MQXFA03 Preload and Outlook on Pre-Series

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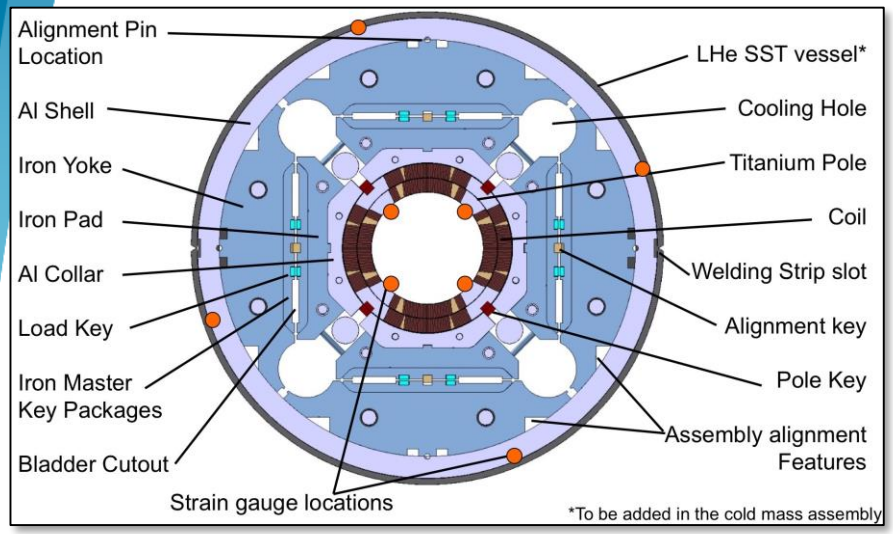
Outline

- Introduction
- Differences between prototypes and pre-series
- Lessons Learned
- Magnet Assembly Processes
- MQXFA03 and Outlook for Pre-Series
- Summary

Differences between Prototypes and Pre-Series



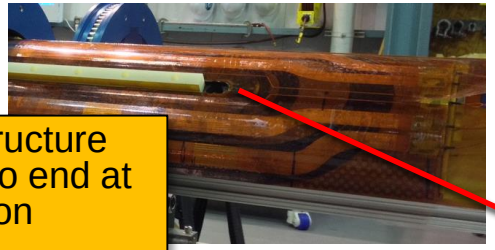
All MQXF magnets have the same cross section

MQXFAP1a/b
1st Prototype
4.0 m mag. length
QXFP Coils
4.56 m yoke length

MQXFAP2
2nd Prototype
And Pre-Series
4.2 m mag. length
QXFA
4.56 m

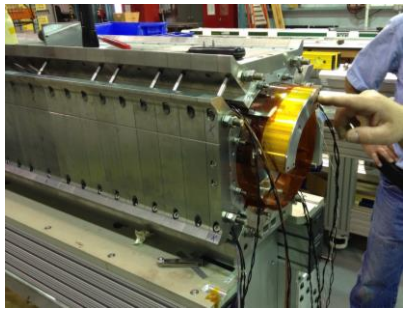
Pre-series structures also have modified shell cutout geometry to reduce stresses

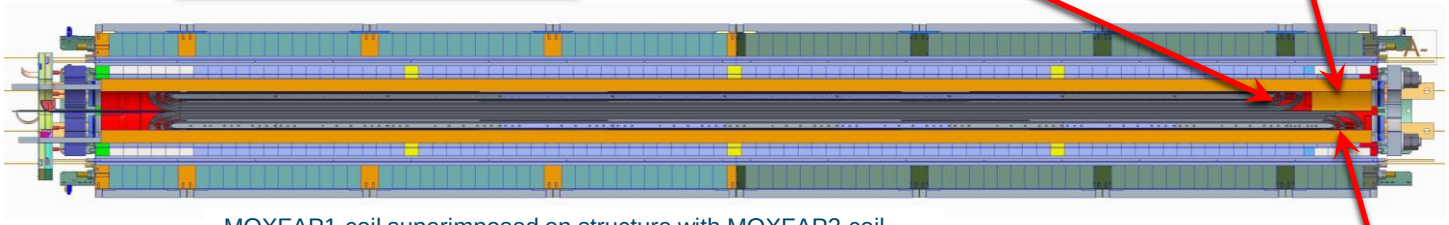
G11 pole alignment keys ended at straight section in MQXFAP1



Pre-series structure pole keys also end at straight section

Stainless steel spacers used as coil extenders for MQXFAP1



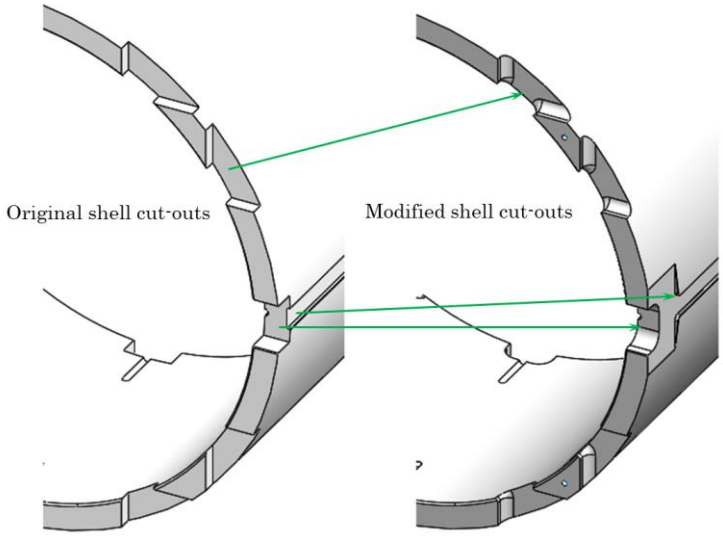


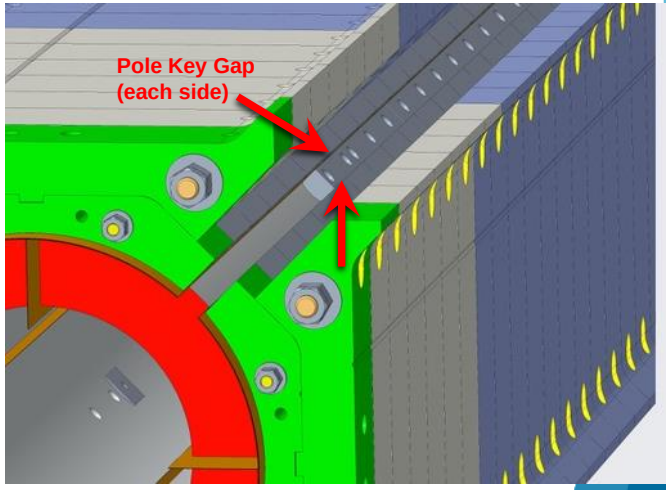
MQXFAP1 coil superimposed on structure with MQXFAP2 coil

Full-length G11 pole alignment keys were used in MQXFAP2

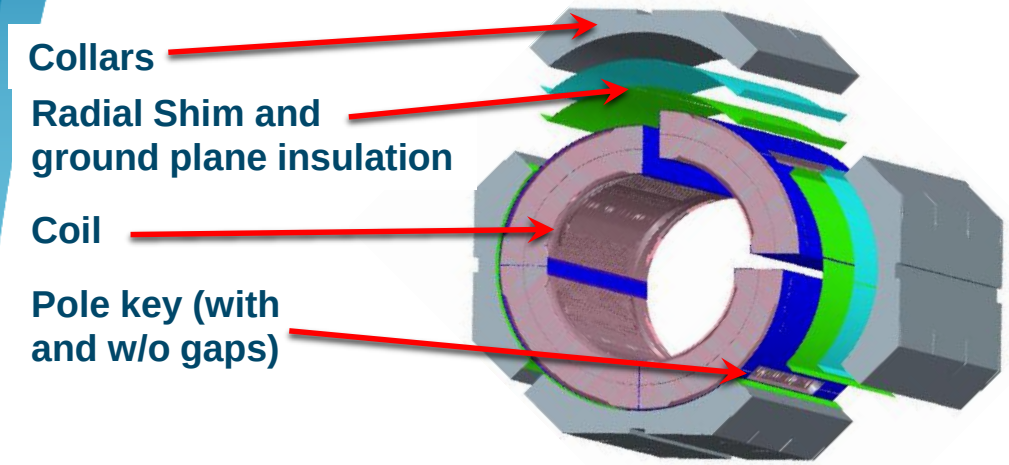
Lessons Learned, Applied to Pre-Series

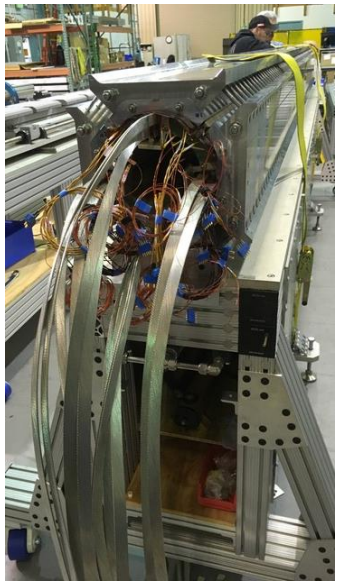
- Shell Design Criteria has since been implemented
  - 10-15 mm radii in the cutouts, end shells modifications
  - Class AA UT inspection of forgings
  - Dye penetrant inspections post-machining
- Reducing shell stress by increasing the pole key gaps
  - Targeting 100-150 μm per side
- Change in Preload operations
  - Evidence suggests a possible path-dependent damage of coil wedge-end spacer interface
  - Preload operations to now incorporate initial axial end load contact, followed by 50% azimuthal & 50% axial, then final azimuthal and full axial preload



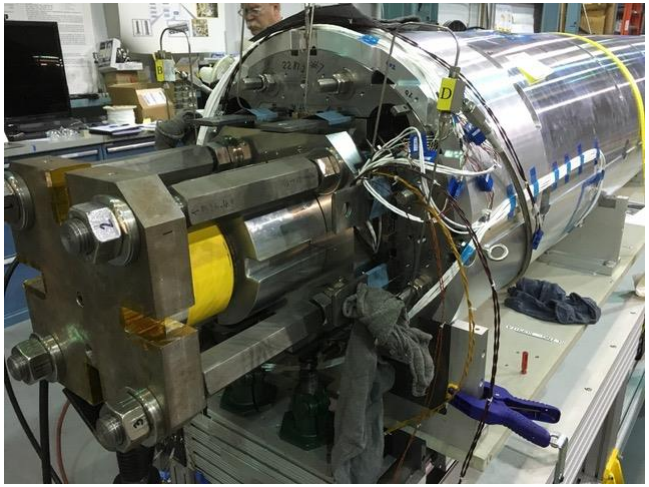


Assembling the MQXFA Magnet



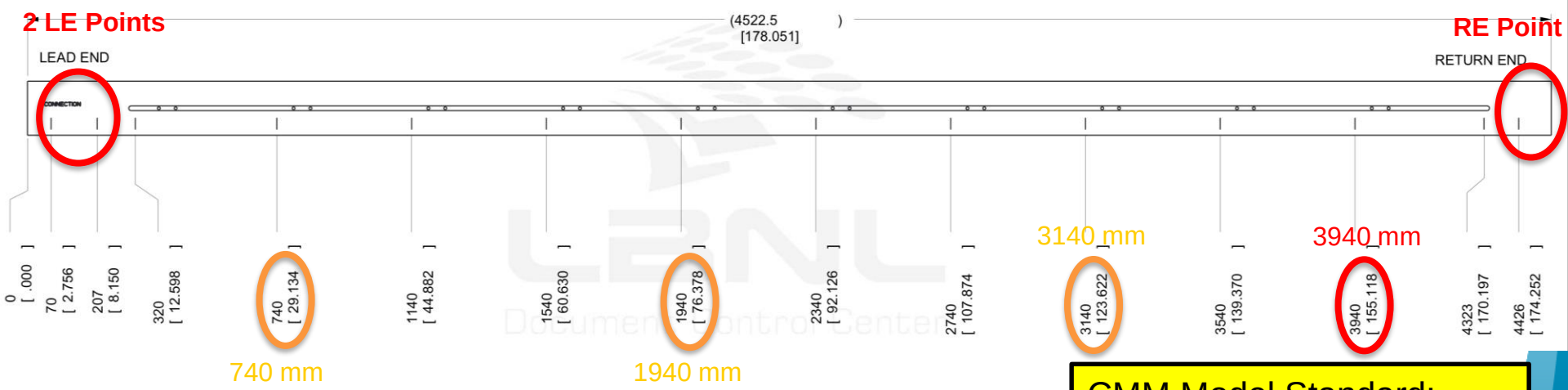


- Fuji (pressure-sensitive) paper exposures are used to examine the contact conditions of the coil and collar
- Iterative adjustments of radial shimming is possible



CMM Measurements

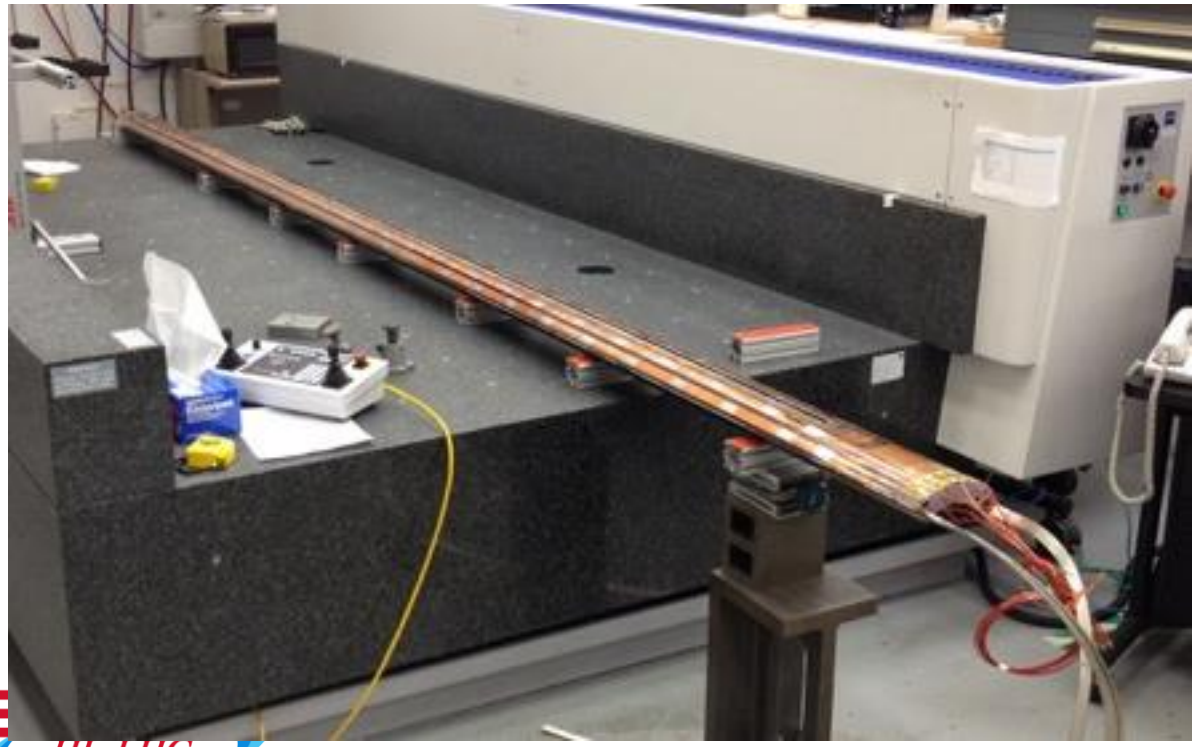
- Coils are measured after receipt
- Cross Section Data was collected in three sections
  - LE Section (2 points)
  - 10 straight section locations (10 points)
  - RE Section (1 point)
- For MQXFA03 SG is only at ~3940 mm location
  - Prior three locations no longer used

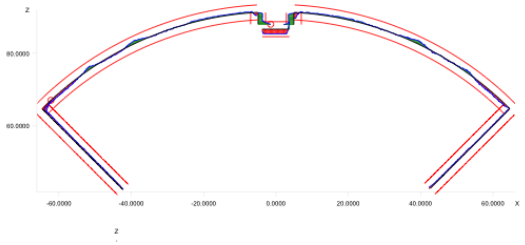


CMM Model Standard:
Inner Radius: 74.75 mm
Outer Radius: 113.376 mm
Midplane offset: 0.125 mm

CMM Measurements

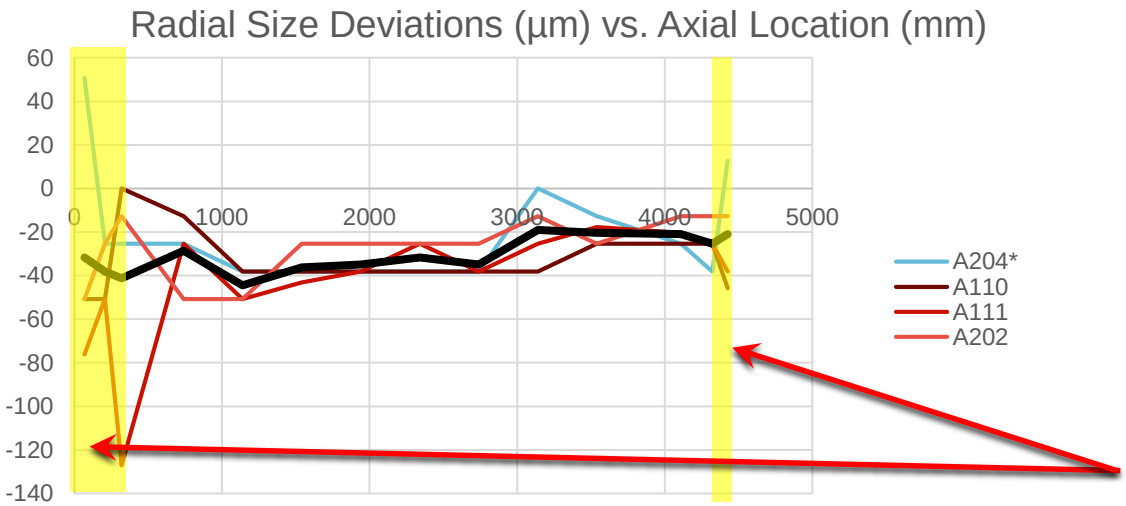
- All LBNL data was taken using a Zeiss Accura for CMM
- Calypso software post-processed data
  - All surfaces were “best-fit” to reference geometry with equal weighting
    - The alignment key was not included in coil 109 measurements
  - ID was not measured (will be with new LBNL CMM system)

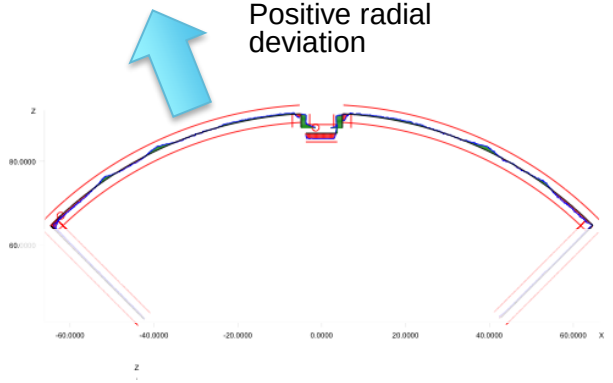




New Leica tracker system will be utilized for later coils, along with Spatial Analyzer (weighted fit will be possible)

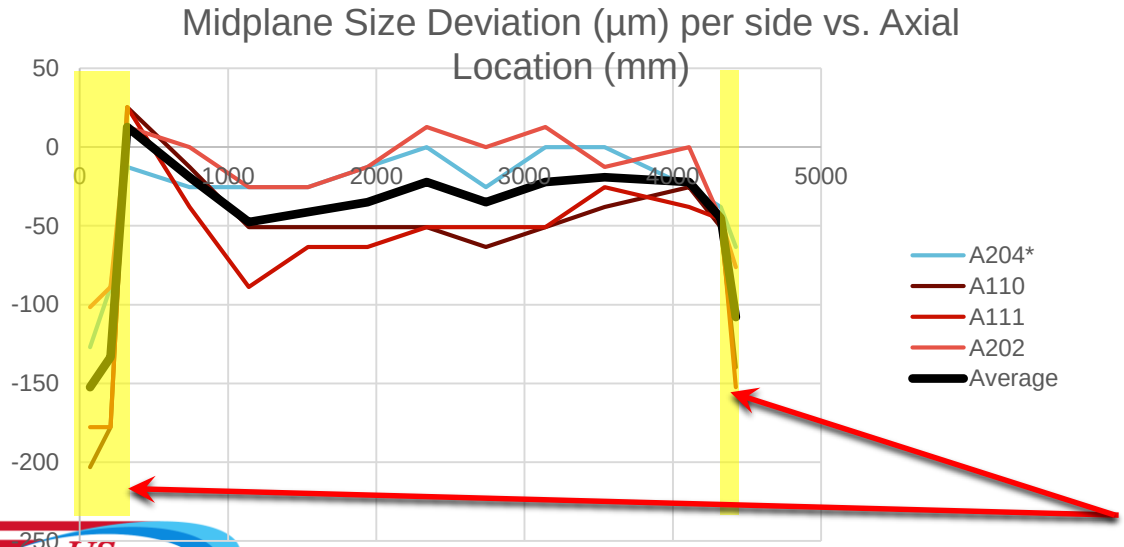
Coil size Plot

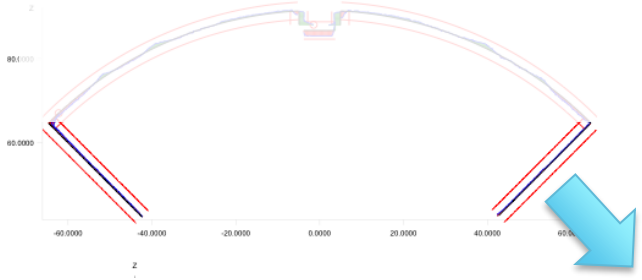




4 Coils average undersized radially ~35 μm

End geometry may need to be defined differently (see next slide)

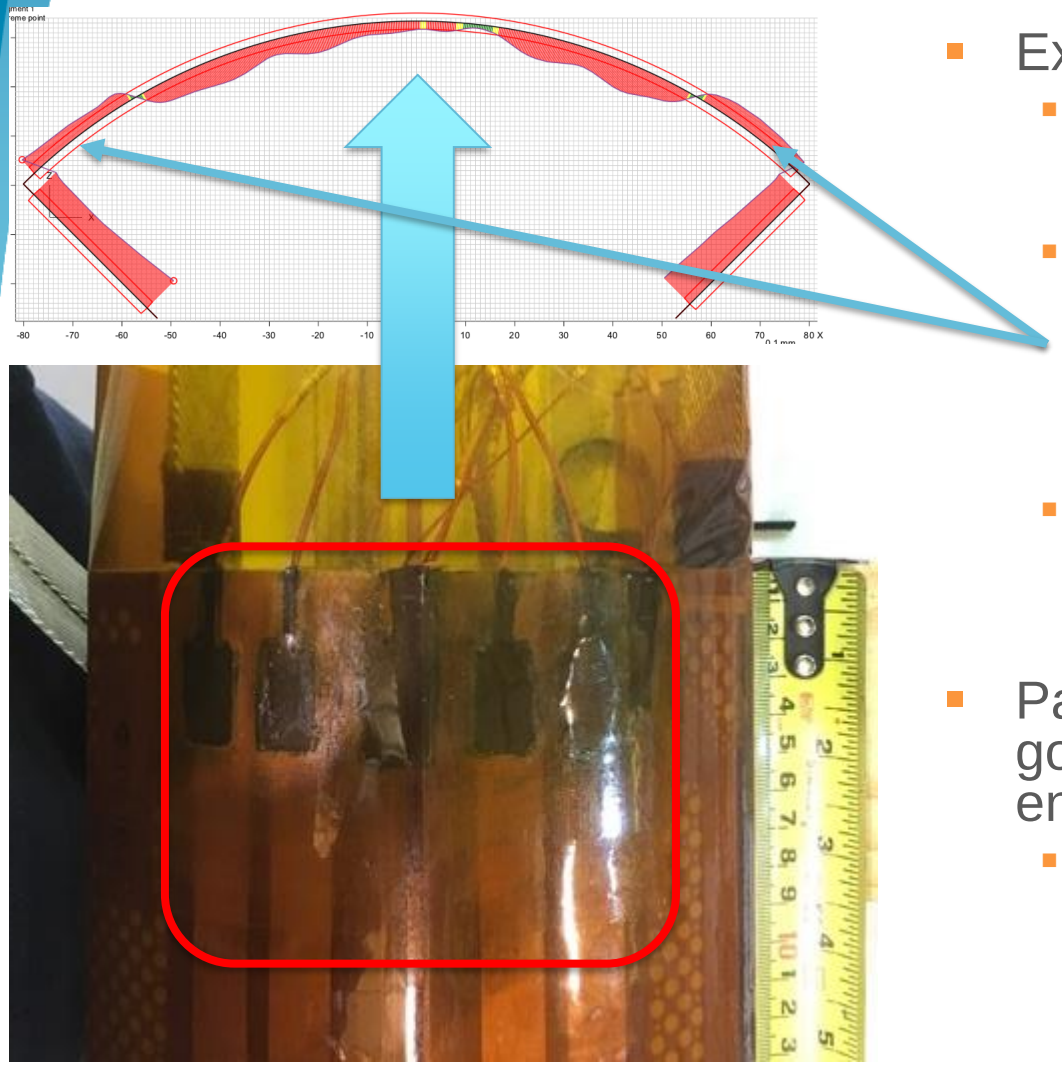




4 Coils average undersized on midplane ~25 μm per side

End geometry may need to be defined differently (see next slide)

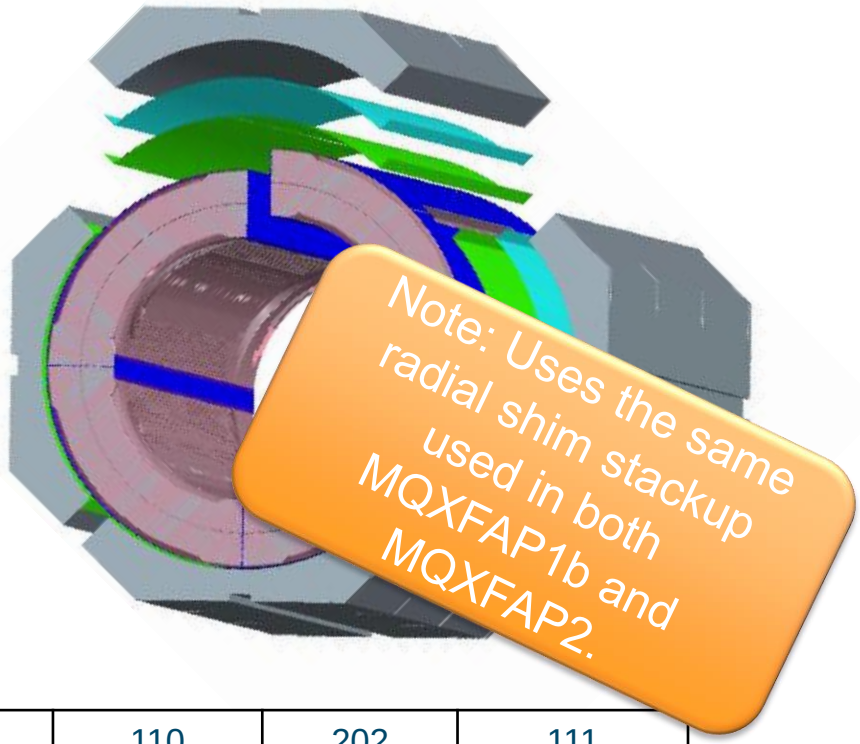
Note on CMM Measurements on end



- Example of profile at 70 mm
  - There is a pocket in the end shoe for the solder connections to be made
  - “Global Fit” of the profile may overstate profile deviations of the OD
    - Net radial and midplane deviations are much smaller than what is indicated by a global fit of all points
  - New Leica system and Spatial Analyzer software may be utilized to minimize this “global fit” error
- Past Fuji paper results showed good exposure even on the ends
  - End-specific shimming likely is not required

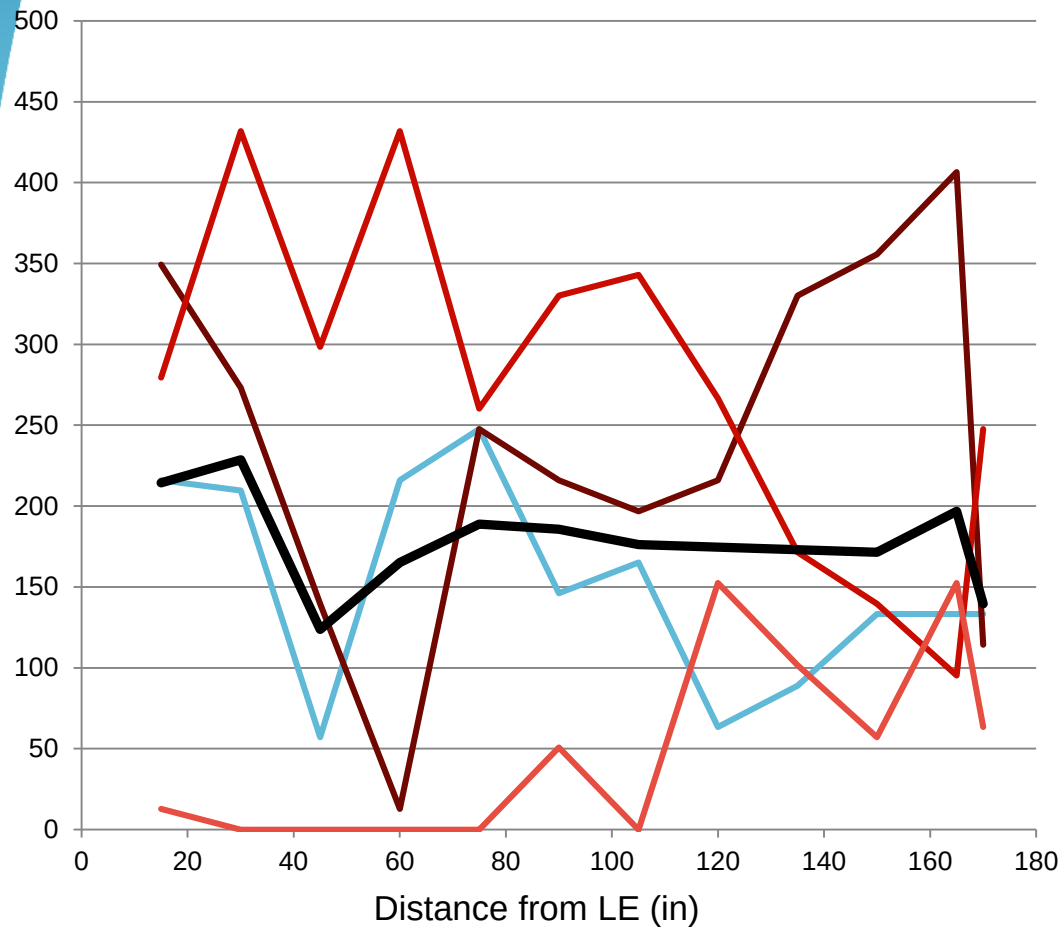
MQXFA03 Coil Pack Build 5 with 204

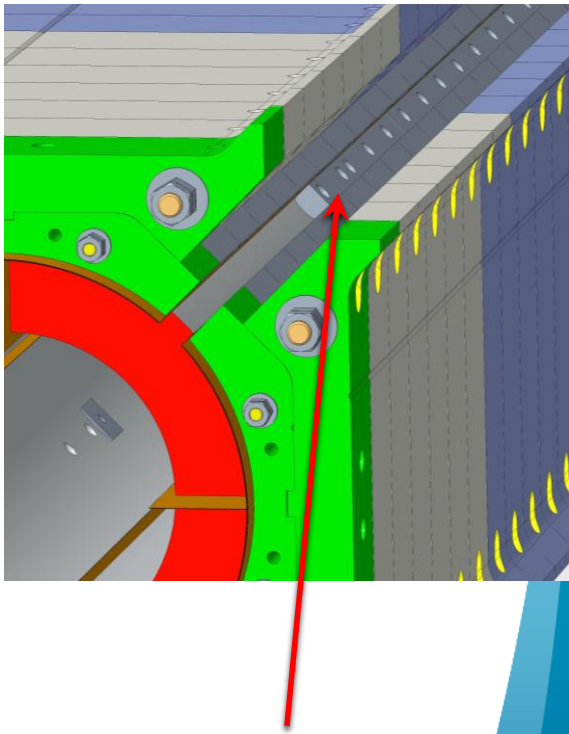
- Nominal Collar R: 114 mm
- Nominal Coil R: 113.376 mm
- Nominal Radial shim = 0.025” (0.624 mm)
  - Plan to still aim for ~0.020”
- Target MQXFA03 radial stack up is ~0.021” (~0.54 mm)
  - 0.0045” Coil GPI + 0.005” + 0.005” & 0.005” G11



	204	110	202	111
Kapton Ground plane insulation	0.0045” (0.114 mm)			
Coil Specific Radial Shim	0	0	0	0
Coil-specific midplane shim (no different end shimming)	0.000” 0.0 mm	0.000” 0.0 mm	0.000” 0.0 mm	0.000” 0.0 mm
Fuji paper	0.000” (0.0 mm)			
Radial Shim	0.005” Polyimide + 0.005” Polyimide + 0.005” G11 (~0.38 mm)			

MQXFA03 Pole Key Gap, microns





Pole Key Gap average ~175 µm per side

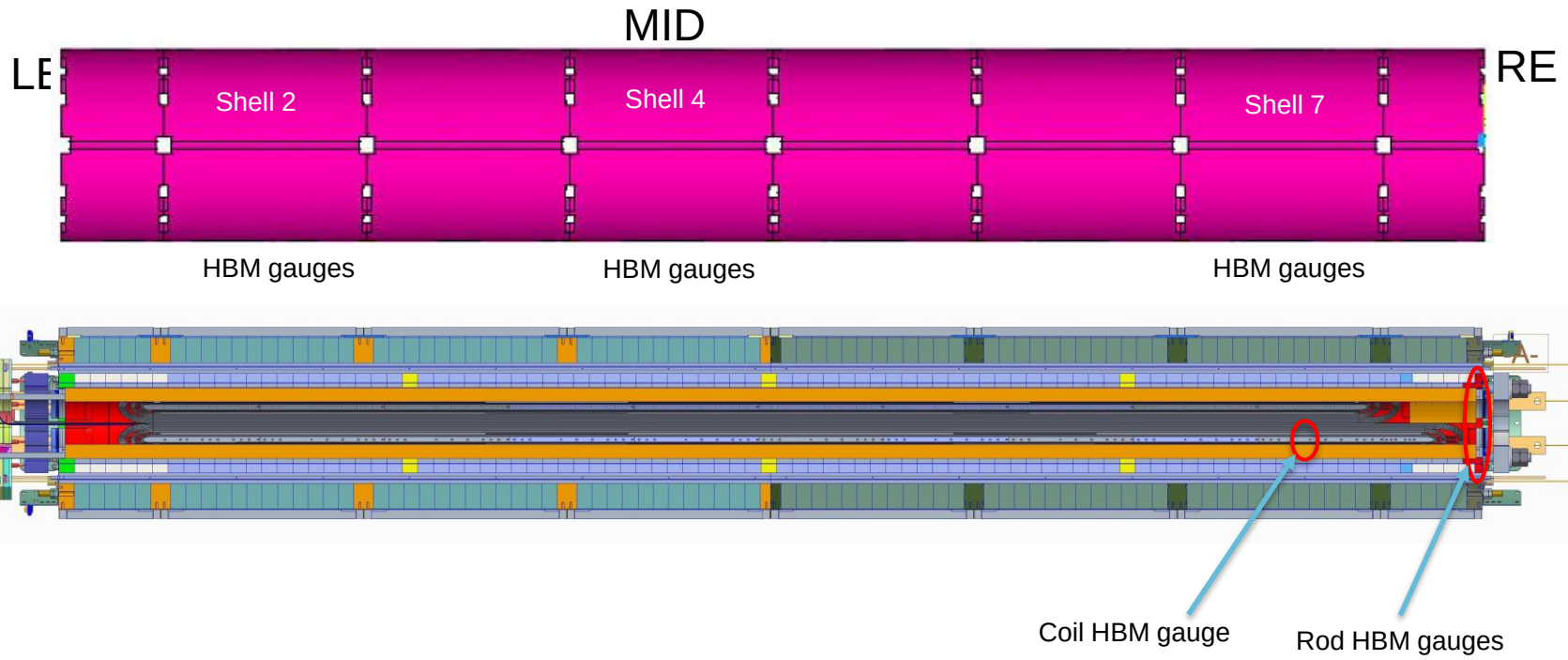
Preload Comparison of the MQXFA Magnets

Short models | Prototype Structures | Pre-series

		MQXFS1a	MQXFS3a	MQXFS1b	MQXFAP1a	MQXFAP2	MQXFAP1b	MQXFA03
R.T.	Coil	-61	-73	***-77***	***-75***	***-74***	***-69***	***-80***
	Shell	72	102	95	72	83	62	53
	Rods	0.2* MN	0.2* MN	0.2* MN	0.36 MN	0.36 MN	0.36 MN	0.58 MN
1.9K	Coil	-81	-92	-101	-88**	-91	-90	*-103*
	Shell	140	178	173	140	153	130	*110*
	Rods	0.6 MN	0.65 MN	0.6 MN	0.85 MN	0.85 MN	0.85 MN	*1.1 MN*
Interference		460 µm	910 µm	720 µm	640 µm	710 µm	510 µm	510 µm
Pole Key Gap[#]		0	-50 µm	0	50 µm	20 µm	75 µm	180 µm

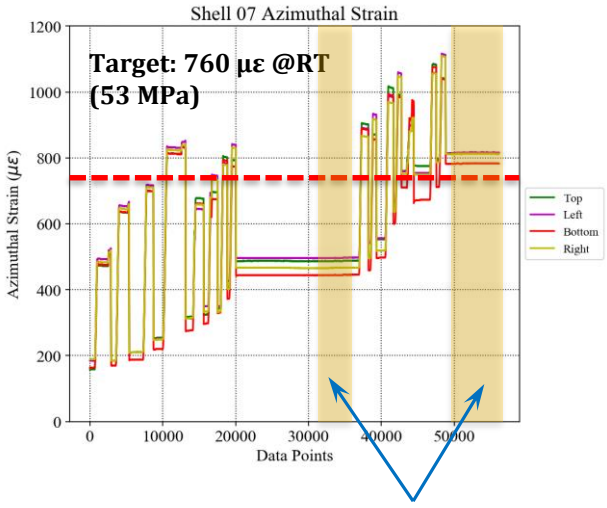
- * Short model rods are made of 7075-T6 Al; long structures use 316L SST
- ** Lost coil gauges on cool down; using FEA estimate based on shell gauges
- [#] Gap per side. Positive values indicate gap, negative values indicate interference

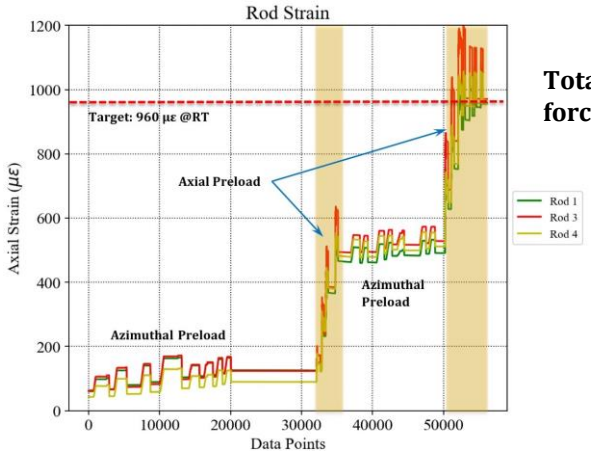
MQXFA03 Strain Gauge Instrumentation



- Axial locations for Strain Gauges:
  - Four HBM Shell Stations (T & Z) on Shells 2, 4, 7
  - Coil gauges (T & Z) only on axial station at 3995 mm from LE
    - Transfer function can be determined from Coil and Shell 7 gauges
- Rods
  - HBM full bridge, on RE

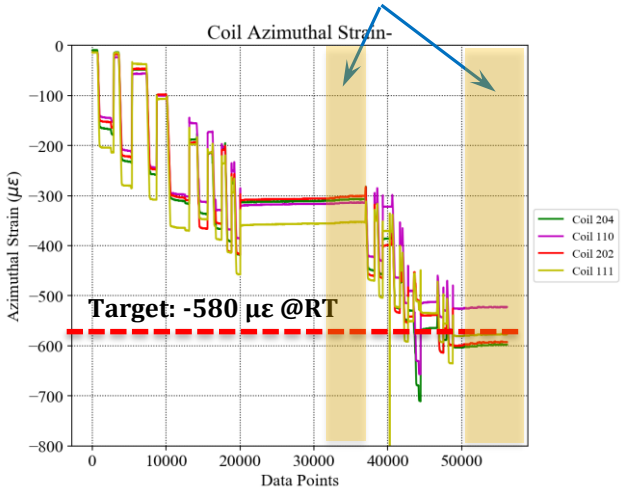
MQXFA03 Gauge Readings at Preload

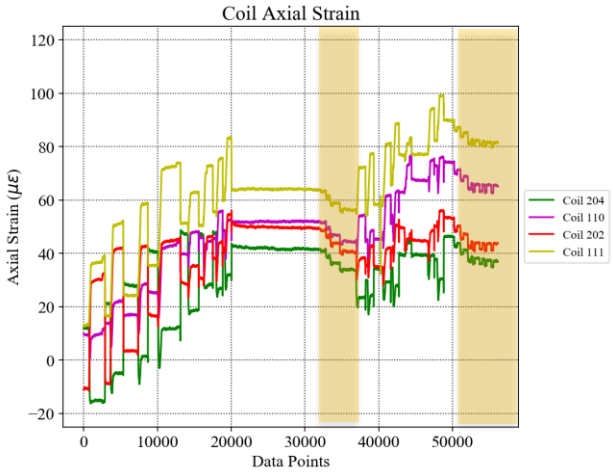


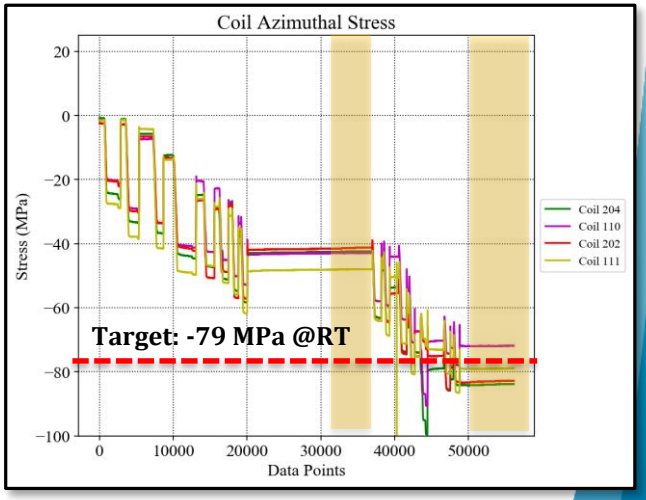


Total R.T. rod force is ~0.58 MN

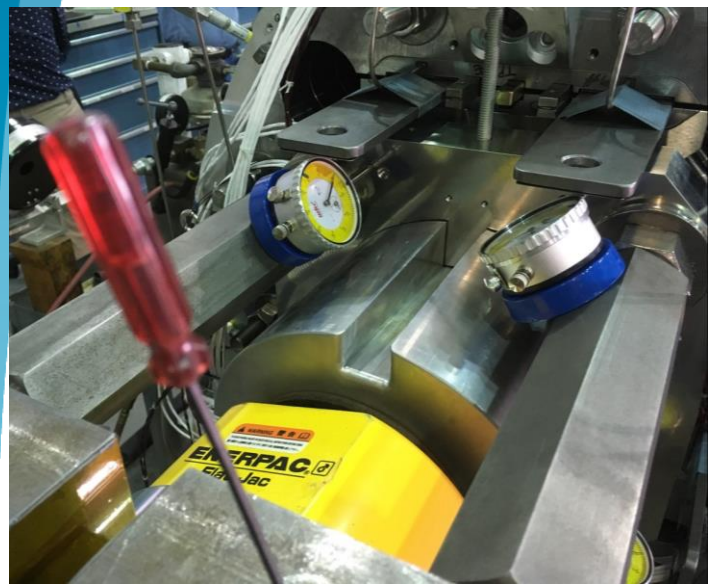
Axial Preload Operations



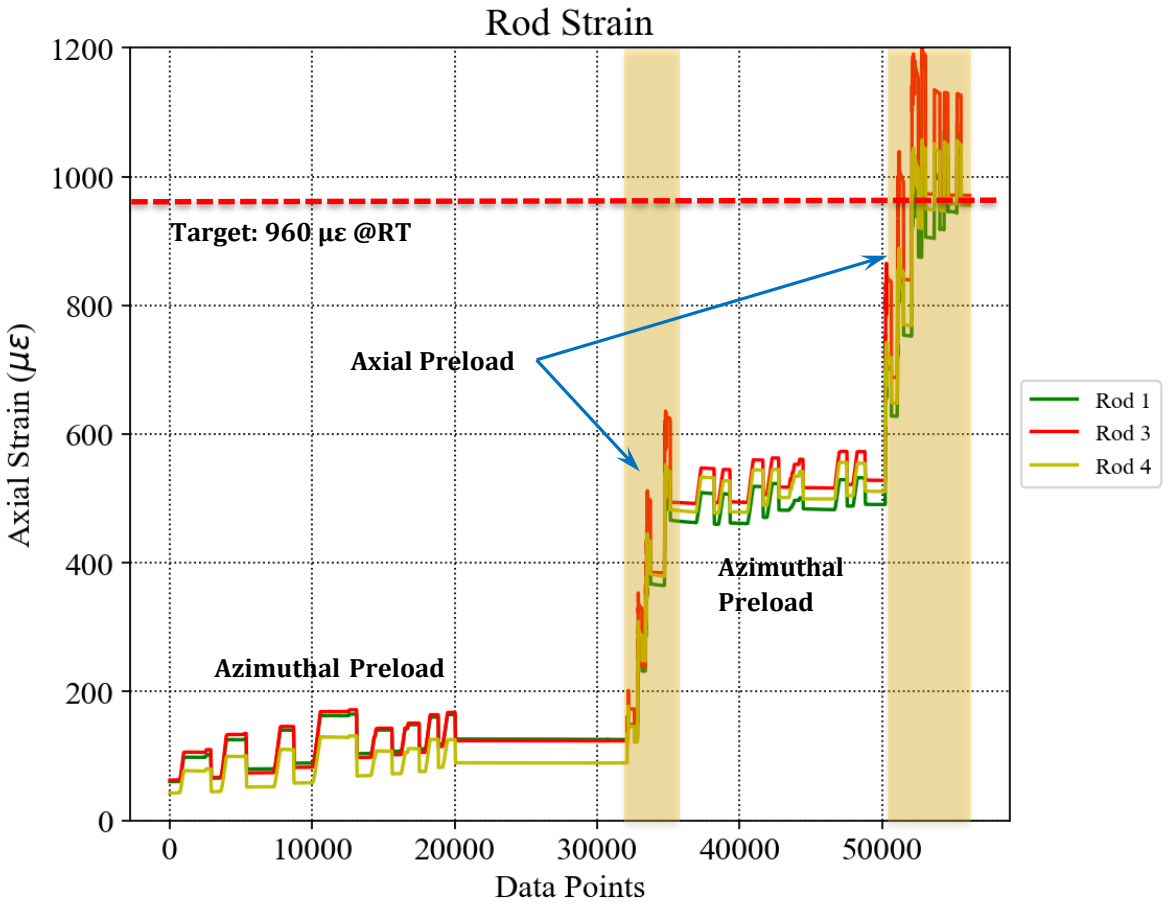




MQXFA03 Gauge Readings at Preload, Rods



Dial indicators were set up to measure all rod extensions to compare with Rod 2

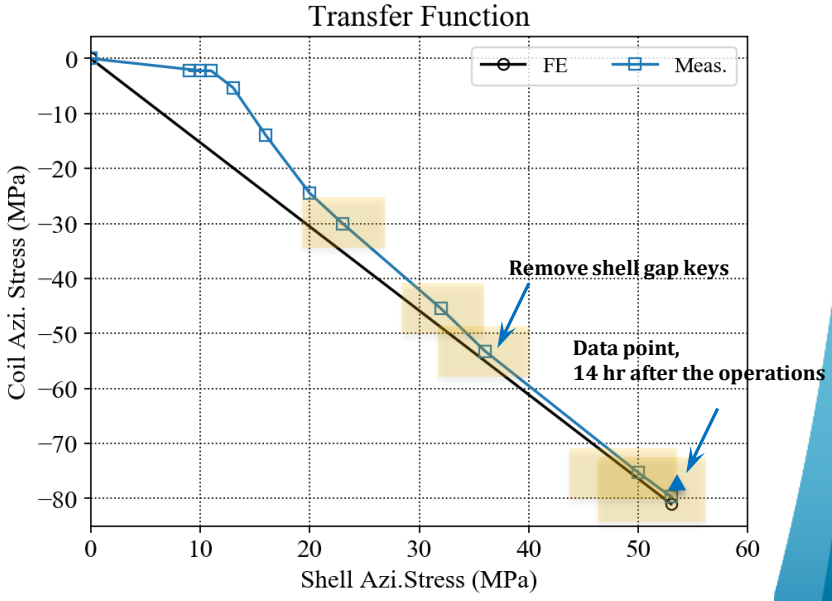


- Rod 2 gauges were damaged during insertion; half-bridges attempted, but signal is not reliable; dial indicators were used to measure all rods to ensure Rod 2 behaved similarly
- Total rods force is ~0.58 MN after preload based on the measurements.

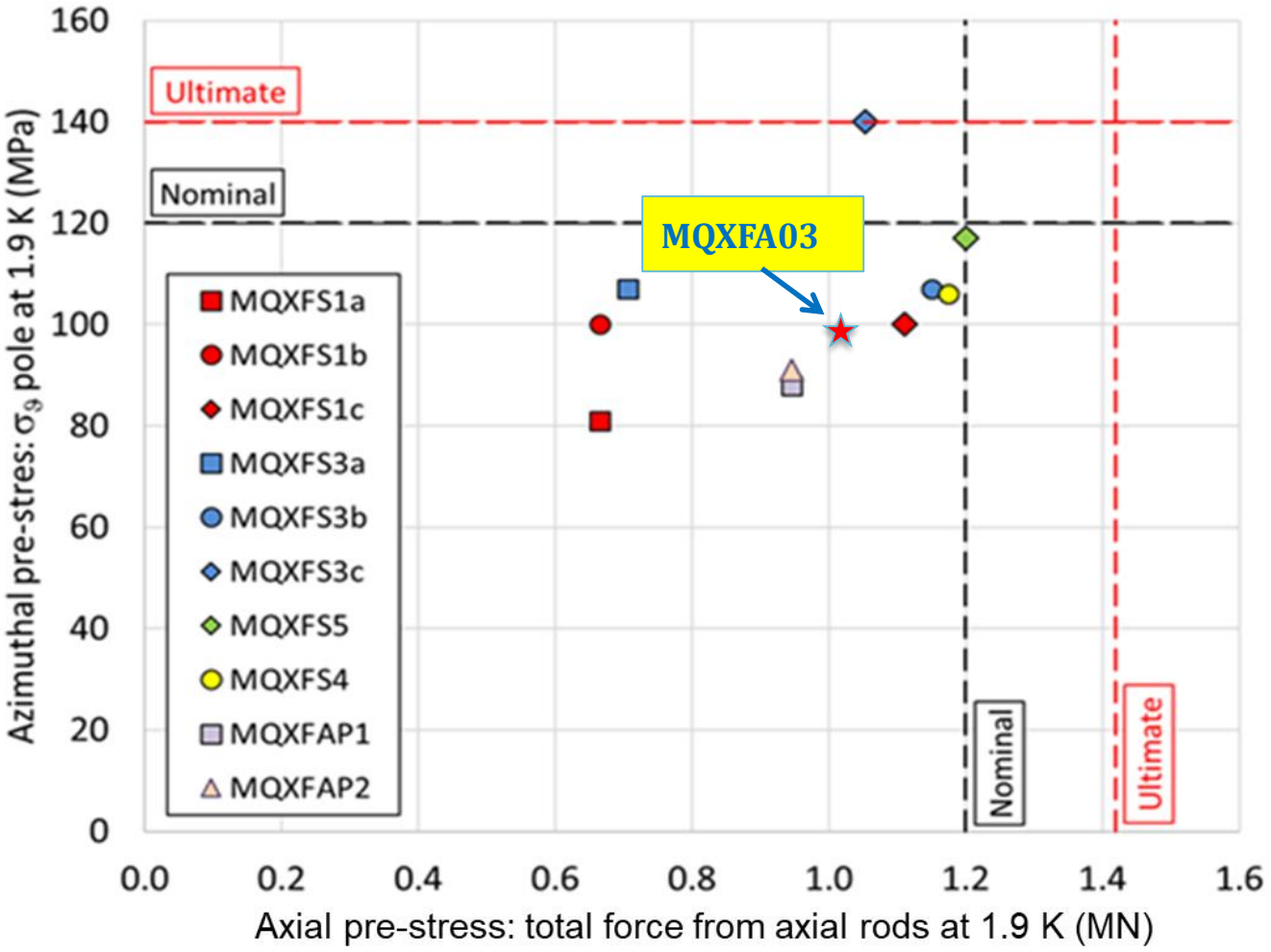
MQXFA03 and Outlook for Pre-Series

		MQXFS1a	MQXFS3a	MQXFS1b	MQXFAP1a	MQXFAP2	MQXFAP1b	MQXFA03
R.T.	Coil	-61	-73	*-77*	*-75*	*-74*	*-69*	***-80***
	Shell	72	102	95		83	62	53
	Rods	0.2* MN	0.2* MN			0.36 MN	0.36 MN	0.58 MN
1.9K	Coil	-81	-92			-91	-90	*-103*
	Shell	140	178			153	130	*110*
	Rods	0.6 MN	0.65 MN	0.6 MN	0.8	0.85 MN	0.85 MN	*1.1 MN*
Interference		460 µm		720 µm	640 µm	710 µm	510 µm	510 µm
Pole Key Gap		0		0	50 µm	20 µm	75 µm	180 µm

- Increased the pole key gaps
  - Machined pole keys
  - Targeted 100-150 µm per side, achieved ~180 µm (basically, no pole key case)
- Preload operations
  - Axial contact made before start of azimuthal preload operations
  - 50% azimuthal target
  - 50% axial target
  - 100% azimuthal target
  - 100% axial preload

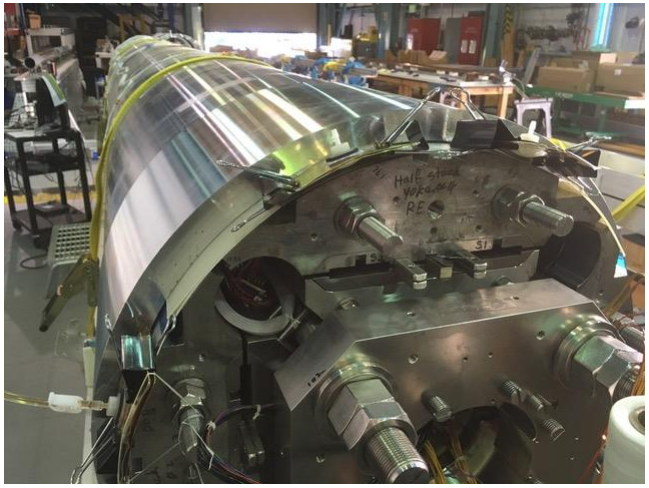


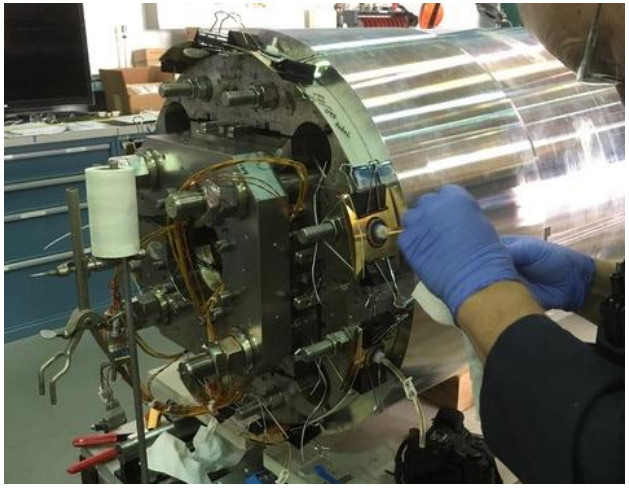
Pole Stress vs. Axial Force Comparisons



Outlook and Near-term Plans

- MQXFA04
  - The ARMCO yokes for A04 will not be fabricated until late 2019 (material is now only arriving)
  - MQXFAP2 is going to be disassembled, conforming parts to be recovered
- Coil Selection Review to take place Oct 30
  - Five coils (4 + 1 spare) to be reviewed
- Magnet expected to be completed ~end of January for testing
- Parts for A05-A08 continue to arrive





Summary

- MQXFA03
  - The first of four Pre-Series magnets is assembled, at BNL for vertical testing
- The prototype magnets have provided lessons learned
  - Changed shell end design to meet the Structural Design Criteria
  - Increased pole key gap to help reduce shell stresses
    - Targeting 100 µm to 150 µm per side
  - Changed operation order of azimuthal and axial preloads
- Parts for A04-A08 are arriving
  - MQXFA04 will be built with recovered MQXFAP2 material
  - ARMCO Pure Iron is arriving at destinations
  - Structural parts are also being delivered

Acknowledgements

- This work is all made possible by an incredible team:
- *Ahmet Pekedis, Josh Herrera, Matt Reynolds, Jordan Taylor, Juan Rodriquez, Heng Pan,*
- *Giorgio Ambrosio, Eric Anderssen, Helene Felice, Paolo Ferracin, Michael Guinchard, Tom Lipton, Joe Muratore, Soren Prestemon, Katherine Ray, Mike Solis, Jim Swanson, Giorgio Vallone, Xiaorong Wang*

- And the rest of the HL-LHC AUP collaboration team

Additional Slides

MQXFA03 Coil CMM Summary, 204 replace 109

Radial Size deviations (inches)				
Loc (mm)	A204*	A110	A111	A202
70	0.002	-0.002	-0.003	-0.002
207	-0.001	-0.002	-0.002	-0.001
320	-0.001	0	-0.005	-0.0005
740	-0.001	-0.0005	-0.001	-0.002
1140	-0.0015	-0.0015	-0.002	-0.002
1540	-0.0015	-0.0015	-0.0017	-0.001
1940	-0.0015	-0.0015	-0.0015	-0.001
2340	-0.0015	-0.0015	-0.001	-0.001
2740	-0.0015	-0.0015	-0.0015	-0.001
3140	0	-0.0015	-0.001	-0.0005
3540	-0.0005	-0.001	-0.0007	-0.001
4110	-0.001	-0.001	-0.0008	-0.0005
4323	-0.0015	-0.001	-0.001	-0.0005
4426	0.0005	-0.0018	-0.0015	-0.0005
Avg 320-4323	**-0.0011**	**-0.0011**	**-0.0016**	**-0.0010**
RMS	0.00120	0.00125	0.00201	0.00117
St. Dev.	0.00052	0.00053	0.00126	0.00055
Max	0	0	-0.0007	-0.0005
Min	-0.0015	-0.0015	-0.005	-0.002
Avg LE	*0.0005	-0.0020	-0.0025	-0.0015
RE	0.0005	-0.0018	-0.0015	-0.0005

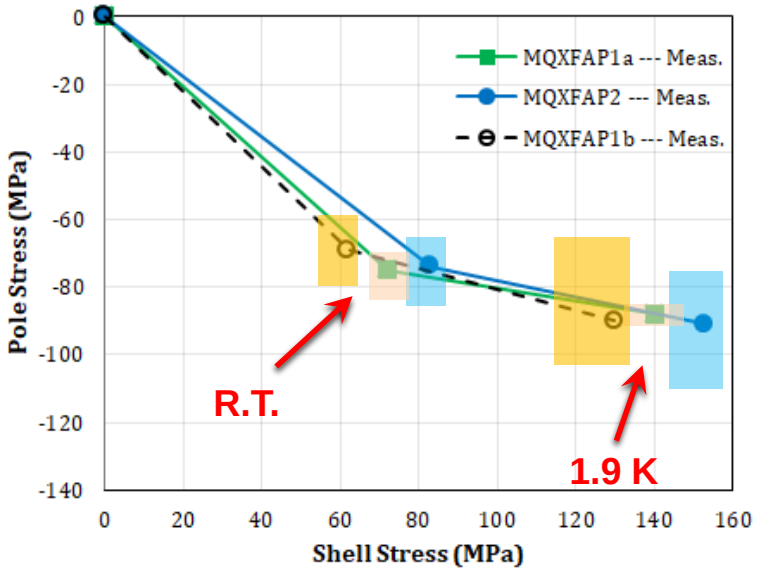
Midplane Size Deviations (inches)				
Loc (mm)	A204*	A110	A111	A202
70	-0.005	-0.008	-0.007	-0.004
207	-0.0035	-0.007	-0.007	-0.0035
320	-0.0005	0.001	0.001	0.0005
740	-0.001	-0.0005	-0.0015	0
1140	-0.001	-0.002	-0.0035	-0.001
1540	-0.001	-0.002	-0.0025	-0.001
1940	-0.0005	-0.002	-0.0025	-0.0005
2340	0	-0.002	-0.002	0.0005
2740	-0.001	-0.0025	-0.002	0
3140	0	-0.002	-0.002	0.0005
3540	0	-0.0015	-0.001	-0.0005
4110	-0.001	-0.001	-0.0015	0
4323	-0.0015	-0.002	-0.0018	-0.0018
4213	-0.0025	-0.0055	-0.006	-0.003
Avg 320-4323	**-0.0007**	**-0.0015**	**-0.0018**	**-0.0003**
RMS	0.00074	0.00175	0.00208	0.00057
St. Dev.	0.00046	0.00104	0.00118	0.00058
Max	0	0.001	0.001	0.0005
Min	-0.001	-0.0025	-0.0035	-0.001
Avg LE	*-0.0043	-0.0075	-0.0070	-0.0038
RE	-0.0025	-0.0055	-0.0060	-0.0030

- *see next slide for LE

Prototype Magnets MQXFAP1a/b

		MQXFAP1a	MQXFAP1b
R.T.	Coil	***-75***	***-69***
	Shell	72	62
	Rods	0.36 MN	0.36 MN
1.9K	Coil	-88*	-90
	Shell	140	130
	Rods	0.85 MN	0.85 MN
Interference		640 µm	510 µm
Pole Key Gap		50 µm	75 µm

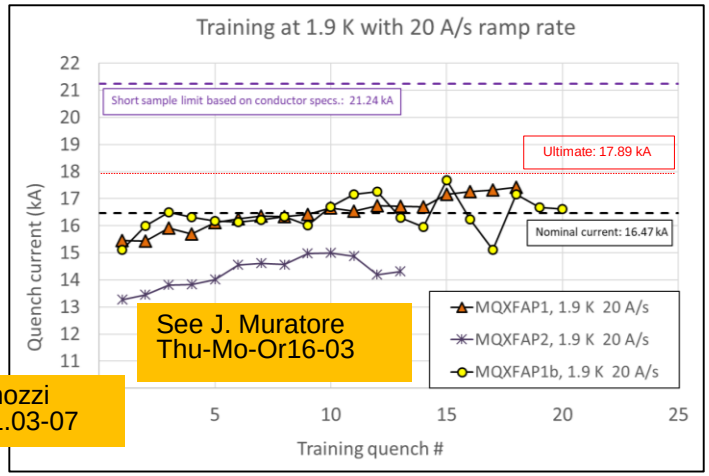
* Estimated from FEA using measure shell gauges (lost gauges on cool down)



- Builds used the same structure
  - Replaced coil 05 with 06 in MQXFAP1b
- MQXFAP1a based on MQXFS1b levels
  - Do not exceed -94 MPa in any location on coil pole
- Targeted -70 to -75 MPa
  - MQXFAP1a at R.T. using 640 µm interference
  - MQXFAP1b at R.T. using 510 µm interference
- Pole keys
  - Fibers are transverse oriented
  - 50 µm gap per side in MQXFAP1a
  - 75 µm gap per side in MQXFAP1b

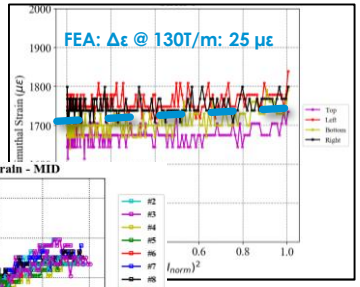
MQXFAP1a Strain Gauge Response

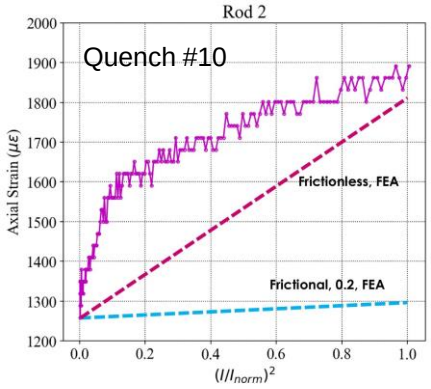
- Shell readings matched FEA models, reached target 140 +/- 8 MPa
- Most coil gauges were lost (debonding) on cool down
  - Only Coil 03 retained all three azim. stations, all showing unloading
  - Coil 04 and 05 retained only one station, 04 seemed least loaded
- Rod gauges did not match either FEA frictional/frictionless models

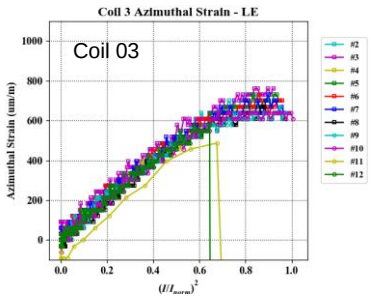


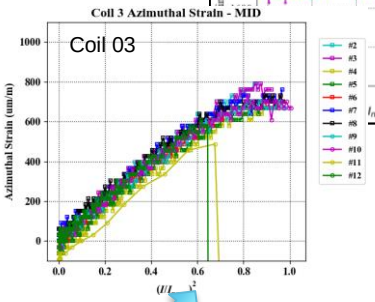
See J. Muratore
Thu-Mo-Or16-03

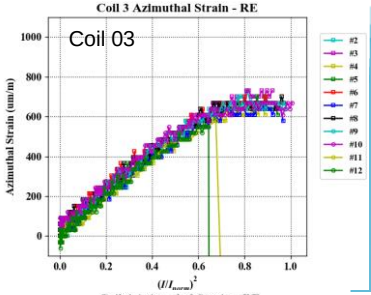
See V. Marinozzi
Mon-Mo-Po1.03-07

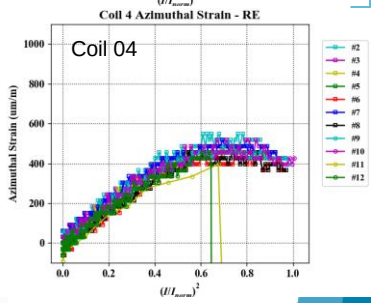


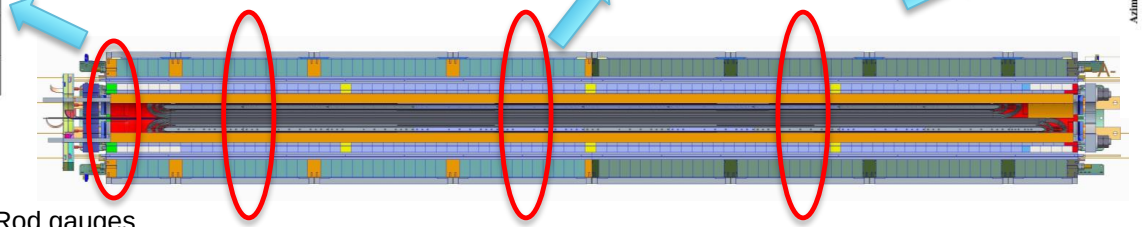












Rod gauges on LE

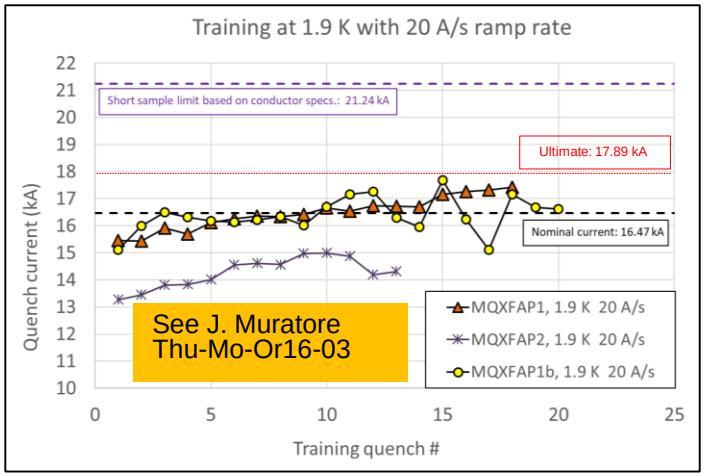
Shell and Coil Station "LE"

Shell and Coil Station "MID"

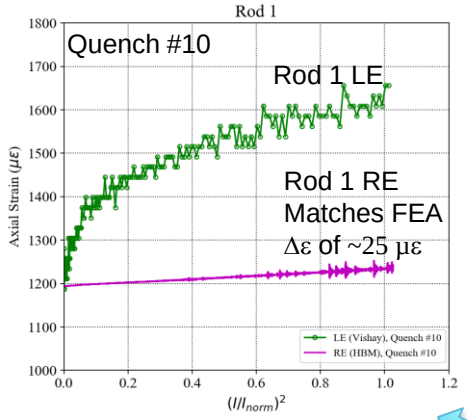
Shell and Coil Station "RE"

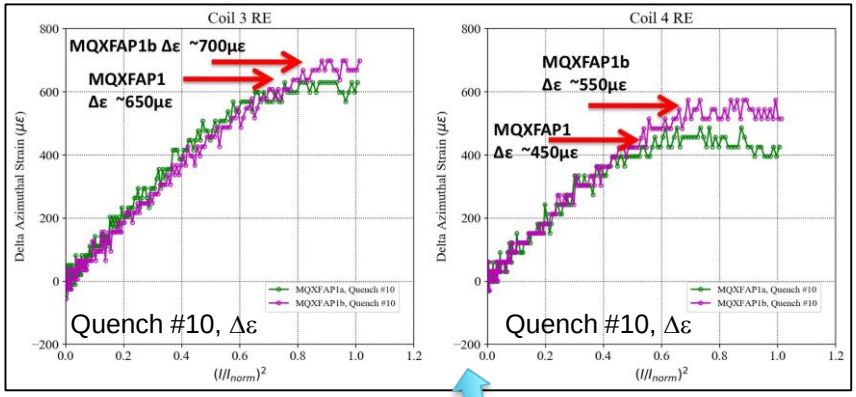
MQXFAP1b Comparison with MQXFAP1a

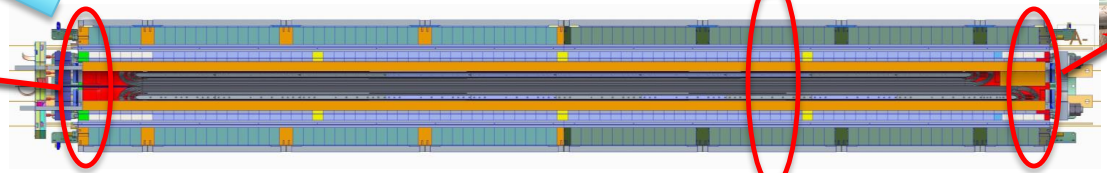
- MQXFAP1b Shell readings also matched FEA models, reached target 125 +/- 6 MPa
- Single coil station (“RE”) installed;
  - Compared with available MQXFAP1a data preload of MQXFAP1b suggest higher preload applied, but still leveling off at ~13 kA
- LE Rod gauges still did not match FEA models, but
  - RE gauges mounted on the same rods match FEA frictionless model



Comparison of MQXFAP1a/b Coils







Rod gauges on LE

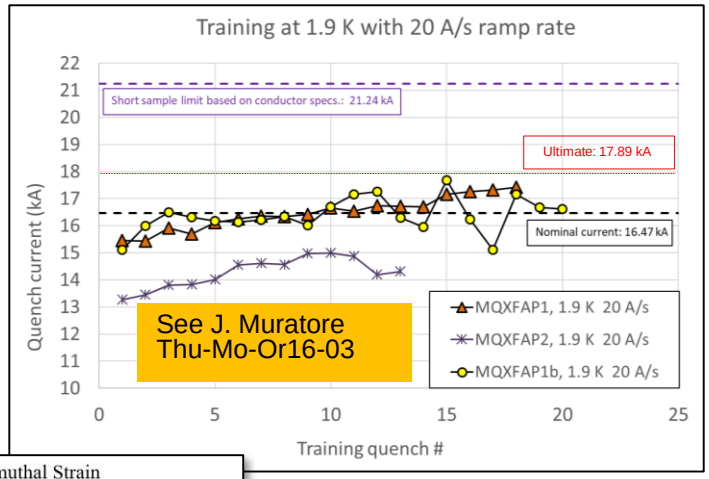
Shell Station “LE”

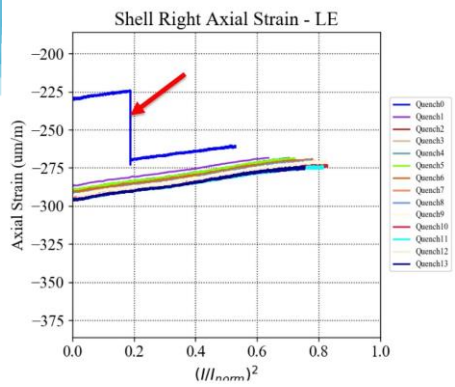
Shell and Coil Station “RE”

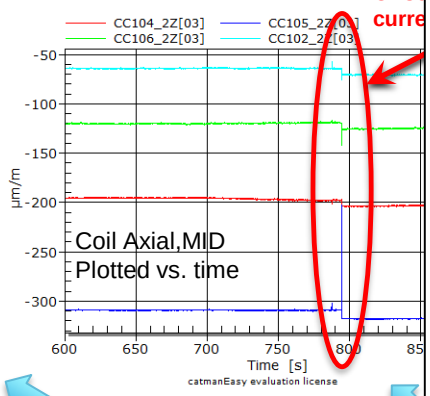
New rod stations on two RE rods

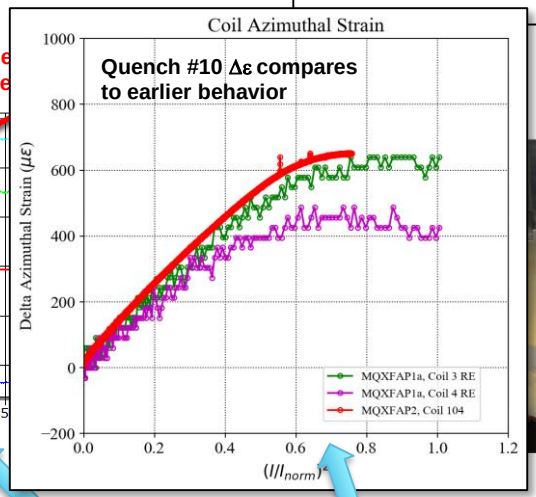
MQXFAP2 Shell Fracture

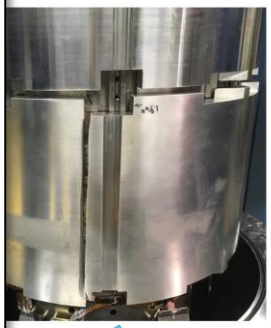
- First quench started around 13 kA
  - Reached maximum of 15 kA
- Fracture of the non-lead-end shell
  - Not directly seen by strain gauges (closest gauge stations ~1m away)
  - Possible “global event” observed on first 12 kA current ramp at ~7 kA
- Despite low training performance
  - Strain gauges behaved as in previous magnets
  - Shell readings matched FEA models, reached target 150+/- 6 MPa
  - Coil stations showed comparable preload (not indicative of low training)
- LE Rod gauges still did not match FEA models

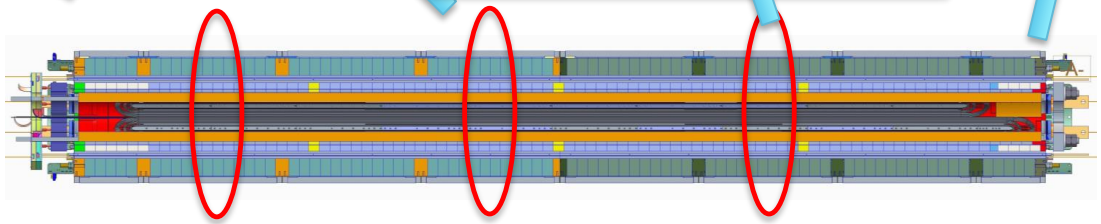












See H. Pan
Mon-Mo-Po1.03-02

Coil 109 Issues Timeline

- All coils passed Acceptance Testing after receipt at LBNL
  - See MQXFA03 Readiness Review material, May 22, 2019
  - https://indico.fnal.gov/event/20781
- After assembly in coil pack
  - Impulse tests showed HF artifacts on impulse test (both Direct and Reversed polarities)
  - Removing connectors did not change result
  - Removing VT twist in wiring also did not change
- Hipot testing (not normally performed at this stage of Coil Pack assembly) was performed
  - Test parameters with Chroma 10973 hipot unit
    - 5 V/sec ramp, 10 µA threshold
  - Resulted in a breakdown from Coil to ILRE end shoe at 114 V
  - Resistive short then became present, at about 3 kOhm
- Decided to replace Coil 109
  - Upon disassembly of coils (but still “paired”), short in Coil 109 now shows ~198 kOhm --evidence of change
- Evaluating options for replacement coil