MQXFB coil fabrication

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14th HL-LHC Collaboration Meeting
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Outline

- Coil fabrication status
- New generation MQXFB coils
- Recent major non-conformities
- Conclusions

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- **Coil fabrication status**
- New generation MQXFB coils
- Recent major non-conformities
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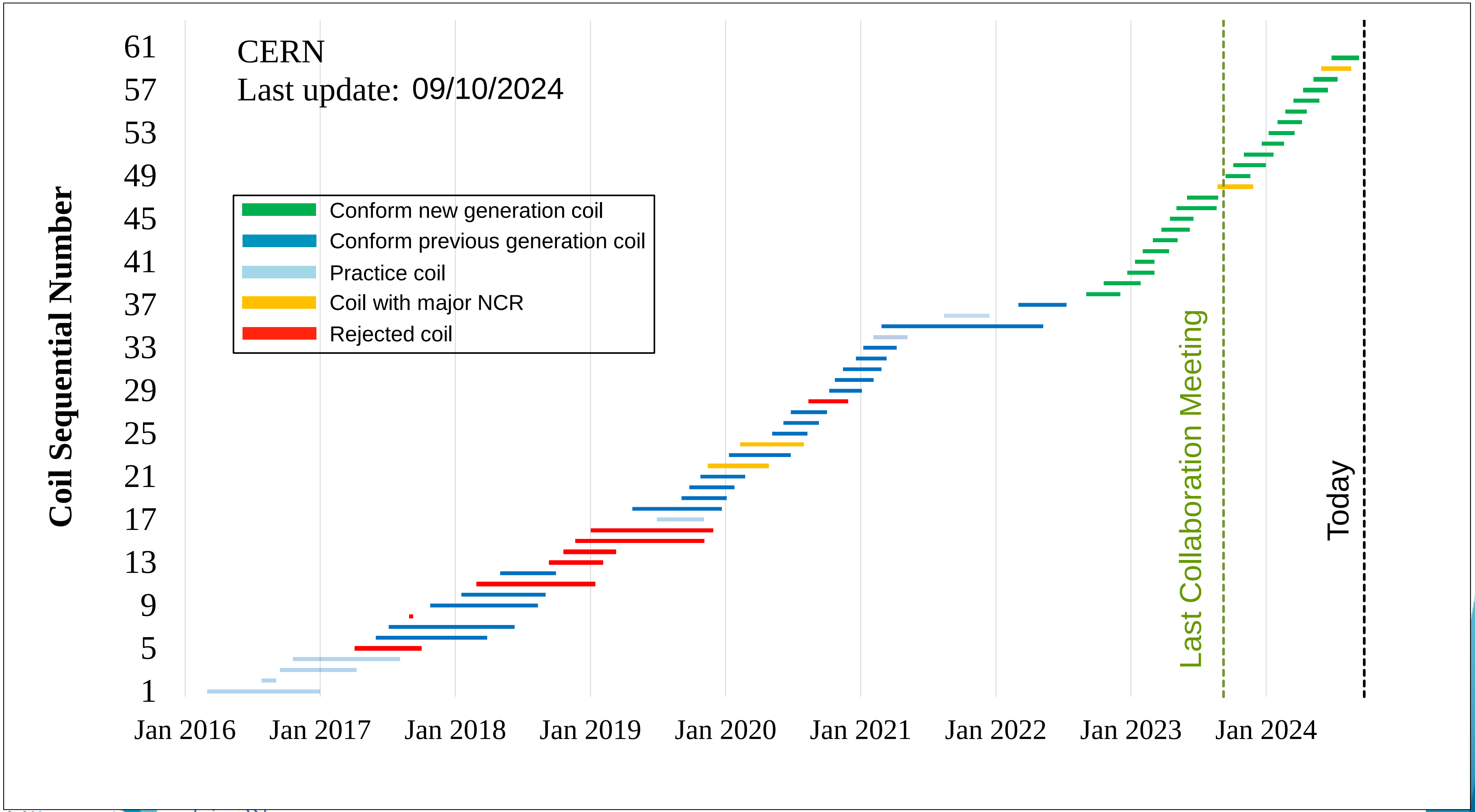
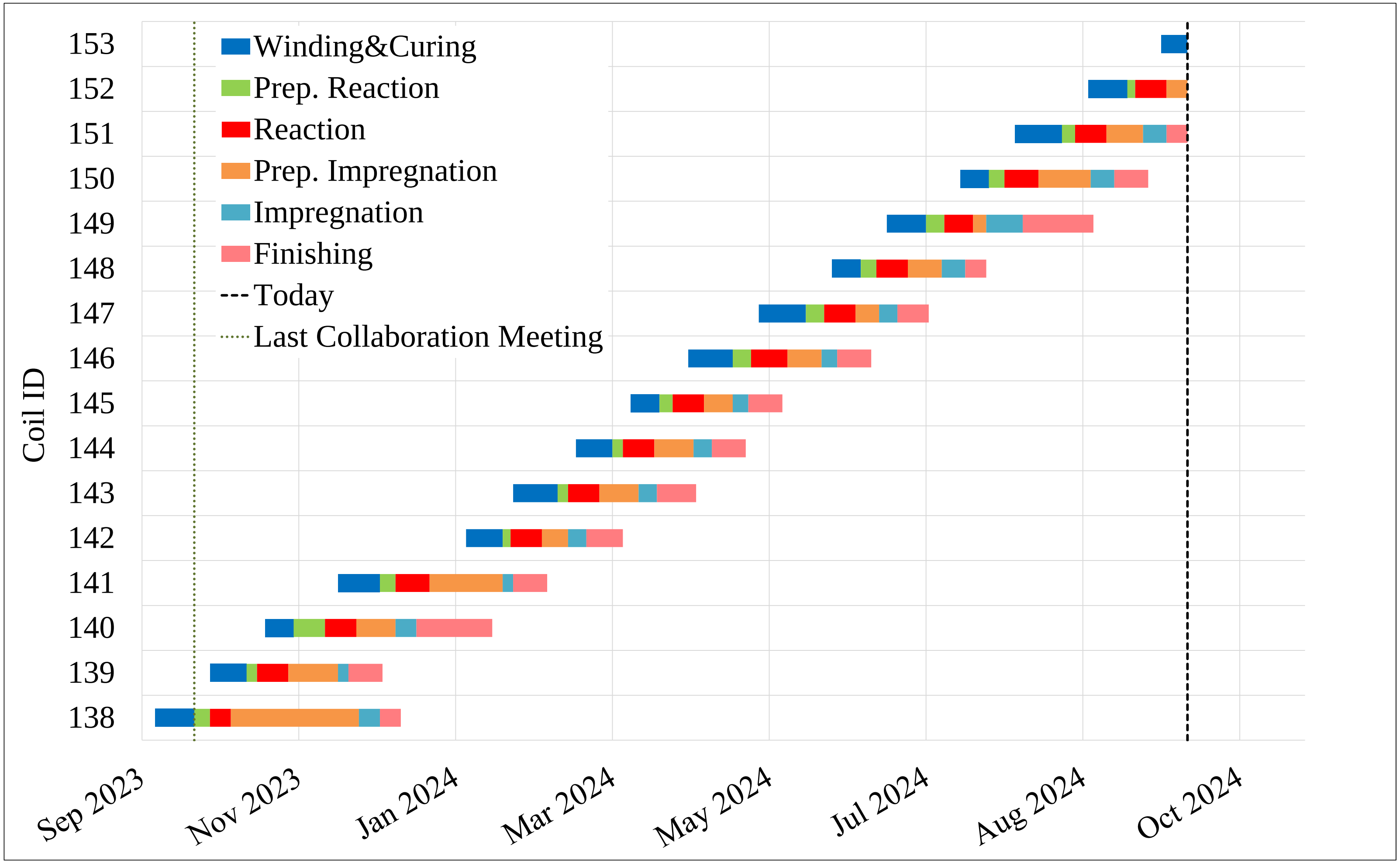
Dashboard

- Since the beginning of the production, *59* MQXFB coils have been manufactured



Dashboard

- From last Collaboration Meeting (indico 1293138) 13 MQXFB coils were manufactured:



Outline

- Coil fabrication status
- **New generation MQXFB coils**
  - **Main modifications**
  - **Measurables**
    - **Coil hump**
    - **Pole gap**
    - **Coil elongation after RHT**
    - **Coil size**
    - **Electrical robustness**
- Recent major non-conformities
- Conclusions

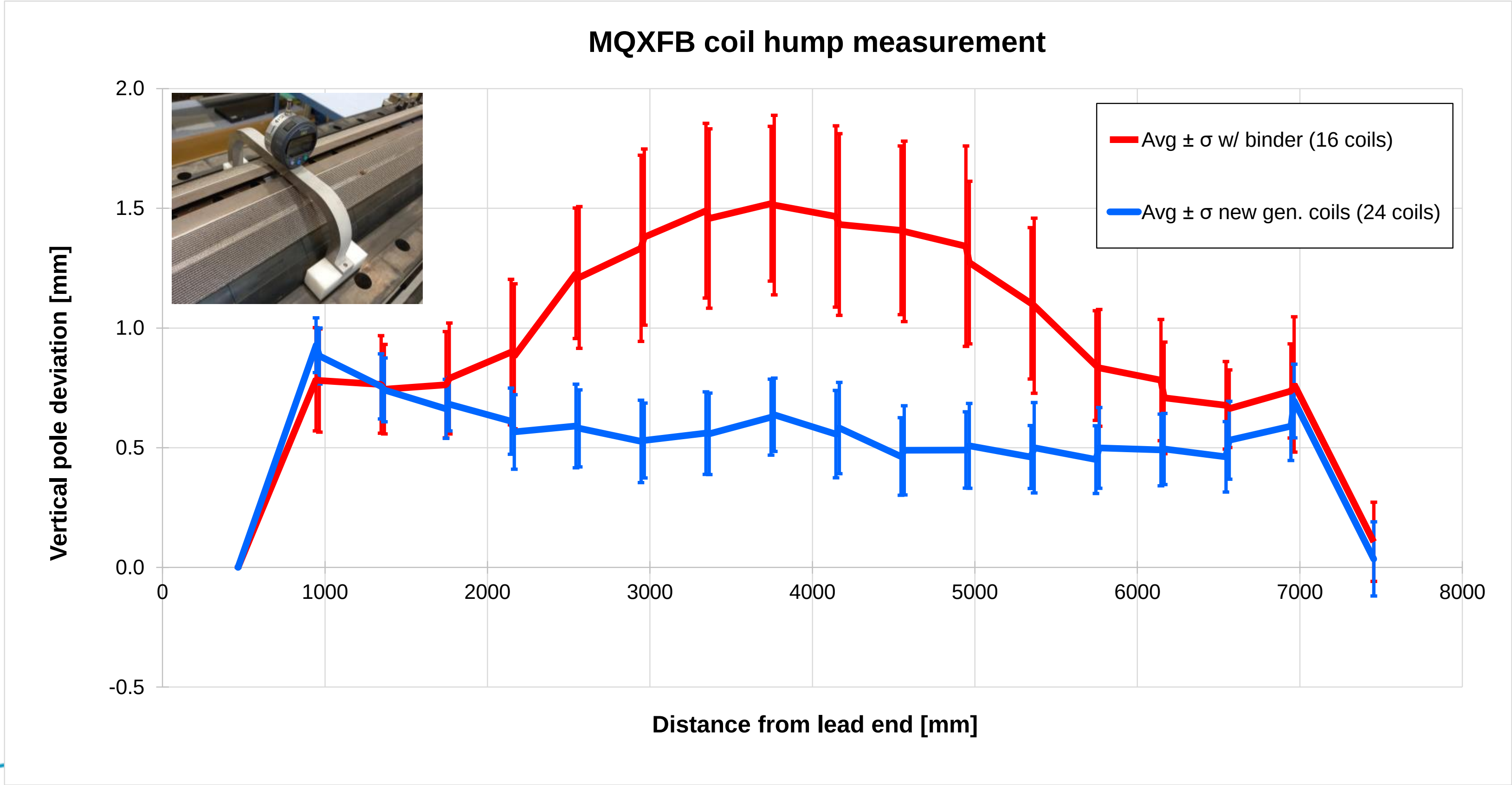
Main modifications (indico 1293138)

- MQXFBP1/BP2 performance limitation prompted stopping the coil fabrication
  - Review of the coil manufacturing process pointed to a possible coil degradation mechanism
    - Coil in a constrained state after RHT due to friction between coil and mold, the energy is released during the mold opening
    - Effect length dependent (not observed in MQXFA and MQXFS coils)
  - Reducing the longitudinal, azimuthal and radial friction between coil and the reaction mold
    - Modifications implemented in the manufacturing steps preceeding the RHT
- The major modifications are*
  - Pole gap increase from 2.0 mm/m to 3.4 mm/m (then optimised to 2.5 mm/m and recently to 2.7 mm/m)
  - Partial compensation of the curing cavity, i.e. reducing the azimuthal size of the unreacted coil
  - Removal of the ceramic binder from the outer layer of the coil

* *N. Lusa et al., "Towards MQXFB Series Coils," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-8, Aug. 2024, Art no. 4003408, doi: 10.1109/TASC.2024.3360928*

Measurables: coil hump

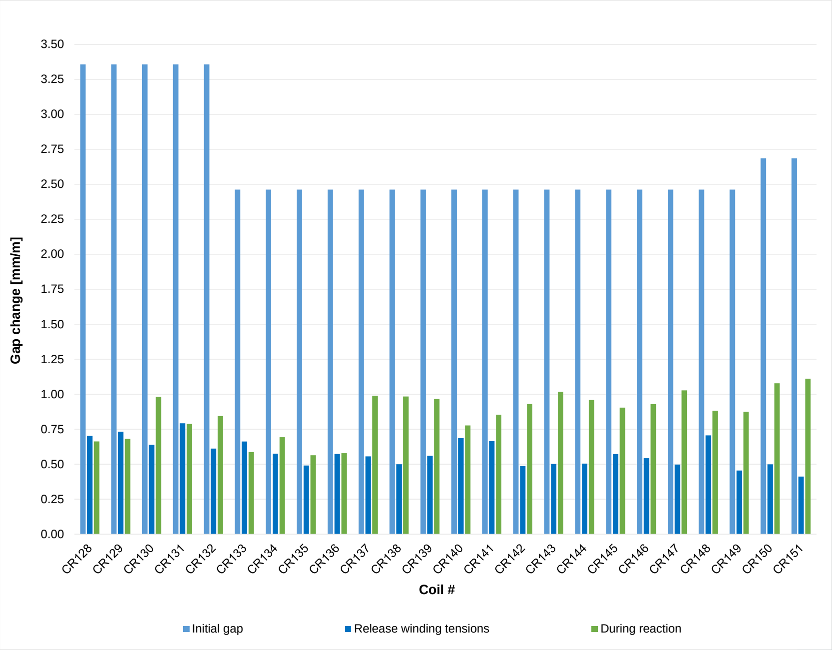
- New generation coils do not show any ‘hump’ after reation heat treatment
  - Significant difference w.r.t. coils cured with binder on both layers
  - Behavior similar to MQXFA coils



Measurables: pole gap

- Pole gaps are set to avoid tensioning the Nb_3Sn sub-elements during the coil fabrication process
- Since new generation coils
  - Pole gap was modified: 3.4 mm/m → 2.5 mm/m → 2.7 mm/m
  - Different pole gap change along the process
    - At CERN the winding tension is lower w.r.t. MQXFA coils
      - 19 kg in the straight part and 7 kg in the ends (MQXFB coils with binder on both layers)
      - New generation MQXFB coils:
        - IL → 19 kg in the straight part and 7 kg in the ends
        - OL → 14 kg in the straight part and 7 kg in the ends

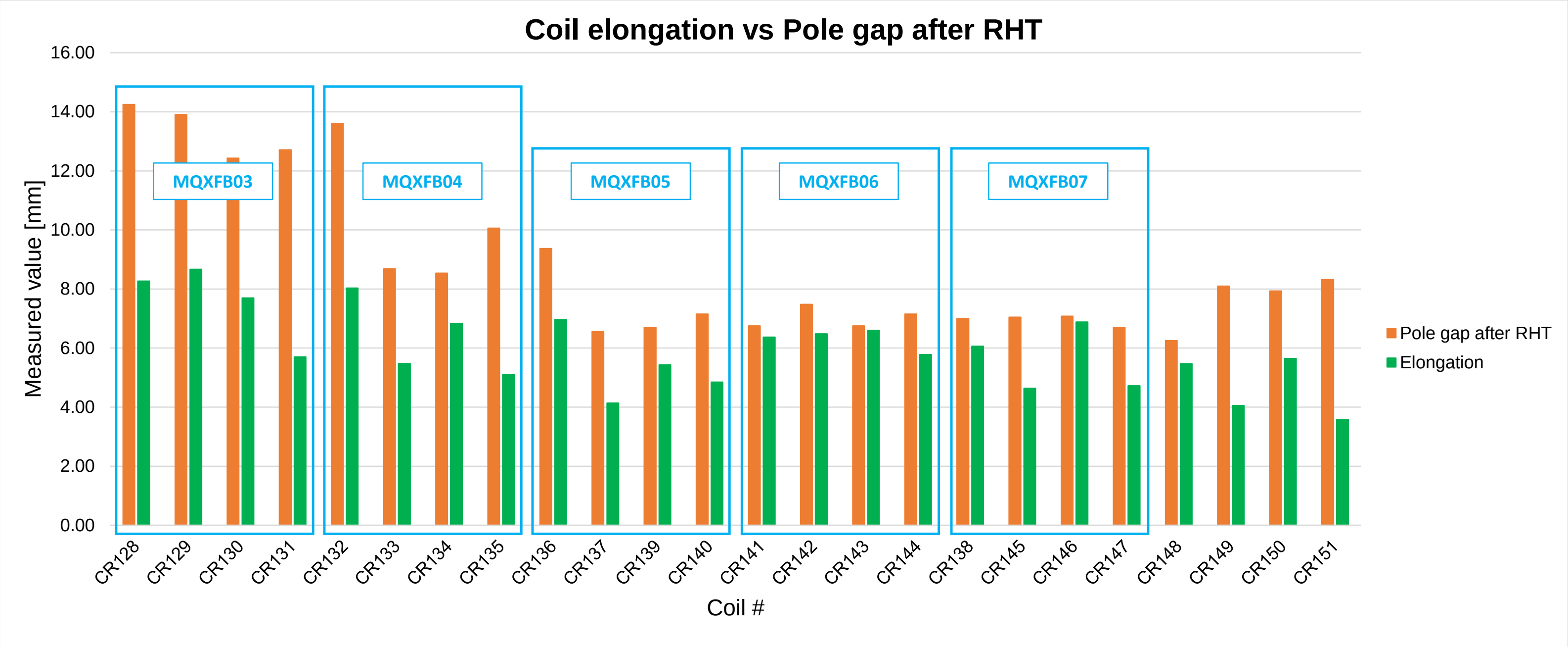
Pole gap change [mm/m]	Release of the winding tension		Reaction heat treatment	
	avg	σ	avg	σ
MQXFA coils	1.39	/	1.14	/
MQXFB coils w/ binder (20 coils)	0.68	0.13	1.00	0.15
MQXFB coils new generation (25 coils)	0.59	0.11	0.84	0.18



Measurables: coil elongation after RHT

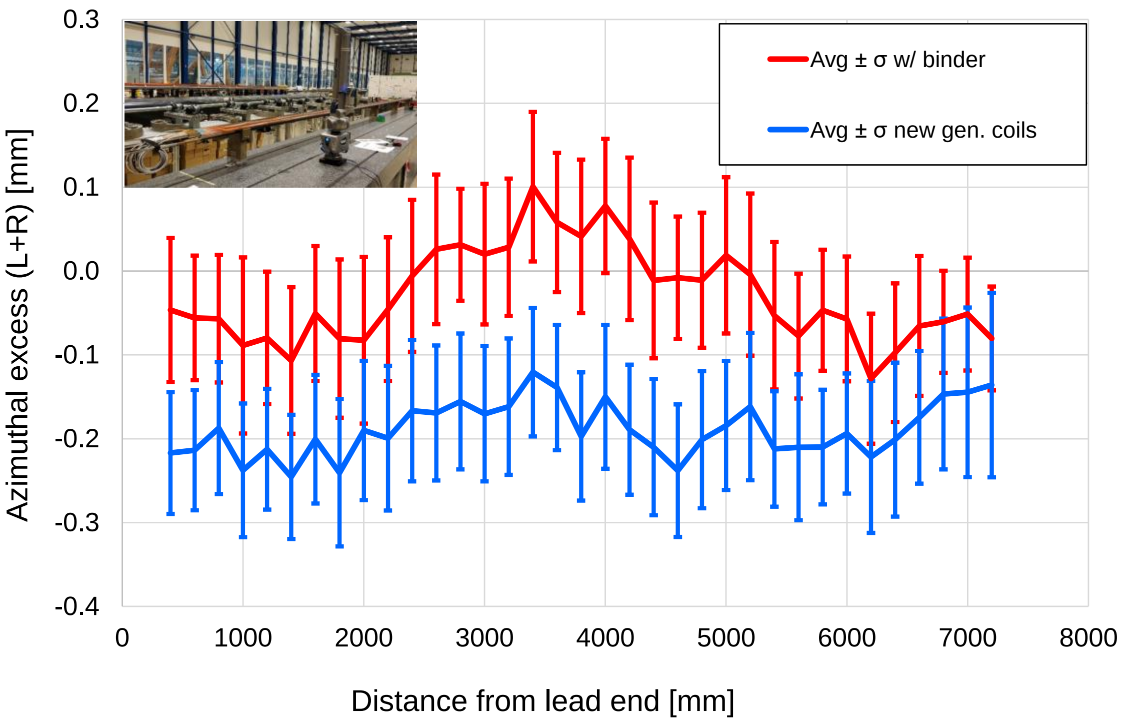
- The reacted coil gradually elongates on both ends during the mold opening
- Pole gap increases during the opening (indico 1220226)

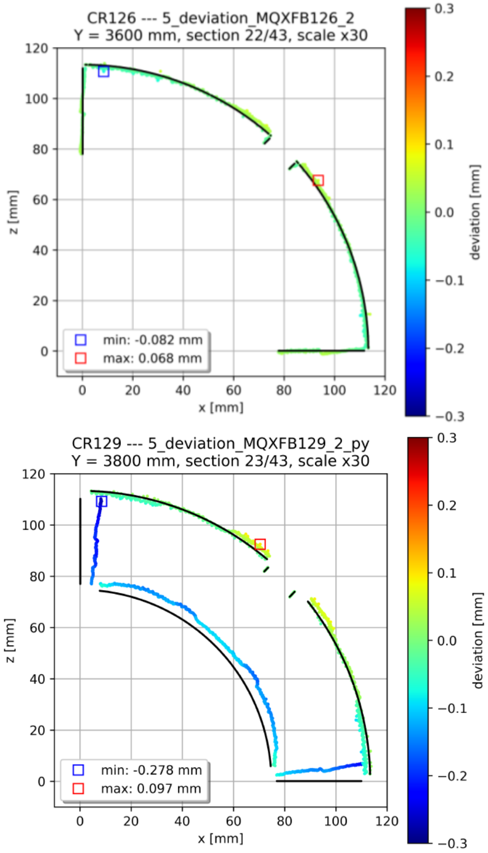
Coil #	Total /L_m [‰]	Manufacturing line
CR127	1.50	CERN w/ binder
CR128 – CR151	0.83	CERN new gen. coils
AUP 146 – 147	0.89	FNAL
AUP 237 – 238	0.88	BNL



Measurables: coil size

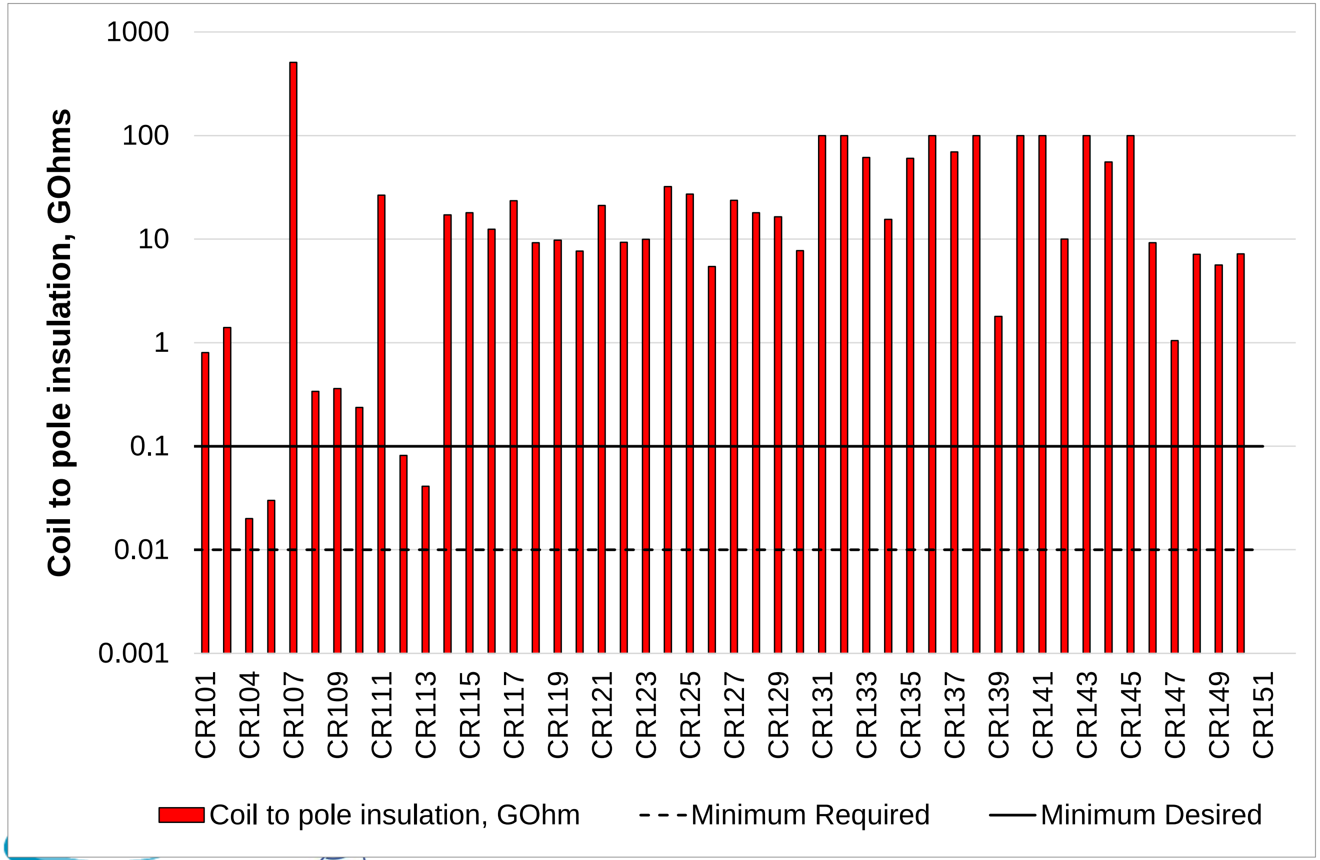
- New generation coils size
  - More uniform along the length
  - Azimuthally smaller and do not present any sign of a ‘fatter’ coil towards the longitudinal center
  - Small wedge in the midplane of the coil of about 89.6° (mock-up test to assess stress indico 1260584)



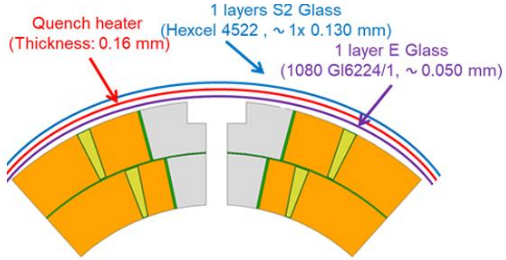


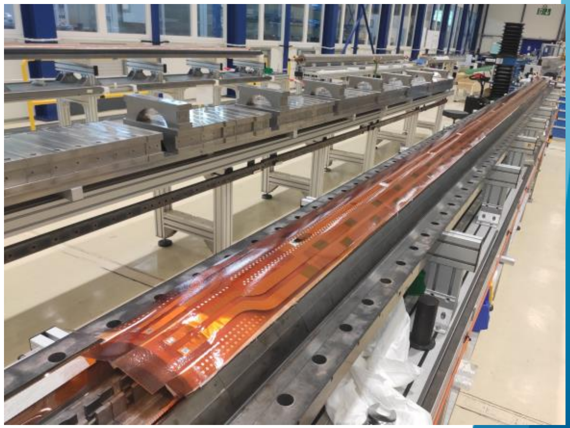
Measurables: electrical robustness

- Since coil CR114, coil to pole insulation always above the minimum desired
  - Use of heat cleaned S2 glass around poles
  - Reduction of ceramic binder amount close to the poles



- QH mini-swap configuration since CR126 with higher voltage qualification test (EDMS 2646046)





Outline

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- New generation MQXFB coils
- **Recent major non-conformities**
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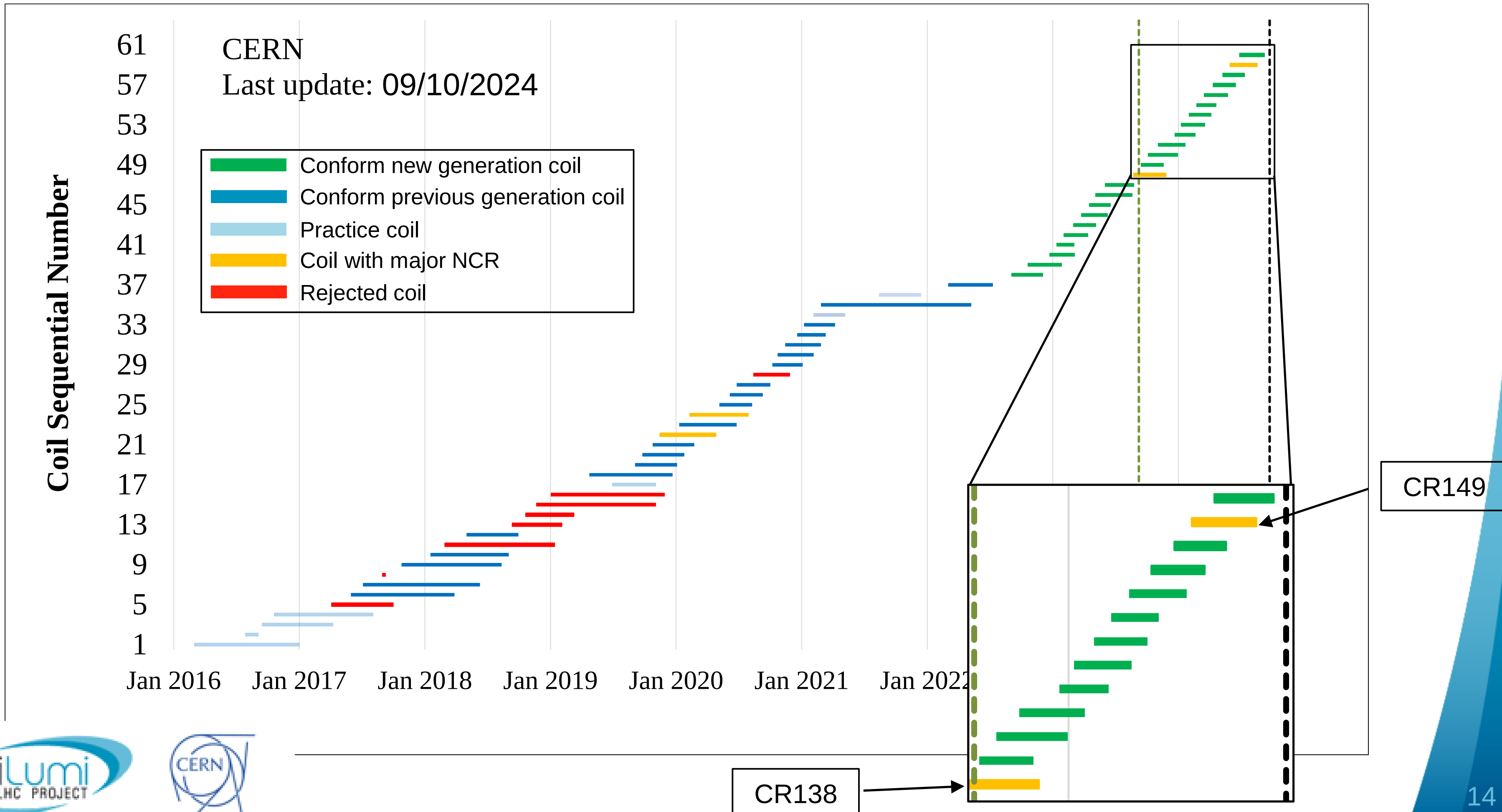
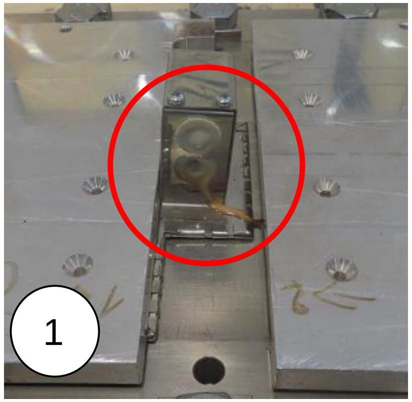
Statistic

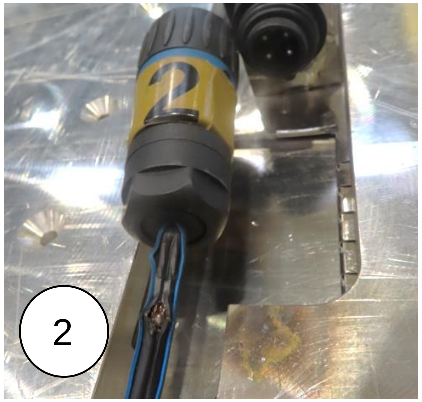
- Over the last year of coil production, we faced two major NCRs (more details in the following slides)
  - Coil CR138, happened during the impregnation process (27/10/2023)
  - Coil CR149, discovered during the demolding post-impregnation (21/08/2024)



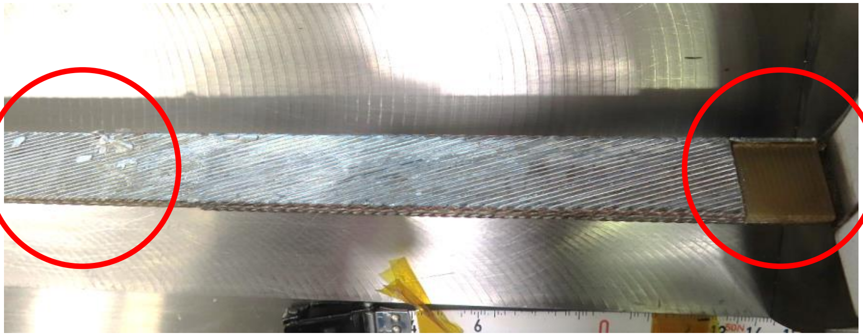
CR138 (NCR 2974448) → Over heating during impregnation cycle

- Instead of degassing at 110°C, the mold was heated up to 250/300°C for 24 hours (best guess based on findings)
  - Stop of the process and investigation of the root causes
  - Opening of the mold to check the reacted, not yet impregnated, coil
- Root cause pointed to human errors
  - The correct TCs were installed in the mold but the wrong connector was plugged in the impregnation machine (11T connector)
  - Short circuit between power connector and heating plate #2 appeared, causing tripping of the circuit breaker and stop of all heaters





1. Plug covers 3D printed in TPU95 at around 245°C
2. Power cable sheats damaged (melting temperature around 300°C)



Action plan and results

- Splice analyses:
  - Splice resistance measurement at RT → Within the acceptable range EDMS 2975146
  - Visual inspection → A leakage/migration of SnAg was observed towards the extremities of the splice EDMS 2975146
  - X-rays to check the quality of the joint compared to a conform splice Nb_3Sn-NbTi sample → X-rays confirmed a migration of the solder from the splice area (about 20% w.r.t. reference) EDMS 2975595
  - Assess the performance degradation of the NbTi cable → NbTi cables were impacted by the overheating (27% of I_c degradation at 8T at 1.8K and around 6% at 0.5 - 2T) EDMS 3007813
- Assess potential damage of the Nb_3Sn reacted cable → No damage
- Visual inspection of the coil → Overall coil ok, S2 glass insulation in the midplane slightly damaged over 400 mm (NCR 3128109)
- Replace of all damaged parts (splice insulation and QH) and installation of fresh S2 glass
- Consolidation of the impregnation machine

Similar NCR of CR138 but on a MQXFA coil

- Magnet MQXFA17 experienced a similar NCR happened on coil CR138 where the NbTi leads were overheated during splicing (EDMS 3119668)
- The magnet was cold tested and did not show any limitation at the level of the splice region
  - The measured splice resistance was within specifications
- CR138 was accepted and assembled in MQXFB07

Coil CR138 in the storage bench prior to start the assembly

CR149 (NCR 3154270) → Defect on the QH after impregnation

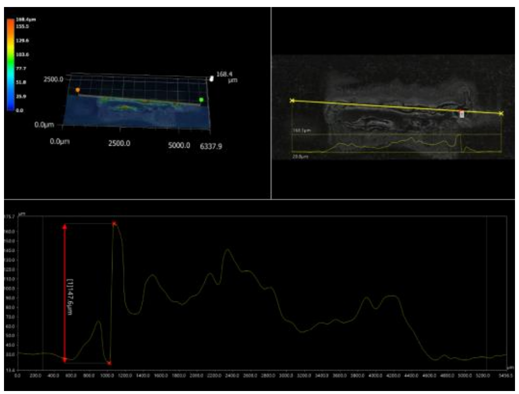
- Superficial defect on the OD impregnated coil at the level of the heater strip at 5750 mm from LE side
- Root cause still to be understood
- Pictures taken during preparation for impregnation were checked
  - No defect was present neither on the OD of the reacted coil nor on the QH surface

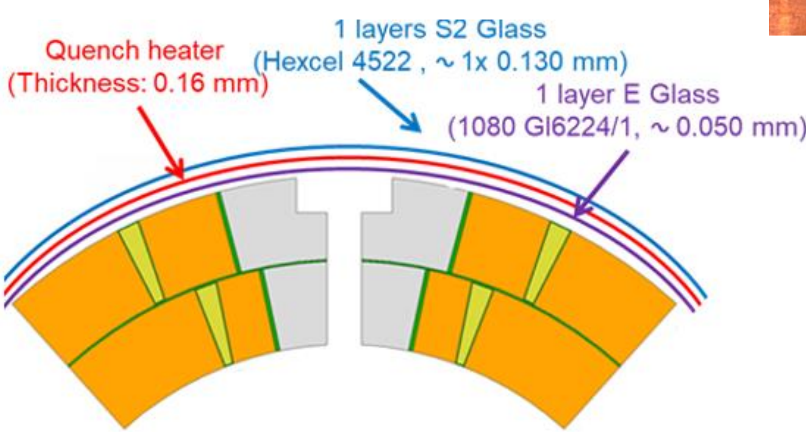
Action plan

- Thanks to EN-MME and TE-MSC-LMF-EE the following steps were performed
  1. Replica of the superficial defect to assess the depth (EDMS 3155368)
  2. Microscopy to better define the defect and its origin (EDMS 3155368)
  3. Staged dielectric test to assess the insulation QH to coil (EDMS 3156284)

Results and proposed repair solution

1. Based on the analysis of the replica the maximum depth of the defect is 150 µm (in principle above the QH)
2. Inspection of the surface showed a shallow cavity with a burnt aspect and no metallic particle was observed
3. The electrical test passed successfully up to nominal (3.7 kV for 120 s)





Proposed “repair” solution

- Slightly superficially scrap the OL of the impregnated coil in correspondence of the defect
- Based on findings, reinforce the insulation QH to coil by adding a polyimide patch underneath the heater strip
- Restore the OD of the coil with a local impregnation
  - Trials ongoing on cut MQXFB coil segment

HiLumi HL-LHC PROJECT

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Conclusions

- MQXFB coil fabrication is advancing at series production rate
  - Target of 1 coil per month
  - During the last 2 years no critical non-conformity leading to coil rejection
- New generation coils feature some modifications aimed at having a more ‘relaxed’ coil after RHT
- Manufacturing data are recorded and monitored and, if needed, small changes are introduced to anticipate potential issues
  - Coil hump
  - Pole gap
  - Coil elongation during reaction mold opening
  - Azimuthal coil size
  - Electrical robustness

} Main coil monitoring parameters

Conclusions

- NCR CR138
  - Root cause: human errors
  - Coil inspected with focus on the splice region
    - All the analises pointed to an acceptable degradation of the NbTi performance
    - No degradation of the Nb_3Sn cable
  - Coil was impregnated and electrically tested successfully at RT
    - Assembled in magnet MQXFB07
- NCR CR149
  - Root cause: still to be understood
  - Inspection revelead a superficial defect at the level of the impregnated S2 glass
  - Coil finished and electrically tested successfully at RT
  - Repair trials ongoing to validate the repair procedure


Thank you!

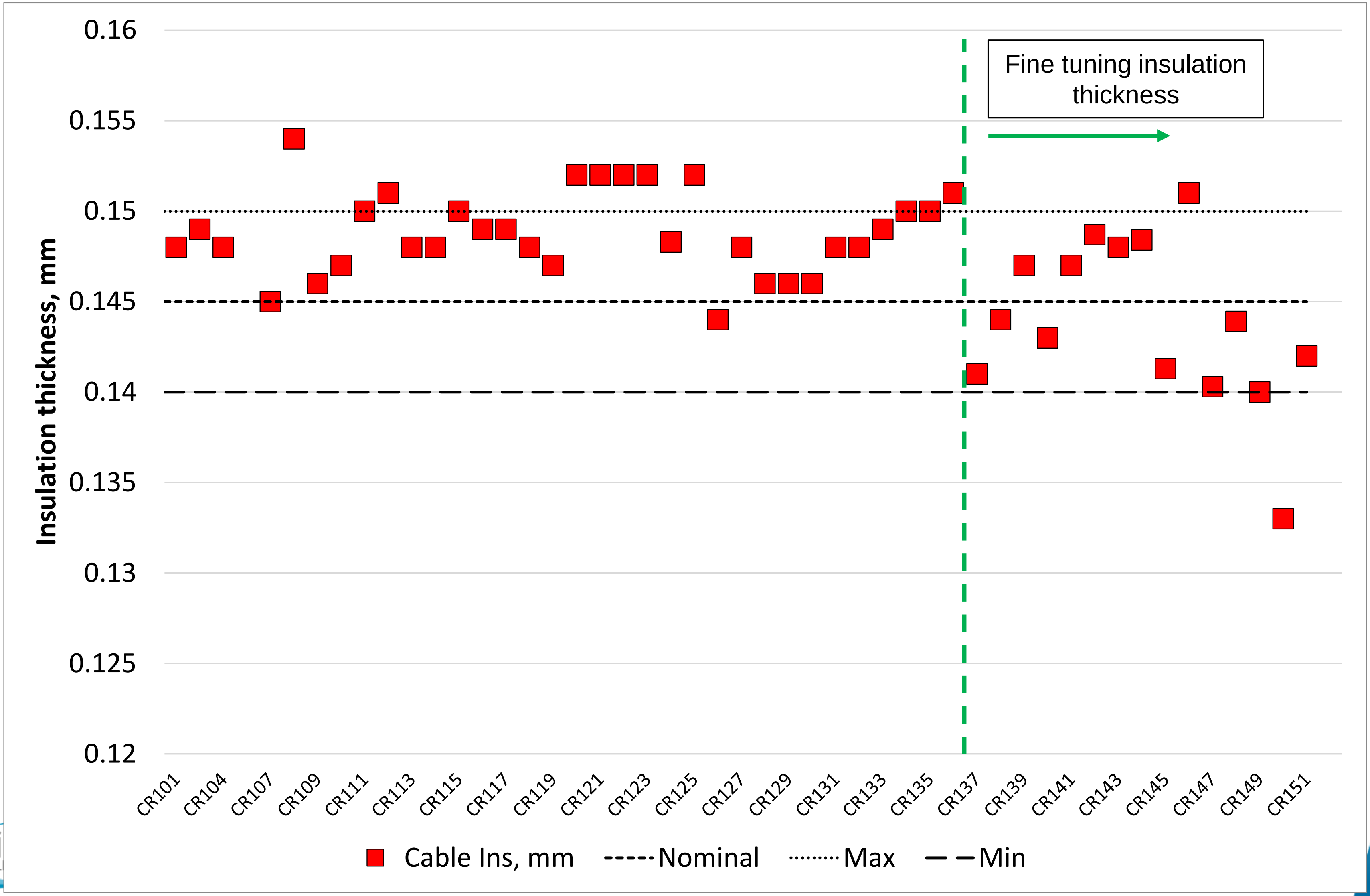
Spare slides

Cable insulation thickness

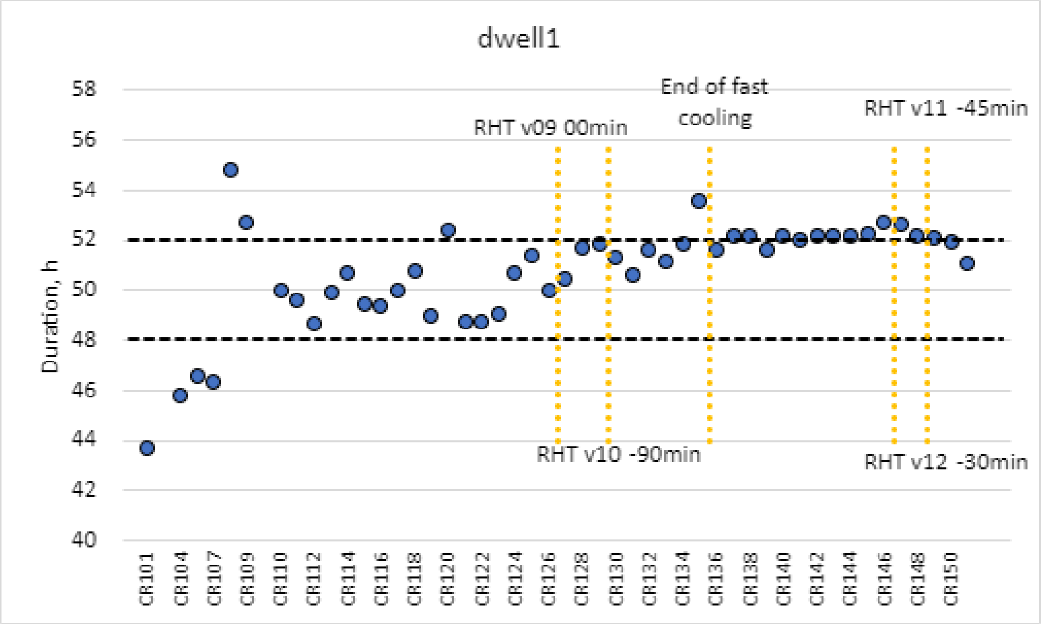
- Target insulation thickness is 145 ± 5 μm
  - Measured insulation systematically above target
  - Fine tuning of the insulation parameters in 2023 → well centered aroud 145 μm
- Since then, recurrent mechanical instability → popped strands detected during the cable insulation inspection
  - Insulated cable HCMQXFBC09-4200419A (used in coil CR143)
  - Insulated cable HCMQXFBC09-4200454A (used in coil CR145)
  - Insulated cable HCMQXFBC09-4200455A (used in coil CR148)
  - Insulated cable HCMQXFBC09-4200409A (used in coil CR149)
  - Insulated cable HCMQXFBC09-4200412A (used in coil CR150)

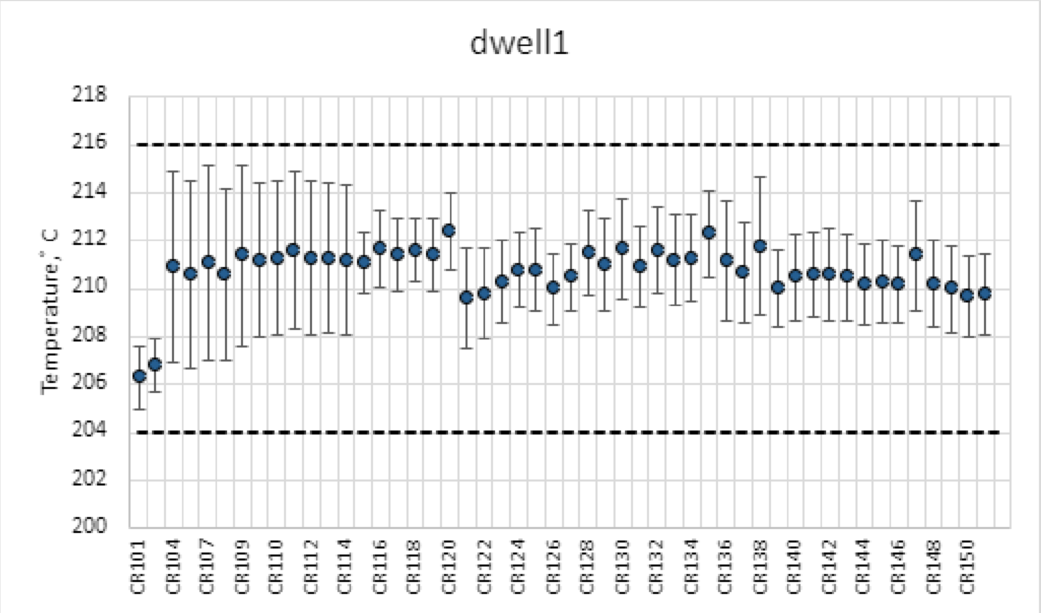
Cable insulation thickness

- Target insulation thickness is 145 ± 5 µm

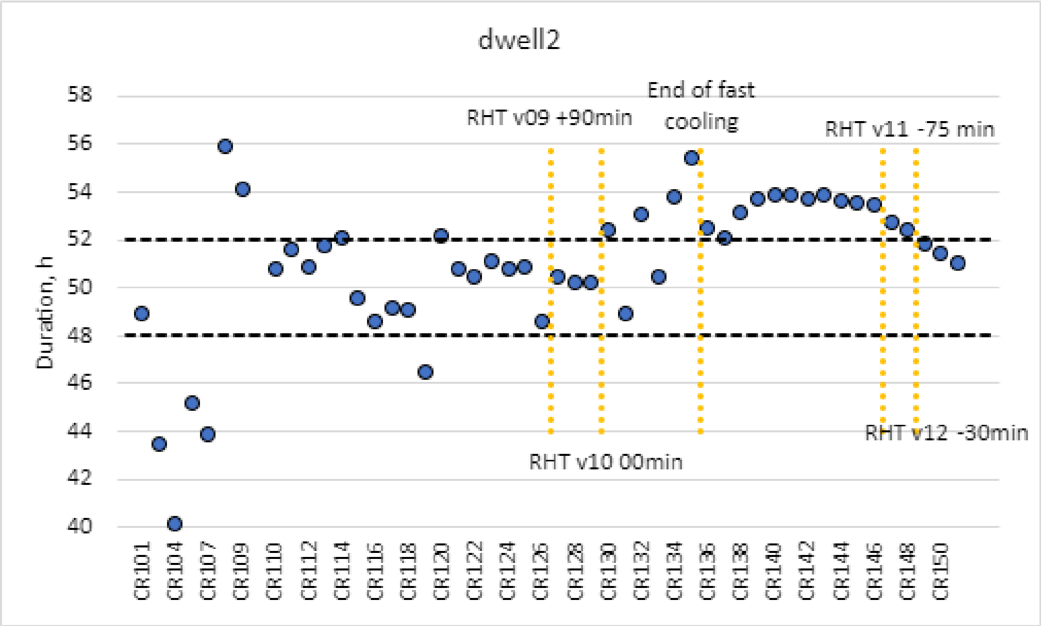


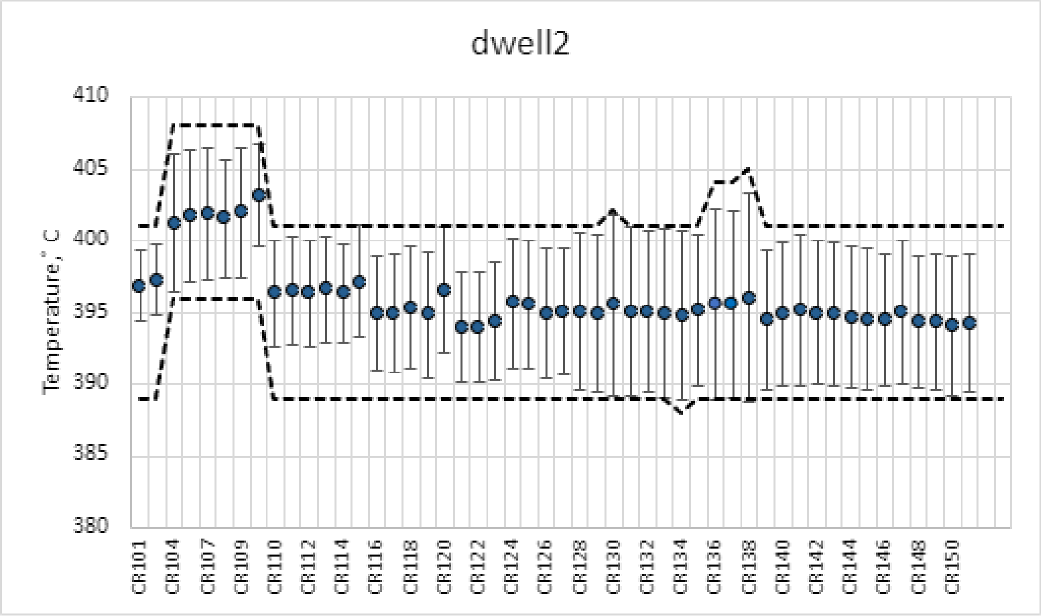
RHT history – dwell1



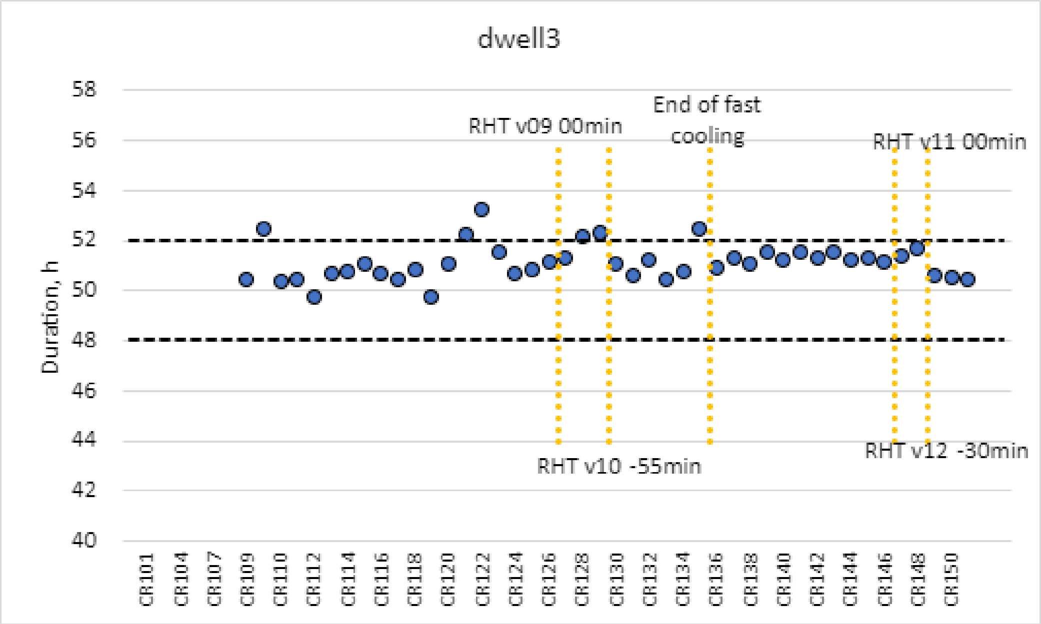


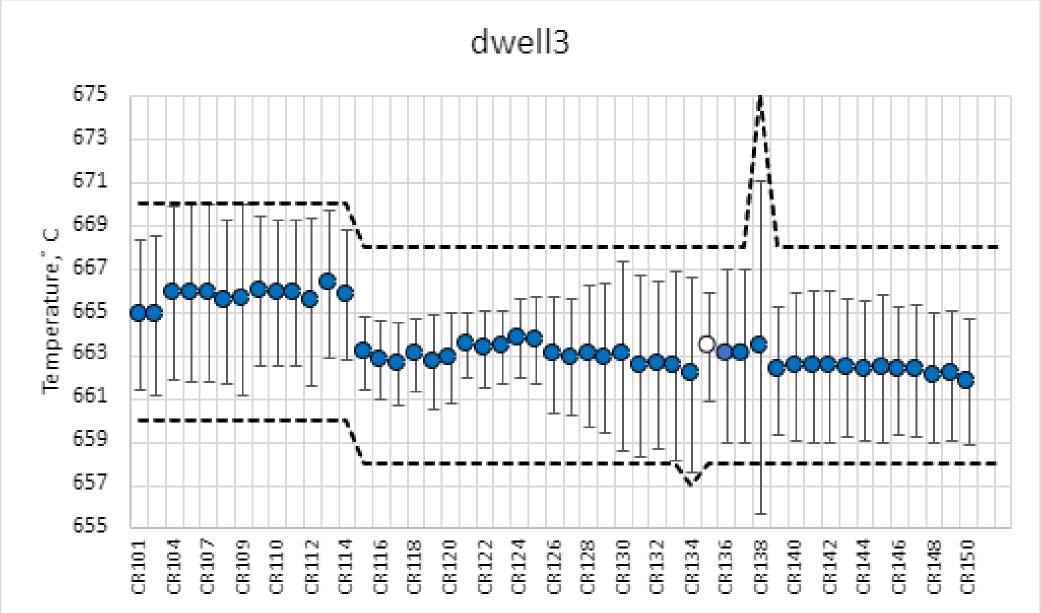
RHT history – dwell2



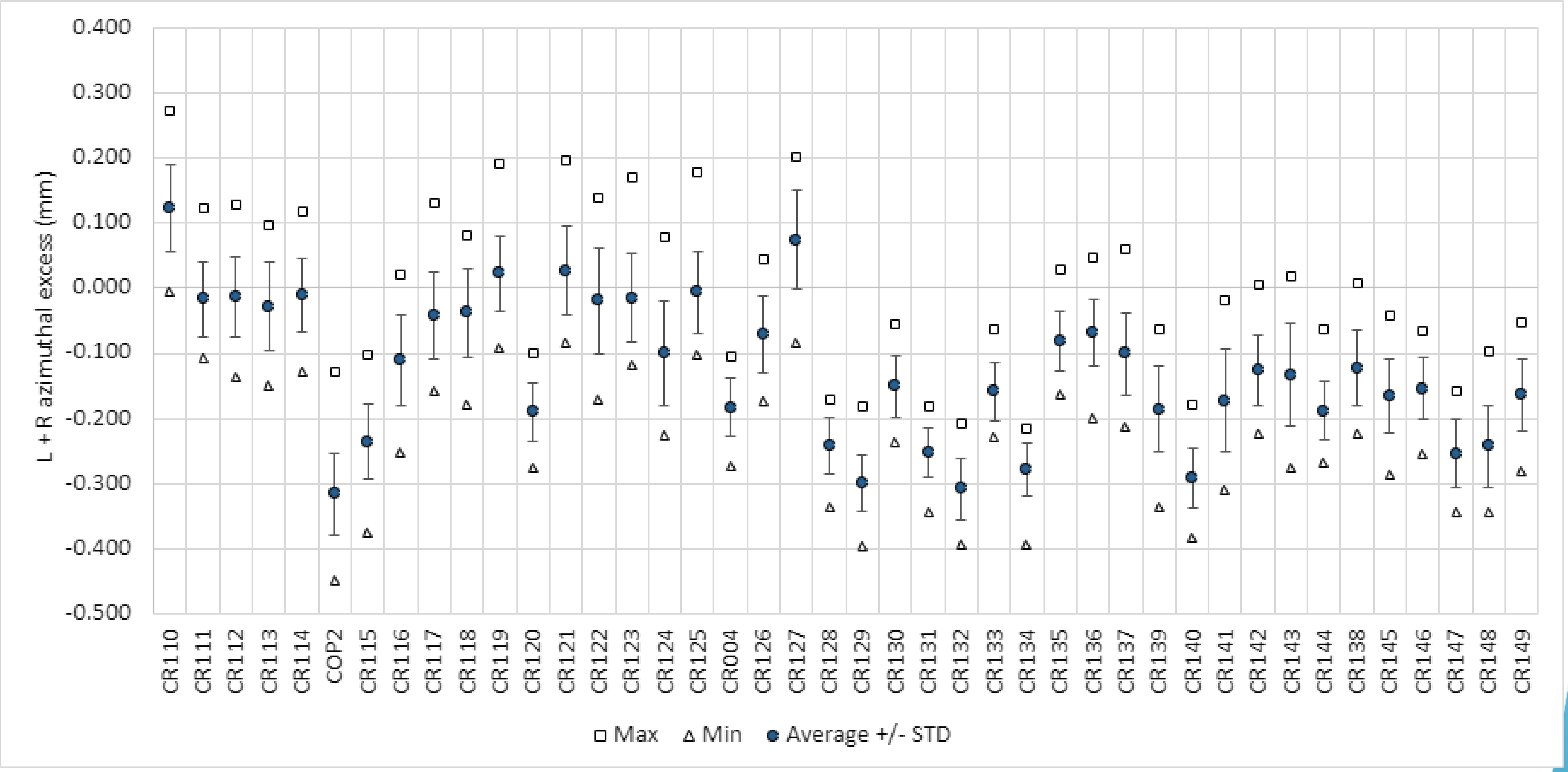


RHT history – dwell3





Coil size: azimuthal excess L+R



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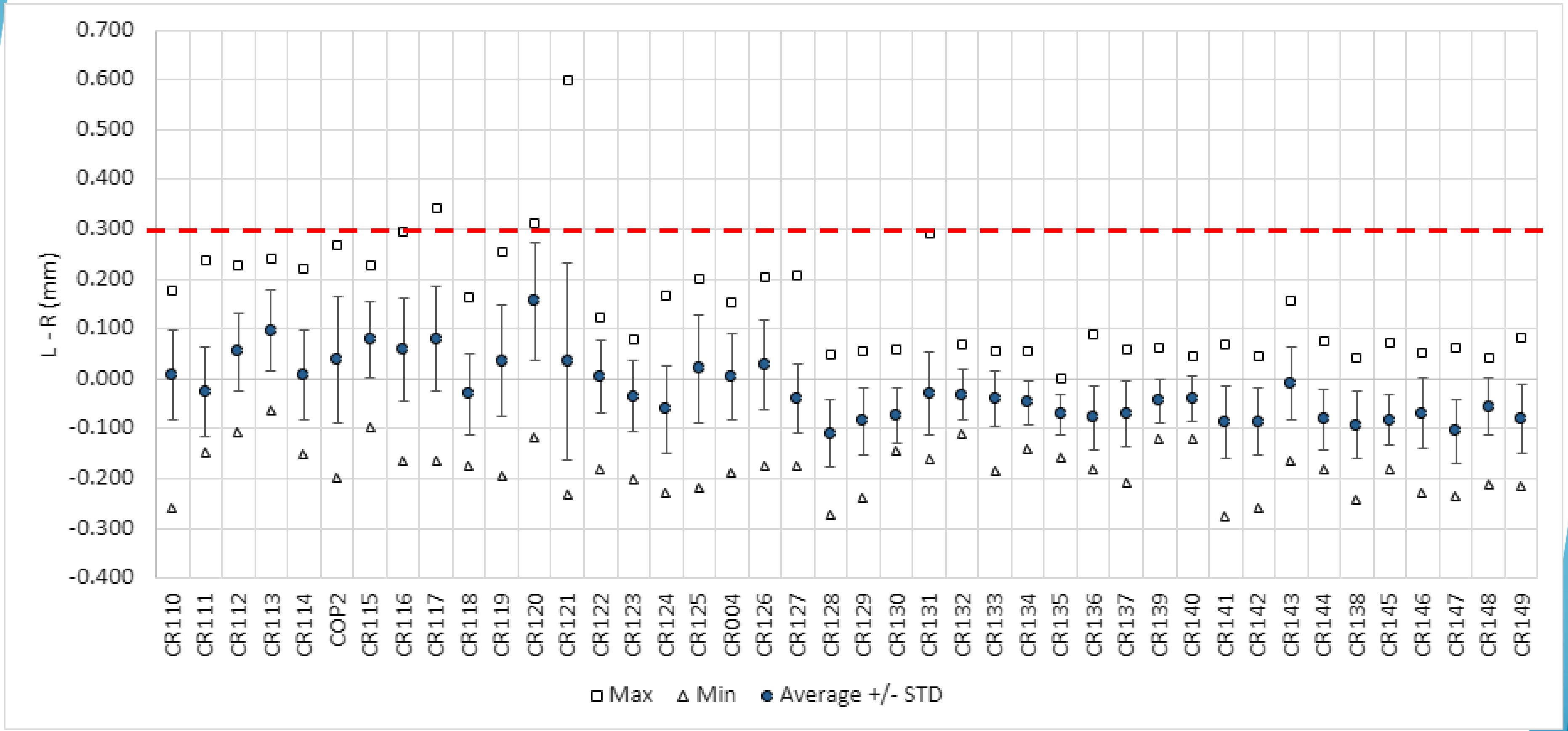
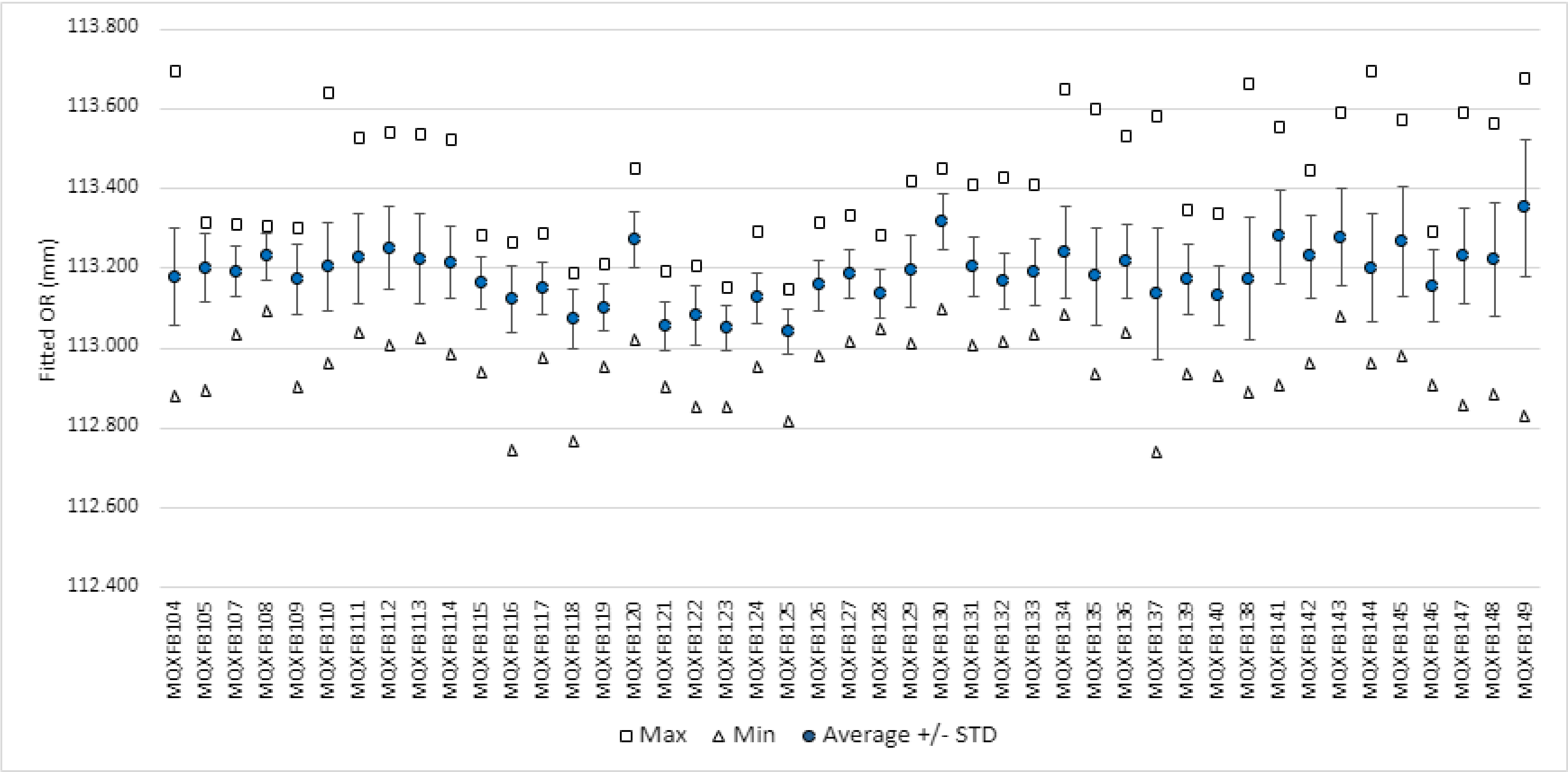
Coil size: asymmetry L-R

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



Coil size: fitted OR



Leakage current impregnated coils