MQXFA Mechanical Assembly and Preload

Daniel Cheng,
For the MQXFA team
28-Sep-23

Acknowledgement

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  - BNL: K. Amm, M. Anerella, A. Ben Yahia, H. Hocker, P. Joshi, J. Muratore, J. Schmalzle, H. Song, P. Wanderer
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Outline

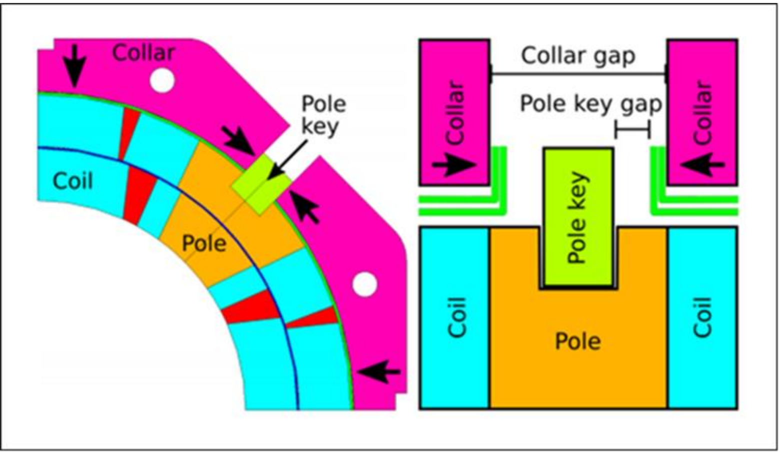
- Progress since last Collaboration Meeting
- MQXFA08b and MQXFA07b Rebuilds
- Lessons Learned and Specification Changes
- MQXFA14b and MQXFA16
- Summary and Conclusion

Progress Since the Last Collaboration Meeting

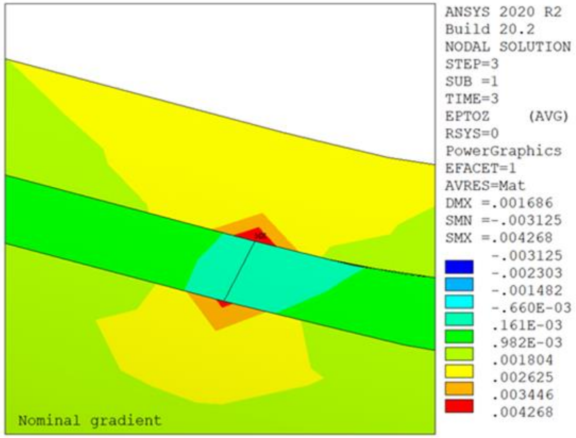
- MQXFA07b and MQXFA08b have been rebuilt
  - *Utilized the revised coil pack squaring procedures and updated gap specifications*
  - MQXFA08b was tested successfully
  - MQXFA07b will be tested in Nov 2023
- MQXFA11 tested successfully
- MQXFA14b was tested successfully
- Updated specifications based on lessons learned
- All Master Agreement orders for all major structures parts received Sep 2023

Recap: Lessons from MQXFA07/08 NCR

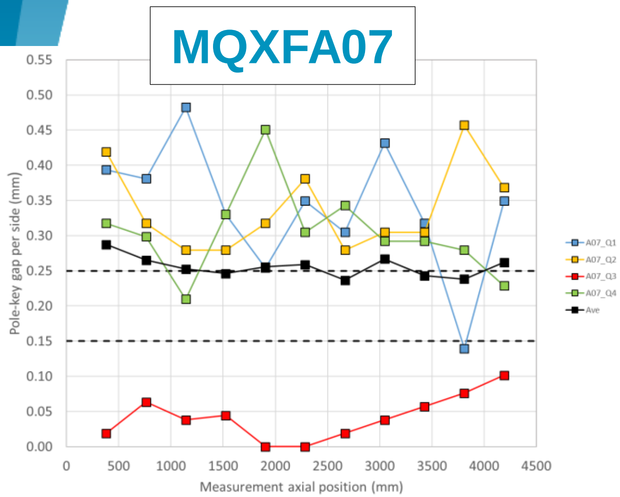
- MQXFA07 and MQXFA08 non-conformity analyses were completed (AUP doc-4293 & 4776; EDMS# 2777612)
  - "Smoking gun" (broken Nb_3Sn filaments) was found through metallographic analysis by CERN team
- Lessons learned:
  - Asymmetry during assembly may be looked-in by prestress
  - 2D asymmetry may cause poor preload in the ends
  - COVID restrictions contributed to these issues
- <u>Causes have been addressed for future magnets</u>

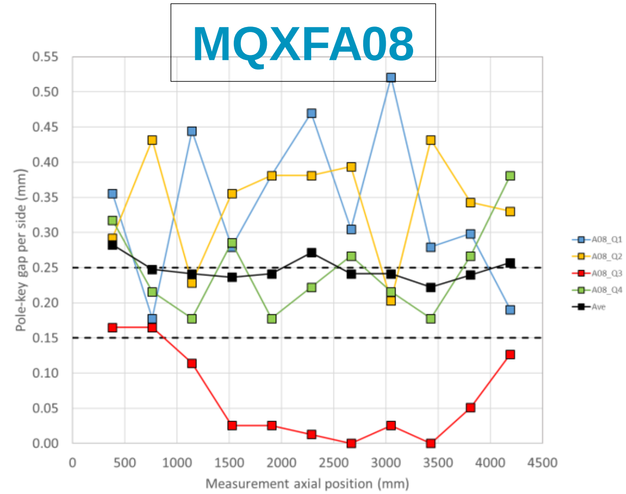


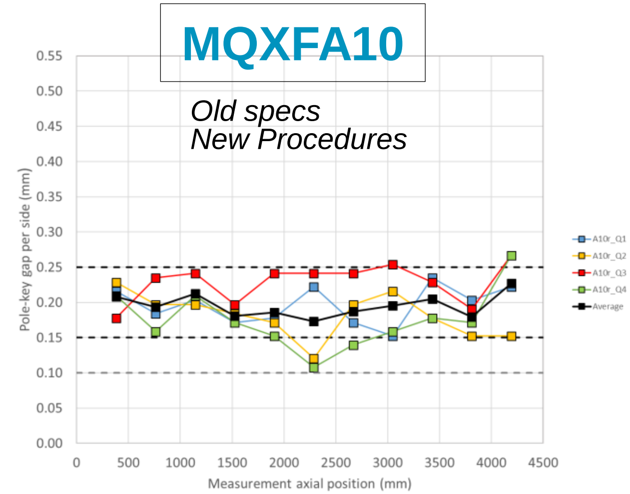
Closed pole key gap in a coil may lead to poor longitudinal preload in the ends of that coil at edge to end-spacer transition



Pole Key Gaps, Old and New Specs

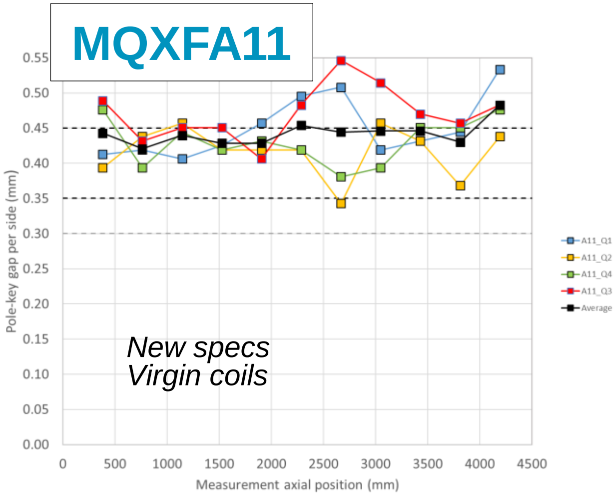


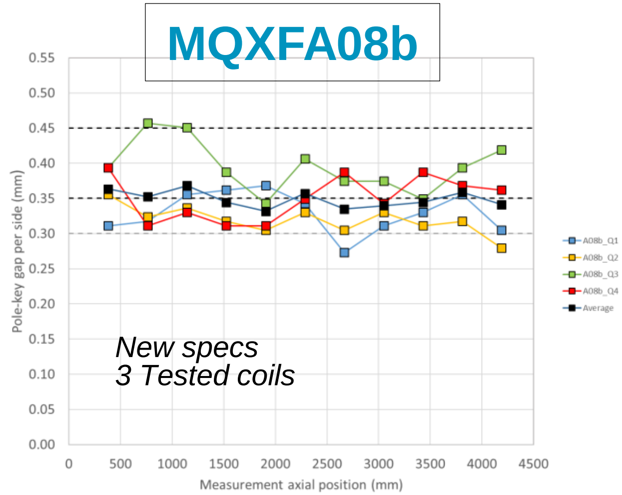


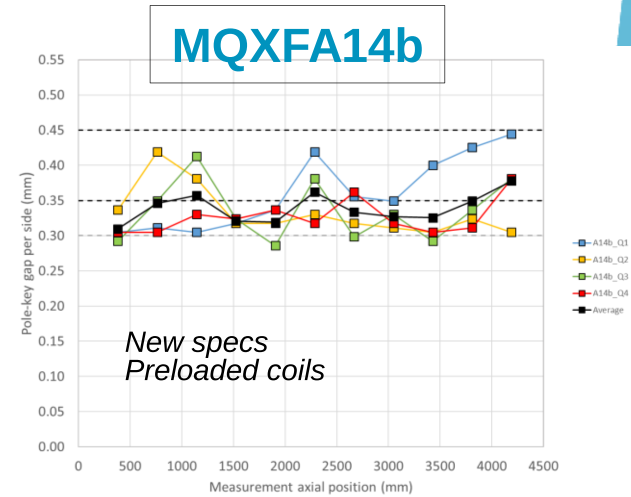


Updated Specification wording in Doc DB 4009 for the pole key gap:

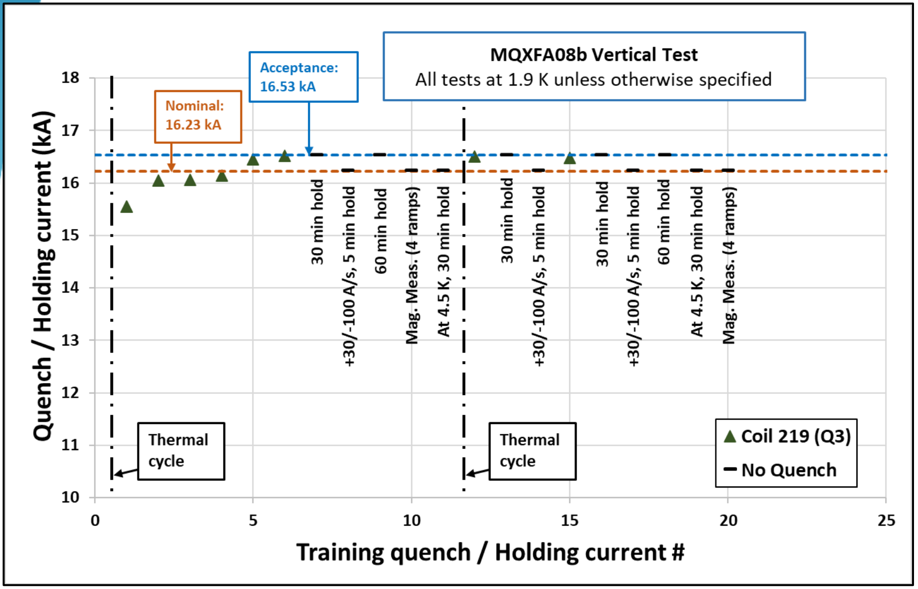
- ***The average pole key gap (per side) among the four coils on each longitudinal location shall be +0.400 ±0.050 mm.***
- ***The minimum pole key gap (per side) in any quadrant and in any longitudinal location shall be > +0.300 mm.***

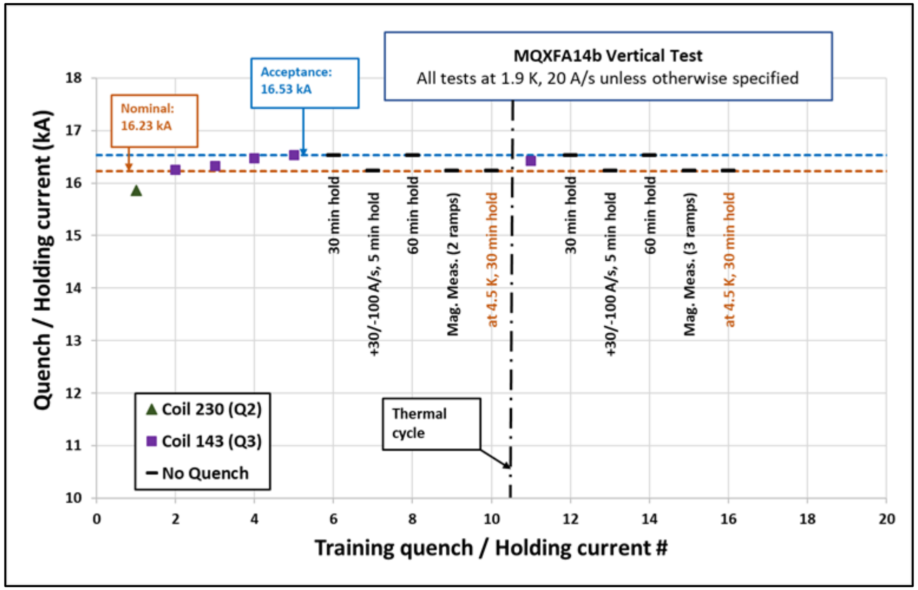


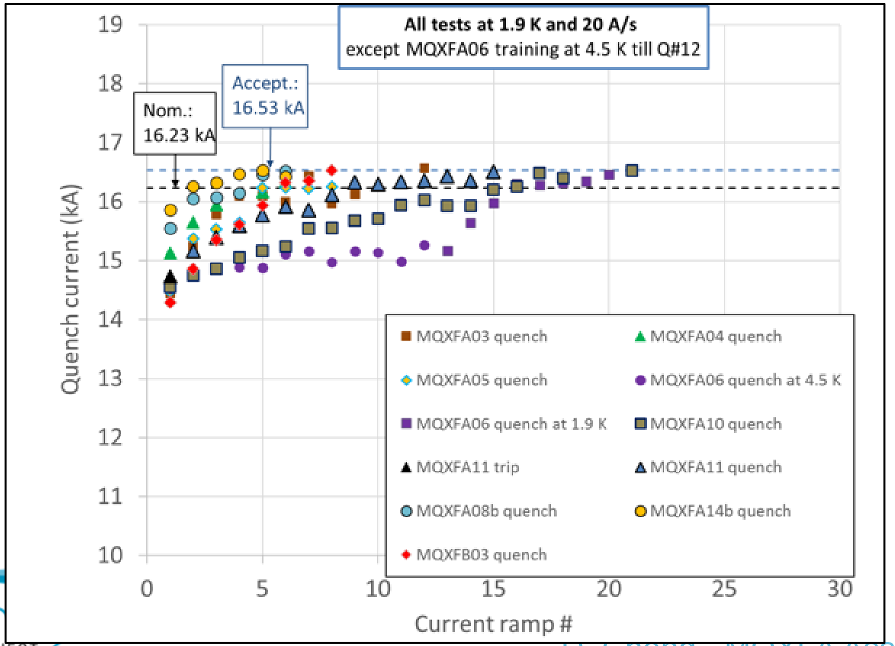




MQXFA08b and MQXFA14b







Outline

- Progress since last Collaboration Meeting
- MQXFA08b and MQXFA07b Rebuilds
- Lessons Learned and Specification Changes
- MQXFA14b and MQXFA15
- Summary and Conclusion

Magnets MQXFA03 to MQXFA15

- MQXFA12 and MQXFA14 both experienced electrical issues during the QC process
- MQXFA15 will be re-preloaded based on lessons learned from MQXFA13

Magnets Assembly & Test History

MQXFA03	VTS Tested OK	*LQXFA/B-01*	
MQXFA04	VTS Tested OK		
MQXFA05	VTS Tested OK	*LQXFA/B-02*	
MQXFA06	VTS Tested OK		
MQXFA07	VTS COVID Limitations, coil replaced	MQXFA07b	***TBT_1***
MQXFA08	VTS COVID Limitations, coil replaced	MQXFA08b	VTS Tested OK
MQXFA09	Assembly NCR (2 coils affected by folded Kapton)	***Cannibalized***	2 coils rejected 2 coils used in 14b and 5, structure used in 11
MQXFA10	VTS Tested OK	*LQXFA/B-03*	*LQXFA/B-04*
MQXFA11	VTS Tested OK		
QXFA12	Assembly NCR (Hipot fail) coils to be replaced	***MQXFA12b***	TBT_4
MQXFA13	VTS Limitations (end prestress), coil replaced	MQXFA13b	***TBT_3***
MQXFA14	Assembly NCR (QH hipot fail), coil replaced	MQXFA14b	VTS Tested OK
MQXFA15	***TBT_2***		

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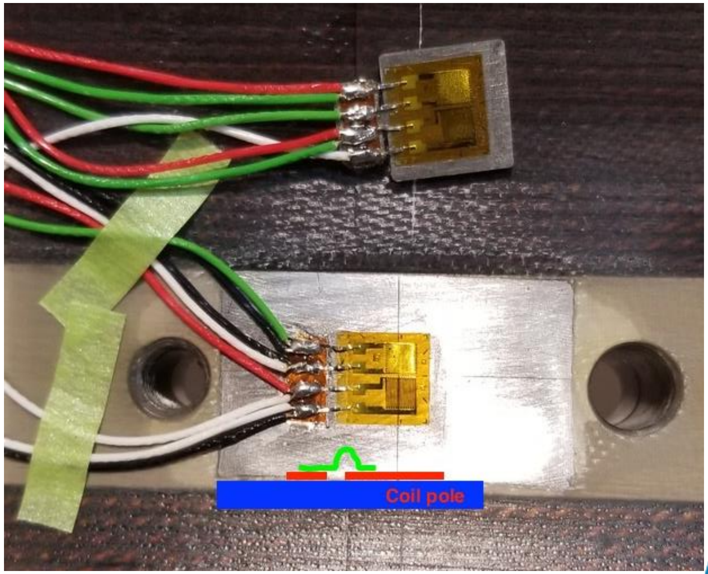
MQXFA12 Lesson: Strain Gauges and Hipot

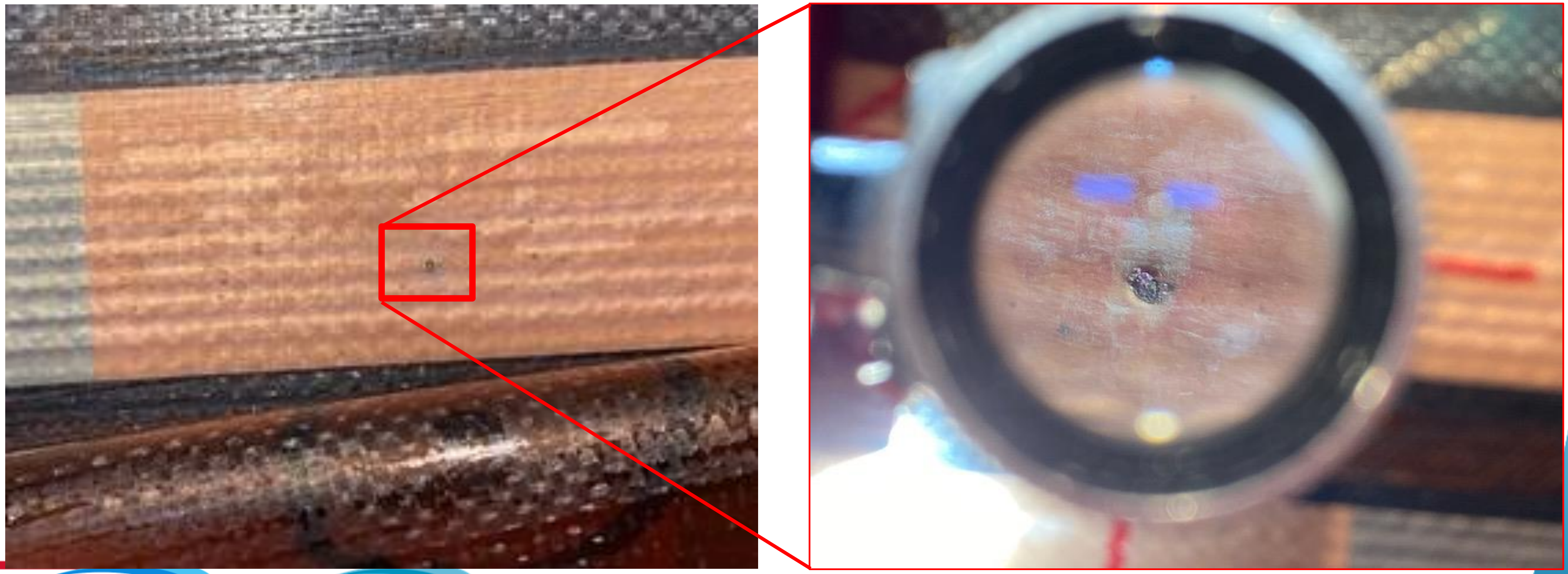
- Issue discovered during final EQC Hipot of MQXFA12 revealed potential weakness of SG to coil pole
  - Cause: SG pins of coils and shells were mixed on one connector

- *All tests after MQXFA08b have had coil SGs disconnected during final hipot test and magnet test campaign*
  - *Shells and Rods can still be present*



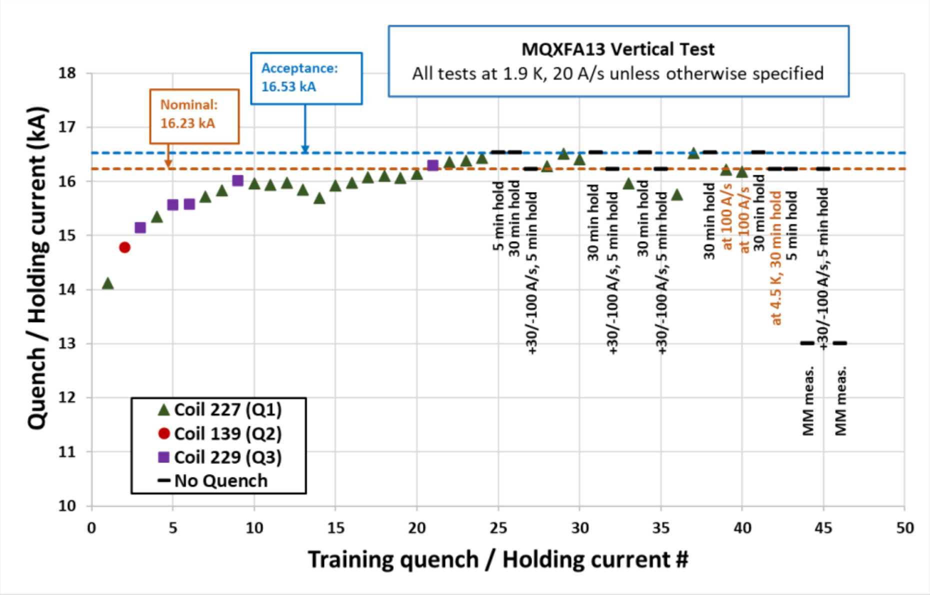
MQXFA14 QH Hipot failure

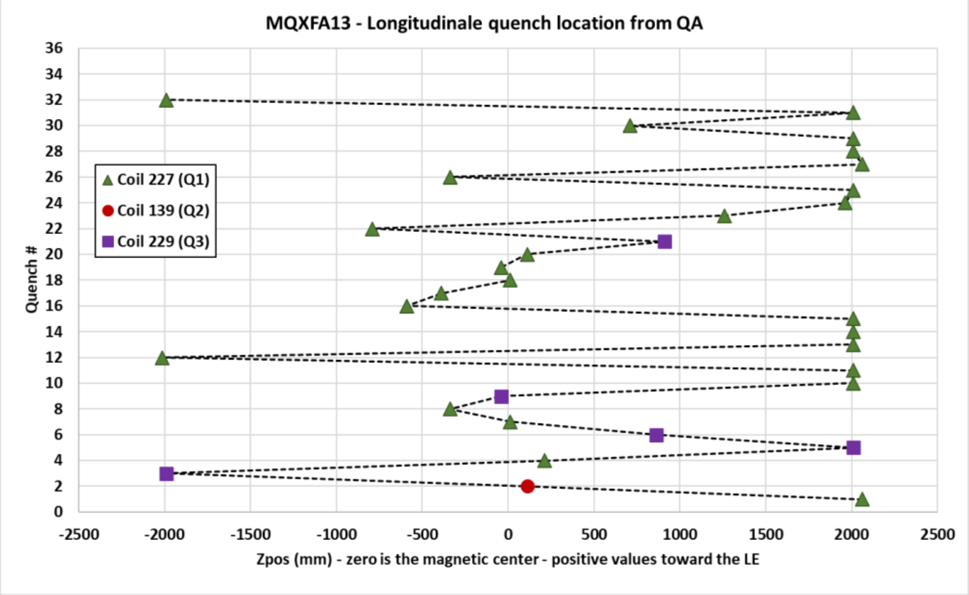
- Coil 142 developed a hipot failure from QH3 to coil during the EQC after preload
  - Glass bead puncture/burn was found upon disassembly
  - Replaced with Coil 217 from MQXFA09
- Similar anomaly was found in a MQXFA15 coil, and it was replaced with the other MQXFA09 coil
  - *Coil fabrication processes no longer use laser-cut fiberglass sheets*



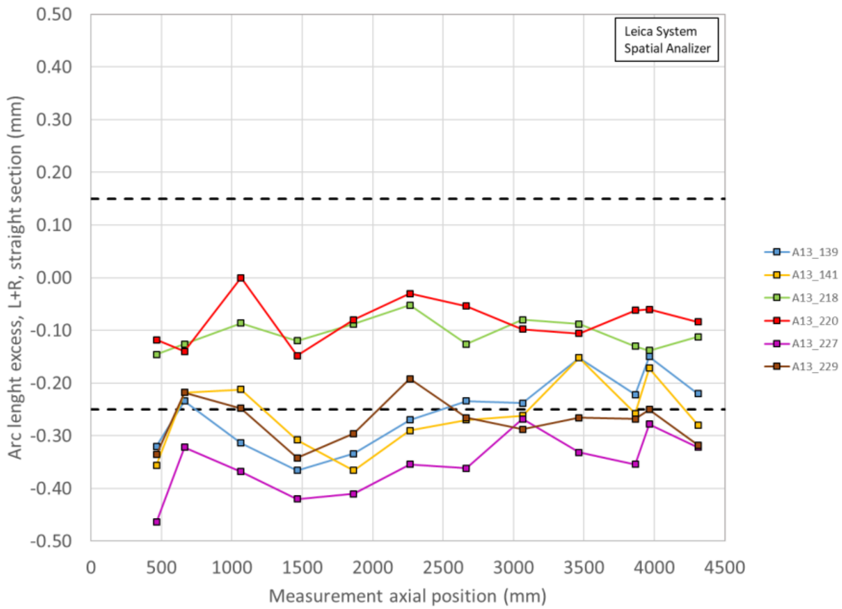
Lessons Learned from MQXFA13

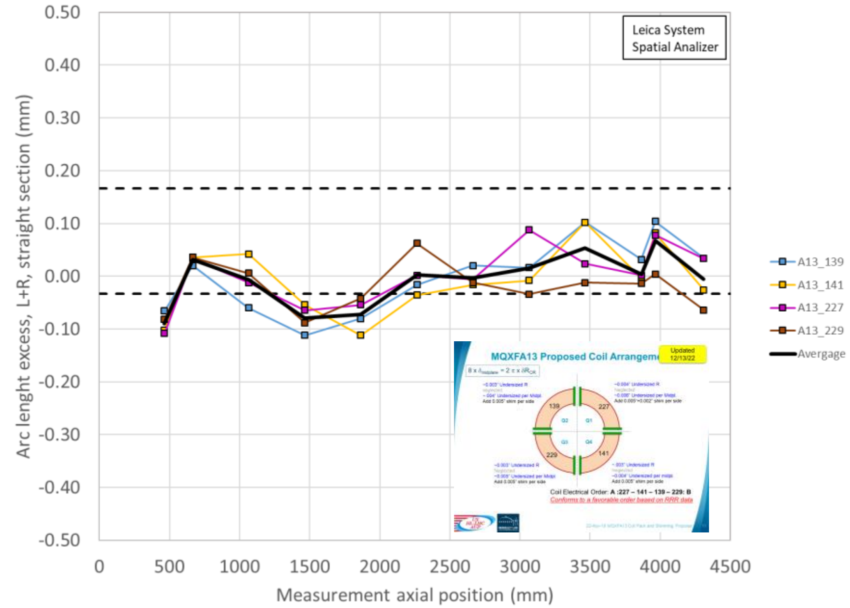
- MQXFA13 investigation
  - Quenches occurred at same location as in MQXFA07/08
- Main suspect: Small arc-length in the ends of all coils caused low pre-load and high strain in the ends.
  - Limiting coil had smallest arc-length of all tested coils
- Preventive actions:
  - Increased the maximum allowable stress during preload: from 110 to 120 MPa
  - Target for minimum loading key size based on coil dimensions



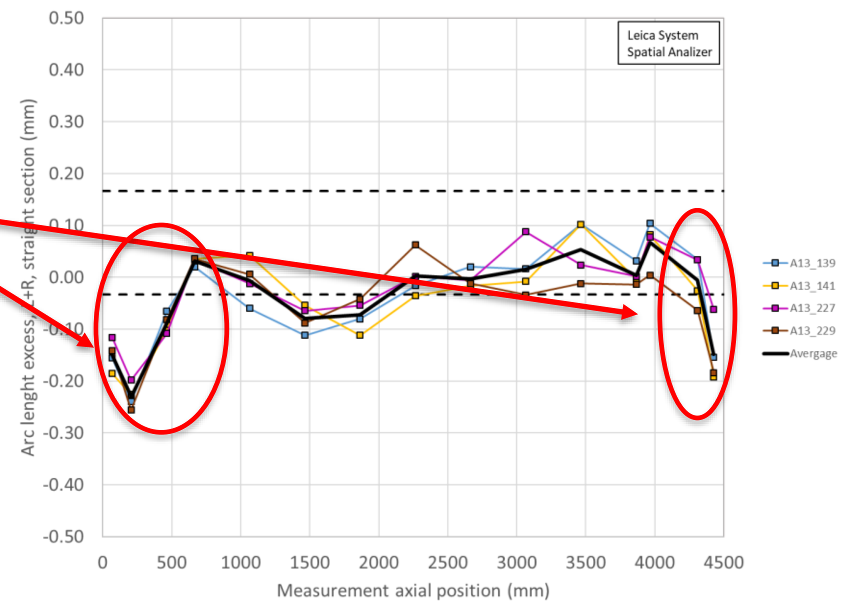


A13 coil size (unshimmed and shimmed)

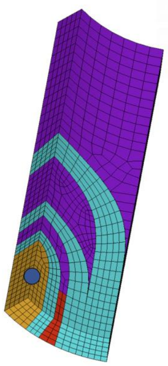


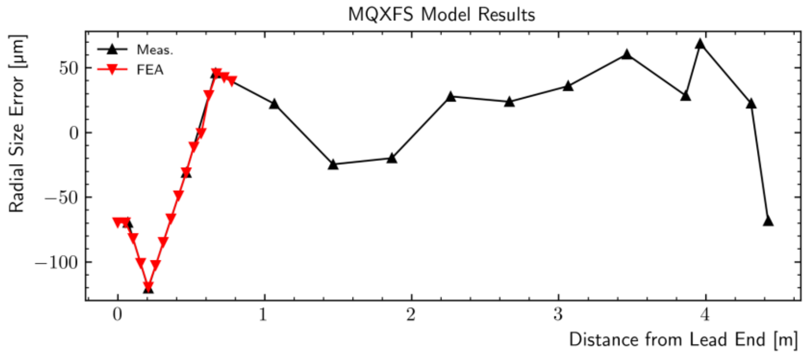


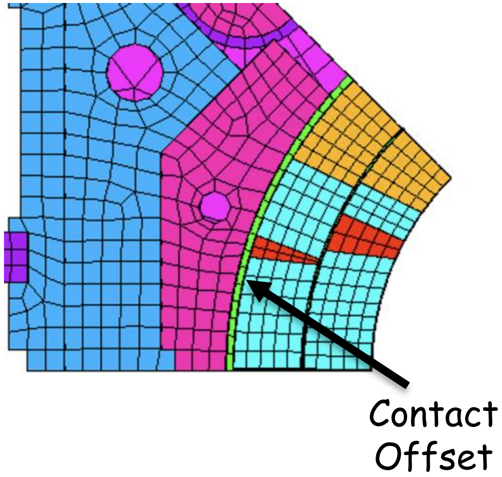
Significant reduction of coil size in the ends
Visible in all magnets



Finite element model assumption

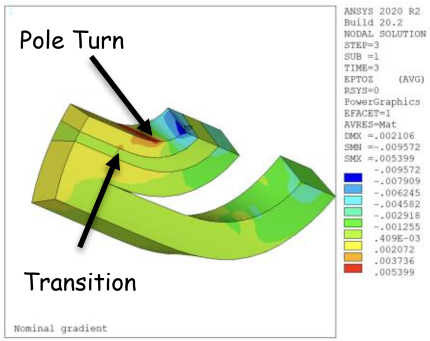




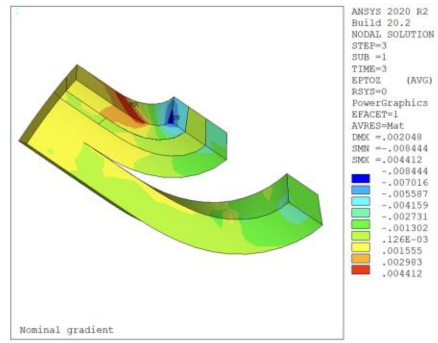


- Study of the impact of the coil pack size on the coil strain
  - in particular in the ‘wedge/end-spacer transition’ region

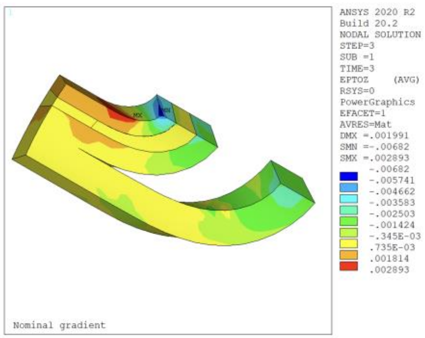
Peak Strain as a function of the pre-stress



A13 - 50 MPa



A13 - 80 MPa

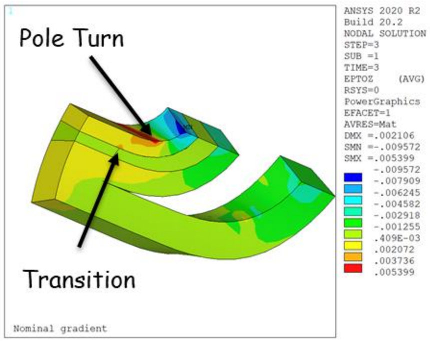


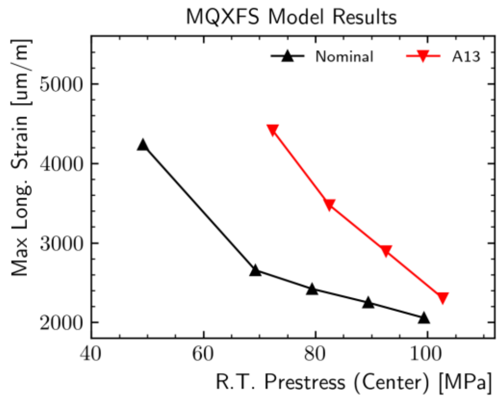
A13 - 100 MPa

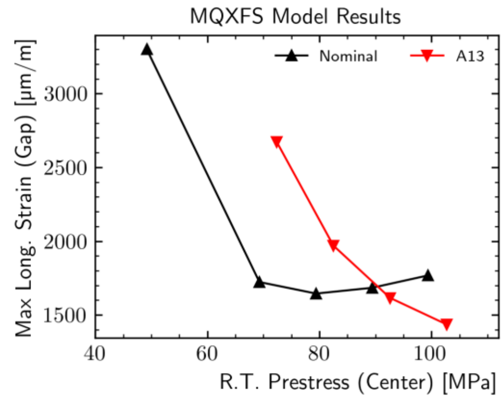
- Strain increases reducing the azimuthal prestress at R.T.
- Two critical locations:
  - Pole turn:

    Real peak might be lower because of some remaining pole turn bonding
  - Wedge/endspacer transition
    - Peak might be significantly higher due to the discontinuity (after a gap opens), not fully captured by the FE model

Peak Strain as a function of the straight section pre-stress

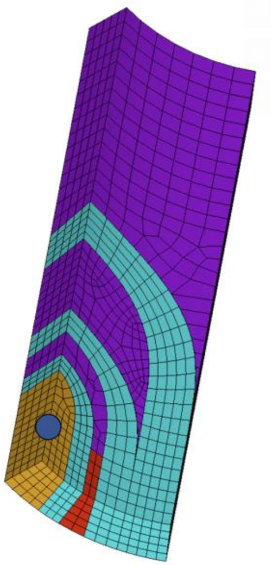


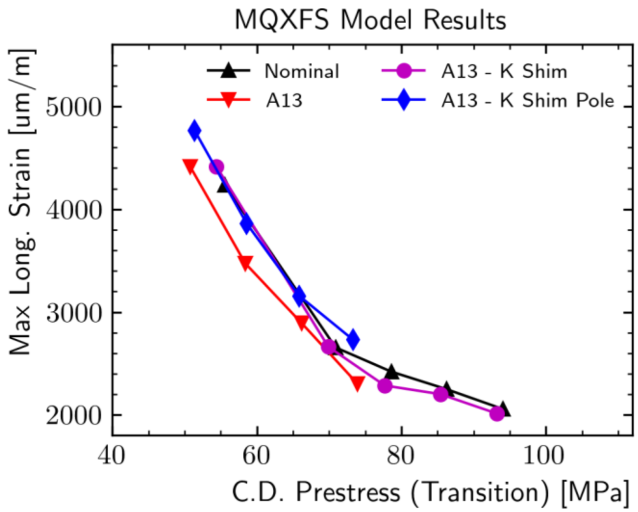




- The peak strain is a function of the applied prestress
- Effect on max strain on the transition seems similar:
  - A13 requires higher room temperature prestress to keep the strain below the ‘knee’

Peak Strain as a function of the local pre-stress





- Pole stress at cold computed on the same z location of the wedge/end-spacer transition
  - Blue/magenta lines represent end-region modifications
  - All the points are on the same lines!
- The effect seems to be controlled by a local prestress loss

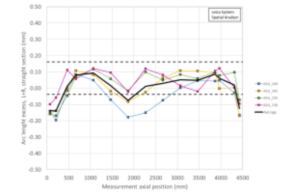
Conclusions finite element analysis

- The size variation of the coil can significantly increase the longitudinal strain in the ends
  - This effect is due to a local prestress loss in the end region

- Possible solutions:
  - Increase the prestress everywhere in the coil
    - *Revise specifications to allow excursion to 120 MPa maximum in coil*
  - Local prestress modifiers (e.g. different keys in the ends)
    - Currently under investigation

Summary
Coil radial (shimmed) deviation and key/shim size

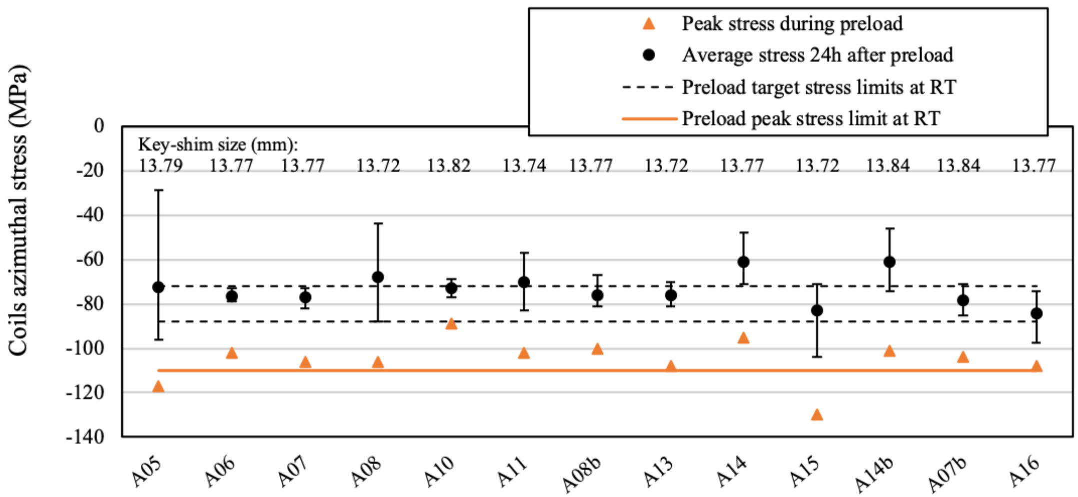
- In A13, small coils and small loading shim

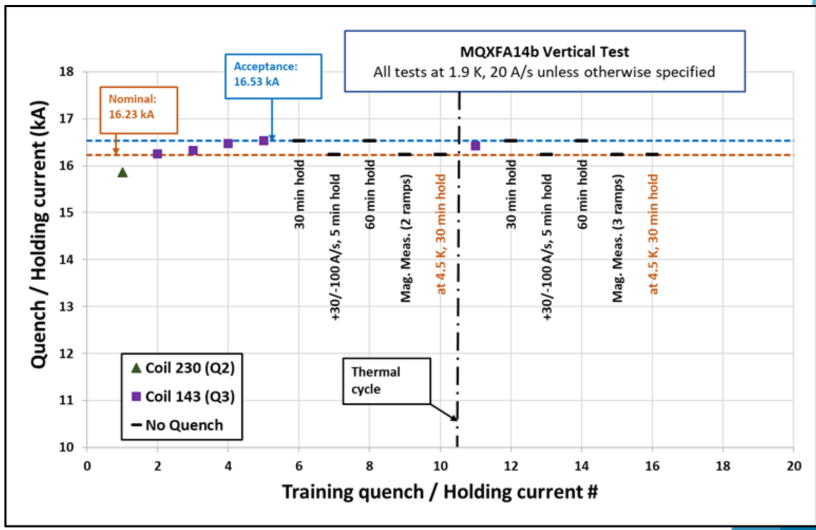


	Ave ss	LE min	RE min	Key	Shim	Shim	Ave ss + shim	LE + shim	RE + shim
	mm	mm	mm	mm	mils	mm	mm	mm	mm
A16	0.024	-0.089	-0.080	13.77	40	1.016	1.040	0.927	0.936
A15	0.001	-0.099	-0.045	13.72	38	0.965	0.966	0.866	0.920
A14b	-0.007	-0.129	-0.106	13.84	43	1.092	1.085	0.963	0.986
A13	-0.004	-0.146	-0.094	13.72	38	0.965	0.961	0.819	0.871
A8b	-0.001	-0.181	-0.136	13.77	40	1.016	1.015	0.835	0.880
A11	0.004	-0.125	-0.047	13.74	39	0.991	0.995	0.866	0.944
A10	-0.092	-0.222	-0.199	13.82	42	1.067	0.975	0.845	0.868
~~A8~~	~~0.029~~	~~0.216~~	~~0.171~~	~~13.72~~	~~38~~	~~0.965~~	~~0.936~~	~~0.749~~	~~0.794~~
~~A7~~	~~-0.035~~	~~-0.139~~	~~-0.114~~	~~13.77~~	~~40~~	~~1.016~~	~~0.981~~	~~0.877~~	~~0.902~~
A6	-0.046	-0.138	-0.178	13.72	38	0.965	0.919	0.827	0.787
A5	-0.024	-0.153	-0.105	13.79	41	1.041	1.017	0.888	0.936

MQXFA14b and MQXFA16 Preloads

- Magnets MQXFA14b and MQXFA16 have been preloaded with this criteria
- MQXFA15 will actually have its preload increased before testing
  - Will be shipped back from BNL in October 2023





Plans and Schedule

- Plans for magnet assembly:
  - MQXFA07b is at BNL for test
  - MQXFA15 preload adjustment in a couple of weeks after MQXFA16 is complete
  - MQXFA16 & MQXFA17 have high priority for test in CA05
  - MQXFA13b and MQXFA12b we be assembled following A16/17/15
  - MQXFA09 was retired
    - 2 coils and structure reused in other magnets

Two MQXFA assembly lines at LBNL

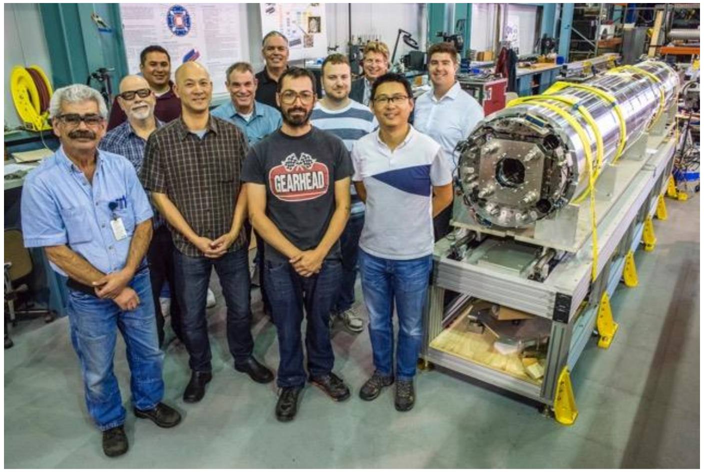
Working Schedule August update:

Magnet Assembly	P6 Schedule	
P6 Label	Start	Finish
MQXFA-16	8-Aug-23	11-Oct-23
MQXFA-17	20-Sep-23	22-Nov-23
MQXFA-18	15-Dec-23	23-Feb-24
MQXFA-19	2-Feb-24	5-Apr-24
MQXFA-20	15-Mar-24	17-May-24
MQXFA-21	26-Apr-24	1-Jul-24
MQXFA-22	10-Jun-24	13-Aug-24
MQXFA-23	23-Jul-24	25-Sep-24
MQXFA-R3	*16-Oct-24*	*26-Dec-24*
MQXFA-R4	*27-Nov-24*	*11-Feb-25*

Summary and Conclusions

- All major parts procurements have been completed
- Three magnets out of eleven did not meet requirements during vertical test. Lessons were learned and changes implemented.
  - Revised specifications from MQXFA07/08 limitations have been successfully implemented in subsequent magnets
  - Lessons learned from the MQXFA13 test has been successfully applied to MQXFA14b: revising specifications and defining load key shim sizes
- Last magnet to be completed around beginning of 2025

Thank you for your attention!



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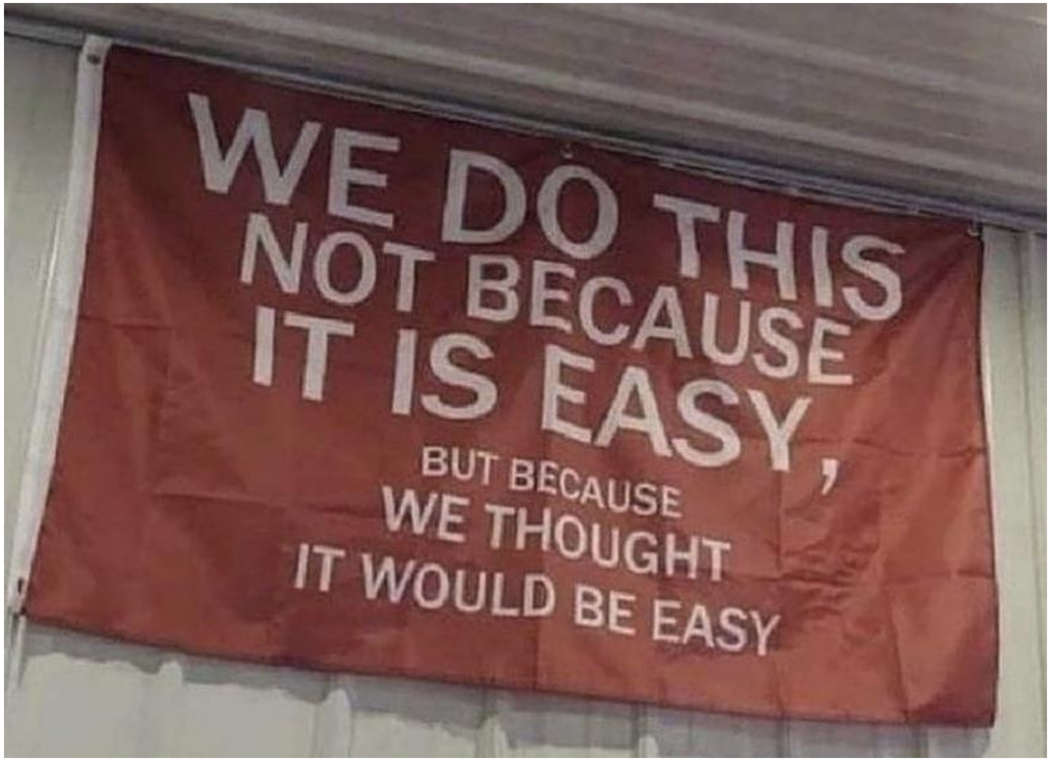
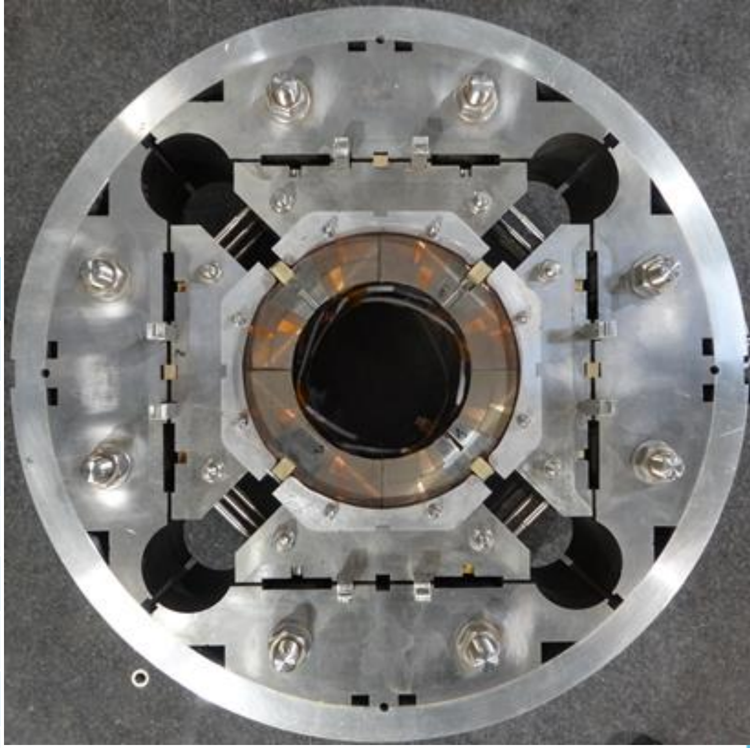
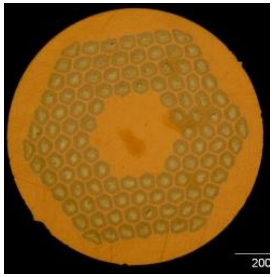


Back up Slides

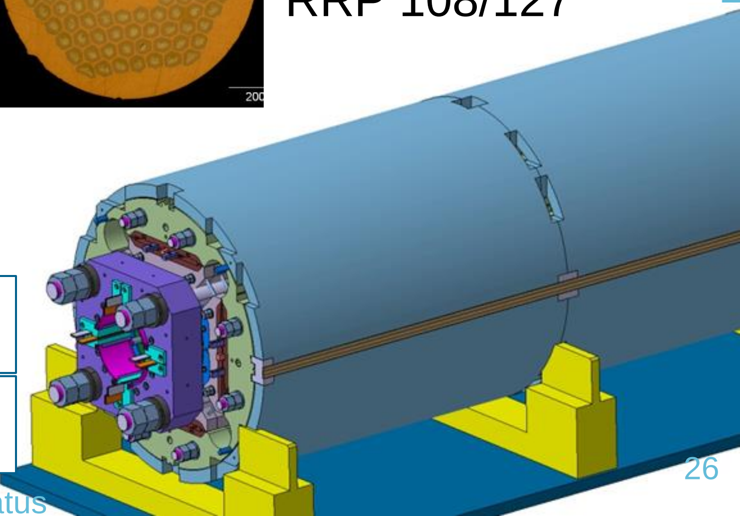
MQXFA/B Design

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.2
Nominal current	kA	16.23
Peak field at nom. current	T	11.3
Stored energy at nom. curr.	MJ/m	1.15
Diff. inductance	mH/m	8.26
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4





Nb_3Sn Conductor
RRP 108/127



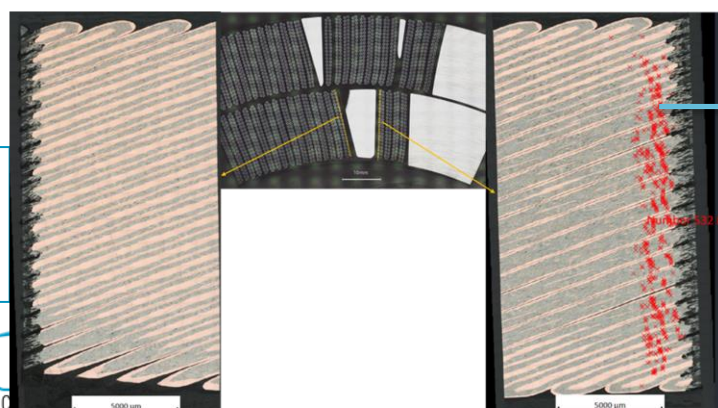
P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

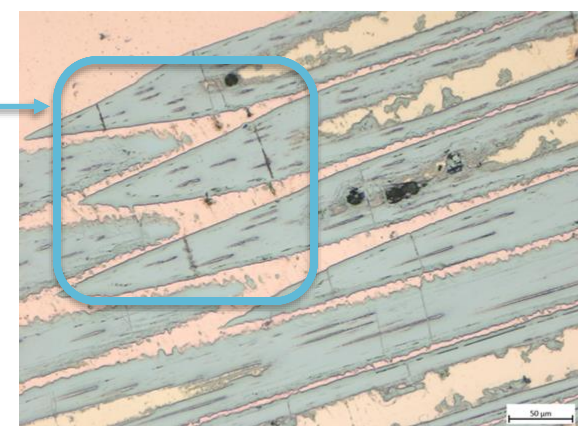
G. Ambrosio et al., "First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC" NAPAC16, FERMILAB-CONF-16-440-TD

Lessons Learned from MQXFA07/08 NCR

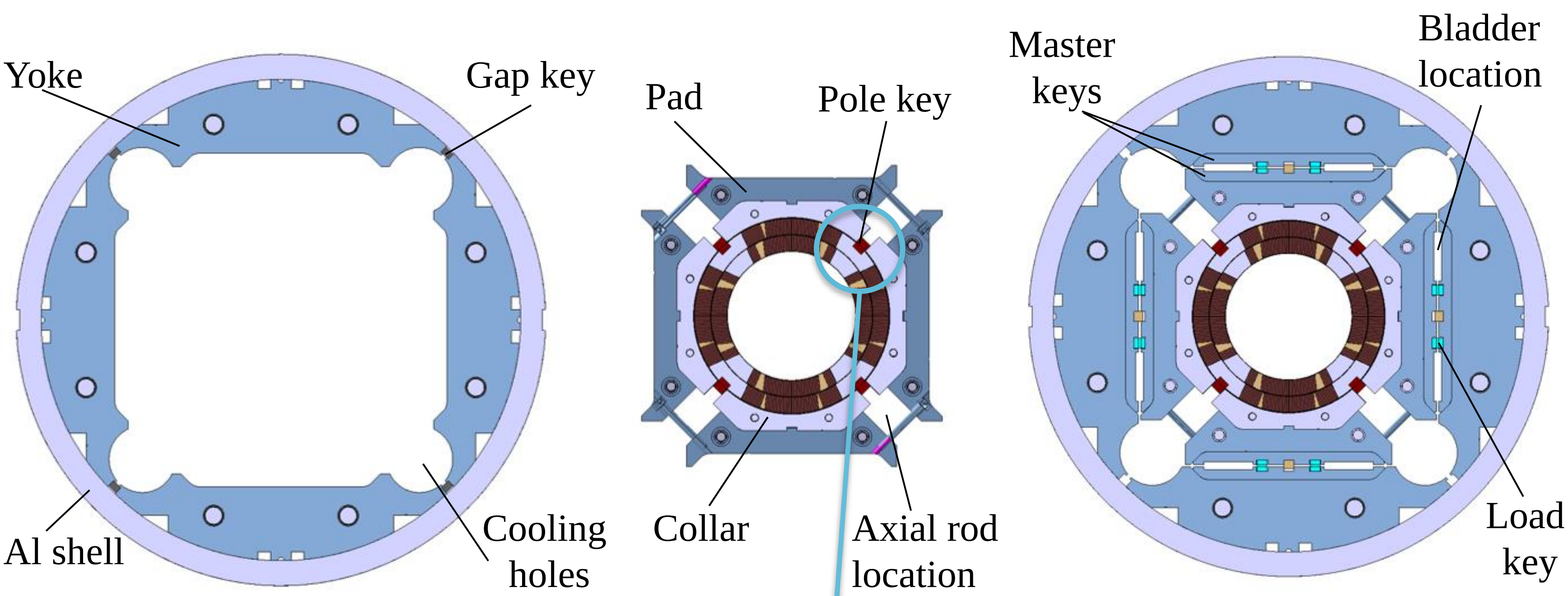
- MQXFA07 and MQXFA08 non-conformity analyses are complete (AUP doc-4293 & 4776; EDMS# 2777612)
  - Smoking gun (broken Nb_3Sn filaments) was found through metallographic analysis by CERN team
  - Two lessons learned:
  - ➔ **COVID attribution: 67%**
  - *Dedicated presentation in Magnet parallel session*
- <u>All causes have been addressed for future magnets</u>

Cable sections with broken filaments (red marks)



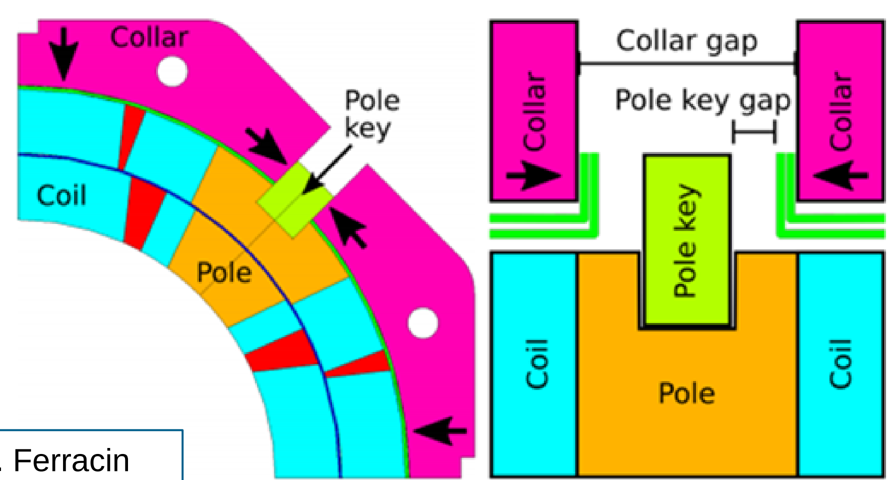


Structure Analysis & MQXFA07 Disassembly



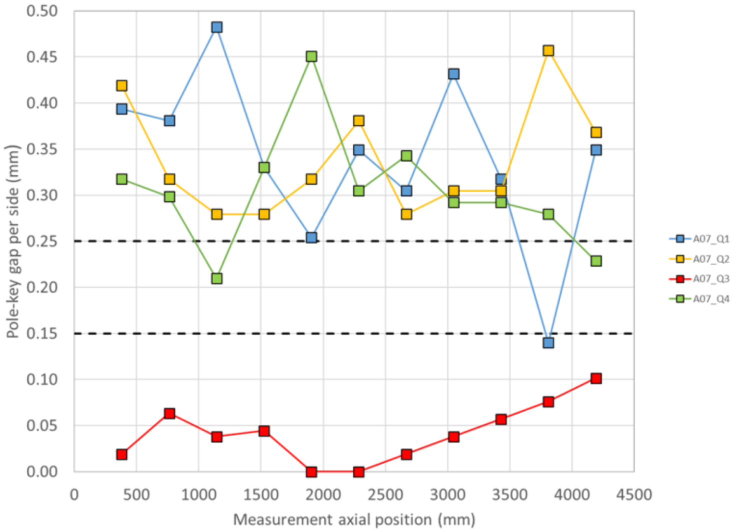
A pole-key gap asymmetry was found during MQXFA07 and MQXFA08 disassembly:

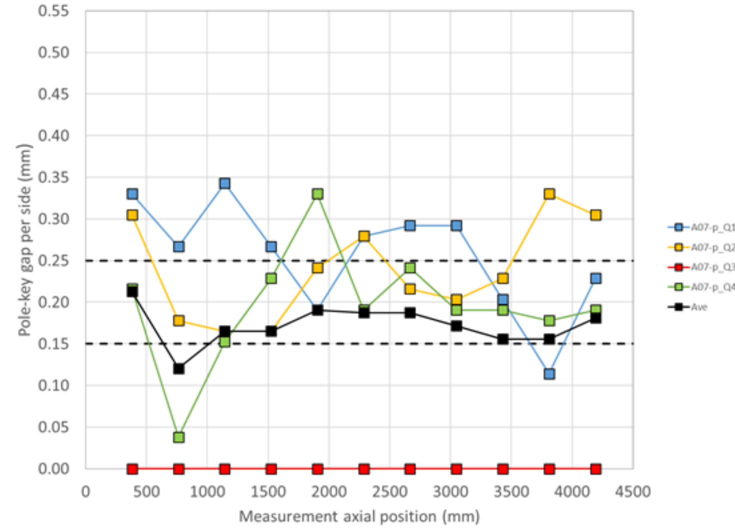
- Gaps closed in quadrant 3
- Gaps open in other quadrants



Courtesy of P. Ferracin and D. Cheng

Pole-key gaps in MQXFA07





- The measured **pole-key gaps** were not as **uniform** in MQXFA07 and MQXFA08 as in past magnets; this is particularly apparent on the **limiting coils** (**Q3** for both magnets)

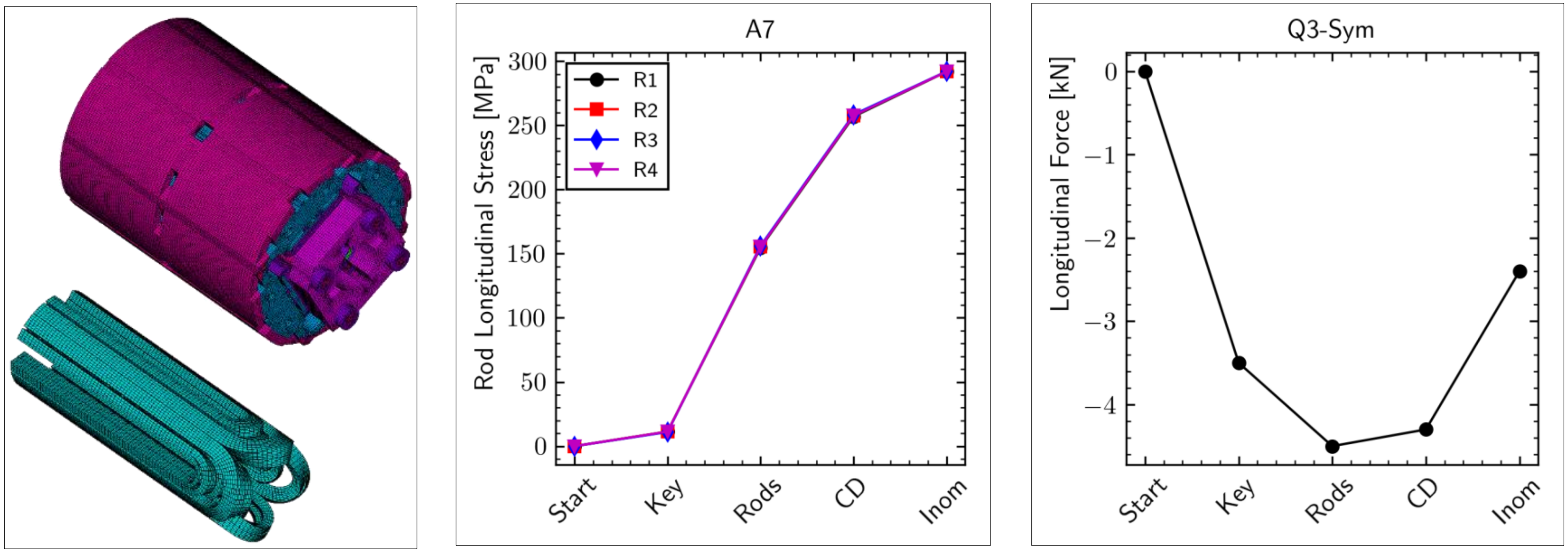
- Only the **total average** (on the 4 keys) was targeted in the **specification**. The underlying assumption was that the **gaps** would be **redistributed** across coils during **loading**.

- **Investigation** of the effect of this non-uniformity on the mechanical performances with **2D** and **3D** FE **models**
  - **2D effect: preload variation within acceptable range**

Courtesy of P. Ferracin and D. Cheng

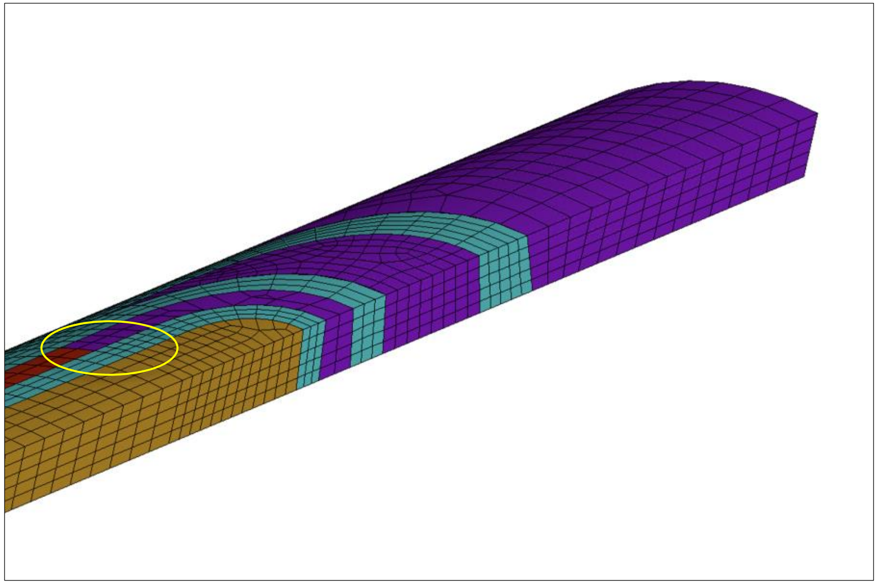
Finite element analysis
360-degrees, full cross-section 3D model

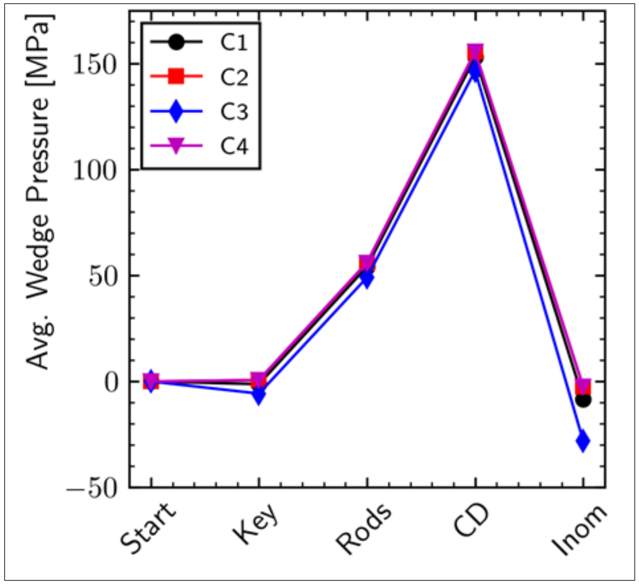
- Axial behavior
  - No difference in the rods stress, but less force axial pre-load on the Q3 coil
    - Lower azimuthal pre-stress results in less friction coil-structure → "axially softer coil"



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

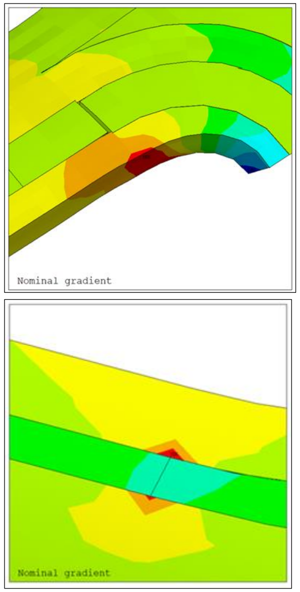
- "a3a4 LE area"
  - Contact between wedge and end spacer in L1
  - Considering bonded conditions
    - Tension occurs in Q3 during excitation

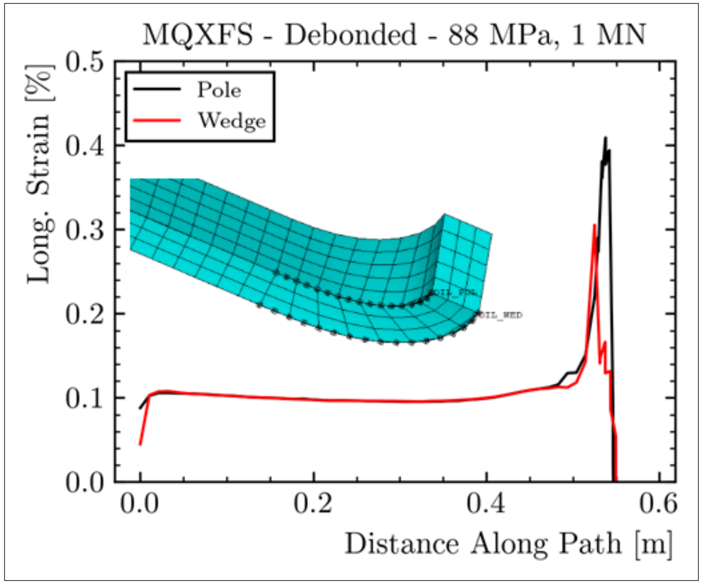




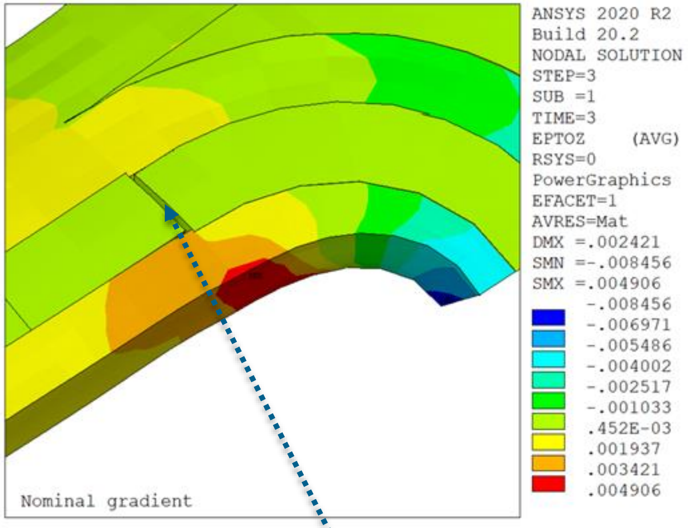
Finite element analysis
45-degrees, octant 3D model

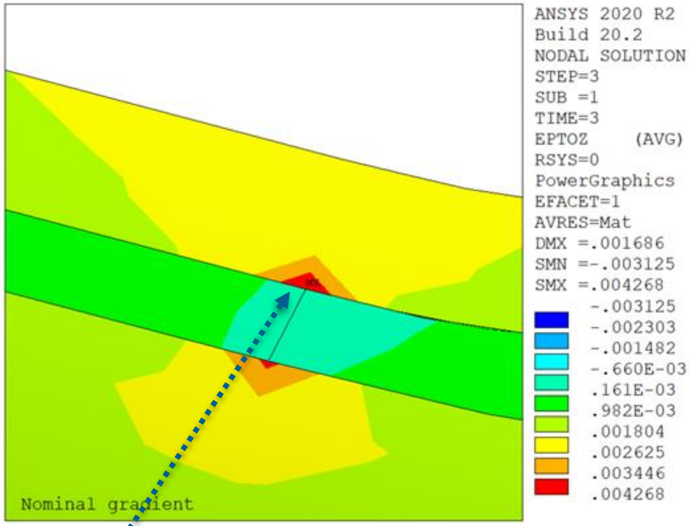
- More detailed analysis with refined meshed
  - Not bonded, so as if epoxy cracking has occurred
  - The gap between wedge and end-spacer, induces a spike in axial strain in the coil, which can reach the 0.4% level
    - larger increase in the turn towards the pole.





Possible Damage at Wedge-Spacer Interface





- **At cold** the coil with less azimuthal preload ends up with **less longitudinal preload**
- **At nominal current** tension develops between the inner wedge and the end spacer, and a (small) **gap** may open
- This may result in high **longitudinal strain** (up to **0.4%**) in that location
  - This location is consistent with quench data
  - Effect is larger on the pole block, but also visible on the mid plane block

LL2

Courtesy of G. Vallone and P. Ferracin