MQXF Coil Fabrication: Observations and Summary

E.F. Holik

Acknowledgements: G. Ambrosio, M. Anerella, R. Bossert, N. Bourcey, E. Cavanna, D. Cheng, D. R. Dietderich, P. Ferracin, A. K. Ghosh, S. Izquierdo Bermudez, S. Krave, A. Nobrega, J. C. Perez, I. Pong, E. Rochepault, G. L. Sabbi, C. Santini, J. Schmalzle, and M. Yu

5th Joint HiLumi LHC-LARP Annual Meeting 2015
CERN, October 26th – 30th

Outline

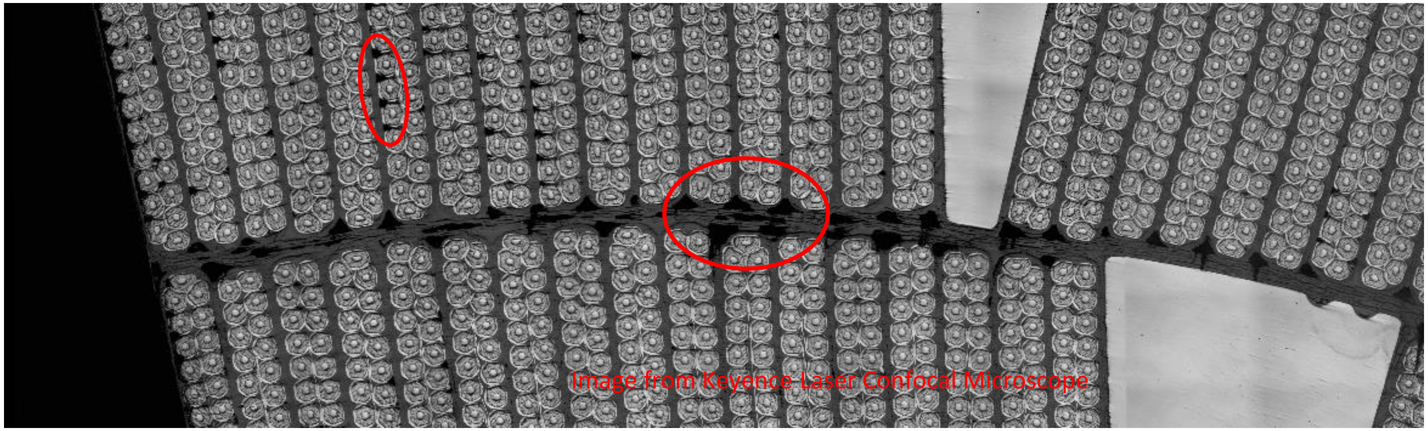
- Coil Fabrication Summary & Overview
- Coil size and asymmetry
- Cable Expansion / Gap Closure
- Cross Section Analysis
- Conclusion

MQXF Coil Overview

- 6 short coils with 108/127 RRP
  - Coil 01 – R&I @ BNL, leaky valve impregnation, was cut
  - Coil 02 – R&I @FNAL, Mirror, 91% SSL @4.2K, Ta ternary
  - Coil 03 – R&I @ BNL, coil in MQXFS01-AS
  - Coil 04 – R @ LBNL, Reversed end parts, Not impregnated…
  - Coil 05 – R&I @ BNL, coil in MQXFS01-AS
  - Coil 06 – R&I @ FNAL, Spare, Slight epoxy voids near LE
- LARP is beginning MQXF 2nd gen
  - Coil 07 – Winding beginning this week, (108/127 RRP)
  - Coils 09 & 10 in queue – 144/169 RRP
- 3 long coils in fabrication
  - Long Coil 01 – Reacted @ BNL, prep for Impreg, For long mirror.
  - Long Coil 01p – R&I @ FNAL, Test for 2nd gen radial insulation.
  - Long Coil 02 – L1 cured, Spare for mirror and first long magnet.

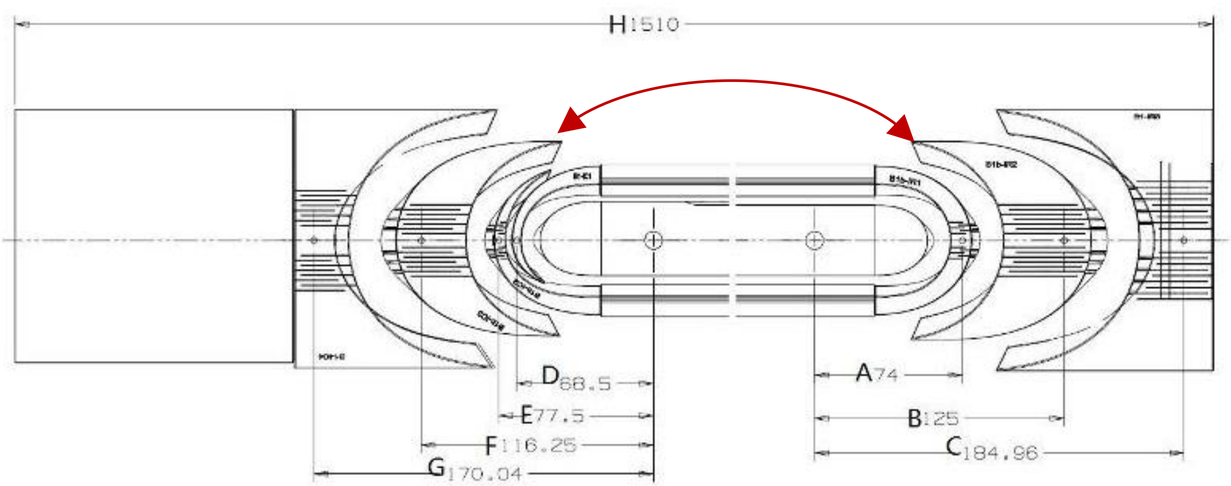
Coil DRs

- Bubbles in Practice Coil 1



Epoxy line valve leaked under vacuum.

- Reversed End Parts in Coil #4

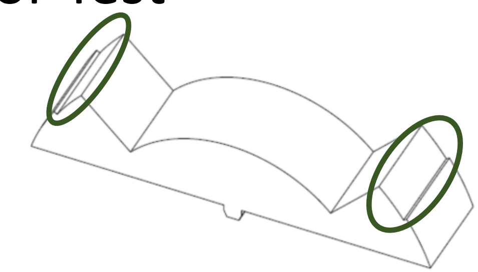


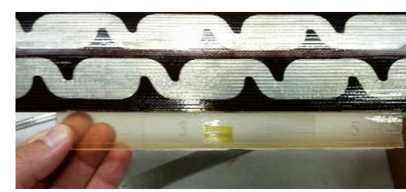
Parts mislabeled by Plasma coating company. Coil Electrically sound.

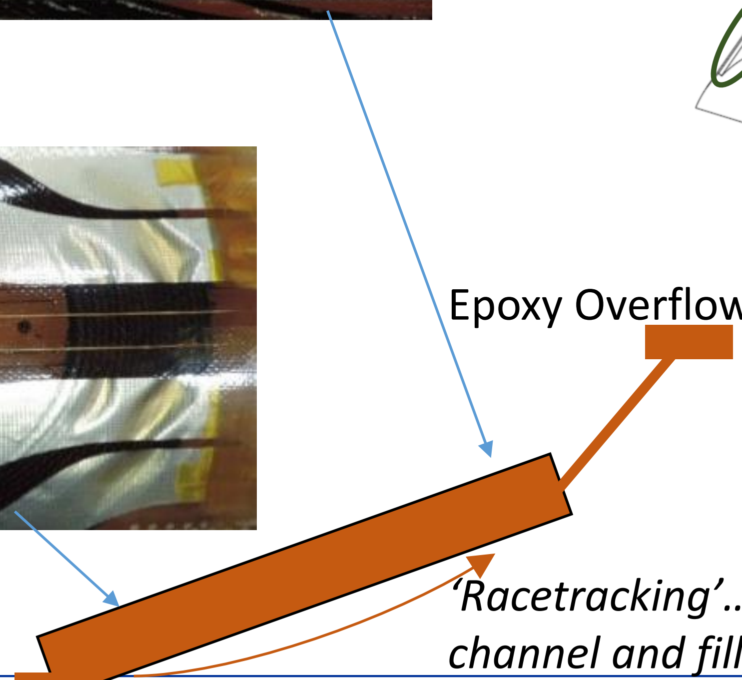
Coil DRs

- Weak Impregnation in Coils #2 and #6 near LE

- Channel will be filled in subsequent coils.
- No adverse effects from Mirror Test







'Racetracking'… Epoxy goes through side channel and fills overflow before filling coil, trapping some air in the process

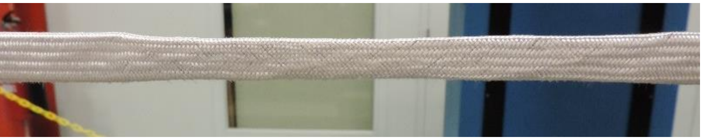
Impregnation

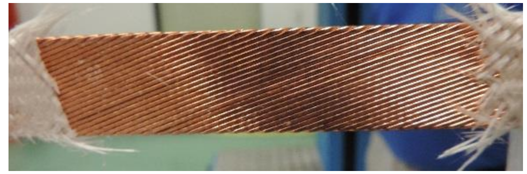
	LBNL	FNAL	BNL
CTD-101k density = 1.03 g/cc	CTD-101k	CTD-101k	CTD-101k
SETUP			
Backout temperature	110°C	55°C (80°C possible) (110°C with strip heaters)	110°C
Bakeout pressure	10 - 100 mT	25 mT	200 - 500 mT
Bakeout time	6 hrs	45 hrs	8 hrs
Dryout Gas flow	none	none	none
Cool down temperature	60°C	55°C	55°C
Coil Orientation	~30° wrt horiz.	~13° wrt horiz.	Vertical
Lead Orientation	Leads up	Leads up	Leads up
EPOXY DEGAS			
Epoxy Volume mixed (1.7 l needed)		22 liters (6 gal.)	
Epoxy degas temperature	50°C - 60°C	?	55°C
Epoxy degas time	?	45 min (2h tot mix/heat)	2 h
Epoxy agitation while degassing	Y	Y	Y
Epoxy Vacuum while agitating	300 mTorr	800 mT	500 mT
Epoxy container depth	?	18"	3.25"
IMPREGNATION			
Initial magnet temperature	60°C	55°C	55°C
VPI coil vessel pressure	1000 mT	2000 mT	500 mT
VPI epoxy vessel pressure	760 Torr	760 Torr	760 Torr
Feed method	pressure diff.	pressure diff.	Peristaltic pump/ΔP
Flow measure method	none	visual (1 cm/s)	pump output
Epoxy flow rate	n/a	7 cc/min	25 cc/min
Fill time (short coil)	1.5 h	1.5 h - 3 h	2 h
Gel / Soak			
Additional Epoxy Through Flow	30 min (line reservoir)	30 min (line resevoir)	none
Backfill (re-absorption)	1"-2" of large tube (~1/10 l [QXF equivalent])	2'-4' of tube (~1/3 liter)	n/a
Epoxy Inlet Valve	Closed	Closed	Open
Epoxy Outlet Valve	Open	Open	Closed
Press/Vac cycles (milking)	2	0	0
VPI Vessel Pressure	760 Torr	760 Torr	500 mTorr
Coil Back pressure	760 Torr	760 Torr	760 Torr
Soak/Gel time @ 50°C - 60°C	15 h	18 h	16 h
CURE			
VPI Vessel Pressure	760 Torr	760 Torr	500 mTorr
Coil Back pressure	760 Torr	760 Torr	760 Torr
Ramp	60°C - 110°C (4 h)	60°C - 110°C (1.5 h)	55°C - 110°C (6 h)
Soak	110°C (4 h)	110°C (5 h)	110°C (5 h)
Ramp	110°C - 125°C (4 h)	110°C - 125°C (1 h)	110°C - 125°C (1.5 h)
Soak	125°C (17 h)	125°C (16 h)	125°C (16 h)

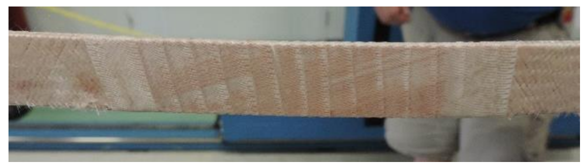
How does the CERN process differ from the LARP labs?

1st Gen Long Coil Fab

- Roped Cable in MQXFP 01 (mirror coil).



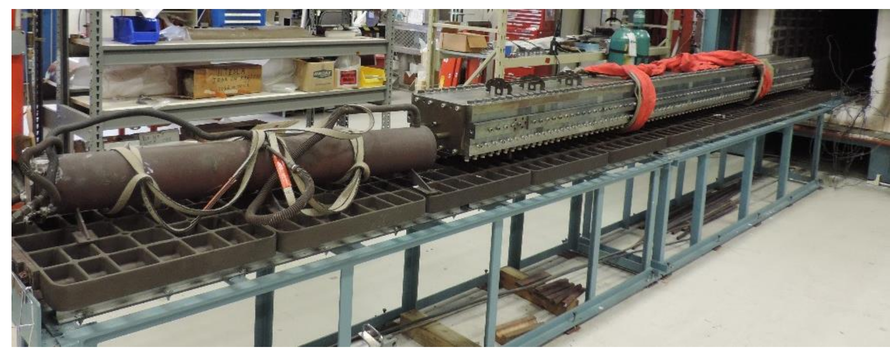




Insulation was removed and the cable was placed back in registration. Insulation repaired with 75 µm E-glass half wrap

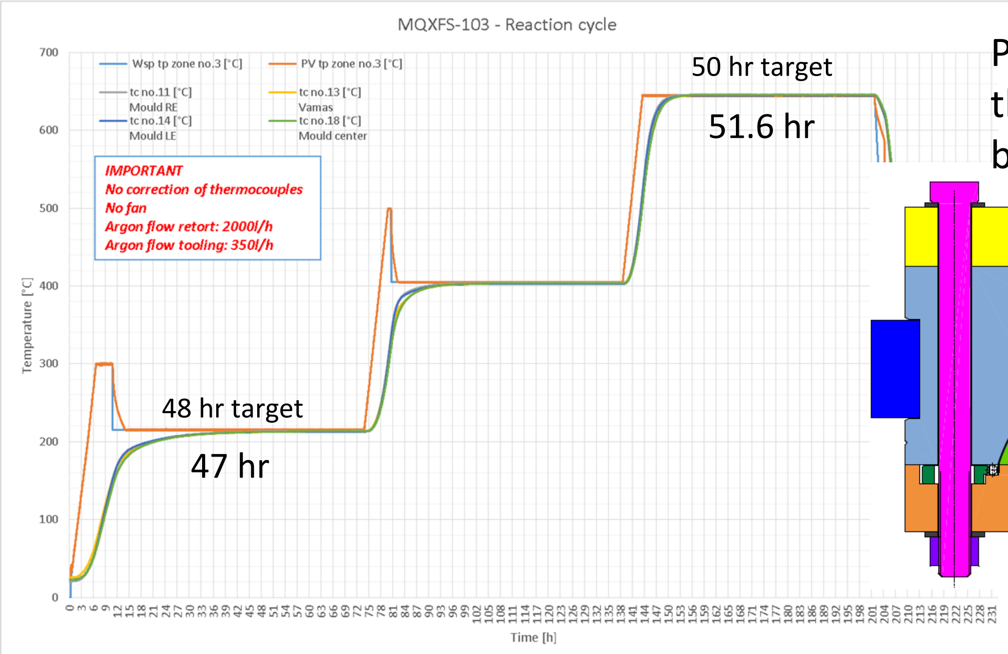
- Additional Insulation in MQXFP 01b practice coil

Additional Radial Insulation to mimic 2nd Gen QXF

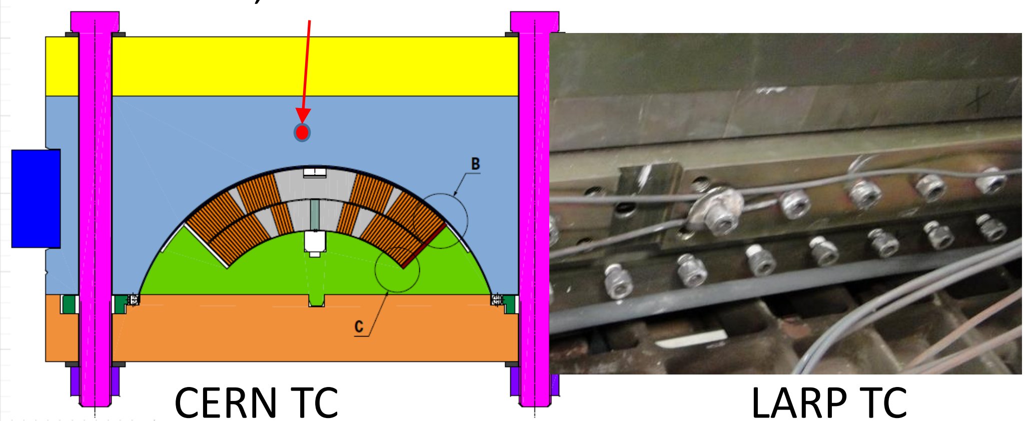


RXN complete

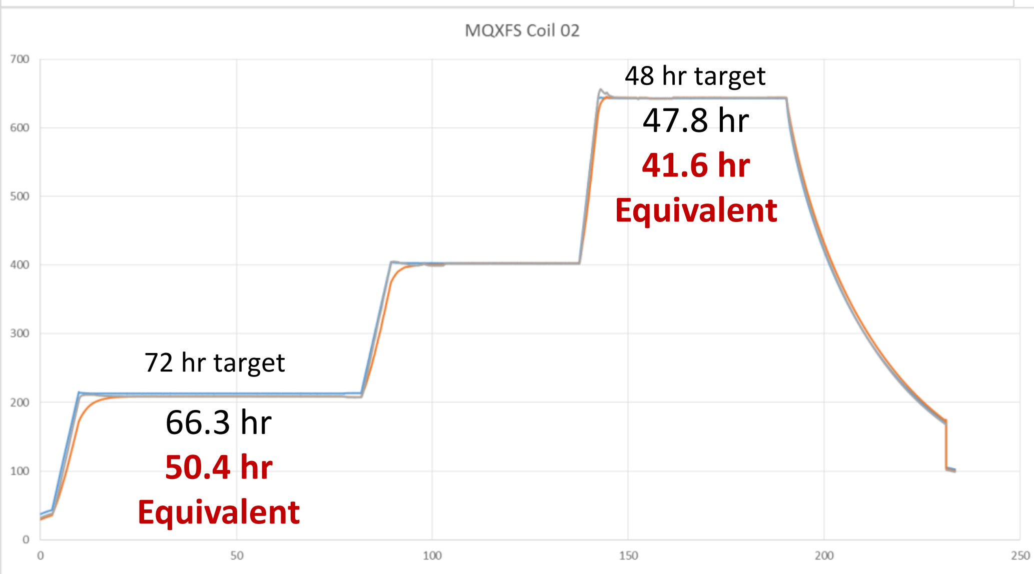
Coil Heat Treatment



Position of the thermocouple in block 5, 16 and 28.



CERN TC LARP TC



- **Equivalent duration** takes into account the estimated lag time.
- Multiple TCs locations were tested recently by N. Bourcey for precise measurement of lag time.

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- Coil Fabrication Summary & Overview
- **Coil size and asymmetry**
- Cable Expansion / Gap Closure
- Cross Section Analysis
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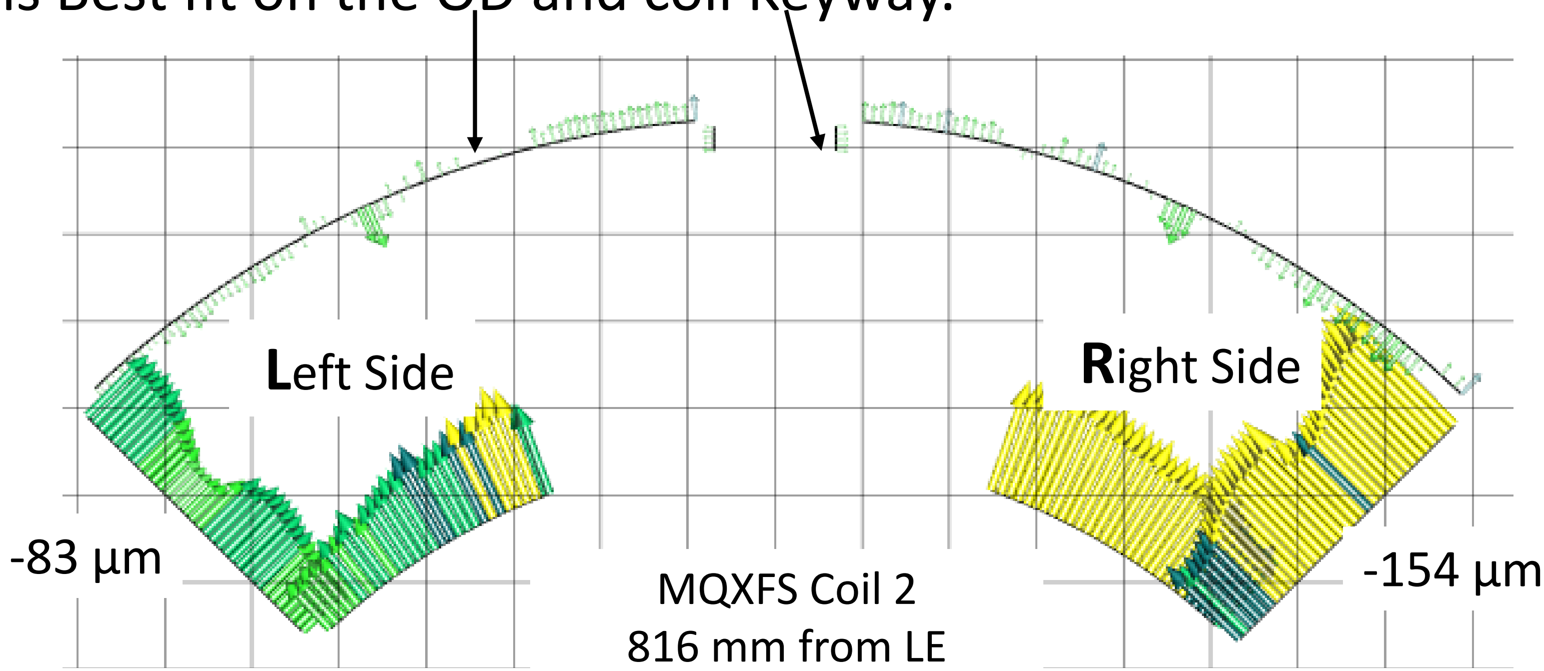
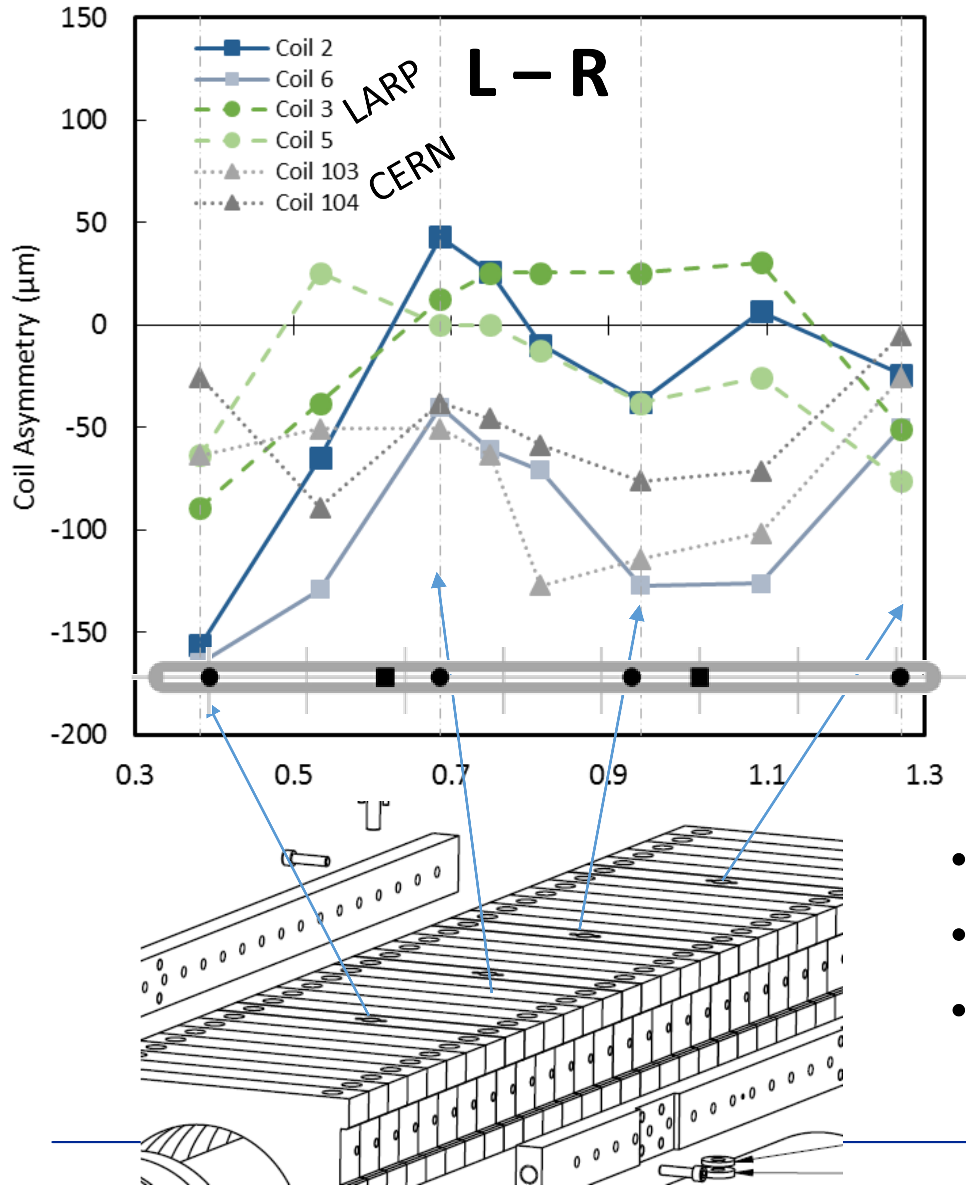
Coil Asymmetry and Size

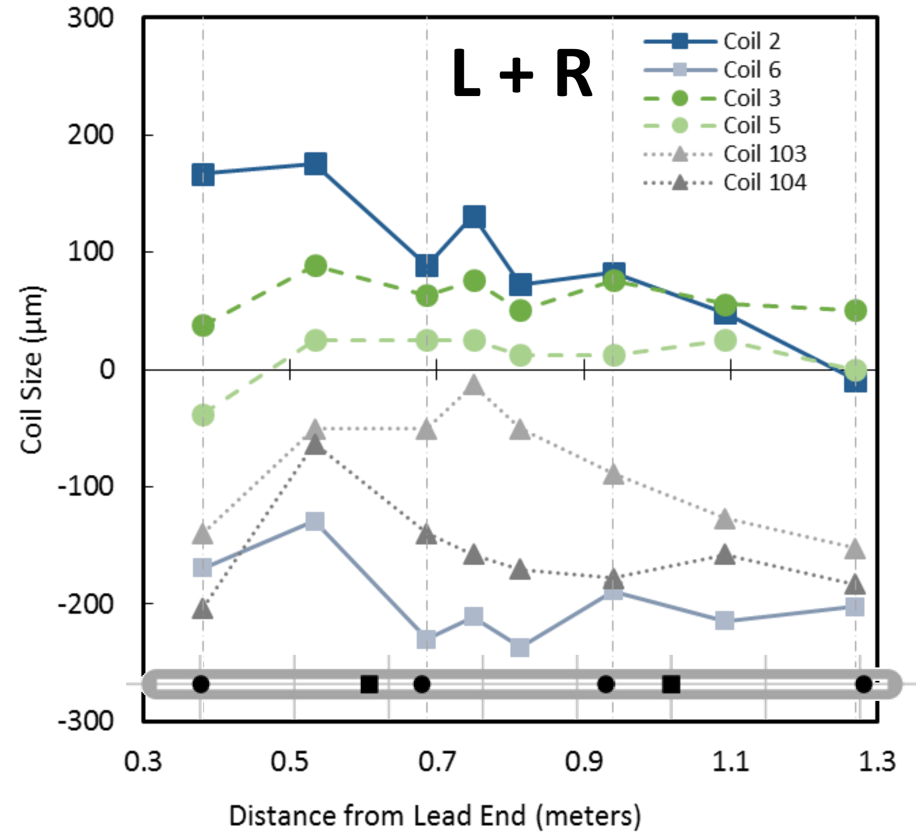
- Coils Best fit on the OD and coil Keyway.



- Coil Size = **L + R** = -237 µm
- Coil Asymmetry = **L – R** = +71 µm

Coil Asymmetry and Size

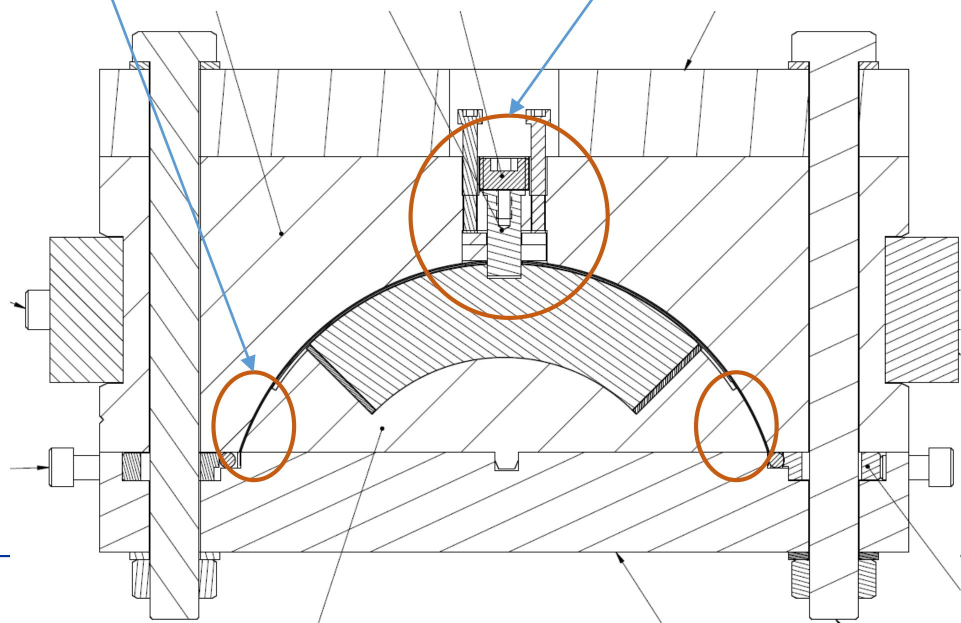




- L – R < 100 µm for < 1 unit a4, a3
- L + R < 50 µm for < 1 unit a3, a6
- How might coil size and asymmetry create undesired preload??? To be explored…

Improving Coil Asymmetry

- Size and Asymmetry is **Tooling Dominated**.
- Add shim between form and mandrel blocks to account for tolerance buildup and create intimate contact between tooling components
- Fabricate additional modified form blocks and select blocks that are ~15 µm within center.



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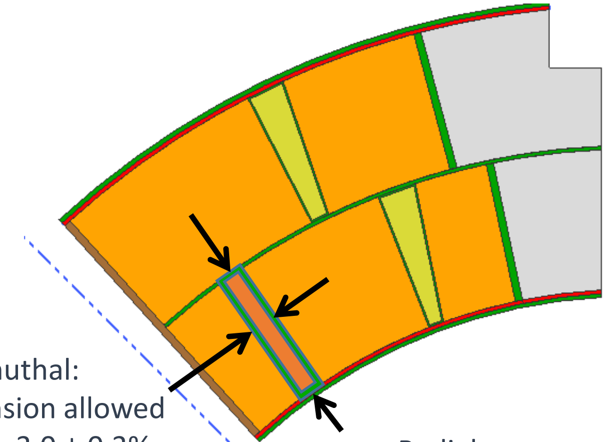
Accommodating Expansion

- Nb_3Sn Cable **expands laterally** when heat treated.
- Nb_3Sn Cable **contracts axially** when heat treated.
- Room is left in coil cavity for cable to expand during heat treatment.
- Gaps are left in the pole to allow cable/coil to contract



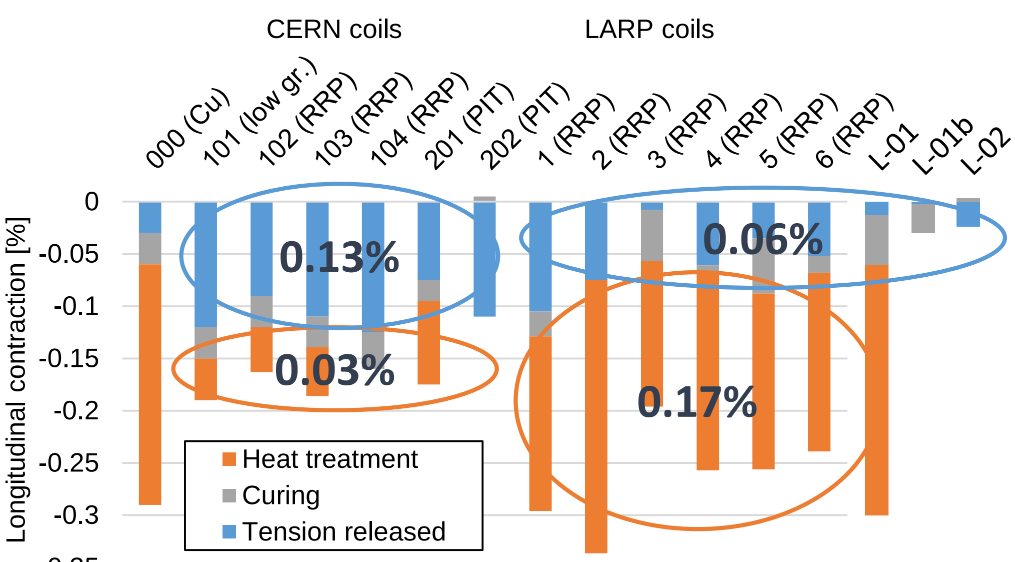
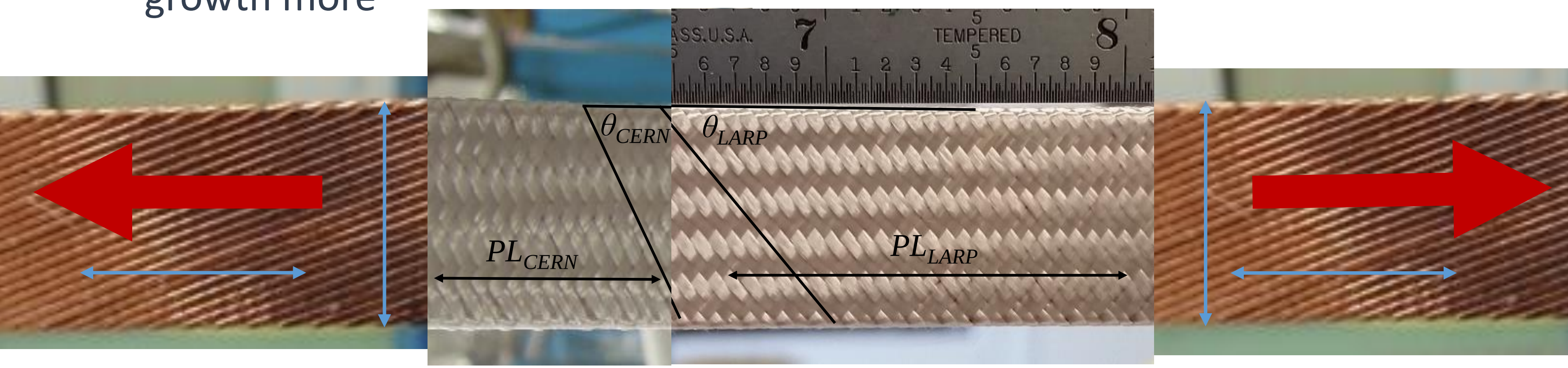


Figure courtesy of E. Rochepault

Releasing the Tension

- LARP Coils Contract Less than CERN when 25 kg of tension is released
- For mechanical stability LARP braided insulation is tighter and initially constricts growth more



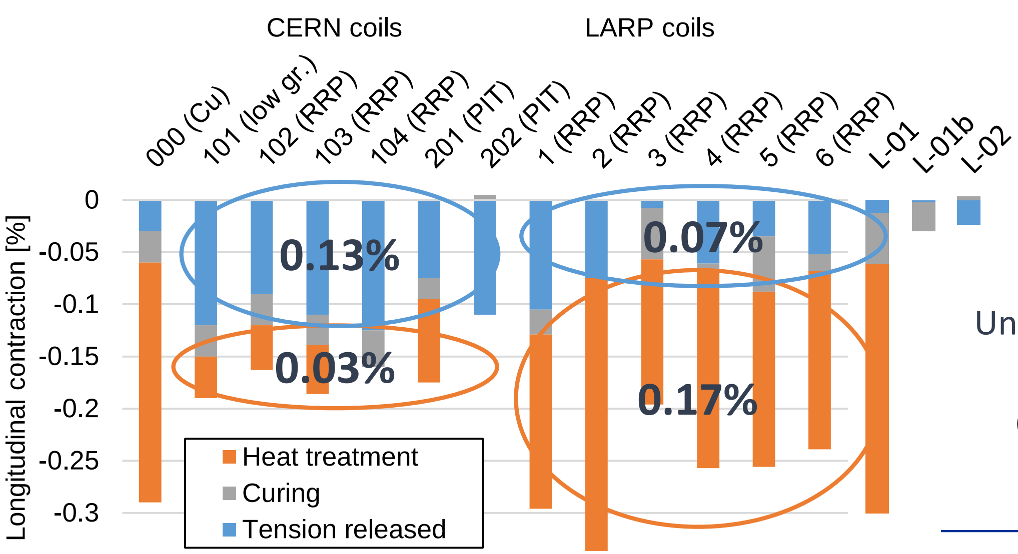
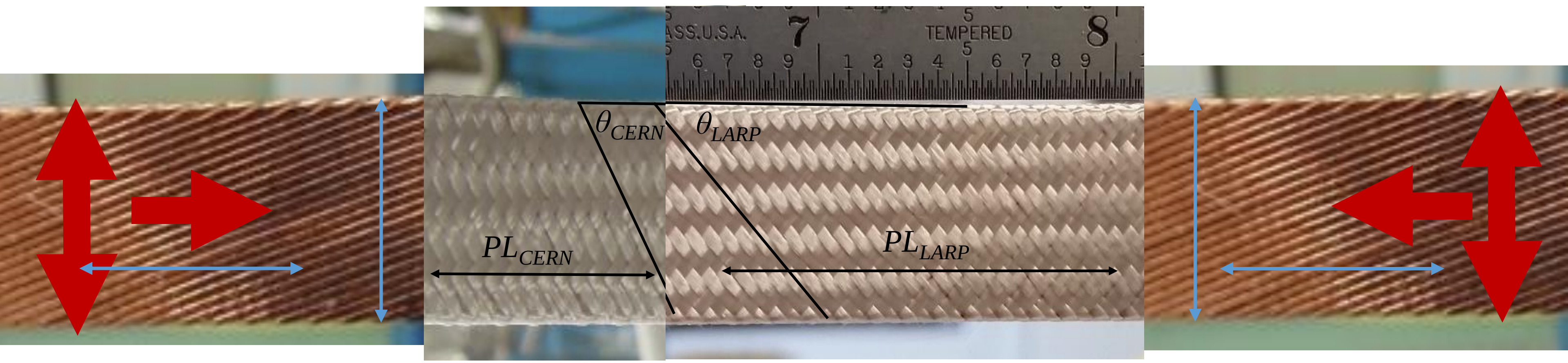


Figure courtesy of E. Rochepault

Width Expansion:
Unconfined Cable 1.4%
LARP Cable **0.3%**
CERN Cable **0.1%**

Altering Expansion

- Both conductors expand similarly when unconfined.
- CERN insulation preferably constricts width growth



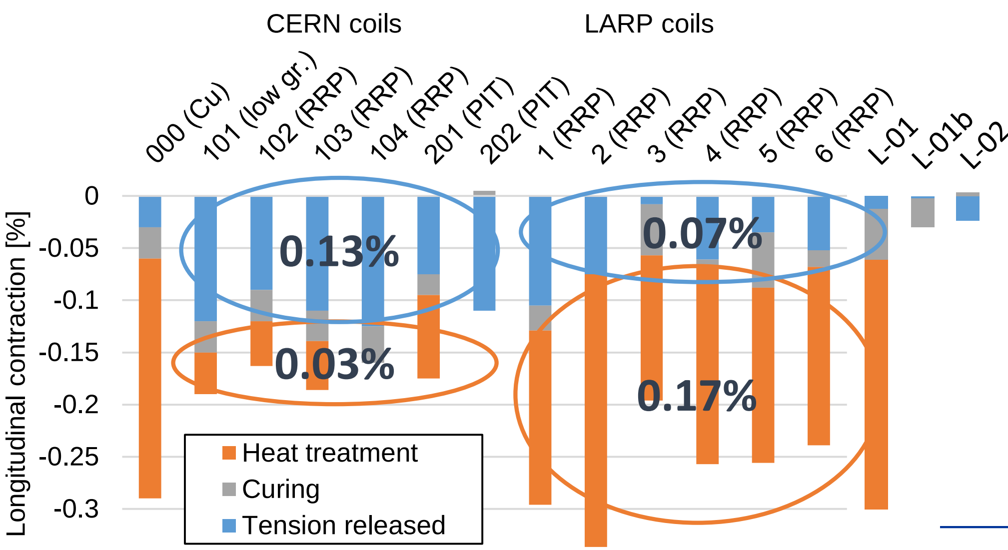


Figure courtesy of E. Rochepault

Width Expansion:
Unconfined Cable 1.4%
LARP Cable **0.3%**
CERN Cable **0.1%**

- Friction between coil and tooling also effects pole gap closure (# layers of mica, pressure between components..., *E. Cavanna*)

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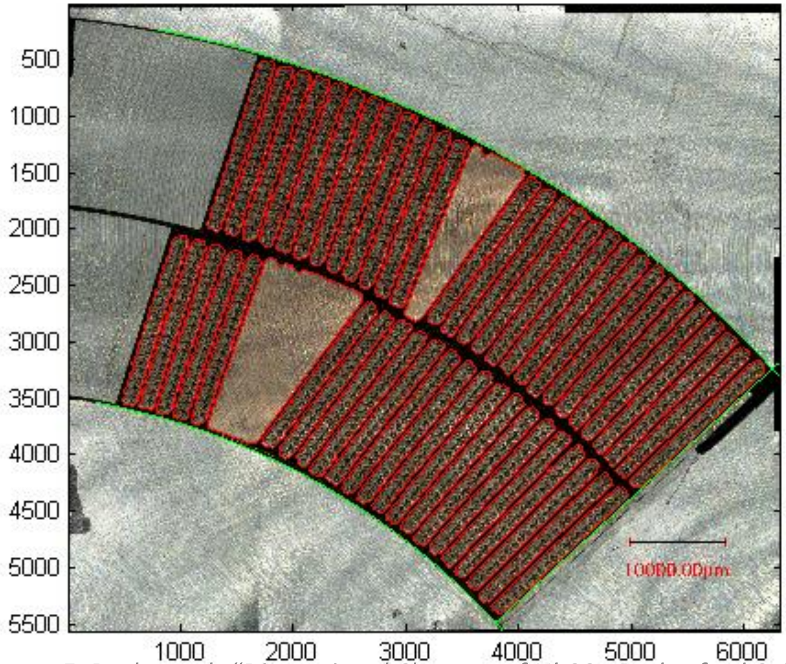
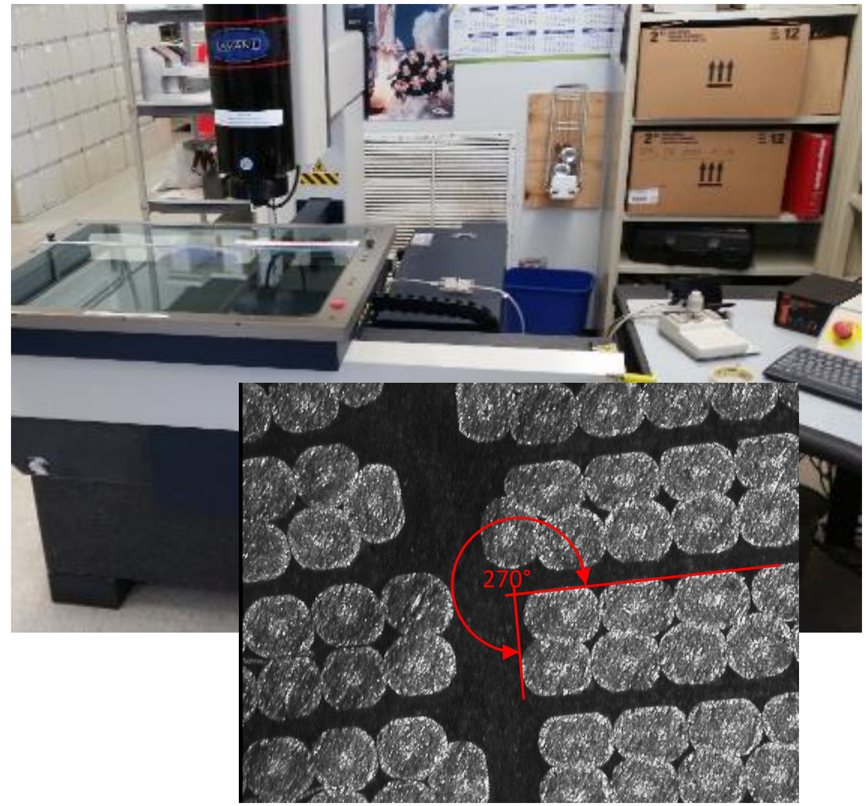
Coil Cross Section Analysis



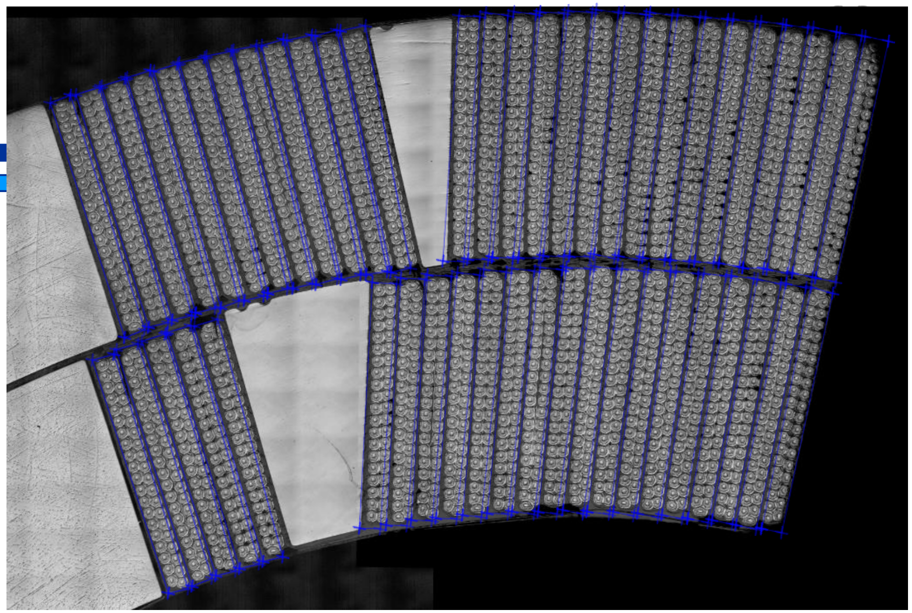
E. Rochepault "Dimensional Changes of Nb3Sn Rutherford Cables during Heat Treatment" This Conference



- CERN coil 101, Turn location from Image analysis and edge detection

- LARP coil 1, Turn location from Optical Coordinate Measurement Machine

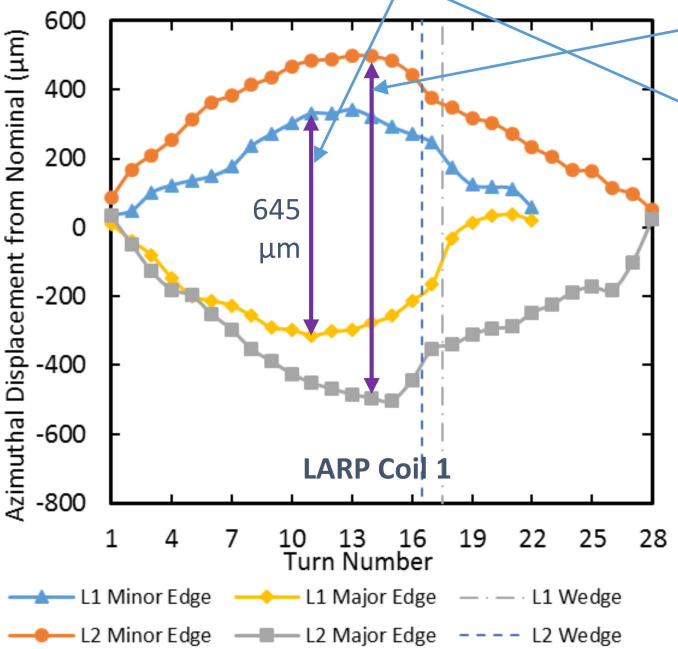
Reduced Expansion → Turn Displacements

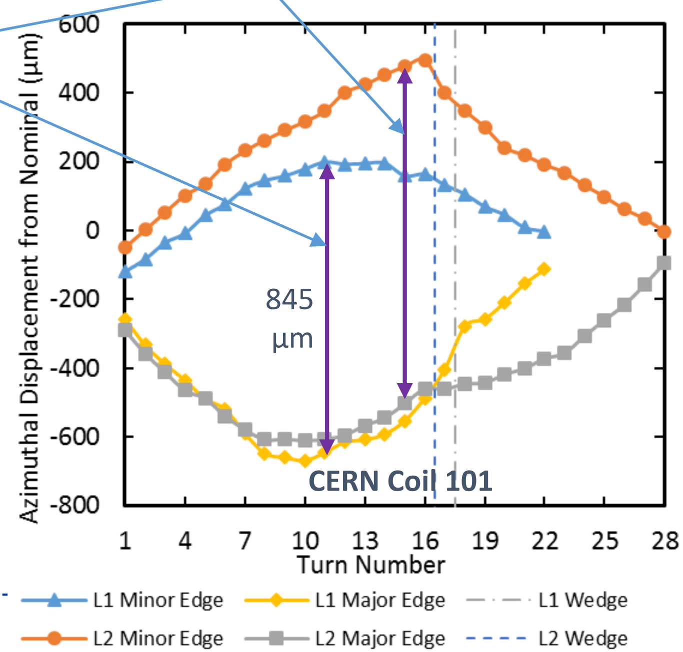


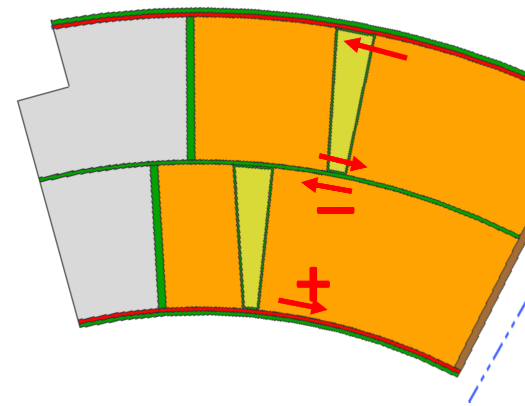
- Azimuthal Free Space
  - Layer 1: **690 µm → 470 µm** in 2nd Gen QXF
  - Layer 2: **880 µm → 600 µm** in 2nd Gen QXF
- Strong similarities between CERN and LARP
- Minor edge tends to shift toward midplane
- Major edge tends to shift toward pole

Peak Layer 1 difference is at middle turn for **both** coils

Peak Layer 2 difference is at middle turn and is **995 µm** for **both** coils

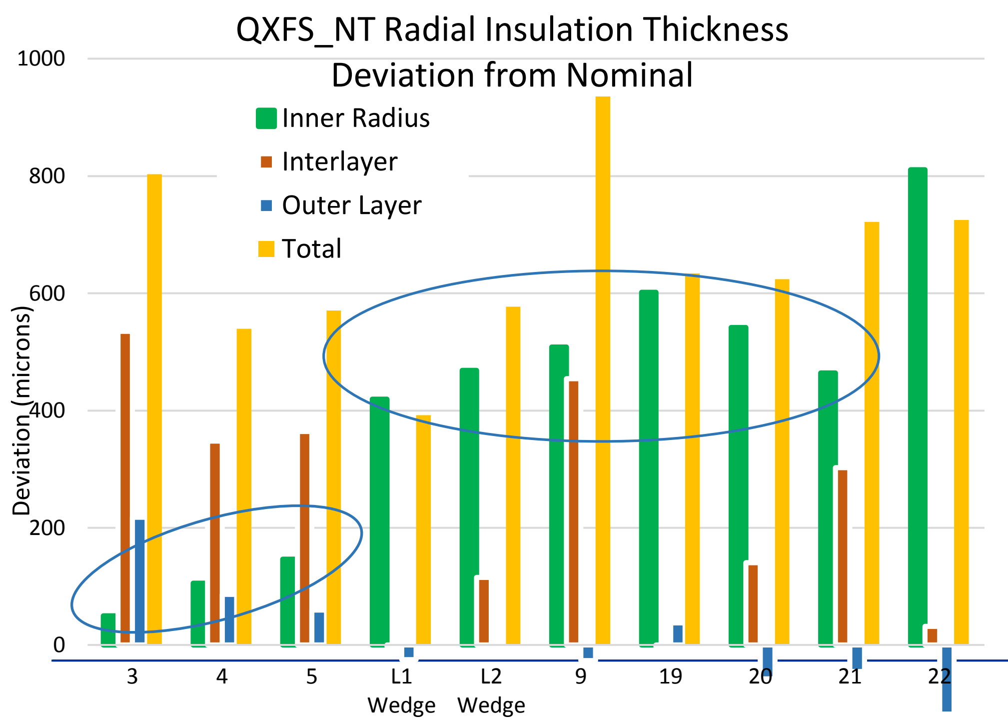


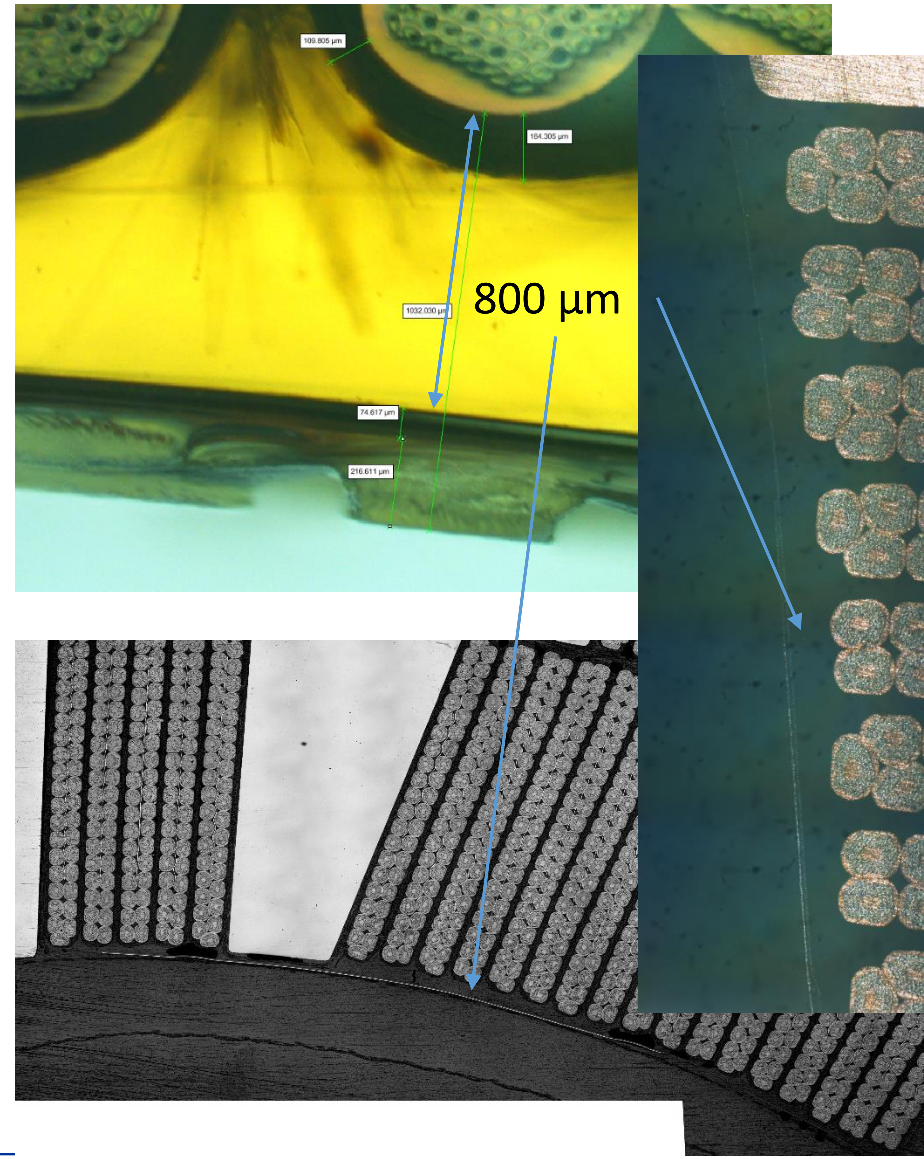




Free space mostly @ ID

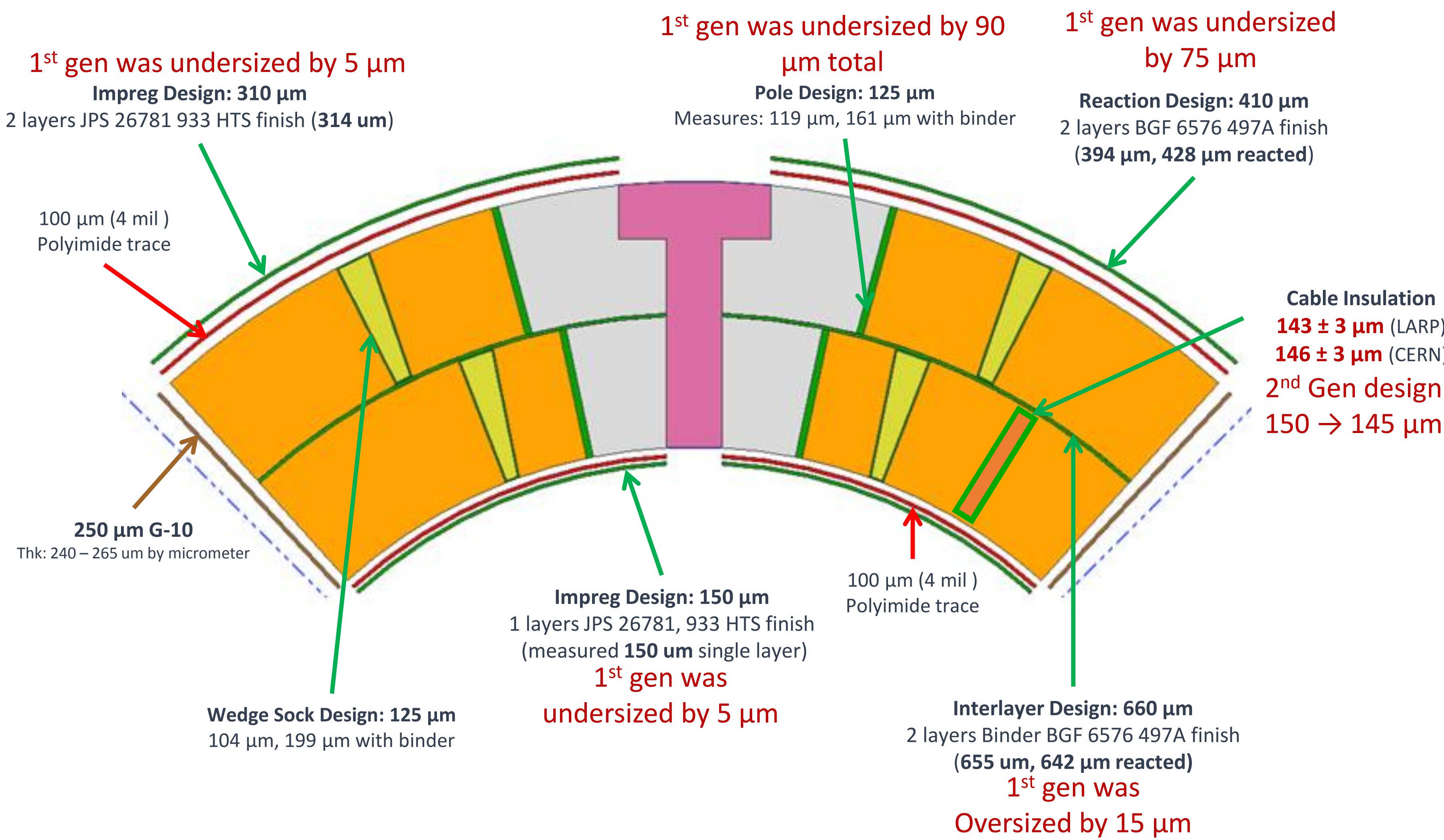
- Radial Free Space
  - CERN **680 µm → 360 µm** in 2nd Gen QXF
  - LARP **600 µm → 280 µm** in 2nd Gen QXF
- ID heater is nominally 200 µm from Cable
- Average distance is ~ 300 µm @ high field and ~700 µm in low field
- New Input parameters for Quench Models





2nd Gen MQXF S2-Glass

10-stack measurements of all insulation → Tighter Material Control



Conclusion

- LARP/CERN has fabricated 13 coils short MQXF coils with **arguably the highest success rate** of any new high-field Nb_3Sn design.
- LARP/CERN is preparing for the **first full assembly test** at FNAL.
- Coil Size and Asymmetry should improve with slight tooling and fabrication adjustments.
- Cable insulation **Reduces Transverse Growth** causing large turn displacement and free space.
- The Inner layer heater is **~300 µm (~700 µm**) in the High (low) field region rather than the designed **200 µm**.
- Increased thickness and tighter measurement in 2nd Gen MQXF insulation should improve turn displacement and may improve inner PH delay times.

Spare Slides

Coil Heat Treatment

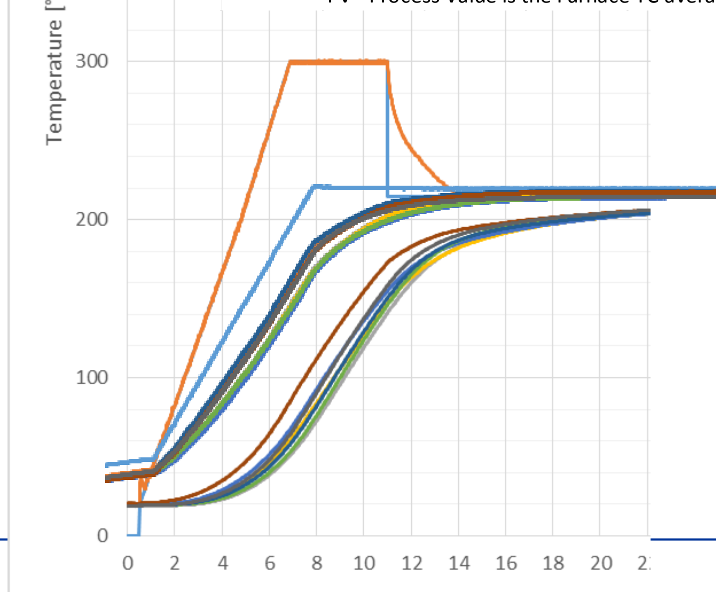
Amount of time Furnace, Retort, and Coil was within 5°C of the set point.

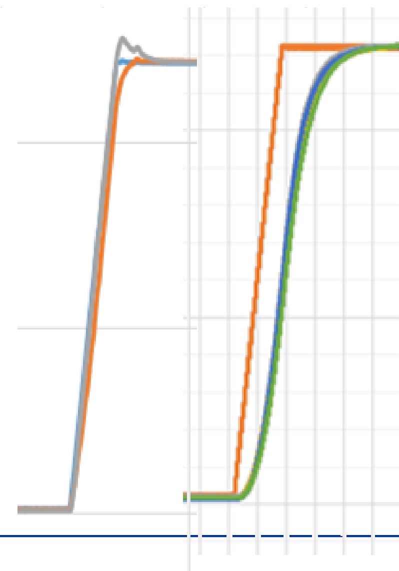
@210°C	(hours)	48 h nom. CERN 103*	72 h nom. LARP Coil 6	72 h nom. LARP Coil 2
enter	PV	5.0 h	8.5 h	9.5 h
205°C	Coil	29.0 h		
	Retort		14.7 h	16.0 h
	witness		9.0 h	9.9 h
	delay	**24.0 h**	**6.2 h**	**6.5 h**
exit	PV	74.0 h	81.0 h	81.9 h
215°C	Coil	76.0 h		
	Retort		81.5 h	82.3 h
	witness		81.4 h	82.4 h
	delay	**2.0 h**	**0.5 h**	**0.4 h**
	Duration	**47.0 h**	66.8 h	66.3 h
Equivalent Duration			**50.5 h**	**50.4 h**
Witness Duration			72.4 h	72.5 h

@640°C		50 h nom. CERN 103	48 h nom. LARP Coil 6	48 h nom. LARP Coil 2
enter	PV	143.5 h	142.0 h	142.2 h
635°C	Coil	151.0 h		
	Retort		142.5 h	142.8 h
	witness		142.1 h	142.1 h
	delay	**7.5 h**	**0.5 h**	**0.6 h**
exit	PV	201.8 h	190.6 h	190.5 h
635°C	Coil	202.6 h		
	Retort		190.7 h	190.6 h
	witness		190.6 h	190.6 h
	delay	**0.8 h**	**0.1 h**	**0.1 h**
	Duration	**51.6 h**	48.2 h	47.8 h
Equivalent Duration			**41.9 h**	**41.6 h**
Witness Duration			48.5 h	48.5 h

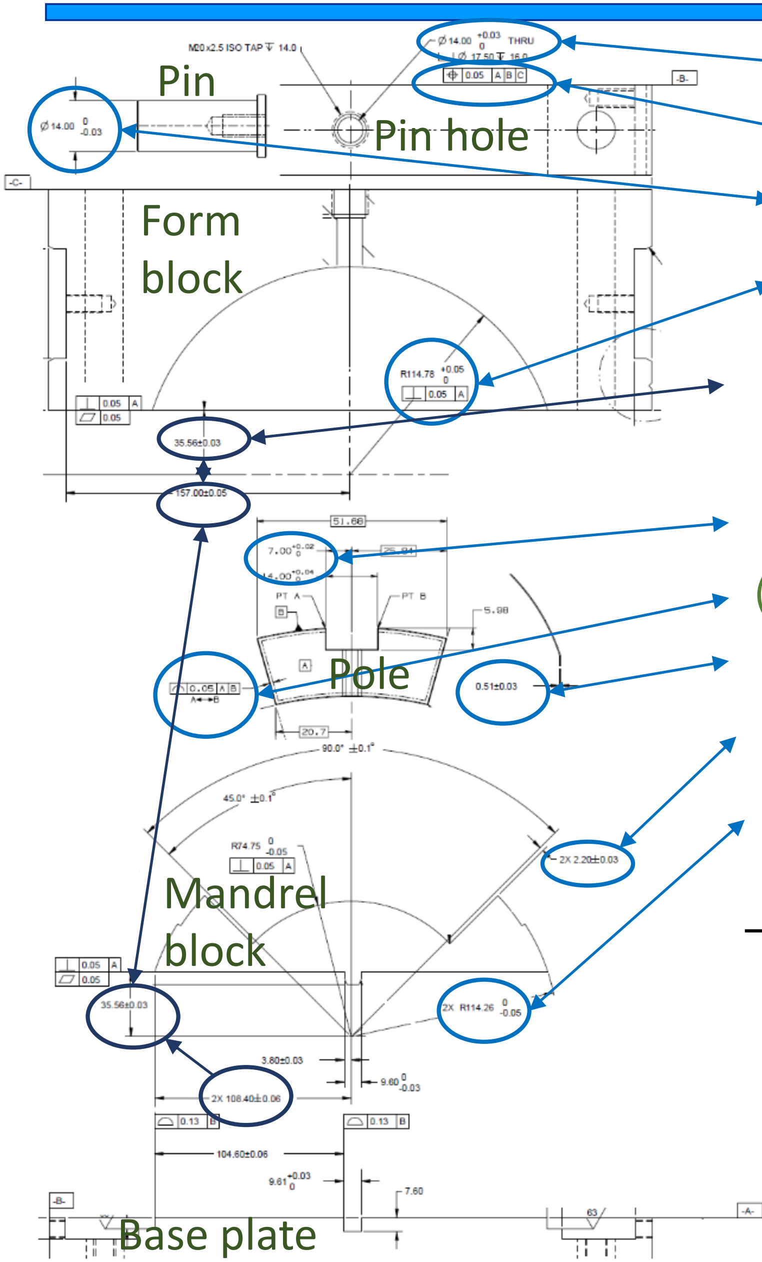
*Included PV overshoot

PV - Process Value is the Furnace TC average to +/- 5°C





Max Tolerance



0.015 mm from hole size

0.050 mm from hole location

0.015 mm from pin size

0.050 mm from form block radius

0.019 mm from form and mandrel block radius centers

(0.110 mm if rigid assembly -> Assembly wouldn't close.)

0.020 mm from pole keyway size

(0.050 mm) from pole edges (only effects turn asymmetry)

0.030 mm from SS outer shim

0.030 mm from mandrel block coil midplane

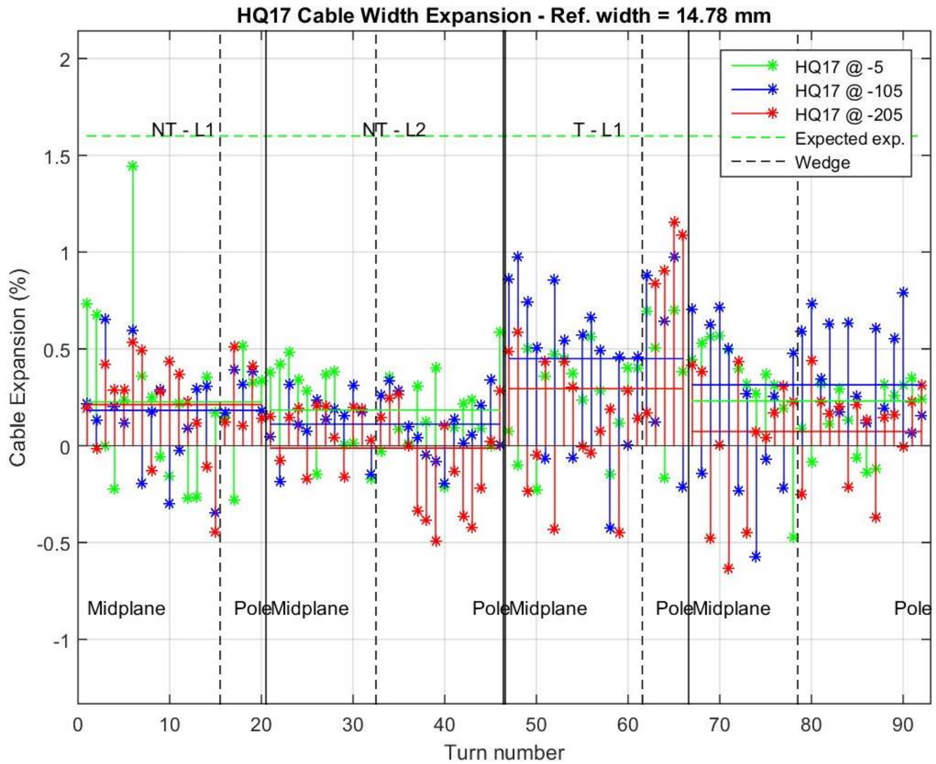
0.050 mm from mandrel block radius

0.010 mm from intrinsic design

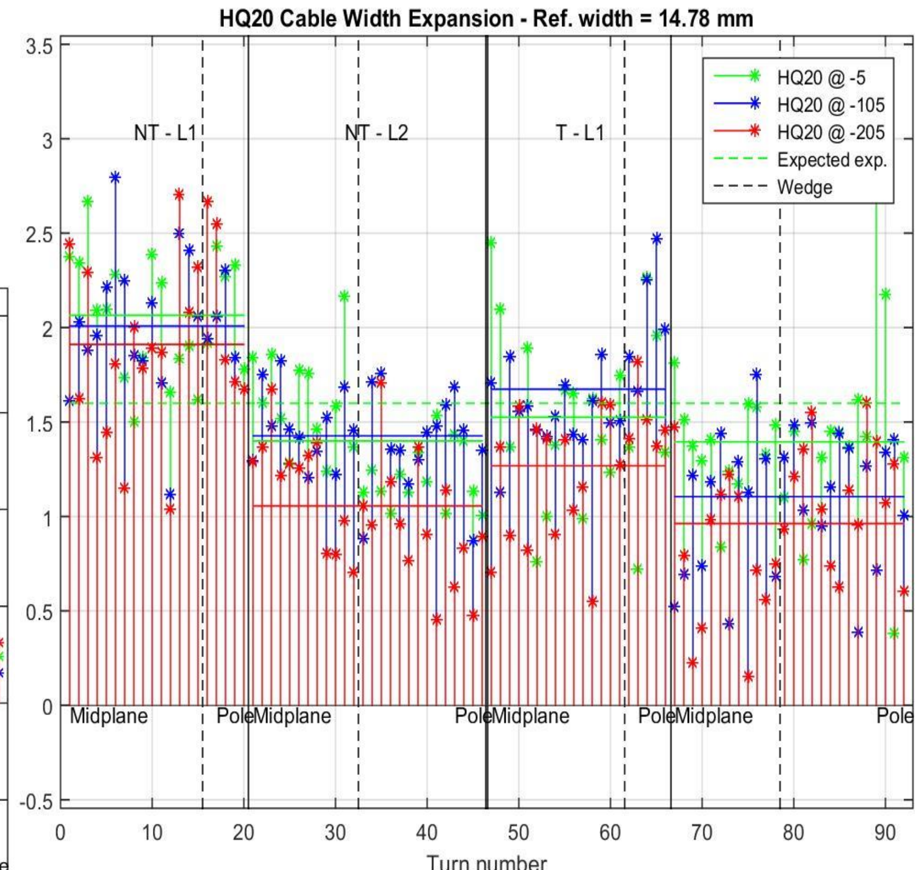
0.289 mm total

-> Maximum L/R asymmetry is **578 um or nearly 23 mils!!!**

HQ02 Coil 17 and 20

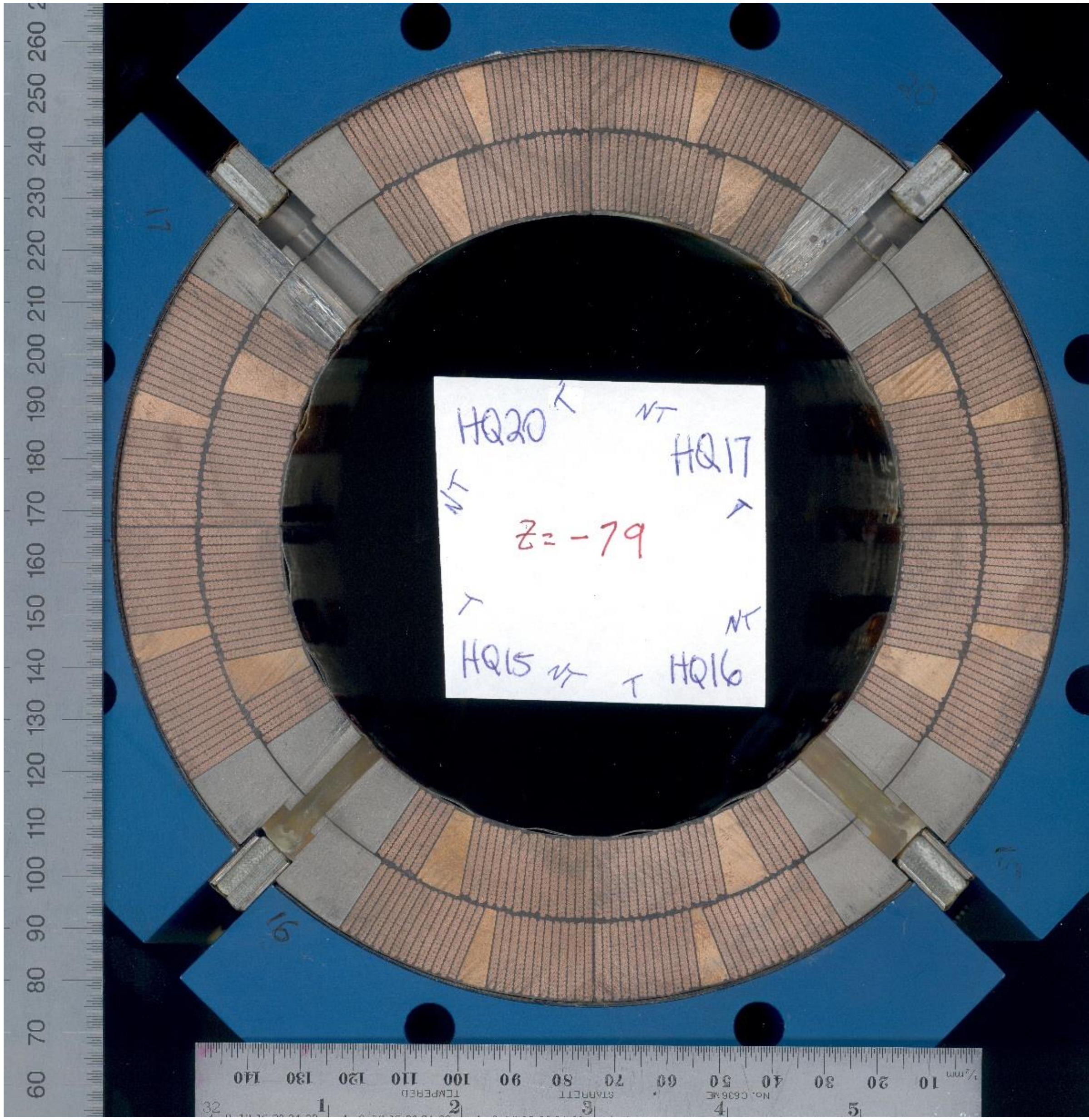


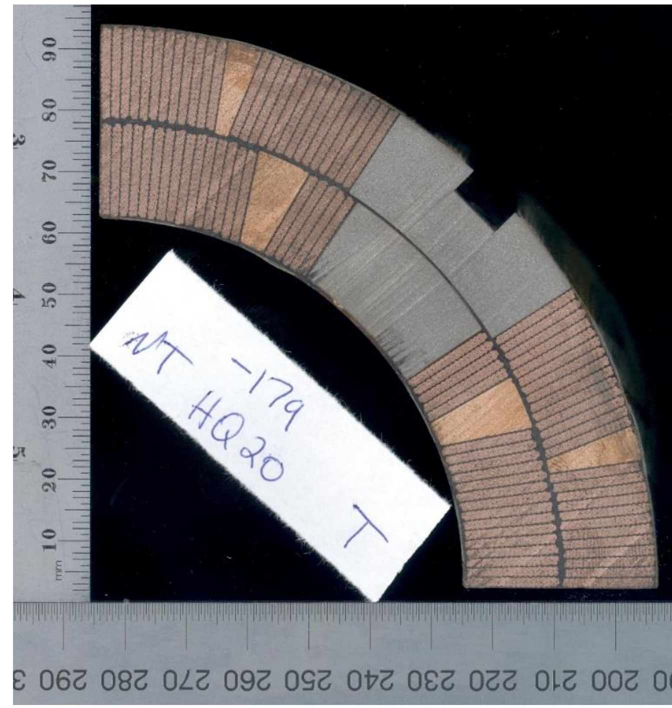
Pole Gap Closure = **0.01%**



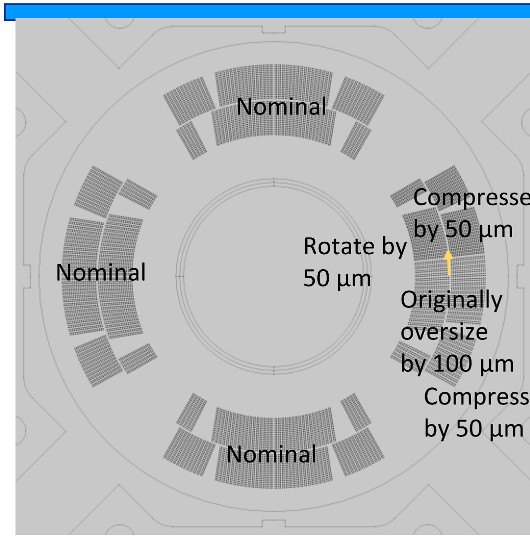
Pole Gap Closure = **0.15%**

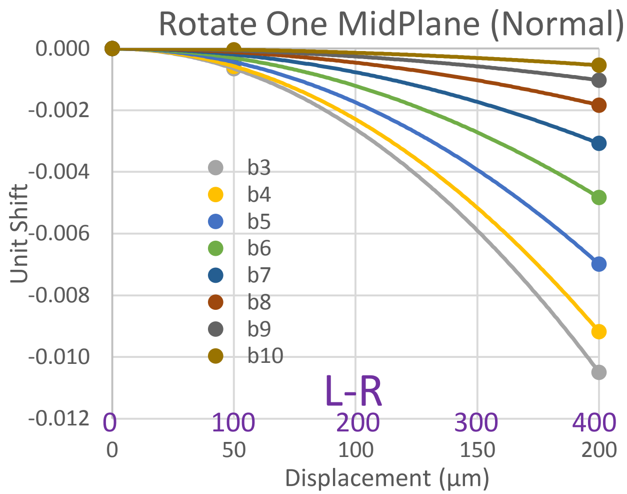
Scans of HQ02

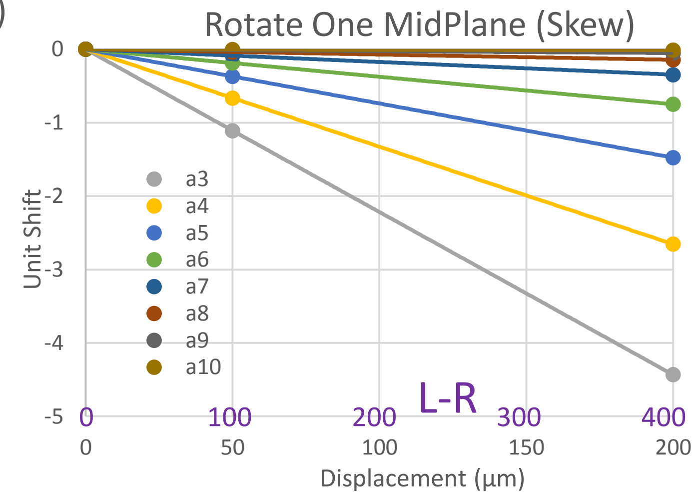


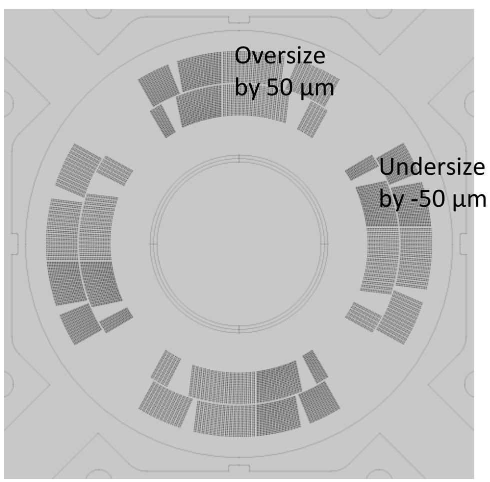


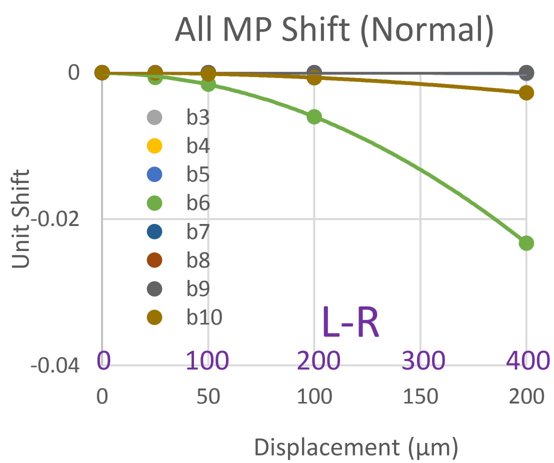
Effect of L – R on Field?





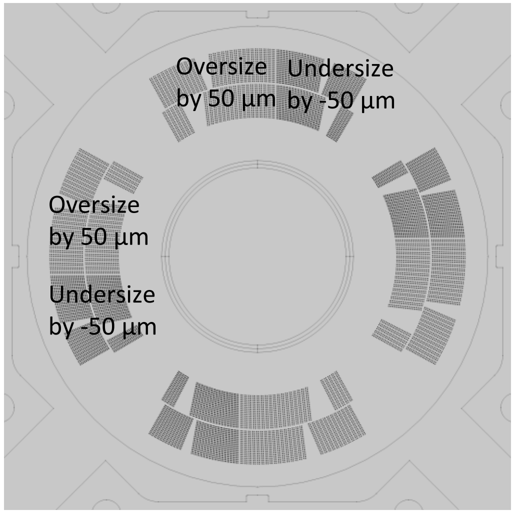


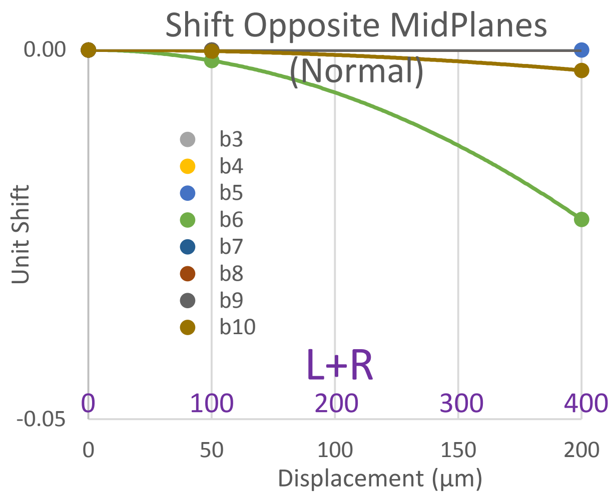


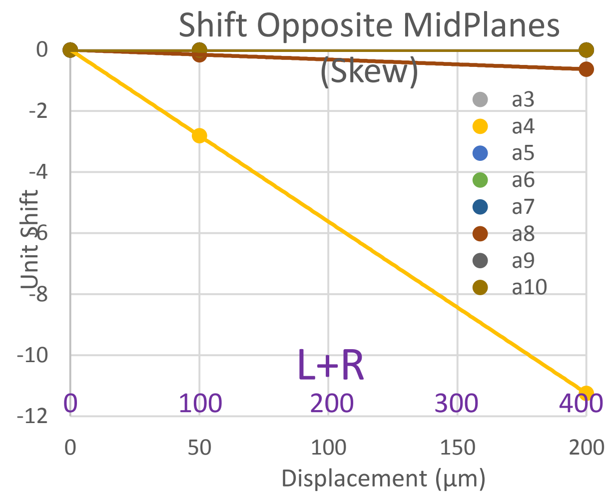


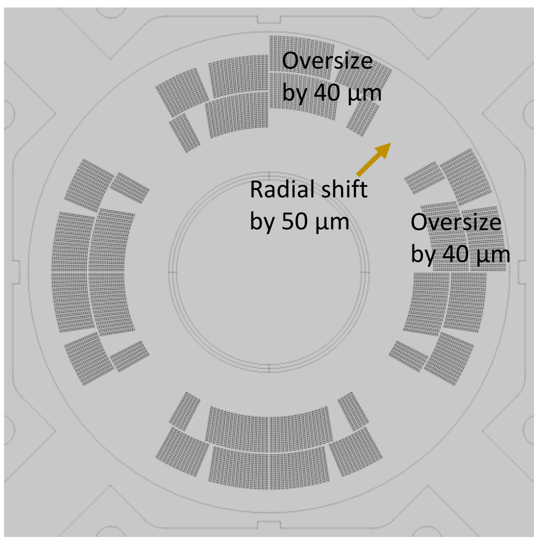
- These estimates suggest that we need at least ~**100 µm of L-R** accuracy to be within ±1 unit
- Effect of several perturbations to QXF Field quality: https://indico.fnal.gov/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=10554

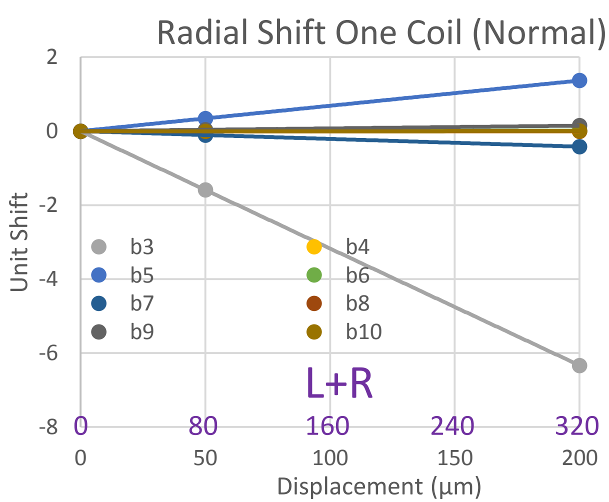
Effect of L + R on Field?

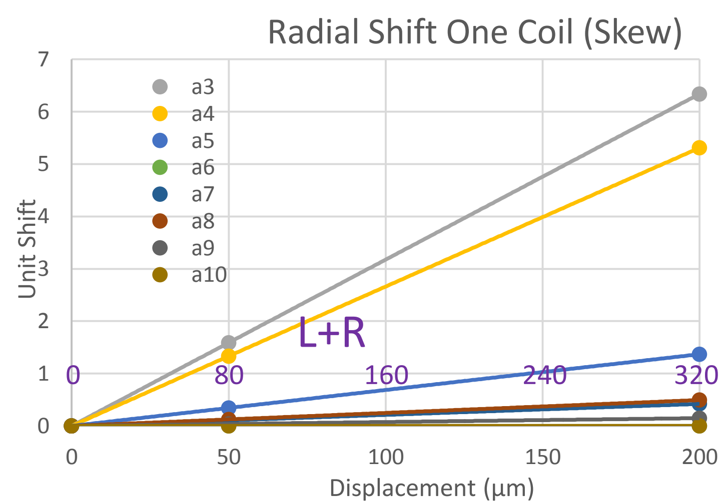






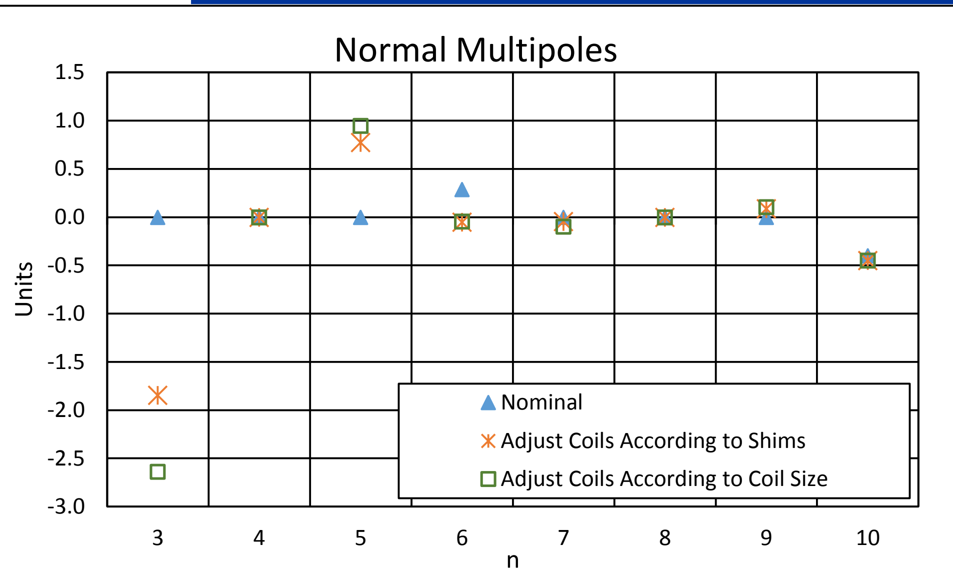


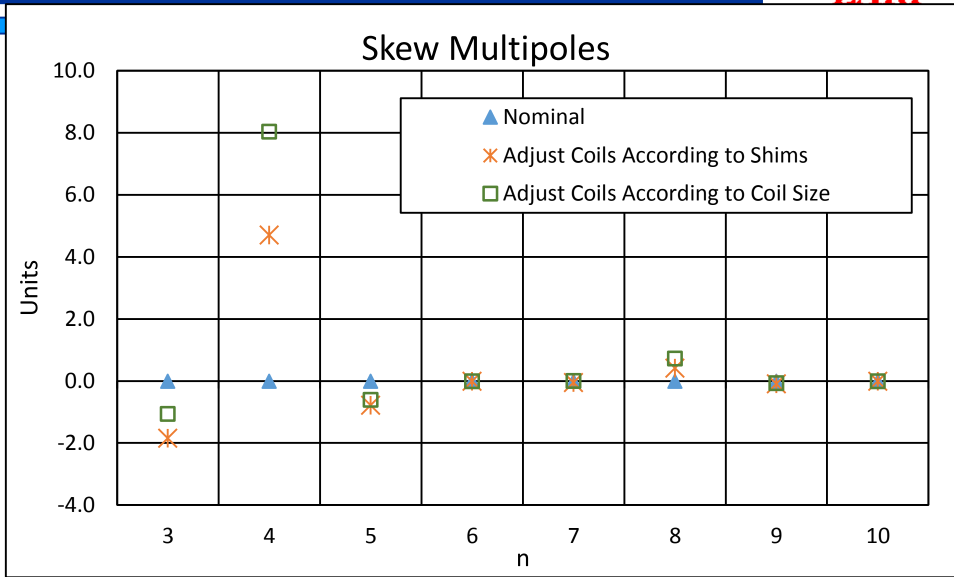


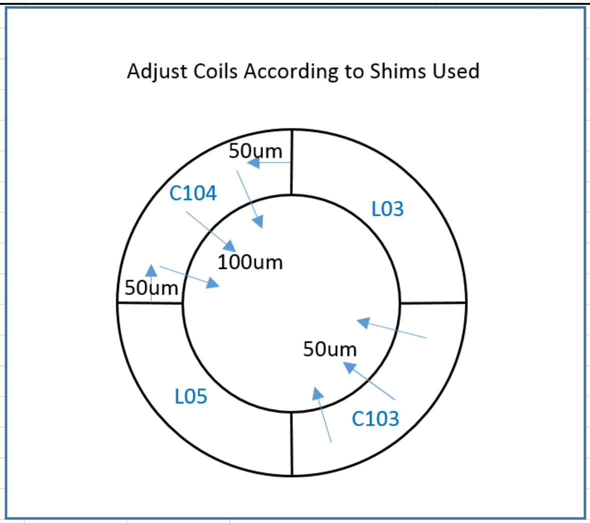


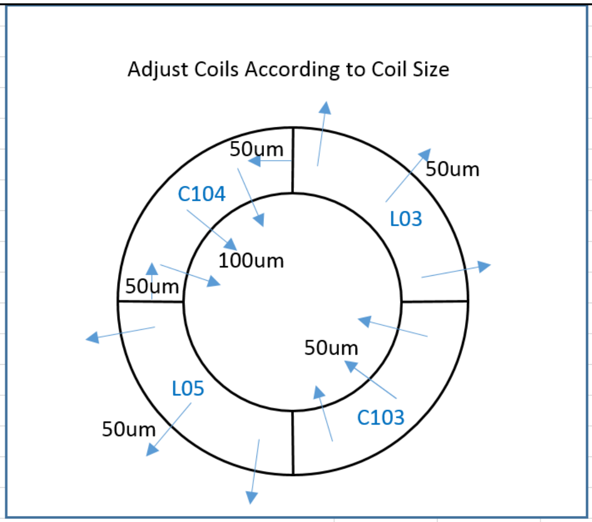
- These estimates suggest that we need at least ~**50 µm of L+R** accuracy to be within ±1 unit

MQXFS-AS, Estimated FQ









Nominal QXF cross sections are used for calculation at nominal current, 1746 A.

Coil C104 midplanes are pulled in 50 um
Coils L03 and L05 are left alone
Coil C103 and C105 are radially pushed in by 50 and 100 um respectively

Coil C104 midplanes are pulled in 50 um
Coils L03 and L05 are drawn out by 50 um
Coil C103 and C105 are pushed in by 50 and 100 um respectively

Goals of Next 2 Weeks…

- HT, TC placement with N. Bourcey
- Cross Section analysis with E. Rochepault
- CMM / FARO with J. Ferradas Troitino
- Coil fab (impreg, materials) with E. Cavanna
- Splice equipment
- Curing setup
- Long coil fab
- 11 tesla
- (ROXIE with S. Izquierdo Bermudez)