significant trapezoidal shape
  - No change from before to after test



MQXFA07 vs A07-p

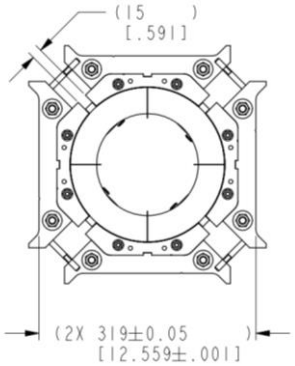


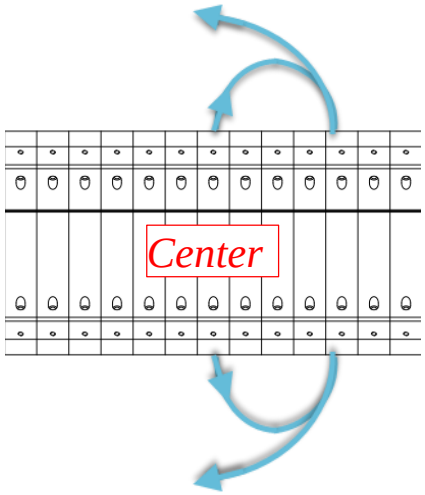
MQXFA08 vs A08-p

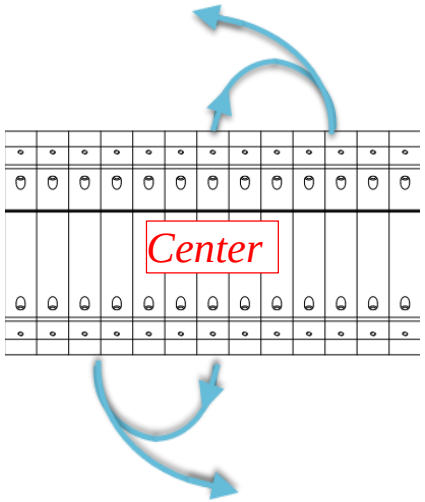


Review of coil-pack fabrication
NCRs or off-normal procedures

- Changes to magnet assembly procedures due to Covid requirements:
  - #1: change in bolting procedure for increasing tech distance

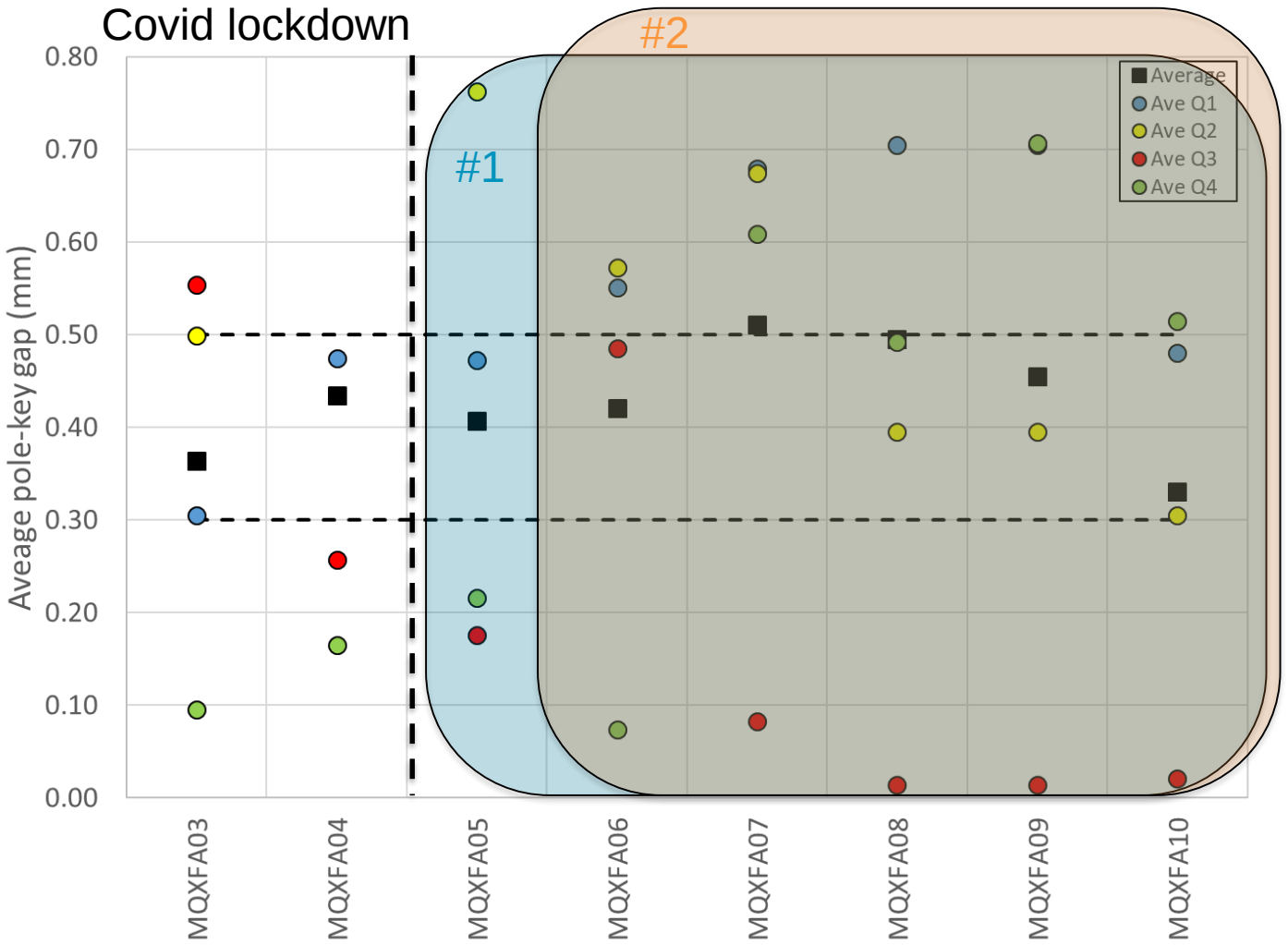






  - #2: the technician who had been leading the coil-pack assembly operations up to magnet MQXFA05 was **removed from that task** (starting from MQXFA06) because not vaccinated.
- Also, end-plate mis-aligned, so magnet unloaded axially and re-loaded

Review of coil-pack fabrication NCRs or off-normal procedures



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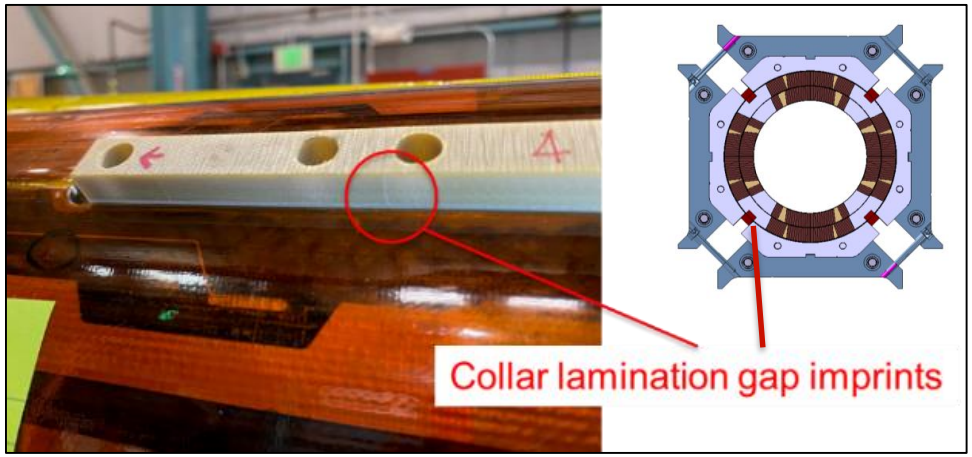
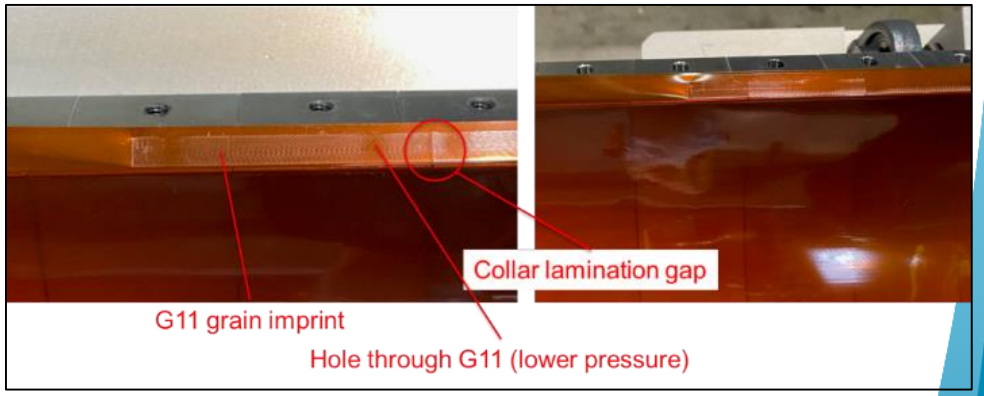
Coil visual inspection

- In Q3, deep imprints in the Kapton indicating collar lamination lines, G11 grain, and “lower pressure” spots at every hole
  - These imprints, all indicative of a higher pressure, not seen in the other quadrants.
- The G11 keys in Q3 also showed high pressure imprints of collar lamination gaps
  - Not observed in the other quadrants.





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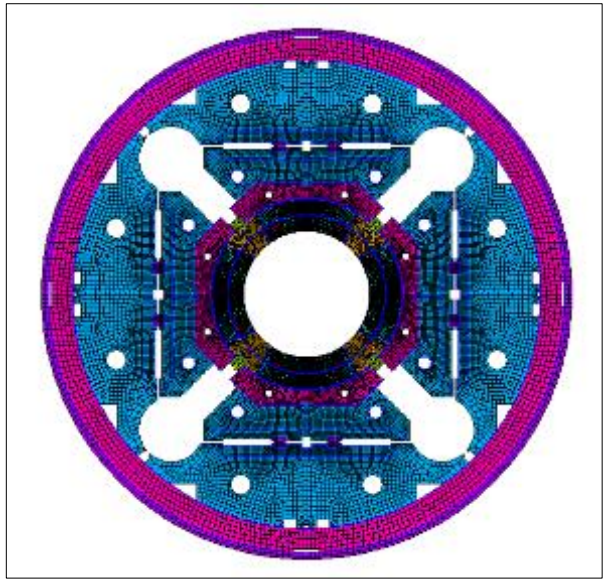
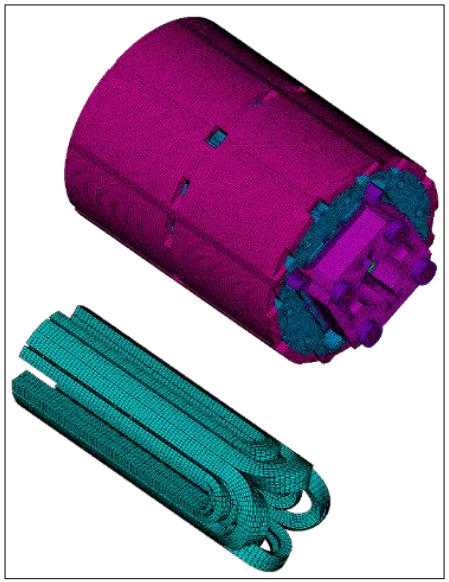
Finite element analysis
Effect of a close pole key gap

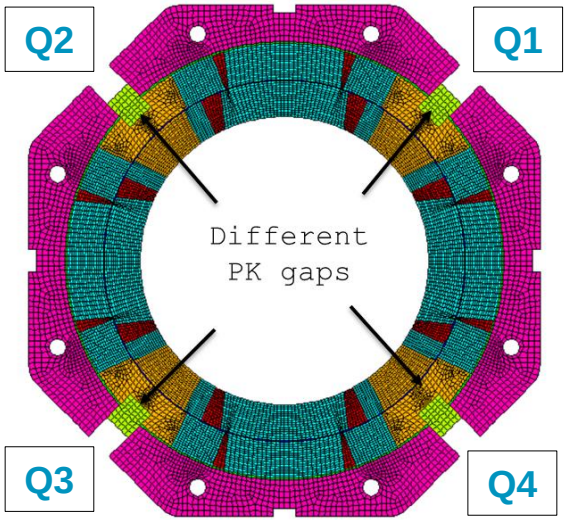
- Three different finite element models:
  - 360-degrees, full cross-section 2D model
  - 360-degrees, full cross-section 3D model (MQXFS)
  - 45-degrees, octant 3D model (MQXFS)

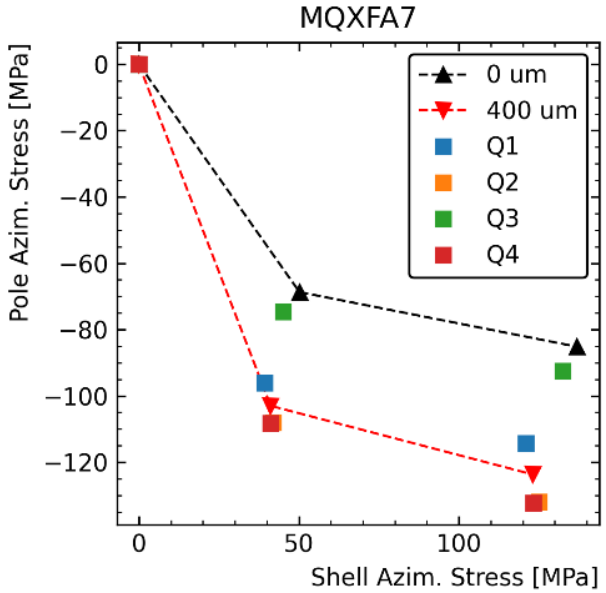




Finite element analysis
360-degrees, full cross-section 2D model

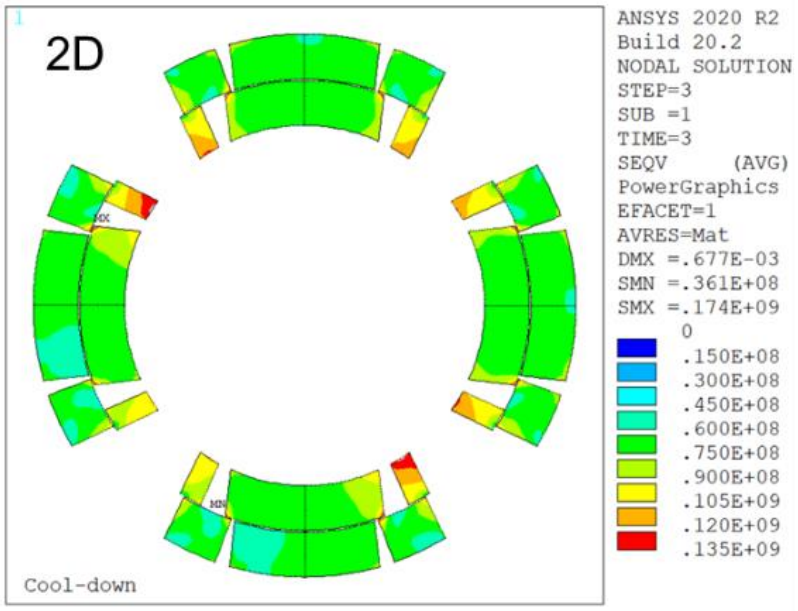
- With a close pole key gap in Q3, the azimuthal pre-stress is
  - Significantly lower (~30 MPa reduction) in the Q3
  - 'Medium' on the opposite side (Q1),
  - "Maximum" on the two remaining quadrants
- This effect is not measured by the strain gauges
  - However, measurement on a single axial location in RE

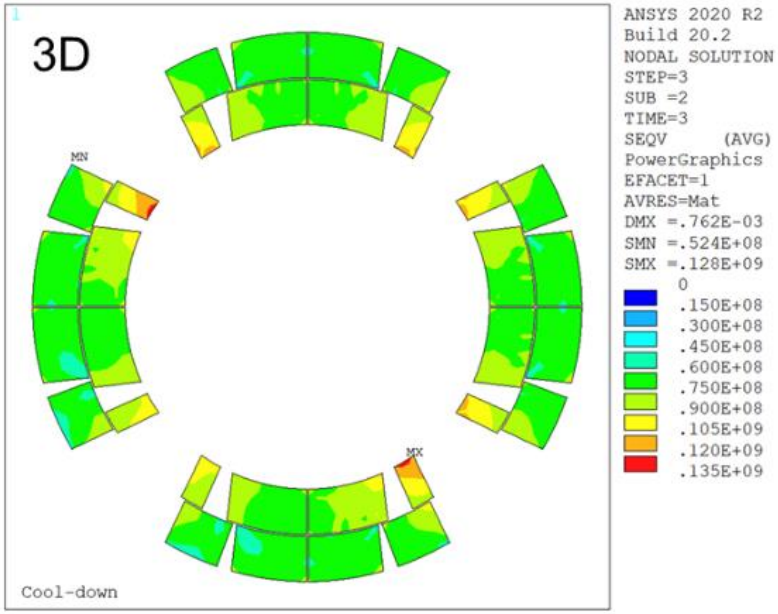




Finite element analysis
360-degrees, full cross-section 3D model

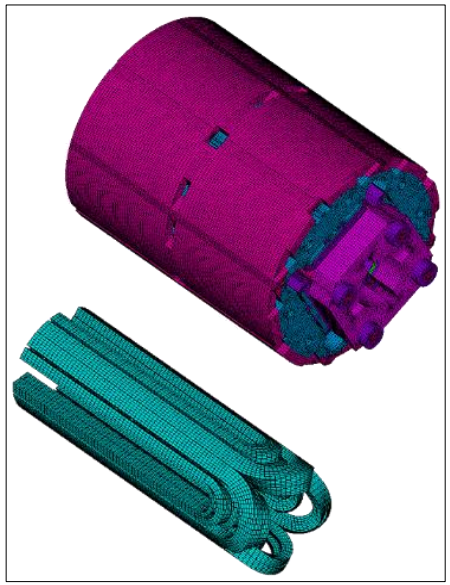
- Lower pre-stress in Q3 confirmed by 3D model

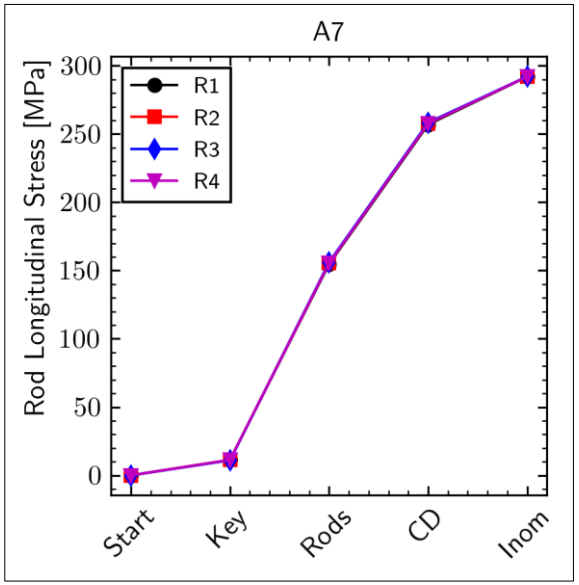


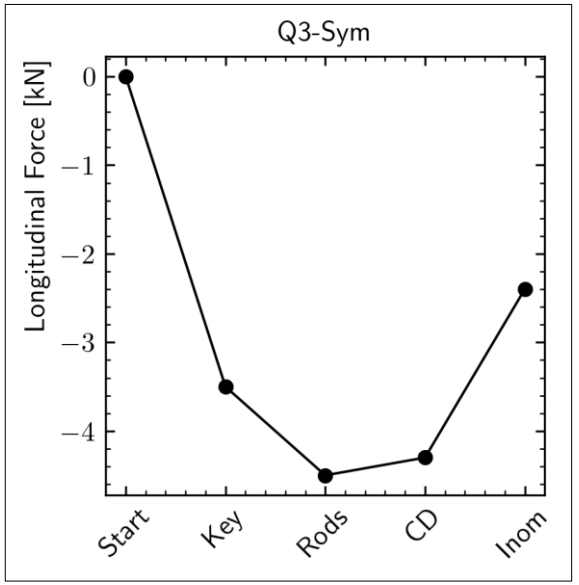


Finite element analysis
360-degrees, full cross-section 3D model

- Axial behavior
  - No difference in the rods stress, but less force axial pre-load on the Q3 coil
    - Lower azimuthal pre-stress results in less friction coil-structure → “axially softer coil”

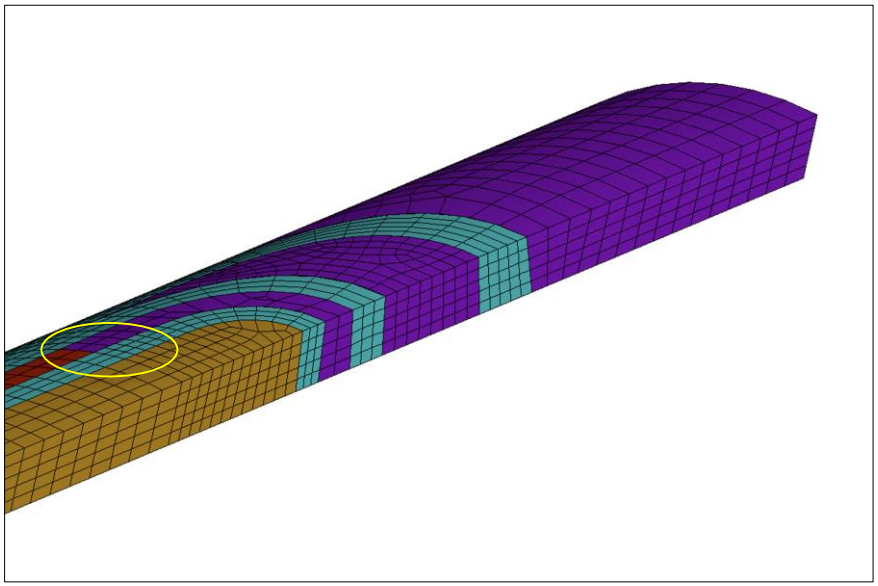


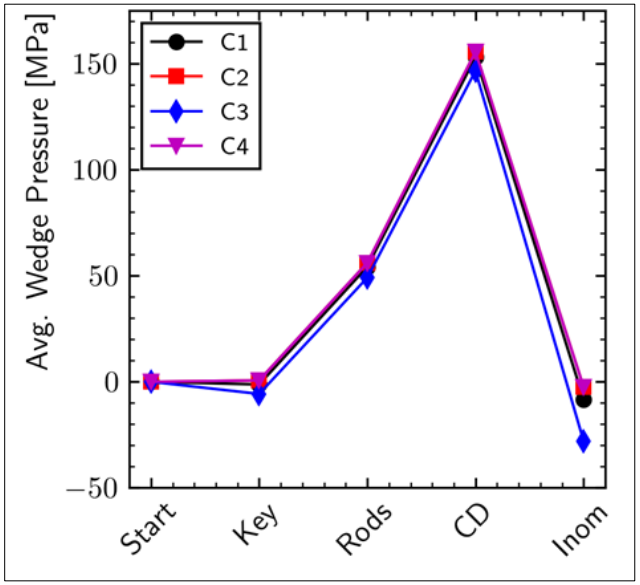




Finite element analysis
360-degrees, full cross-section 3D model

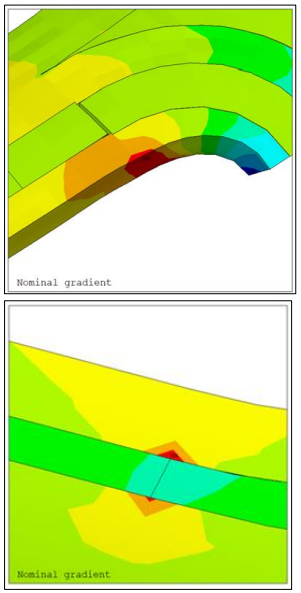
- “a3a4 LE area”
  - Contact between wedge and end spacer in L1
  - Considering bonded conditions
    - Tension occurs in Q3 during excitation

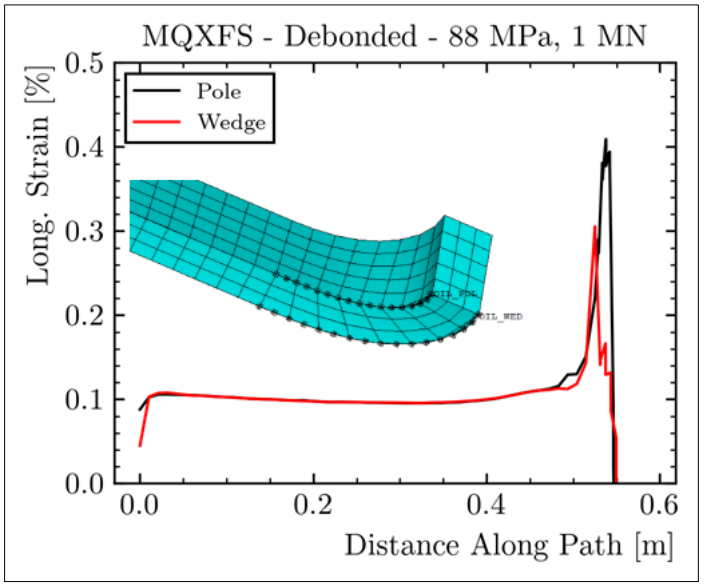




Finite element analysis
45-degrees, octant 3D model

- More detailed analysis with refined meshed
  - Not bonded, so as if epoxy cracking has occurred
  - The gap between wedge and end-spacer, induces a spike in axial strain in the coil, which can reach the 0.4% level
    - larger increase in the turn towards the pole.





Outline

- MQXFA07/A08 test results
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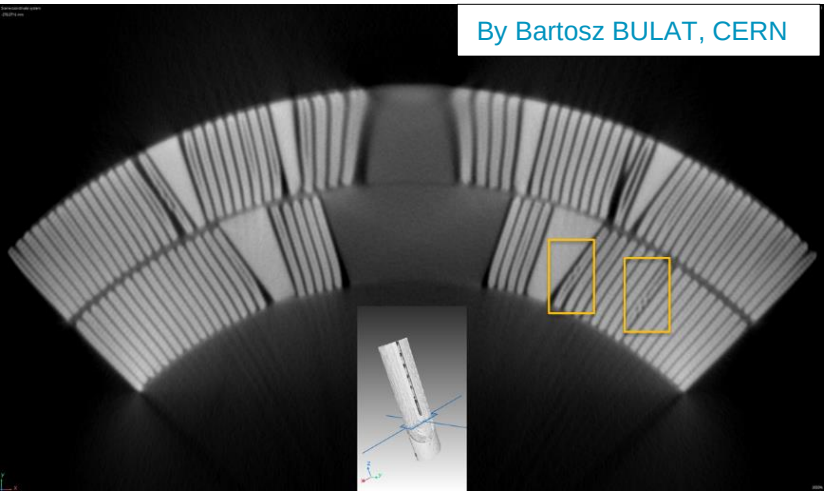
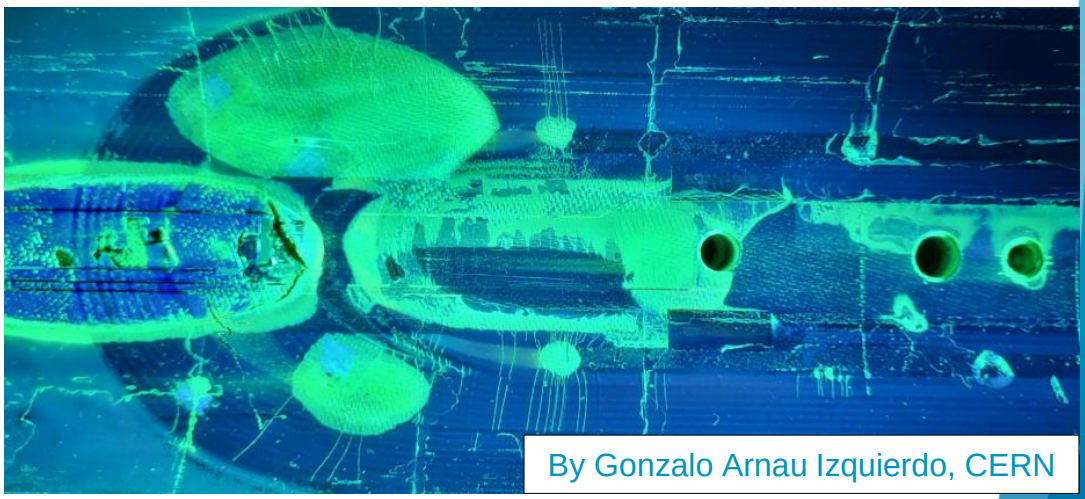
CT scan and die penetrant test

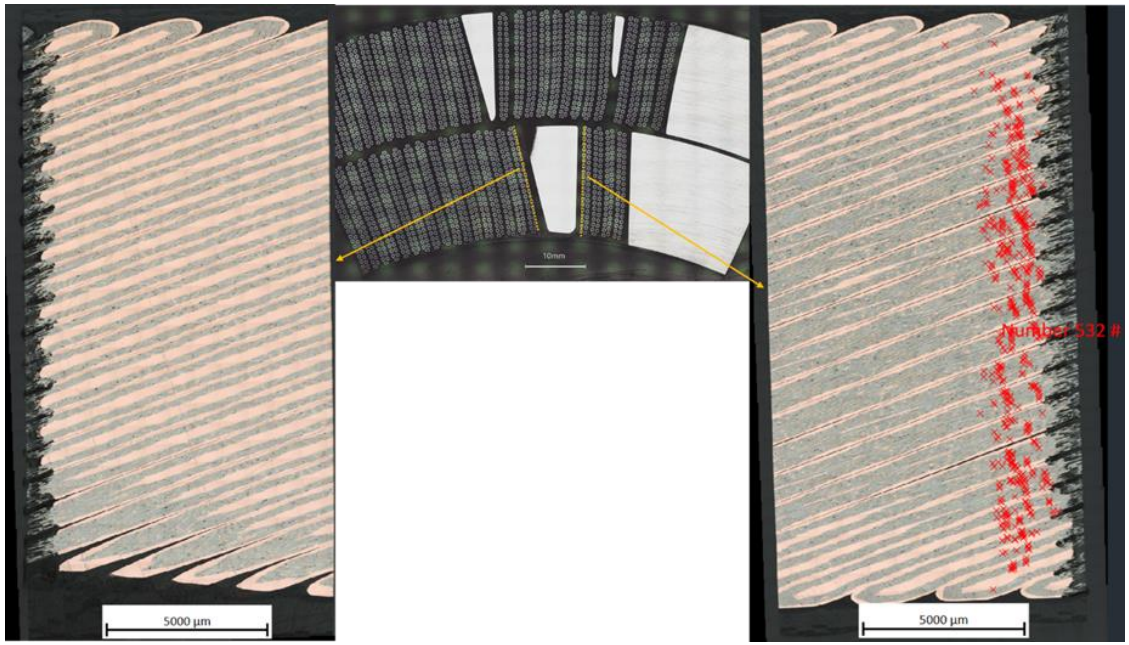
- In total 12 popped strands between LE and RE
  - But only one in the a3a4 segment, LE
- Bubbles/blisters also in the wedge - end-spacer interface
  - Horizontal cracks seen by die-penetrant test at CERN

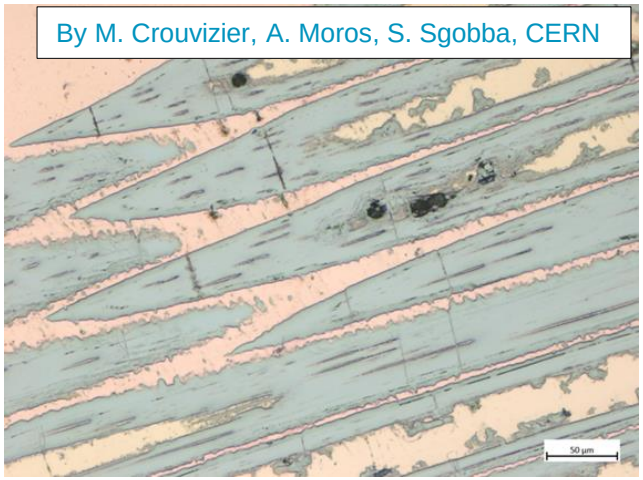


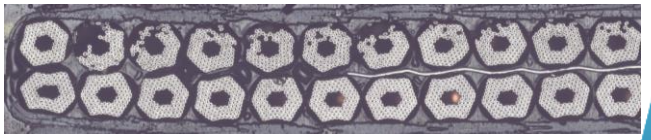


Metallurgical inspection

- Longitudinal cuts of first row of Rutherford cables adjacent to the end spacer/copper wedge transition
  - Localized field of cracked filaments, especially at pole block, between resin and copper wedge







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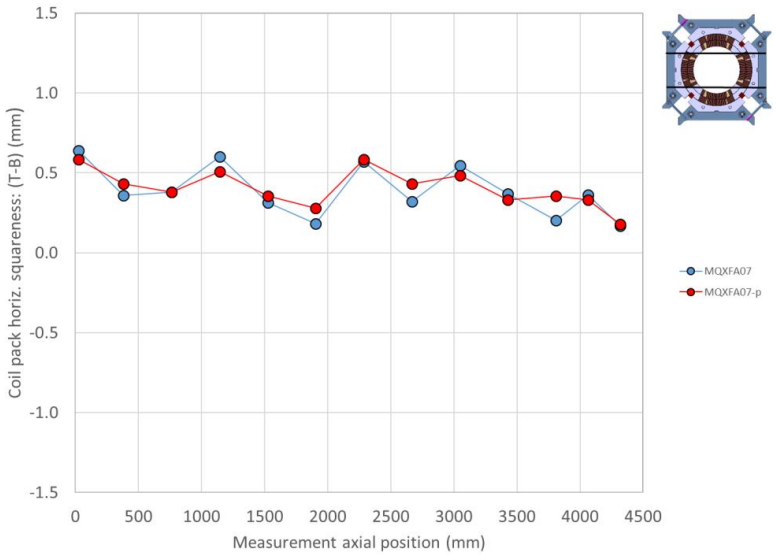
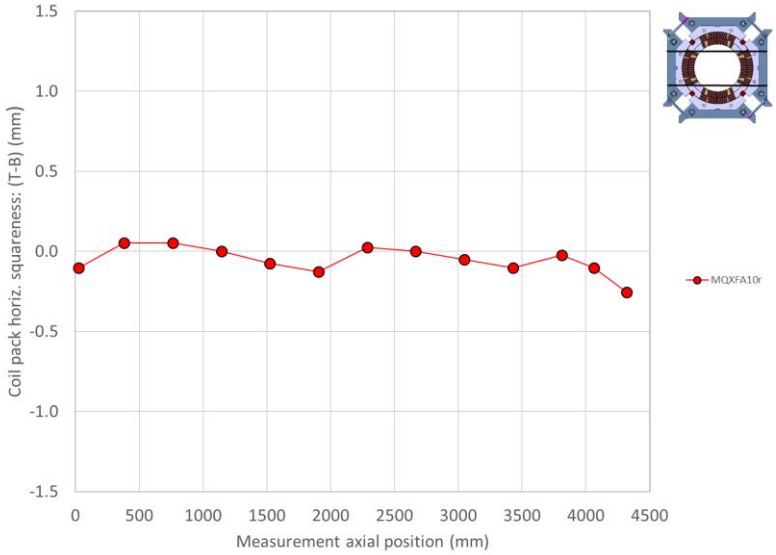
New assembly procedure

- Before
  - start with squaring, then torqueing
- Now
  - Start with counter-trapezoidal shape
  - Then squaring while torqueing
- More intensive use of pole-key shims and collar spacers

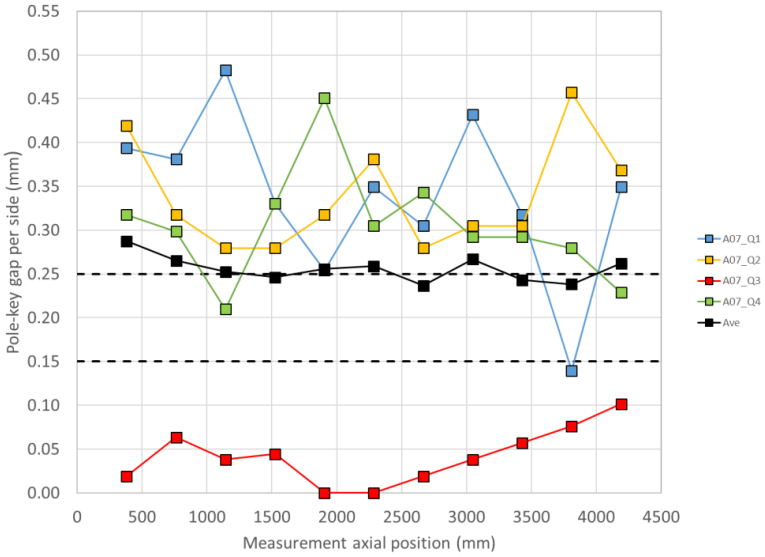




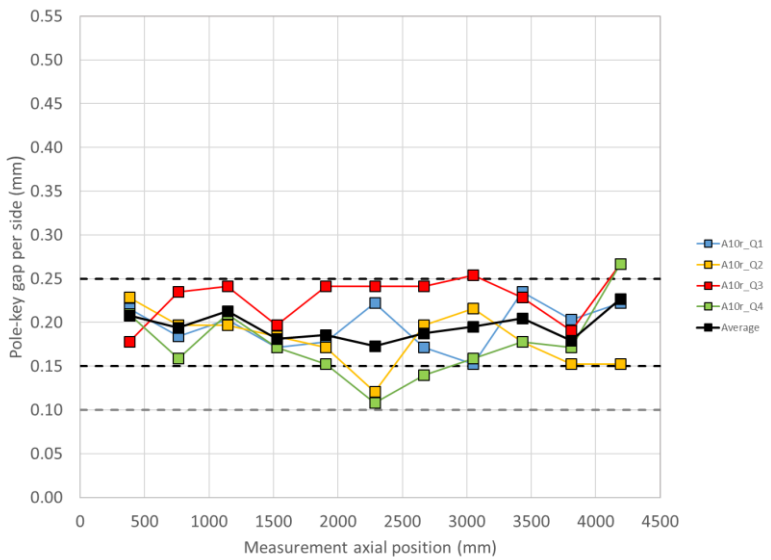
New specifications

- First we set a local minimum of pole key gap
  - Min. > 0.100 mm
    - Implemented in A10, which met the test requirements

MQXFA07



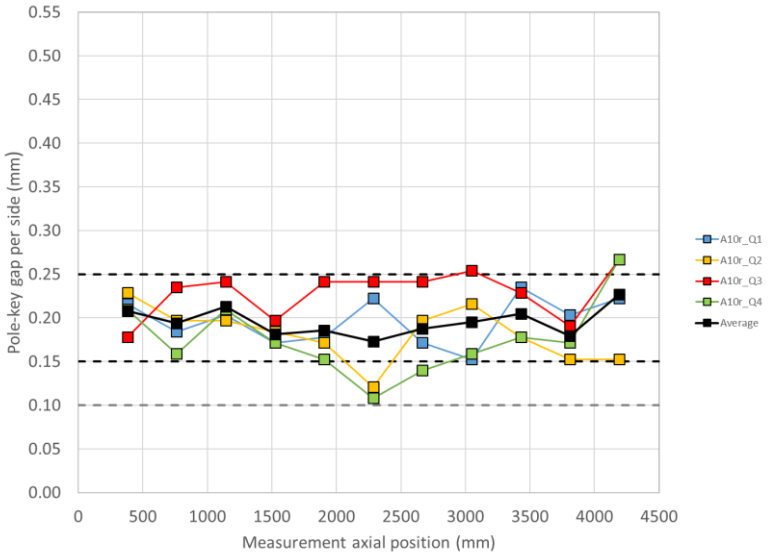
MQXFA10



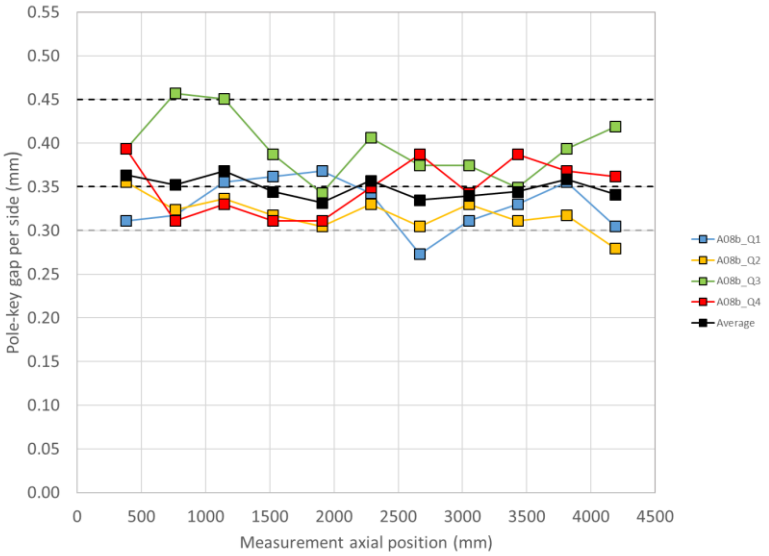
New specifications

- Then we increased the pole key gaps for the following magnets
  - Ave. > 0.350 mm, min. > 0.300 mm
    - Implemented in A8b

MQXFA10



MQXFA8b



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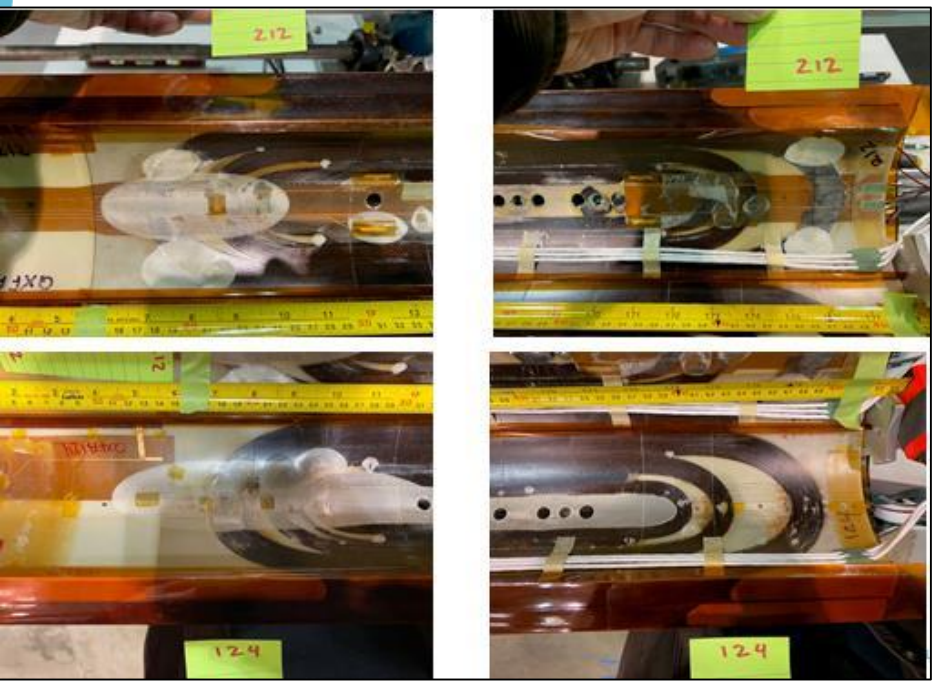
Conclusions

- MQXFA07-A08 limited by quenches in “a3a4 LE”
  - Interpretation: self-field instability triggered by a local degradation
- Post-test coil-pack meas. and coil visual inspection
  - Pole key gap closed in Q3 (quenching coil)
  - Covid impact on both coil and magnet fabrication
- 2D-3D finite element analysis
  - In Q3, lower ϑ pre-stress, more tension in wedge/end-spacer
    - Debonding → spike in coil axial tension → strand damage → self-field instability behavior
- Confirmed by metallographic inspection
  - Cracked filaments between resin and copper wedge
- New assembly procedure and target gaps implemented
  - Implemented in MQXFA10 that met test requirements

Appendix

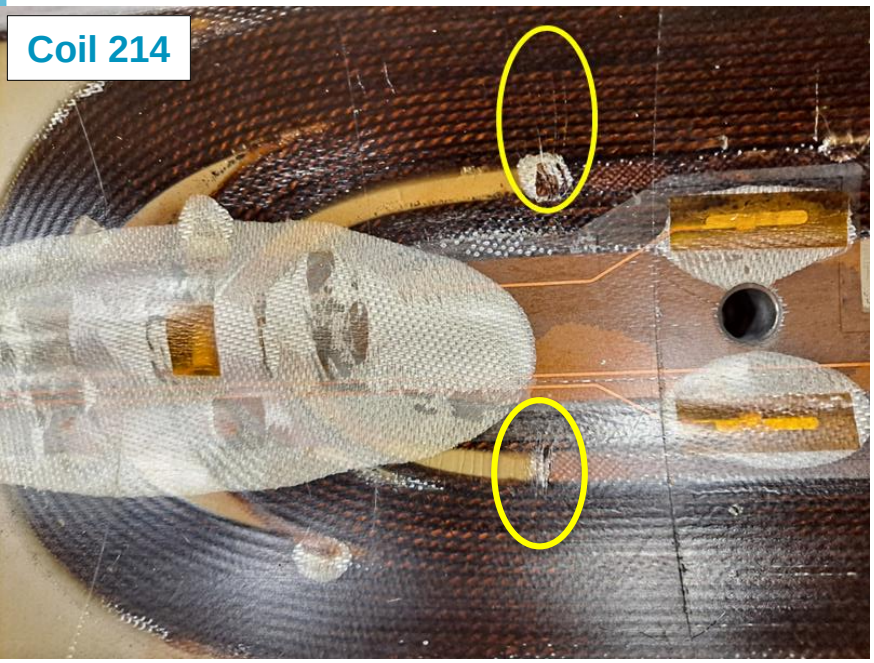
Coil visual inspection (II)

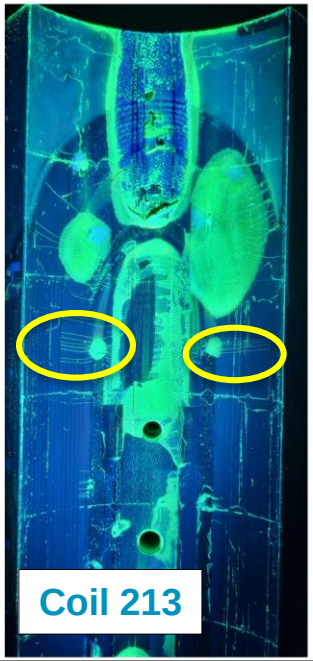
- The coil inner surface was characterized by many bubbles/blisters, predominantly on the LE
  - Also in the wedge/end-spacer interface



Die penetrant test

- Within the “critical zone” (a2a3…quench antenna…)
  - Bubbles/blisters also in the wedge - end-spacer interface
    - Observed in all coils
  - Horizontal cracks seen by die-penetrant test at CERN

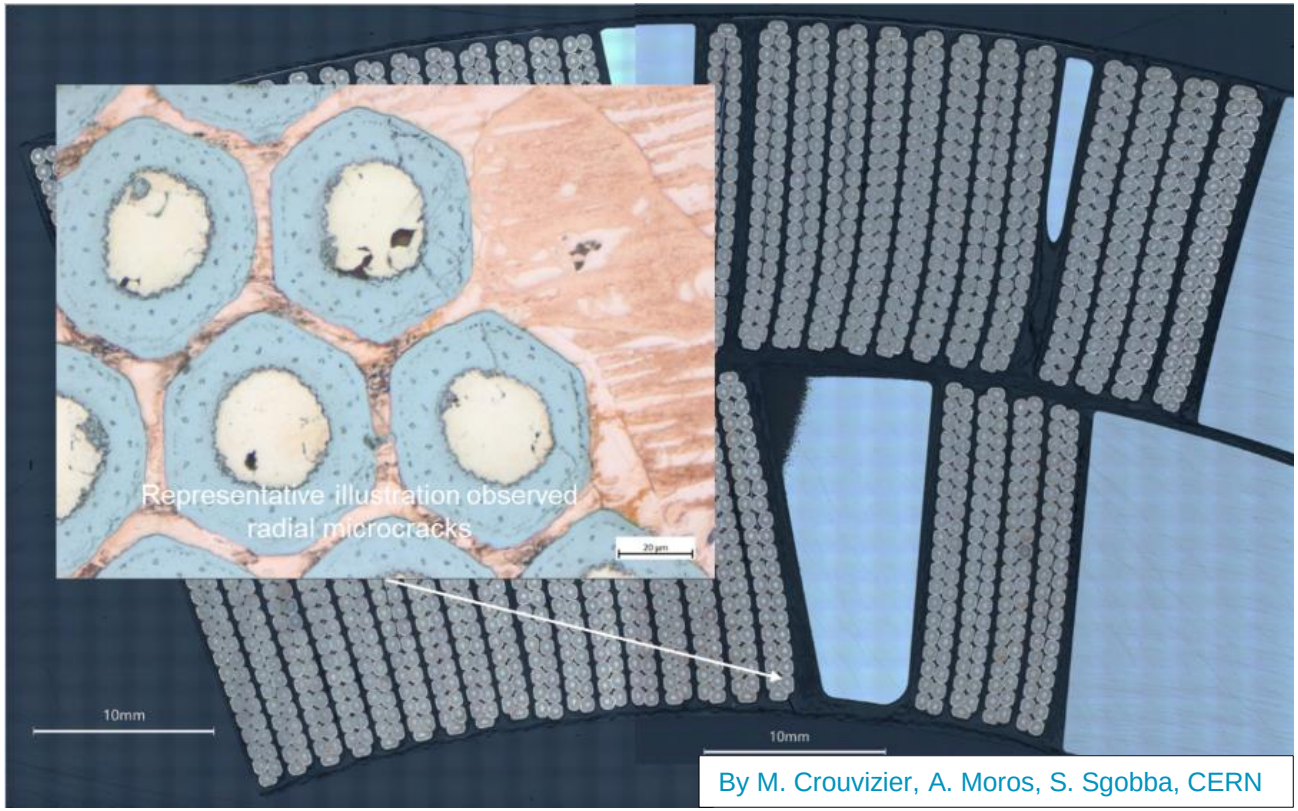




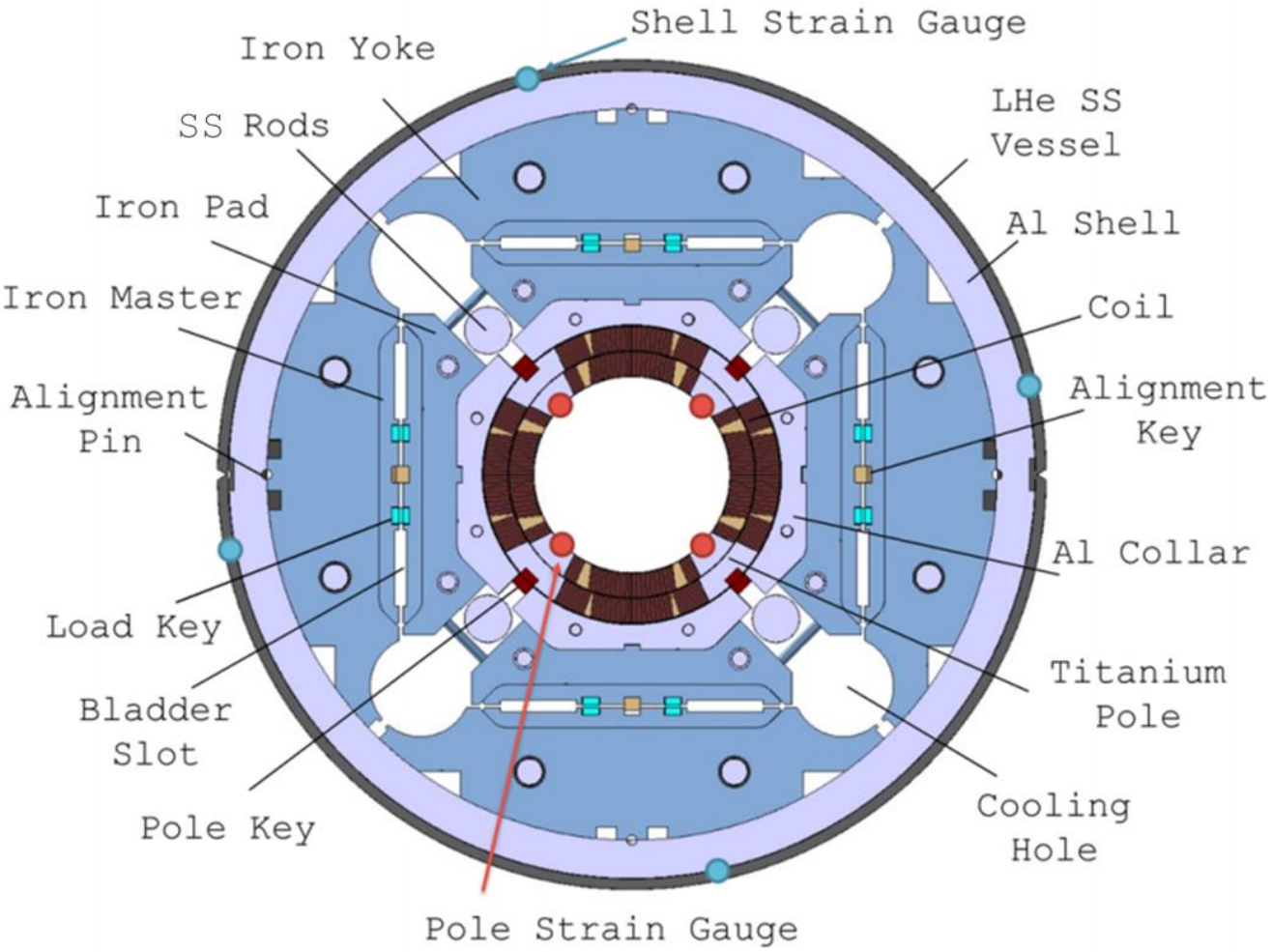
By Gonzalo Arnau Izquierdo, Alexandre Porret, CERN

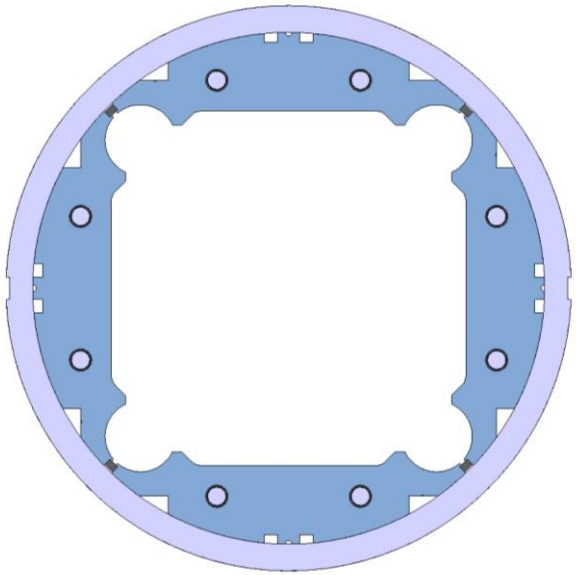
Metallurgical inspection

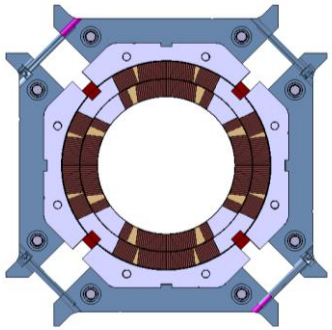
- Inspection of SC filaments did not reveal any major events.
  - Some radial “closed” microcracks can be observed
  - No collapsed filaments

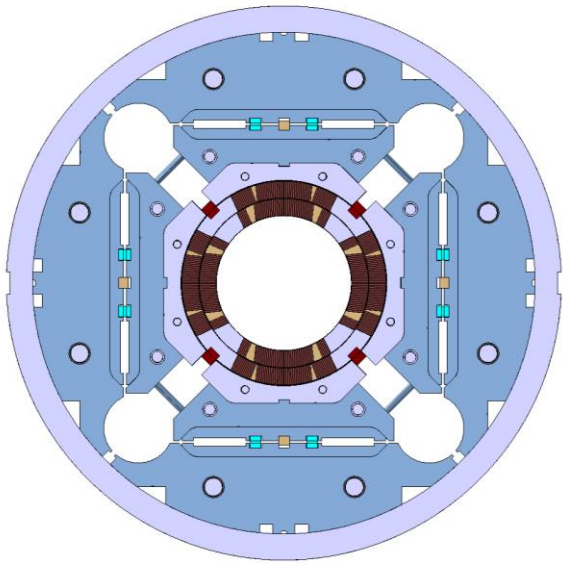


By M. Crouvizier, A. Moros, S. Sgobba, CERN

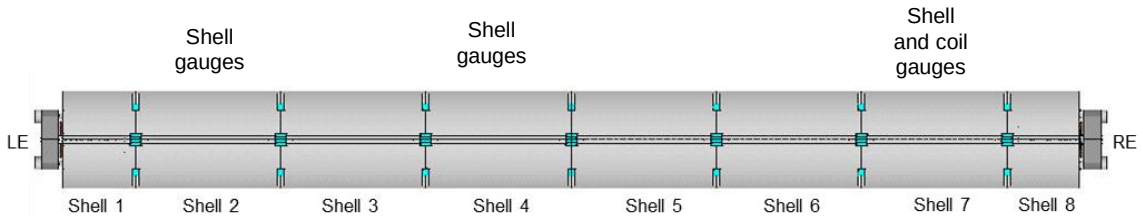

Shell Strain Gauge
Iron Yoke
SS Rods
Iron Pad
Iron Master
Alignment Pin
Load Key
Bladder Slot
Pole Key
Pole Strain Gauge
LHe SS Vessel
Al Shell
Coil
Alignment Key
Al Collar
Titanium Pole
Cooling Hole

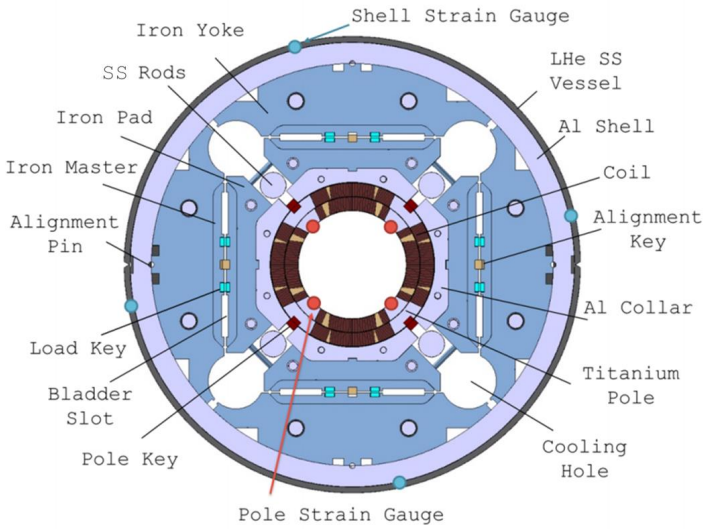






- On strain measurements….
  - Strain gauge locations
    - Shell: 3 axial location, 4 quadrants, azimuthal and axial
      - Shell 2, shell 4, shell, 7
    - Coil: 1 axial location, 4 coils (pole), azimuthal and axial
      - Center of shell 7
    - Axial rods: 1 axial location, 4 rods, axial





- On strain measurements….
  - Six fiber optic gauges installed on Q1 and Q2:
    - Three azimuthal (Z-gauges)
    - Three axial gauges (T-gauges)
  - They are located at three positions along the coils:
    - 700 mm
    - 1900 mm
    - 3800 mm