MQXFB09 Coils:
Coil fabrication, manufacturing data and NC

N. Lusa, S. Izquierdo Bermudez, L. Baudin, A. Vieitez Suarez, P. M. Quassolo, L. Grand-Clement, R. Berthet

On behalf of MQXFB Coil Fabrication and QA team

https://indico.cern.ch/event/1510575/

06/02/2025

Coils for MQXFB09

- **Virgin coils available at the time of assembling MQXFB09**
  - Coil 109: Spare coil of MQXFBP1 (no b_6 correction)
  - Coil 114: Quarantined, due to the electrical insulation issue QH to coil
  - Coil 116: Quarantined, due to conductor damage during handling
  - Coil 122: Conform previous generation coil
  - Coils 152-153-154-155: proposal for MQXFB09

Outline

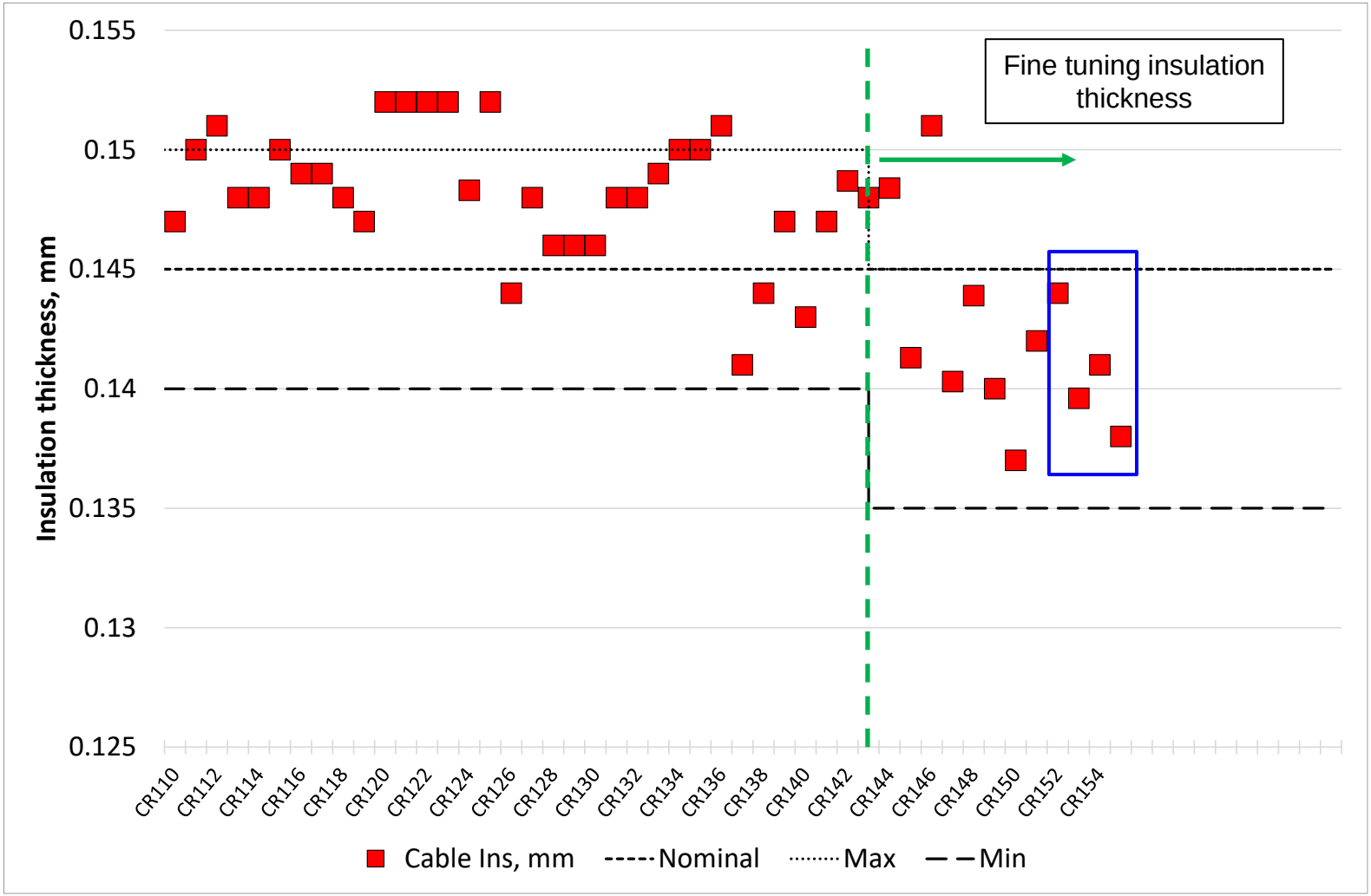
- Manufacturing data
- Non-conformities
- Conclusion/Proposal

Outline

- Manufacturing data
  - Analysis of MQXFBP2 coils and comparison improvements with respect to MQXFBP1 available here
  - Analysis of MQXFBP3 coils and comparison improvements with respect to MQXFBP2 available here
  - Analysis of MQXFB02 coils and comparison improvements with respect to MQXFBP3 available here
  - Analysis of MQXFB03 coils and comparison improvements with respect to MQXFB02 available here
  - Coil fabrication data and non-conformities of MQXFB04 coils available here
  - Coil fabrication data and non-conformities of MQXFB05 coils available here
  - Coil fabrication data and non-conformities of MQXFB06 coils available here
  - Coil fabrication data and non-conformities of MQXFB07 coils available here
  - Coil fabrication data and non-conformities of MQXFB08 coils available here
- Non-conformities
- Conclusion/Proposal

Cable insulation thickness

- Target insulation thickness is 145 (+0 µm/-10 µm)



Reaction and impregnation fixture closure

REACTION

- The torque required to close the fixture is directly linked to the number of heating cycle the bolts were subjected to
  - Nominal torque required: 160 Nm
  - For B09 coils nominal torque was required (no need to further increase the torque)

IMPREGNATION

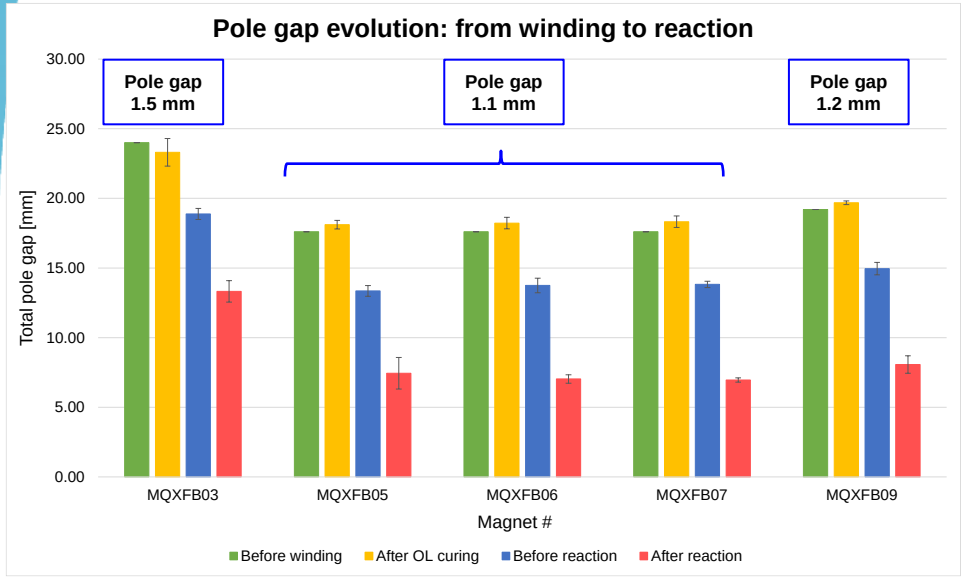
- Very reproducible from coil to coil
  - OL impregnation closure: 60 Nm
  - IL impregnation closure: 120 Nm (never needed more)

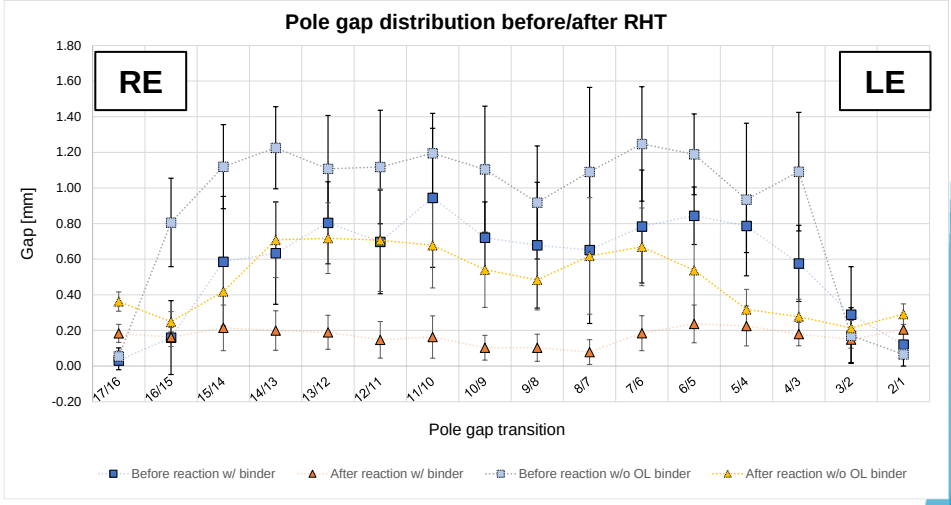
Coil elongation during reaction fixture opening

Coil elongation during reaction fixture opening						
Magnet	**Coil #**	**CS [mm]**	**NCS [mm]**	**Total [mm]**	**Total/L_m**	**Fab. Line**
B03	CR128, 129, 130, 131	2.6 - 4.2	3.1 - 4.8	5.7 - 8.7	0.8 - 1.2 ‰	CERN
B04	CR132, 133, 134, 135	2.1 - 4.3	2.9 - 3.8	5.1 - 8.0	0.7 - 1.1 ‰	
B05	CR136, 137, 139, 140	2.0 - 3.4	2.1 - 3.6	4.1 - 7.0	0.6 - 1.0 ‰	
B06	CR141, 142, 143, 144	2.9 - 3.4	2.8 - 3.7	5.8 - 6.6	0.8 - 0.9 ‰	
B07	CR138, 145, 146, 147	2.0 - 3.4	2.6 - 3.5	4.6 - 6.9	0.6 - 1.0 ‰	
B08	CR148, 149, 150, 151	1.6 - 2.8	2.0 - 2.9	3.6 - 5.6	0.5 - 0.8 ‰	
B09 (proposal)	CR152	2.9	3.3	6.2	0.9 ‰	
	CR153	2.3	2.3	4.6	0.6 ‰	
	CR154	2.7	3.2	5.9	0.8 ‰	
	CR155	2.3	2.3	4.6	0.6 ‰	
	AUP 146 -147	2.9 - 3.6	0.6 - 0.4	3.6 - 4	0.8 ‰ - 0.9 ‰	FNAL
	AUP 237 -238	1.6 - 2.1	1.6 - 2.1	3.1 - 4.1	0.7 ‰ - 1 ‰	BNL

Pole gaps

- In new generation MQXFB coils pole gaps in the middle of the coil are not closed after reaction, as it is the case for AUP coils

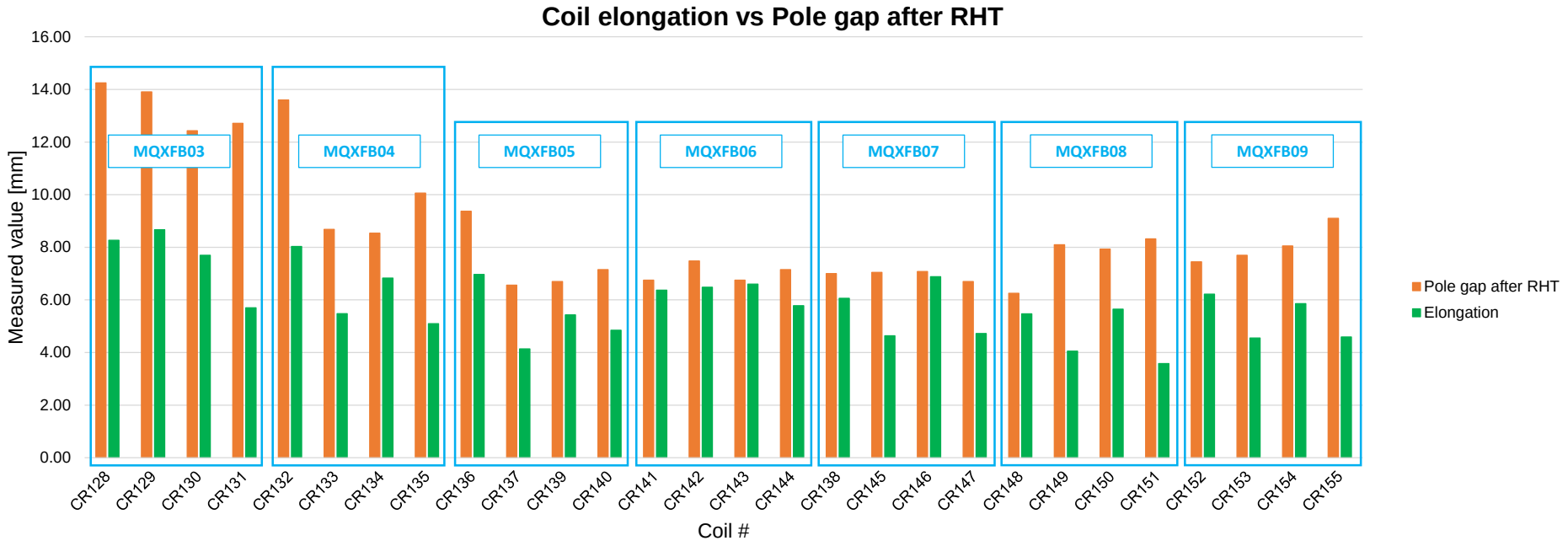




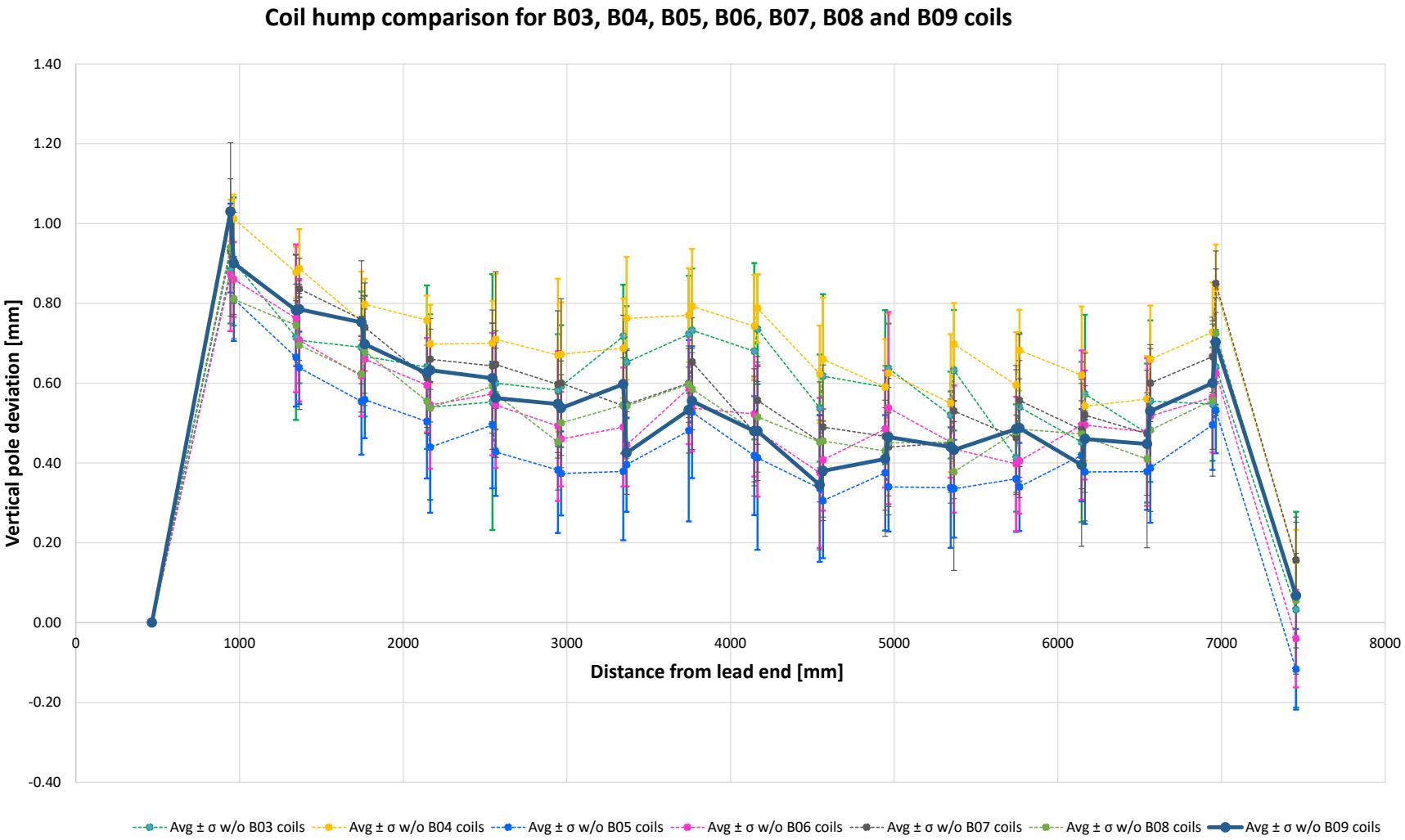
Pole gaps vs Coil elongation

- The reacted coil gradually elongates on both ends during the mold opening and pole gap increases (indico 1220226)
- From coil CR150 pole increased: 2.46 mm/m → 2.69 mm/m

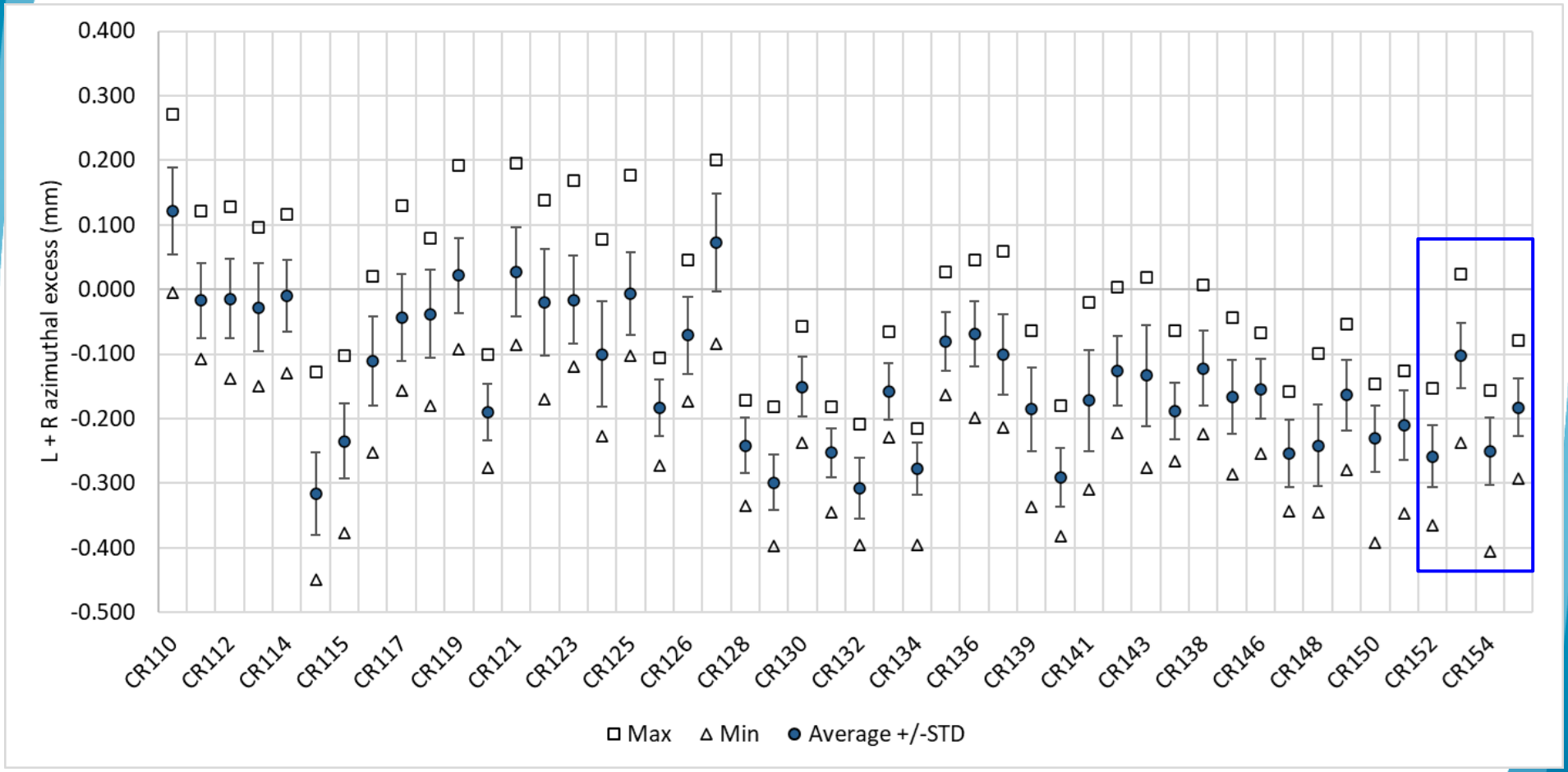
Coil #	Total /L_m [‰]	Manufacturing line
CR127	1.50	CERN w/ binder
CR128 – CR155	0.82	CERN new gen. coils
AUP 146 – 147	0.89	FNAL
AUP 237 – 238	0.88	BNL



Coil hump after reaction

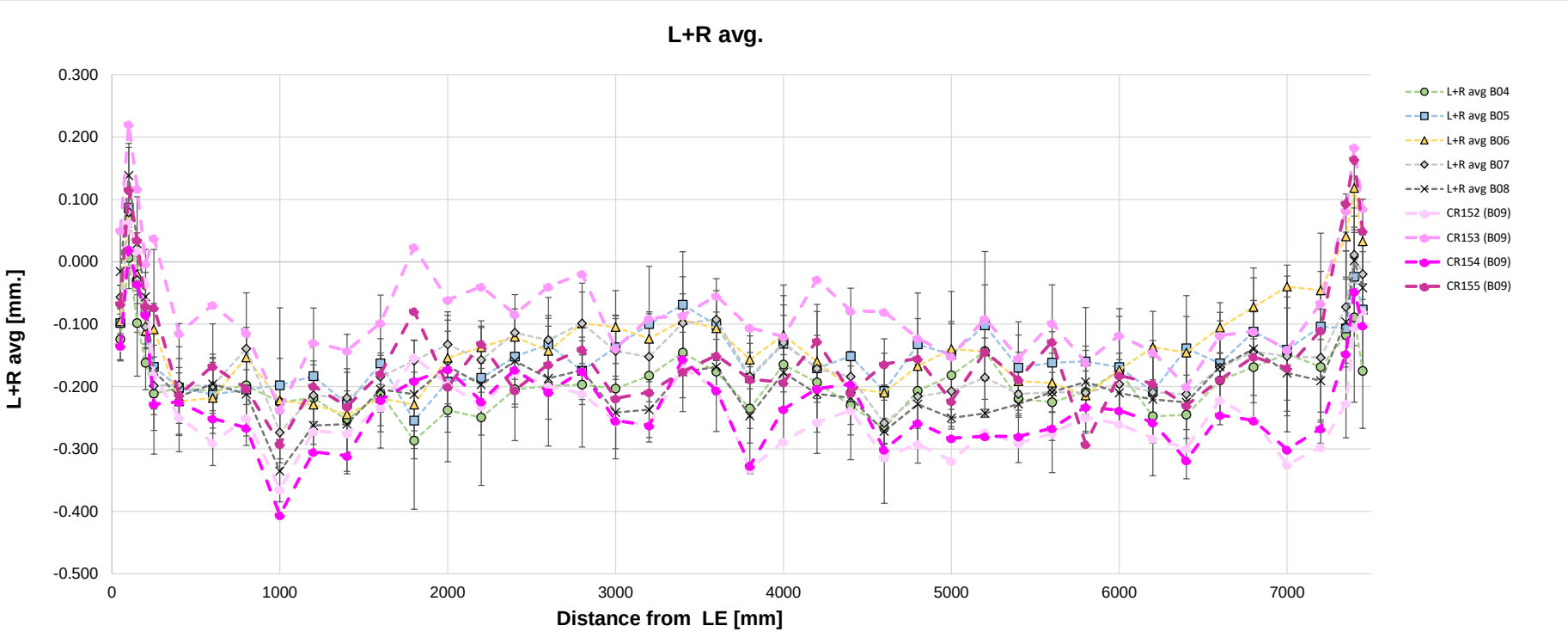


Impregnated coil geometry (Faro arm) - L+R



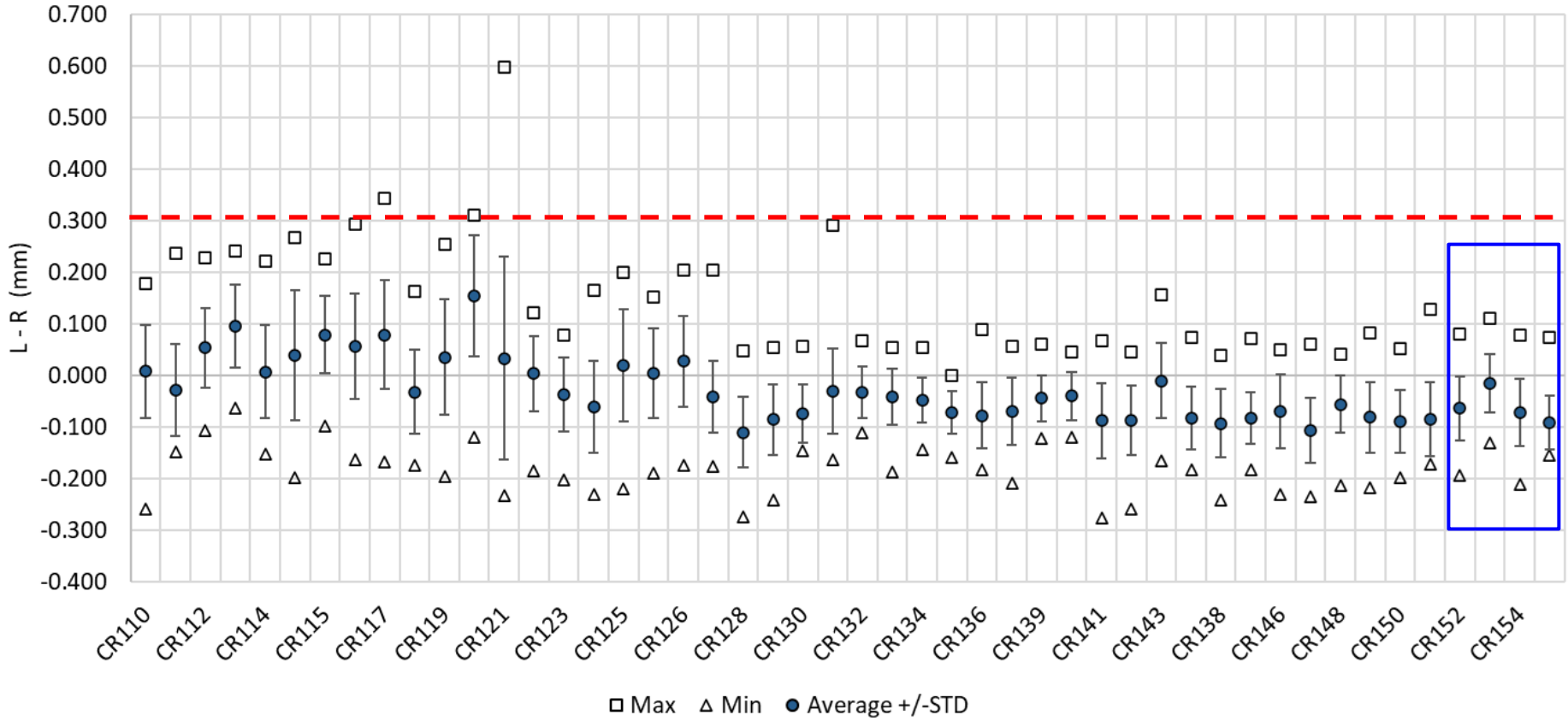
Impregnated coil geometry (Faro arm) - L+R

- The coils do not have ‘belly’



Impregnated coil geometry (Faro arm) – L-R

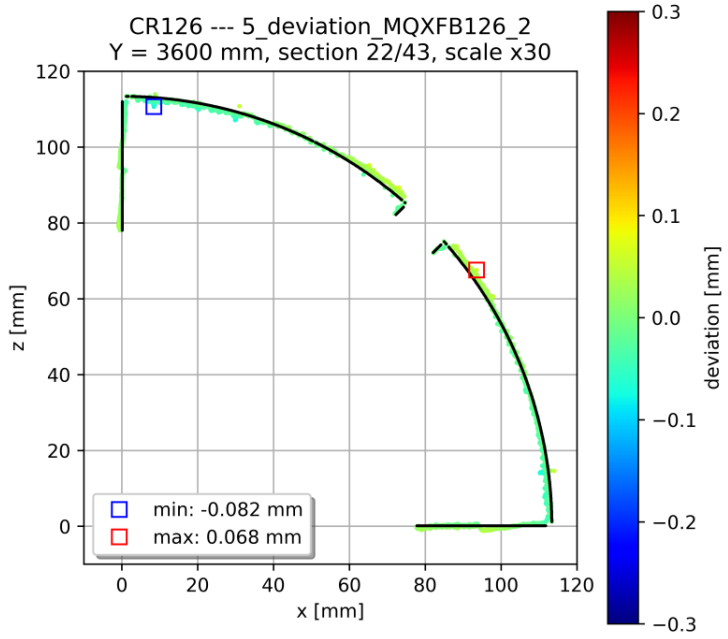
- In terms of asymmetry, within specification (<0.3 mm) → no need of pole key machining



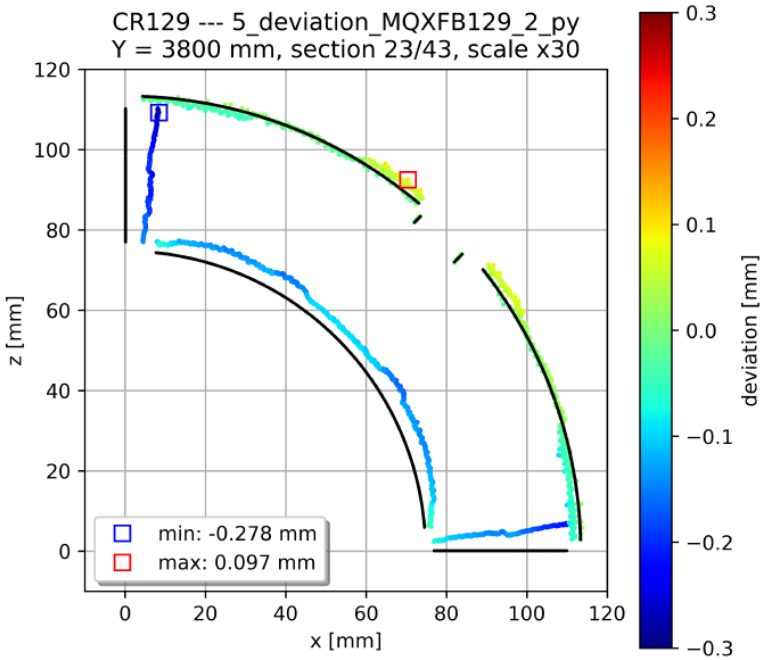
Impregnated coil geometry (Faro arm)

- Systematic behavior in terms of coil shape to previous coils without binder: mid-plane has a little ‘wedge’ (the coil covers 89.6 degrees instead of 90 degrees)
- Based on FEM we expect ≈ 15 MPa increase in the mid-plane stress (inner edge) under conservative assumptions, confirmed with a mock-up test, see https://indico.cern.ch/event/1260584/

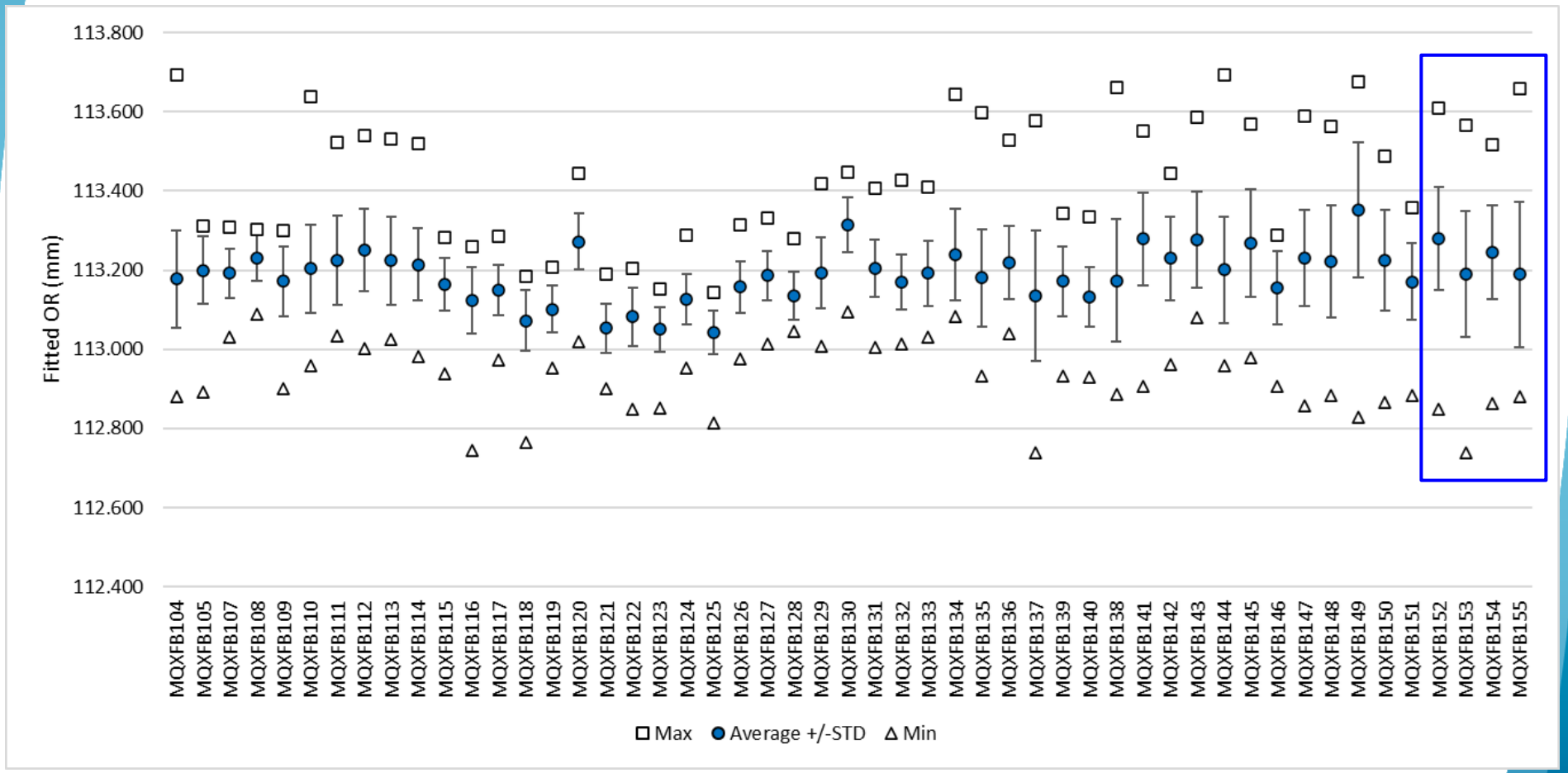
Typical cross-section standard coil



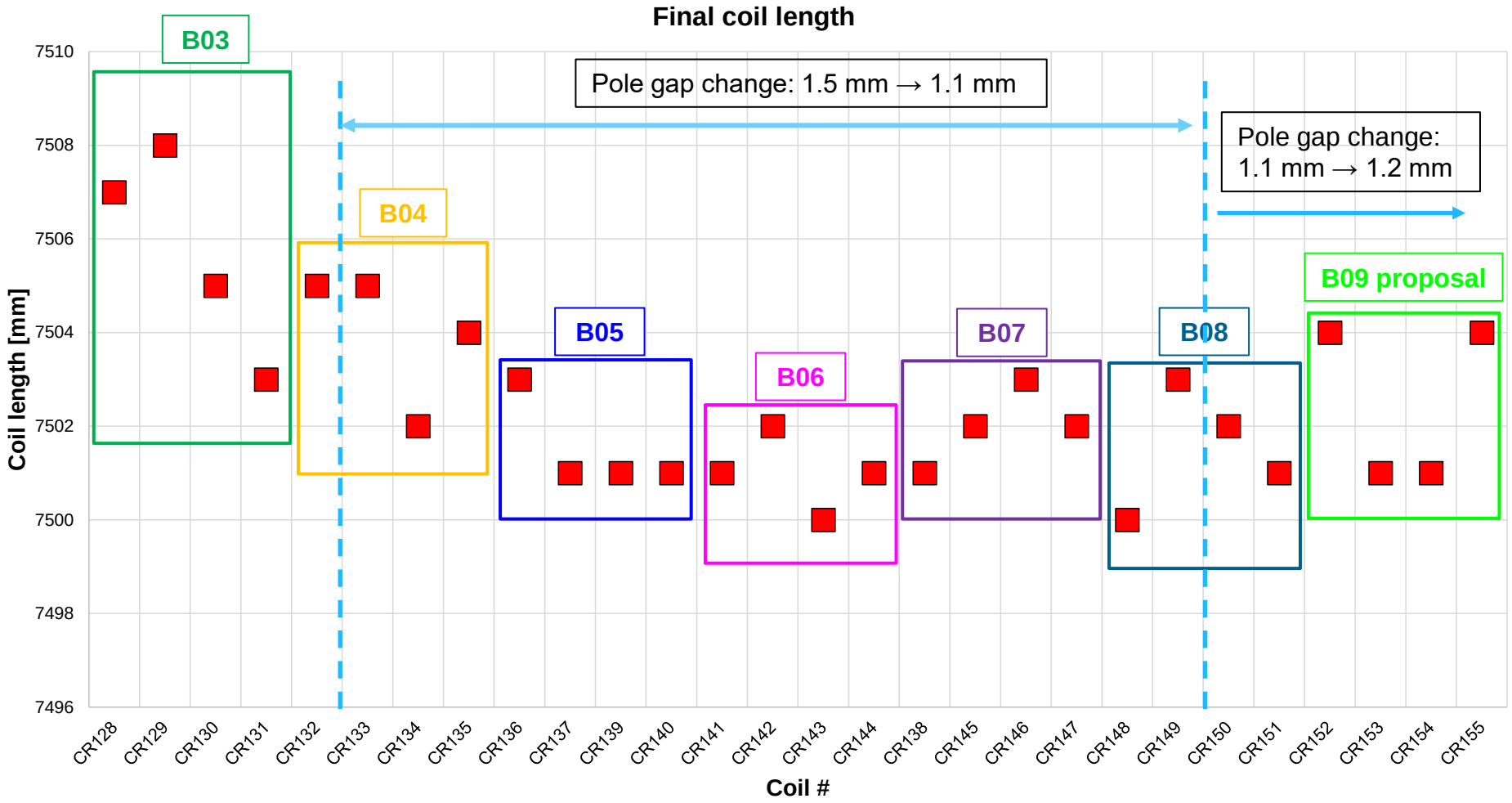
Typical cross-section coil without binder in the OL



Impregnated coil geometry (Faro arm) - OR



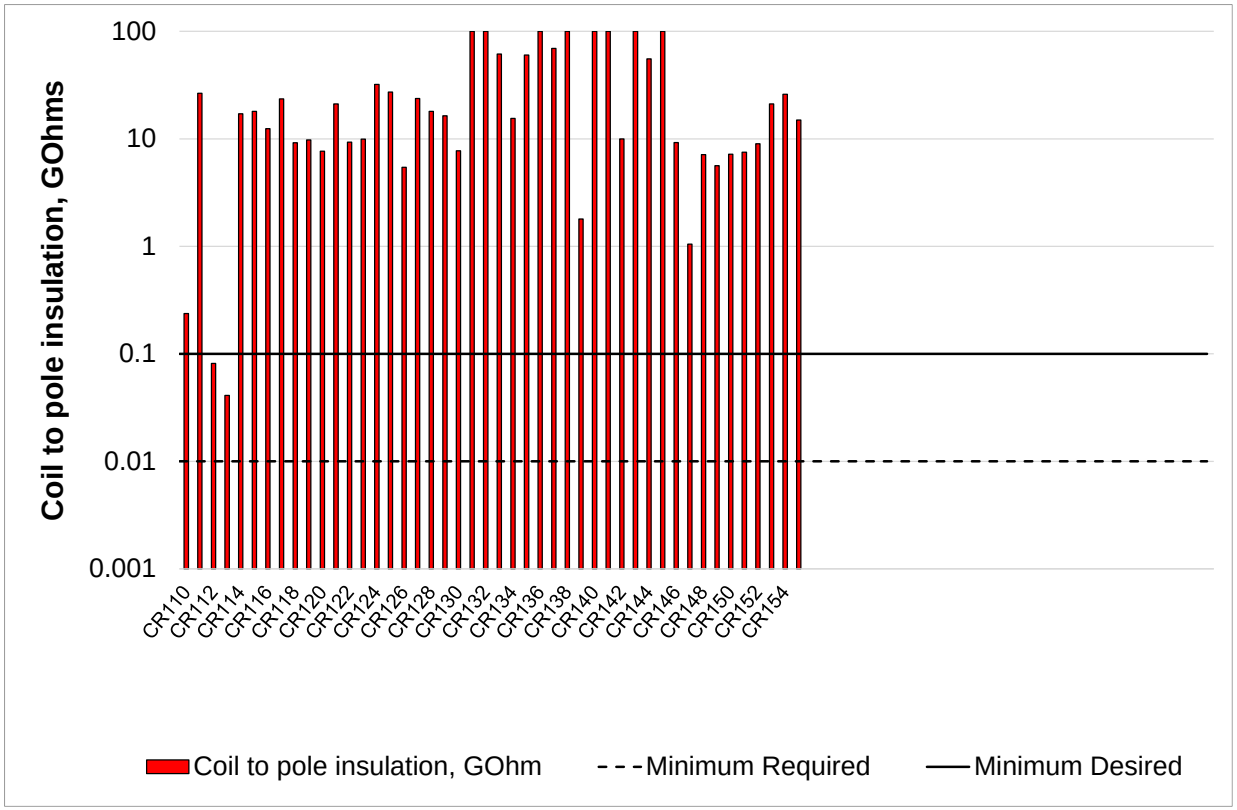
Final coil length



Dielectric strength

Coil to pole

- Since coil 114, coil to pole insulation always above the minimum desired thanks to the reduction of ceramic binder and the use of heat cleaned fiber glass around the pole

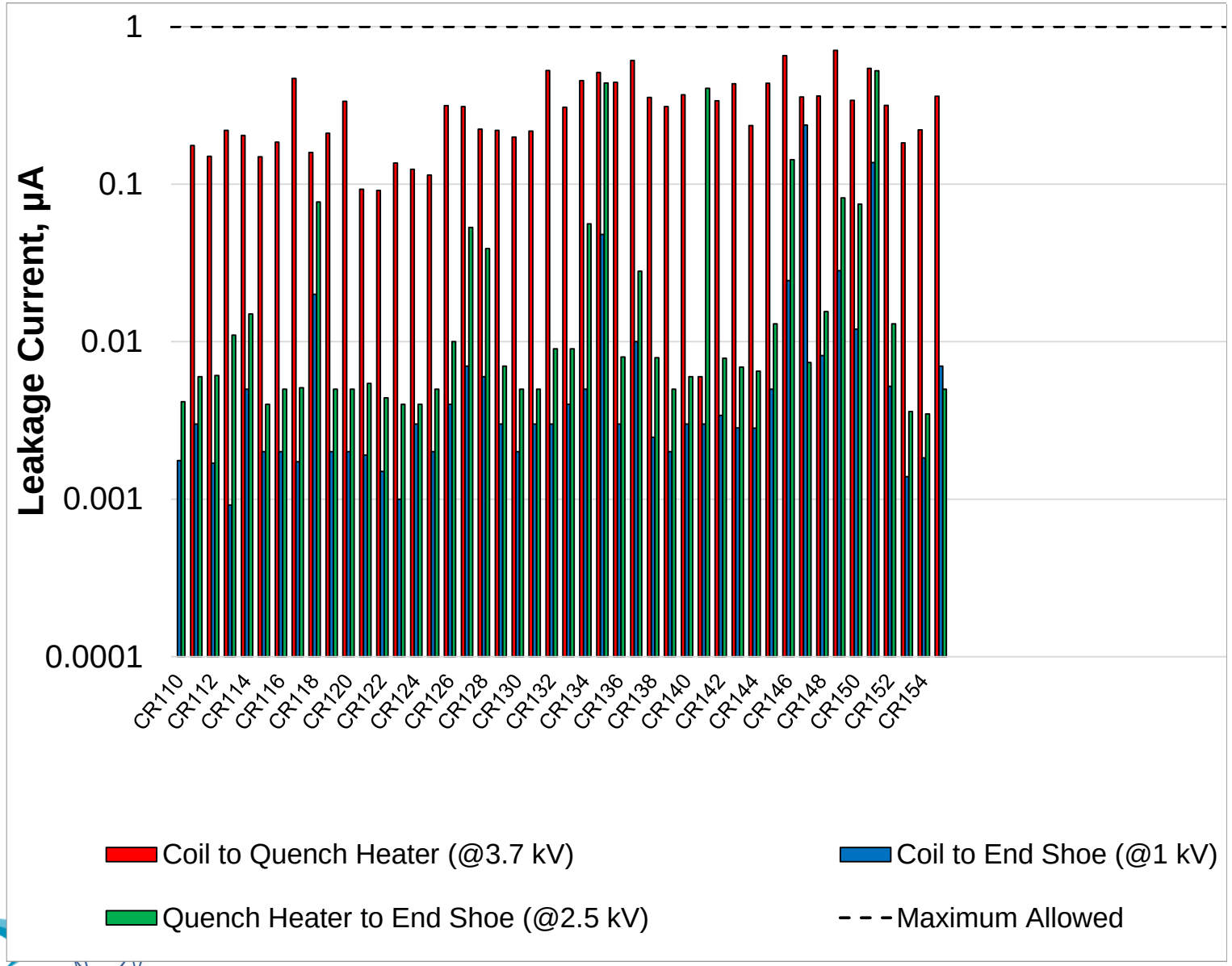


From production performance monitoring plots EDMS 2374351

QH to coil

- From coil 126, 'mini-swap' quench heaters with improved fabrication process and higher qualification test voltages (see EDMS 2646046)

Dielectric strength



Outline

- Manufacturing data
- Non-conformities
- Conclusion/Proposal

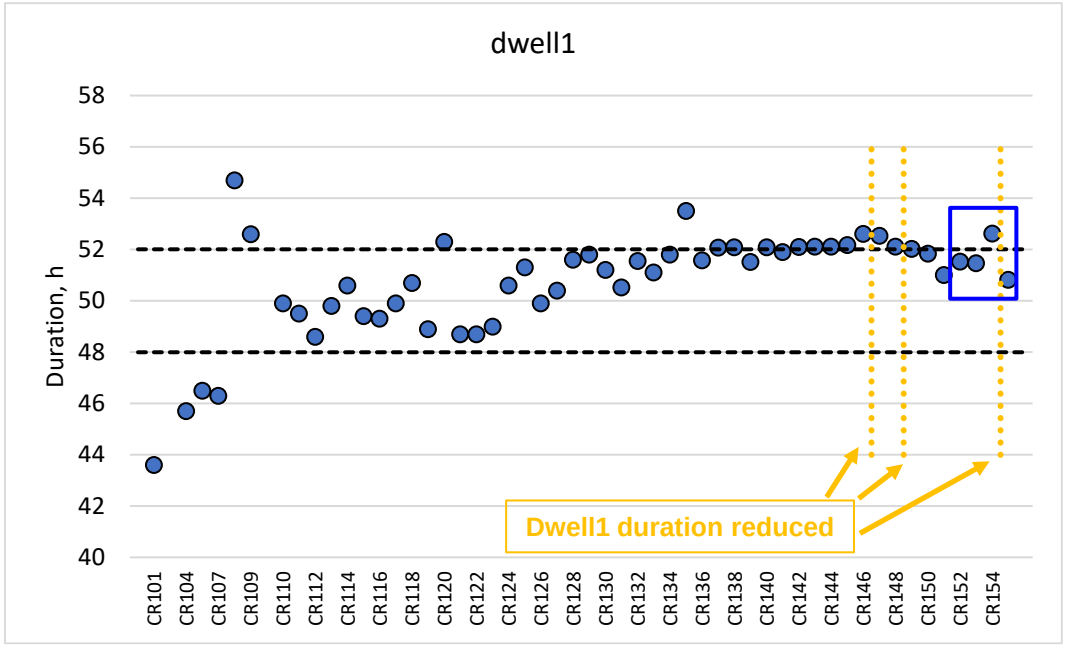
Analysis of non-conformities

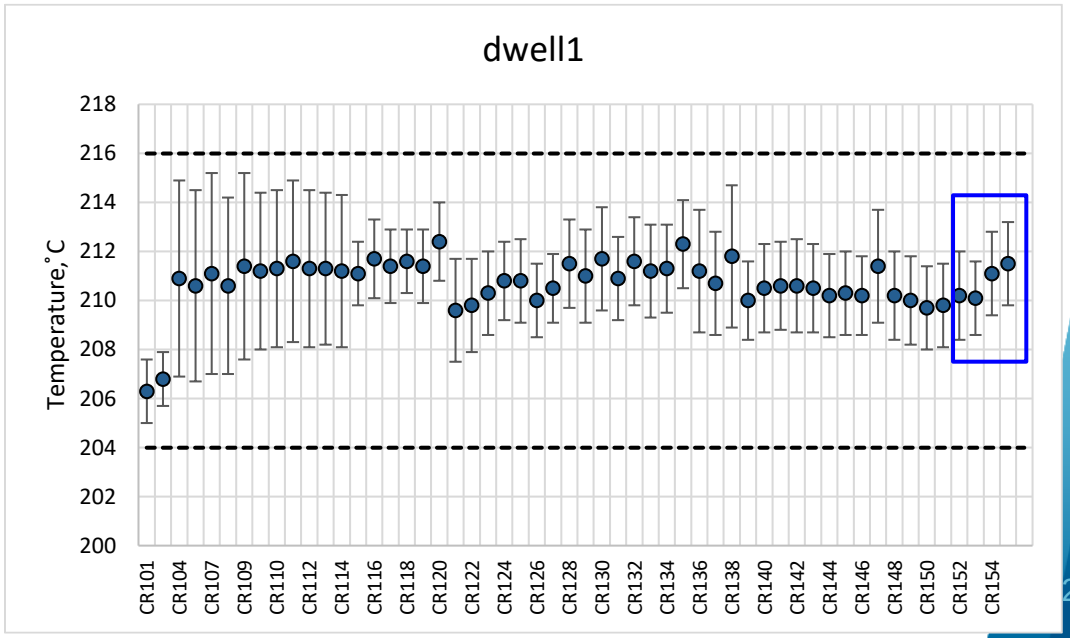
CR152	3190542	Particle trapped in the OD of the impregnated coil	Non-critical level 2
CR153	3202424	Low inductance at 100Hz before impregnation	Non-critical level 1
	3202419	Temperature drop during epoxy post-curing plateau	Non-critical level 1
	3194348	Particle trapped in the OD of the impregnated coil	Non-critical level 2
CR154	3202409	Dwell1 and dwell2 durations out of specification	Non-critical level 1
	2884016	Dwell3 H/2 out of specification	Non-critical level 1
	3212214	Three particles trapped in the OD of the impregnated coil	Non-critical level 2
	3221974	Inductance at 10Hz slightly above the limit after impregnation	Non-critical level 2
CR155	2884016	Dwell3 H/2 out of specification	Non-critical level 1
	3221969	Non-standard handling of the impregnation mould	Non-critical level 1
	3231379	Impregnation defects on the OD of the coil	Non-critical level 1

Very minor, not described in further detail in the slides
Described in detail in the next slides
Series of minor nonconformities in heat treatment, see next slides

RHT NCR – dwell1

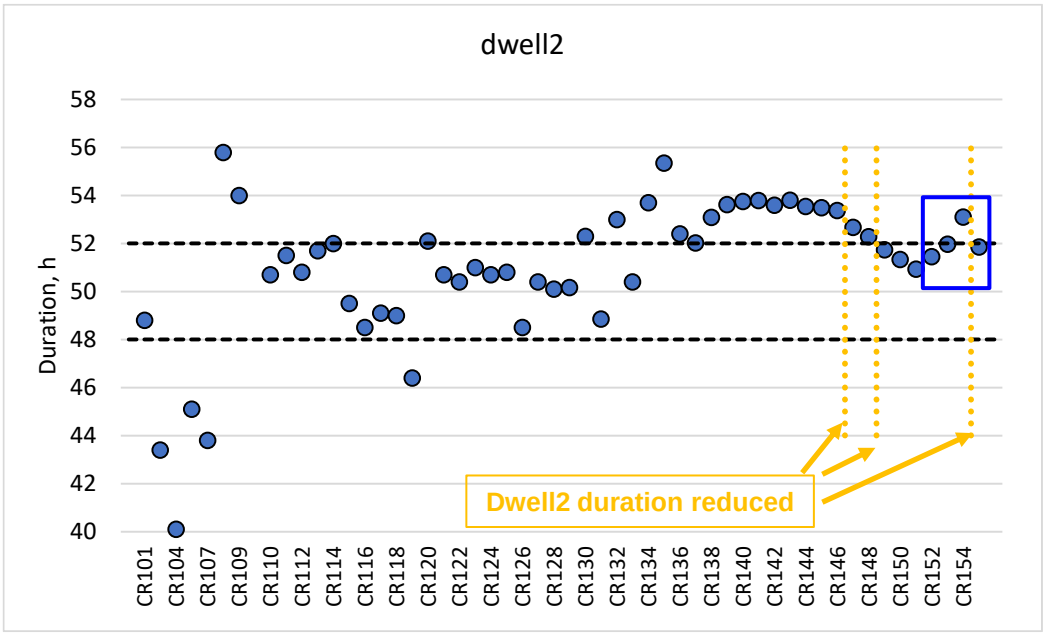
- The duration of dwell1 is slightly out of specification in 1 out of 4 coils:
  - CR152: 51.53 h
  - CR153: 51.47 h
  - CR154: 52.62 h
  - CR155: 50.82 h
  - Spec. 52 h maximum allowed
- Temperature homogeneity within specification

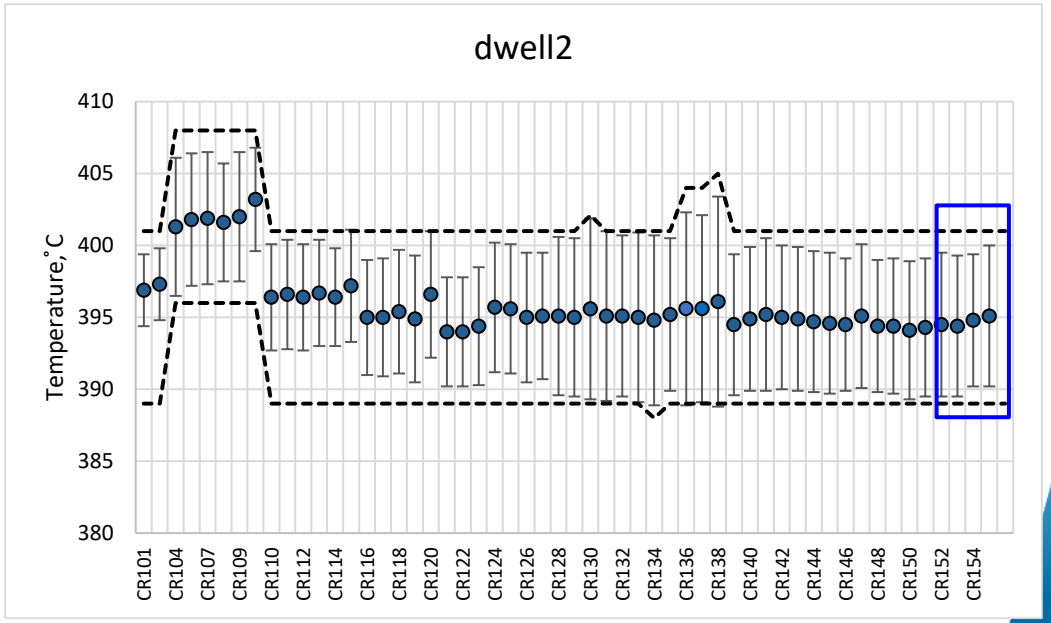




RHT NCR – dwell2

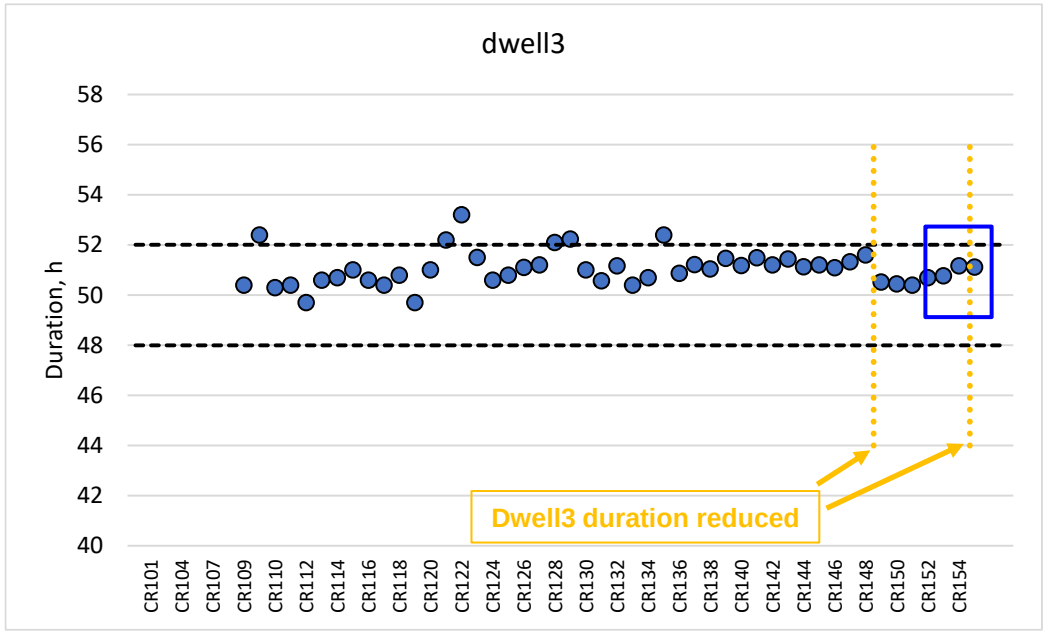
- The duration of dwell2 is out of specification for 1 coil out of 4:
  - CR152: 51.45 h
  - CR153: 51.98 h
  - CR154: 53.11 h
  - CR155: 51.86 h
  - Spec. 52 h maximum allowed
- Temperature homogeneity within specification

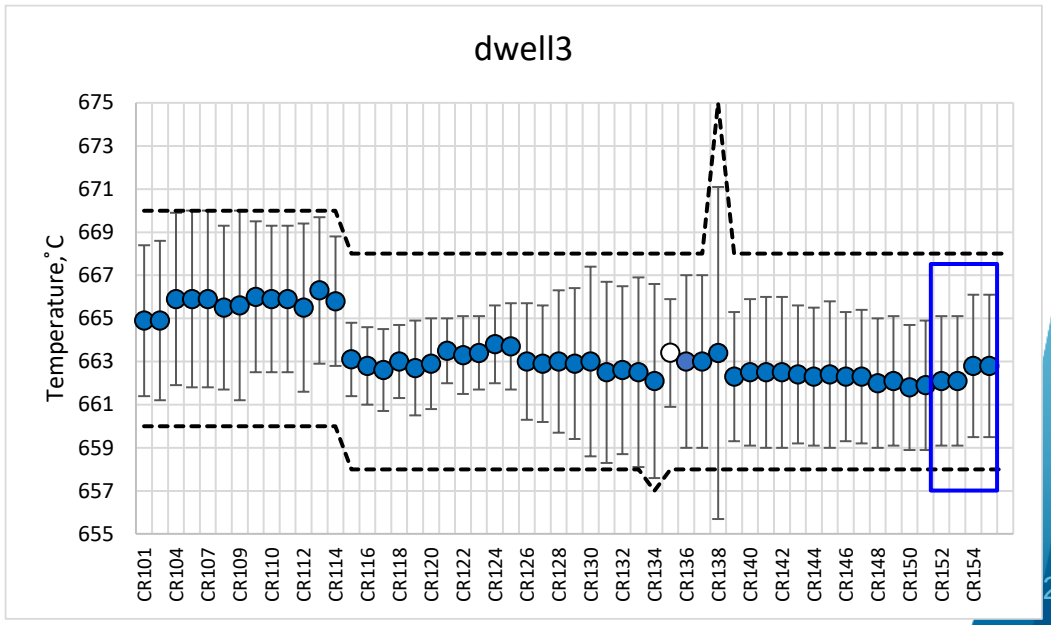




RHT NCR – dwell3

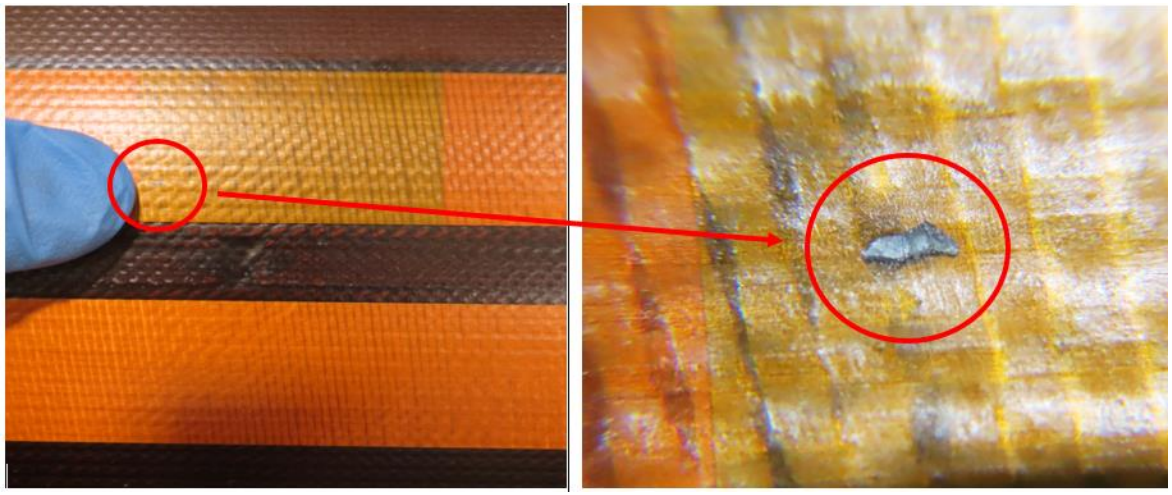
- The duration of dwell3 is within specification for the 4 coils (52 h max. allowed)
- Temperature homogeneity within specification but dwell3 H/2 out of specifications for 2 out of 4 coils
  - CR152: 3°C
  - CR153: 3°C
  - CR154: 3.3°C
  - CR155: 3.3°C
  - Spec. 3°C





CR152 (NCR 3190542) → Particle trapped in the OD of the impregnated coil

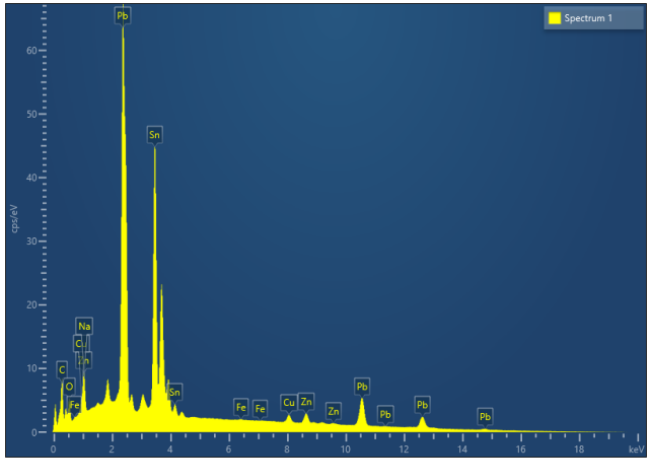
- During the QA inspection after impregnation, a partcle on the OD of the coil was noticed at 6940mm from lead end side at the level of the heater strip
  - Length of the particle was about 1.2 mm
  - Metallic aspect
  - Visually on top of the QH



- The OD of the coil was slightly scraped to extract the trapped particle (same process followed for coil CR149 (EDMS 3154270)
  - The collected particle was analyzed by SEM-EDS thanks to EN-MME team
- Local repair of the scratched area was performed with epoxy resin

CR152 (NCR 3190542) → Particle trapped in the OD of the impregnated coil

- The SEM-EDS analysis clearly revealed that the particle was mainly composed of lead and tin (EDMS 3184842)

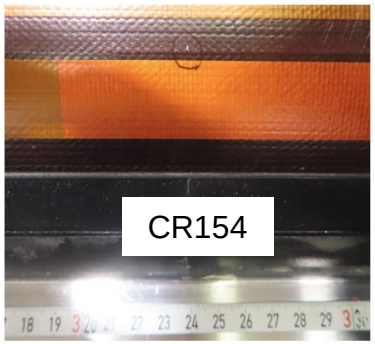


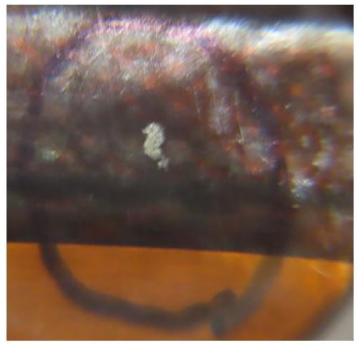
EDS spectrum: Pb 51.2 wt% - Sn 37.1wt% with traces of Zn, Cu, O and Na

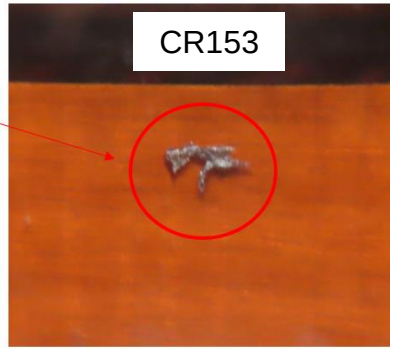
- Cause:
  - Most likely a small chip of SnPb was trapped in the S2 glass while preparing the fiber for installation
  - Both the S2 glass preparation and the pretinning of the QH connexions are performed on the same bench, which apparently was not cleaned well enough
  - CORRECTIVE ACTIONS:
    - Improve the cleaning of the bench using adhesive roller before each use
    - Add QA controls when installing the S2 glass on top of the coil

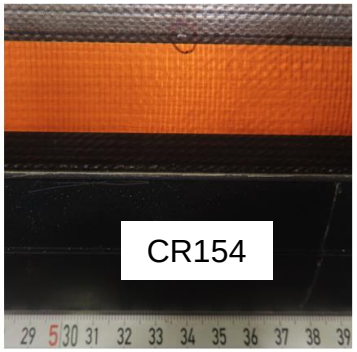
CR153 (NCR 3194348) and CR154 (NCR 3212214) → Particles trapped in the OD of the impregnated coils

- Those coils revealed particles trapped in the OD during the QA inspection after impregnation
  - CR153
    - 1 particle at 6580 mm from LE side
  - CR154
    - 3 particles at 3240 mm, 4670 mm and 5340 mm from LE side
  - Length of the particles about 1 mm and below
  - Greylish aspect





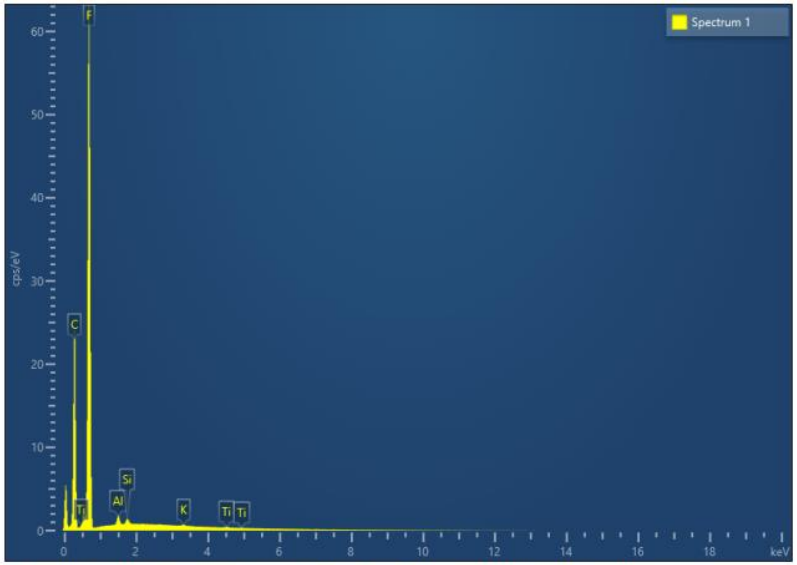




- The OD of the coil was slightly scraped to extract the trapped particle (same process followed for coil CR152 (EDMS 3190542)
  - The collected particle was analyzed by SEM-EDS thanks to EN-MME team
- Local repair of the scratched area was performed with epoxy resin

CR153 (NCR 3194348) and CR154 (NCR 3212214) → Particles trapped in the OD of the impregnated coils

- The SEM-EDS analysis clearly revealed that the particle was mainly composed by fluor and carbon (EDMS 3195498)

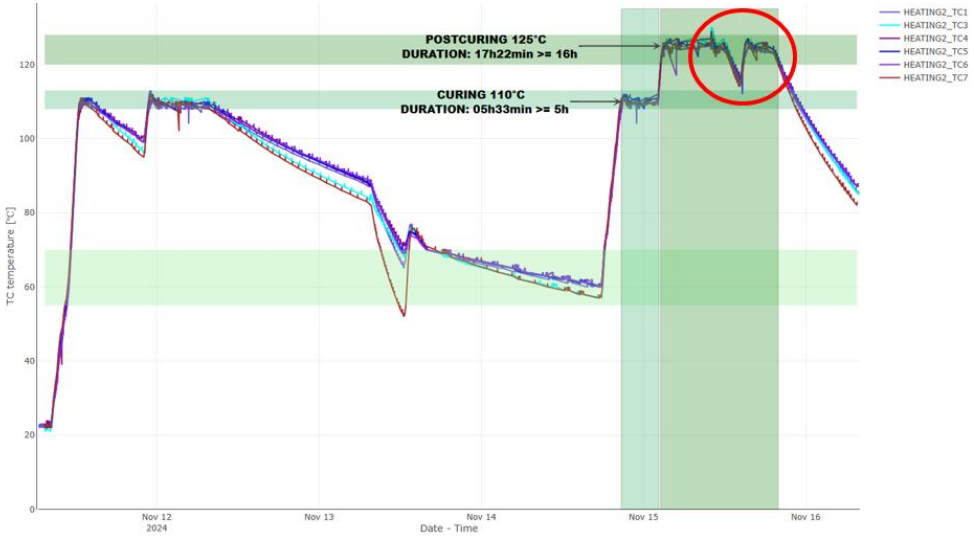


EDS spectrum #1: fluor and carbon are mainly present. Traces of titanium, silicon and potassium. Aluminium signal may come from the SEM chamber.

- Cause:
  - Given the chemical composition of the extracted particles, the origin is attributed to the degradation of the radial filler PFA coating which is in contact with the OD of the coil
  - CORRECTIVE ACTIONS:
    - Restart the coil fabrication in 2025 with a new set of PFA coated radial fillers

CR153 (NCR 3202419) → Temperature drop during epoxy post-curing plateau

- During the analysis of the impregnation cycle, a temperature drop related to the post-curing plateau was observed (EDMS 3203617)
  - Duration of the drop about 3h reaching a minimum temperature of 114°C (nominal 125°C)



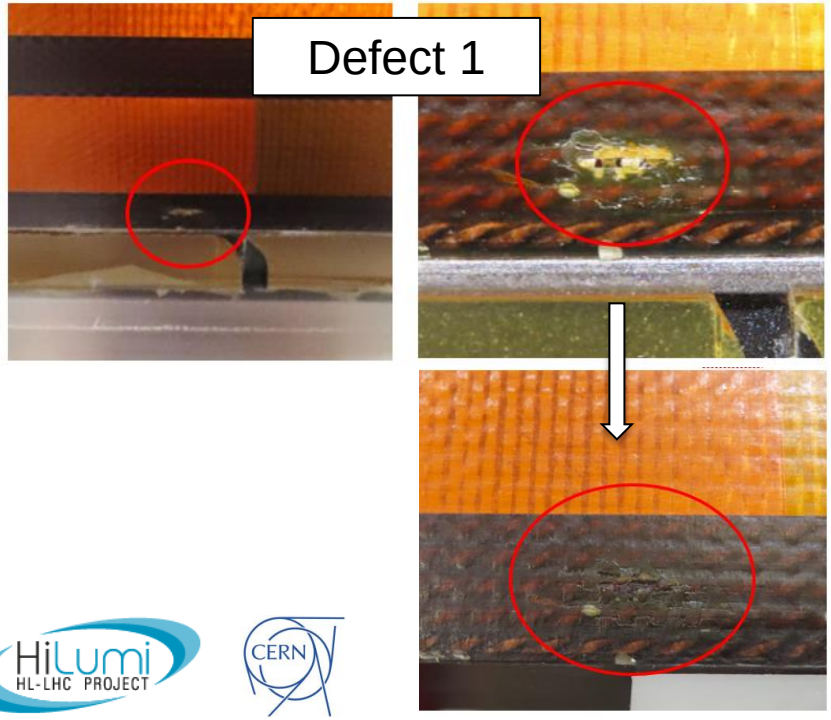
- The cause is to be attributed to an error made by the operator during the cleaning of the magmix who switched off accidentally the heaters circuit breaker
- The DSC analysis of the standard sample collected from each impregnated coil showed no significant differences w.r.t. a standard post-curing cycle

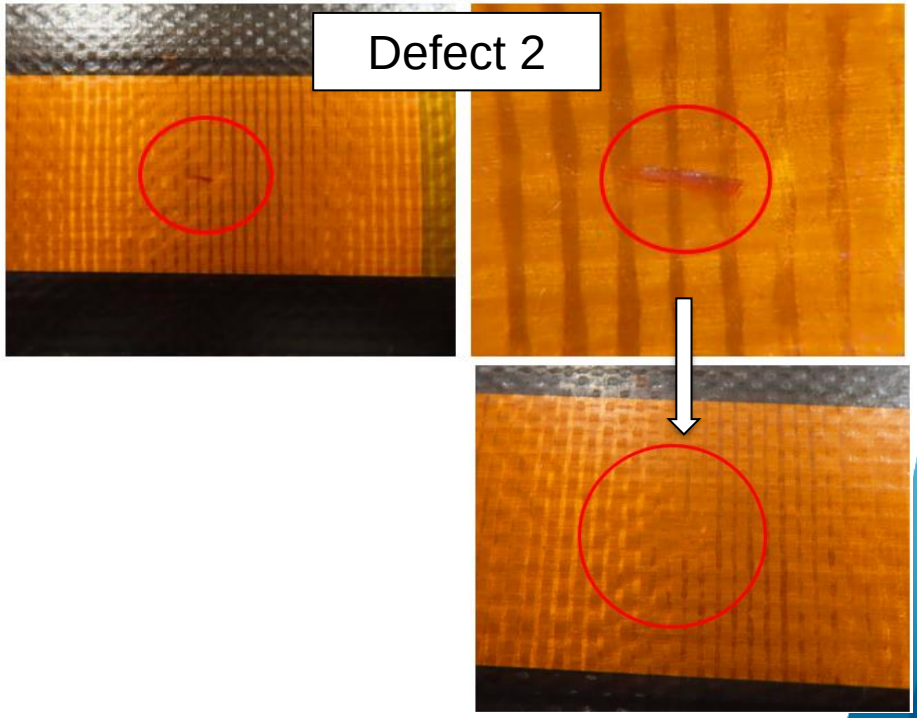
CR155 (NCR 3221969) → Non-standard handling of the impregnation mould

- Due to the unavailability of the overhead crane in building 180, the handling of the impregnation mold was performed with a 55t heavy-duty truck crane
  - The usual dedicated lifting beam was used
  - Very smooth handling
  - No sign of mechanical deformation of the mold w.r.t. standard handling

CR155 (NCR 3231379) → Impregnation defects on the OD of the coil

- During the visual inspection of the coil after impregnation, 2 defects were observed on the OD of the coil
  - Defect 1:
    - At 5800 mm from LE appeared like a small dry area
    - Repaired by local injection of epoxy
  - Defect 2:
    - At 7240 mm from LE revealed a trapped polyimide particle (most likely coming from the trimming of the QH)
    - Repaired by slightly scratching the OD of the coil and local application of epoxy





Outline

- Manufacturing data
- Non-conformities
- Conclusion/Proposal

Conclusion/Proposal

- Use CR152 - CR153 - CR154 - CR155 for MQXFB09 assembly
- The coil instrumentation will begin next week, and the magnet loading is planned for the last week of March

Thank you!