MQXFB07 Coils:
Coil fabrication, manufacturing data and NC

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On behalf of MQXFB Coil Fabrication and QA team

https://indico.cern.ch/event/1431144/

11/07/2024

Coils for MQXFB07

- **Virgin coils available at the time of assembling MQXFB07**
  - 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 coil
  - <u>Coils 138*-145-146-147: Coils proposed for MQXFB07</u>
    - Coil 138 was quarantined, due to overheat during impregnation process preceding epoxy injection

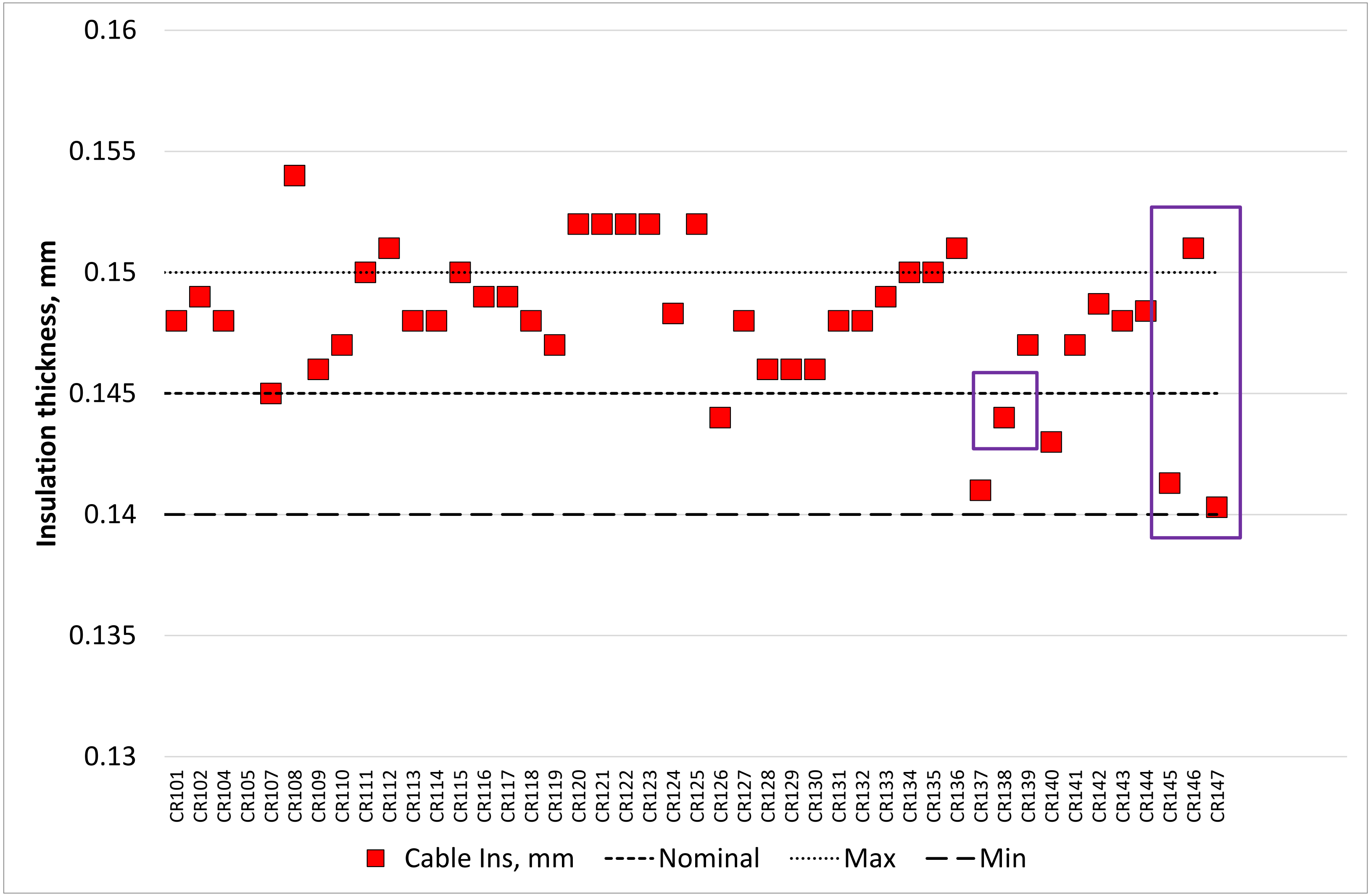
Outline

- 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
- Non-conformities
- Conclusion/Proposal

Insulation thickness



Torque monitoring during reaction fixture closure

- 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 B07 coils nominal torque was required (no need to further increase the torque)

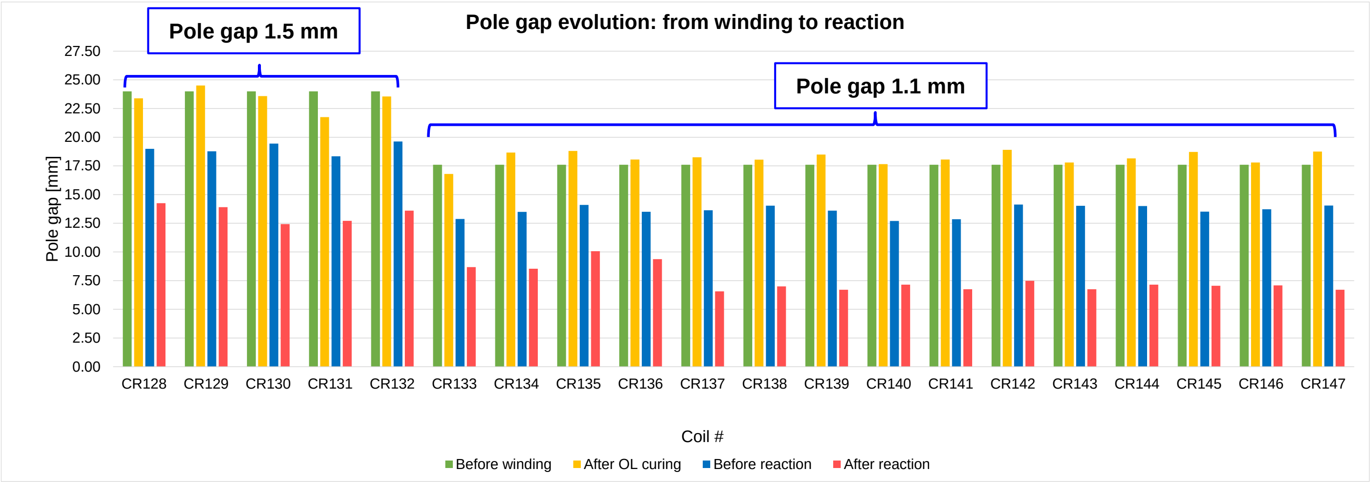
Torque applied to close the reaction fixture (M20 bolts) [Nm]				
	CR138	**CR145**	**CR146**	**CR147**
Final torque applied to the fixture	**160**	**160**	**160**	**160**

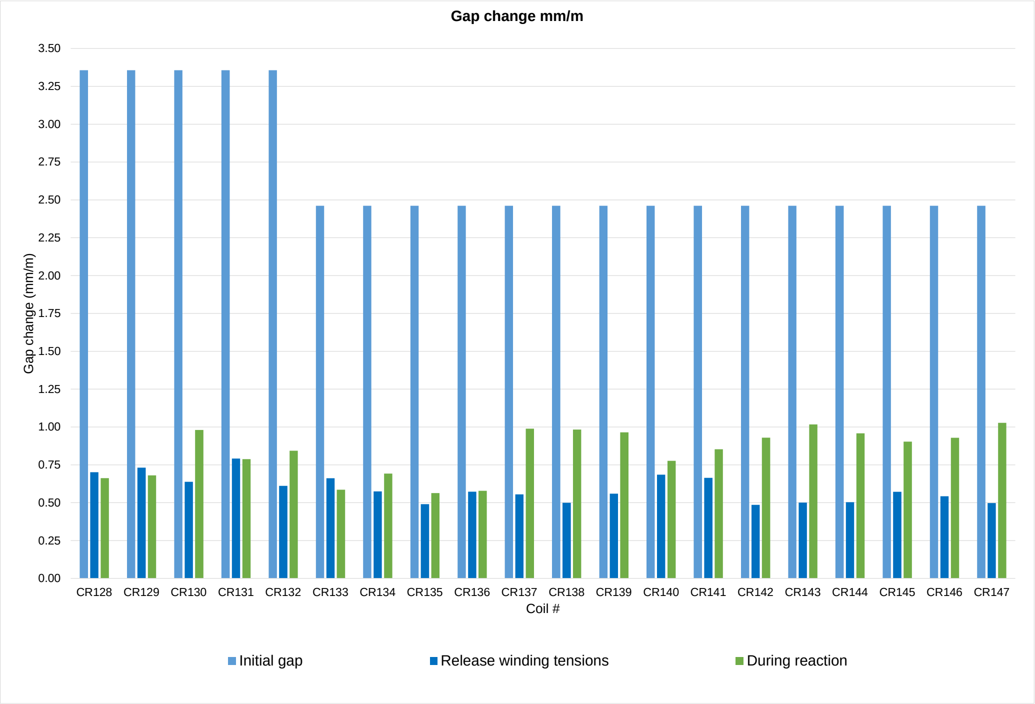
Coil elongation during reaction fixture opening

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 (proposal)	CR138	2.7	3.3	6.0	0.8 ‰	
	CR145	2.0	2.6	4.6	0.6 ‰	
	CR146	3.4	3.5	6.9	1.0 ‰	
	CR147	2.1	2.6	4.7	0.7 ‰	
	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

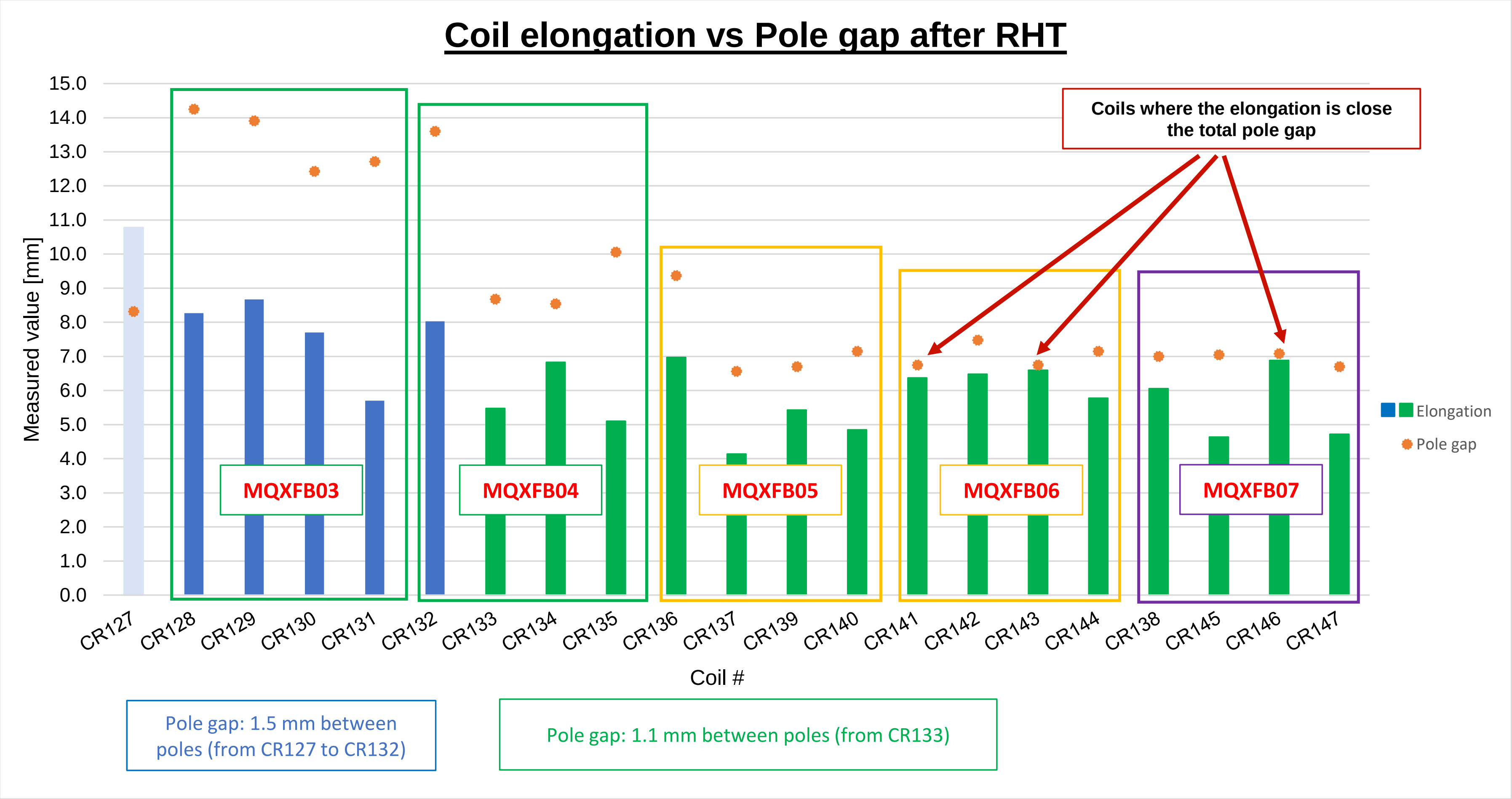
- In the latest coils (CR127-CR144), pole gaps in the middle of the coil are not closed after reaction, as it is the case for AUP coils (see additional slides)



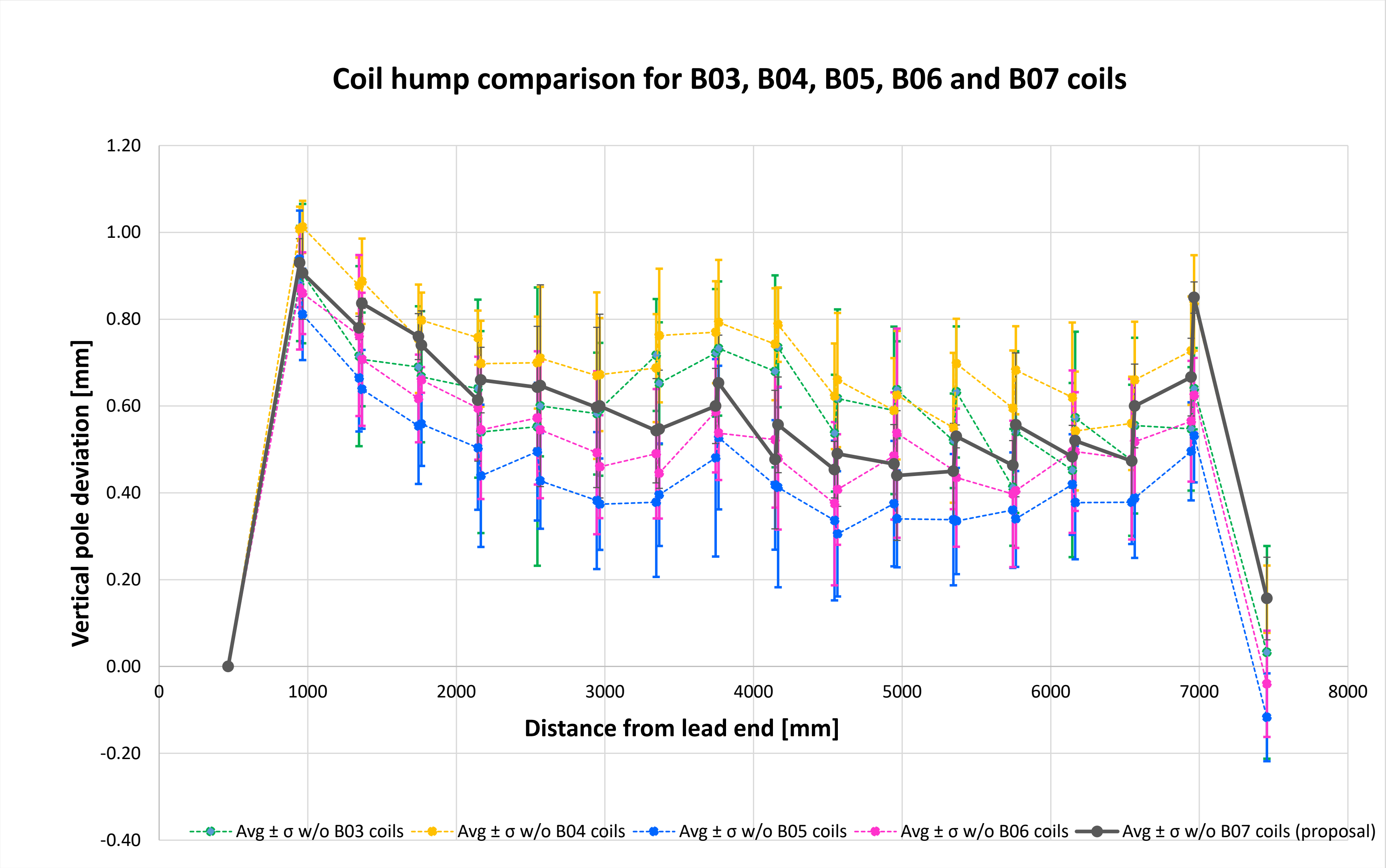


Pole gaps vs Coil elongation

- To avoid tensioning the SC cable, the total pole gap must be higher than the coil elongation
  - The plotted total pole gap correspond to minimum value (feeler gauge measurement, precision 0.05 mm)
  - The coil elongation measurement is done using dial gauges (much more precise, precision 0.01 mm)
- Pole gap will be increased in the next CR150

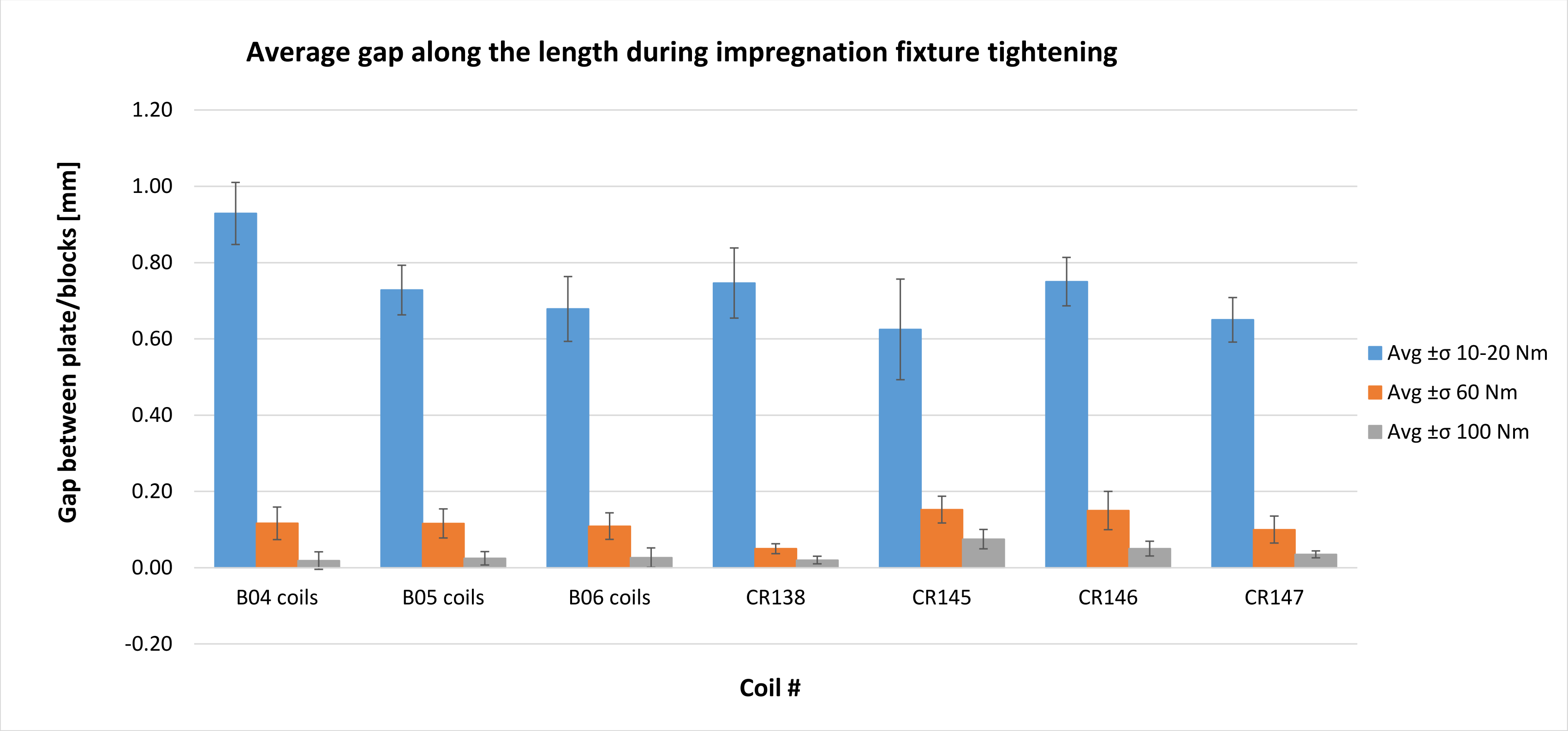


Coil hump after reaction



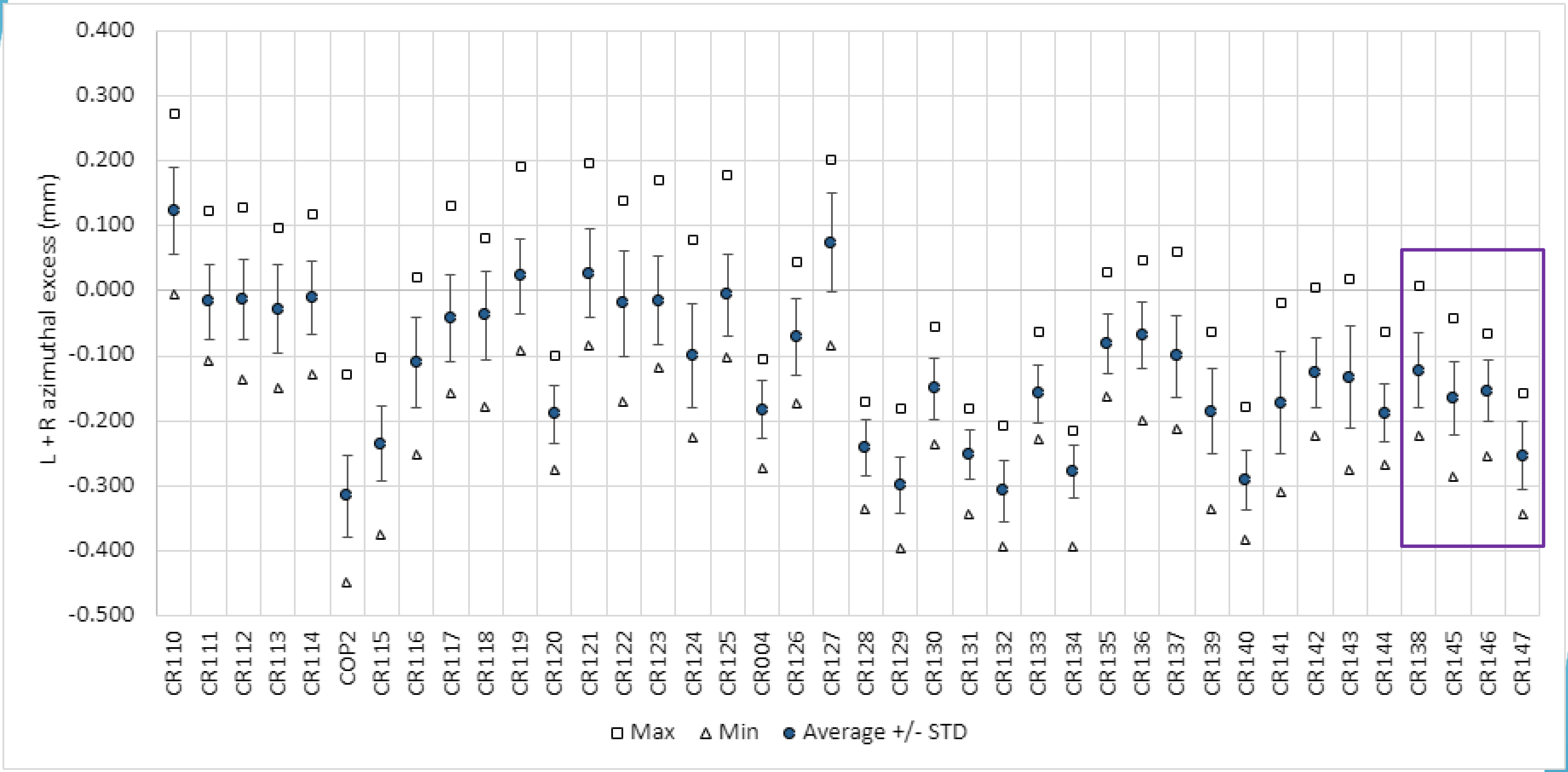
Impregnation fixture closure

- Very reproducible from coil to coil
  - OL impregnation closure: 60 Nm
  - IL impregnation closure: 120 Nm (never needed more)
- Gap between blocks/plate is measured at determined steps of the closure
- Since coil CR142, 1st tightening step at 20 Nm (instead of 10 Nm)



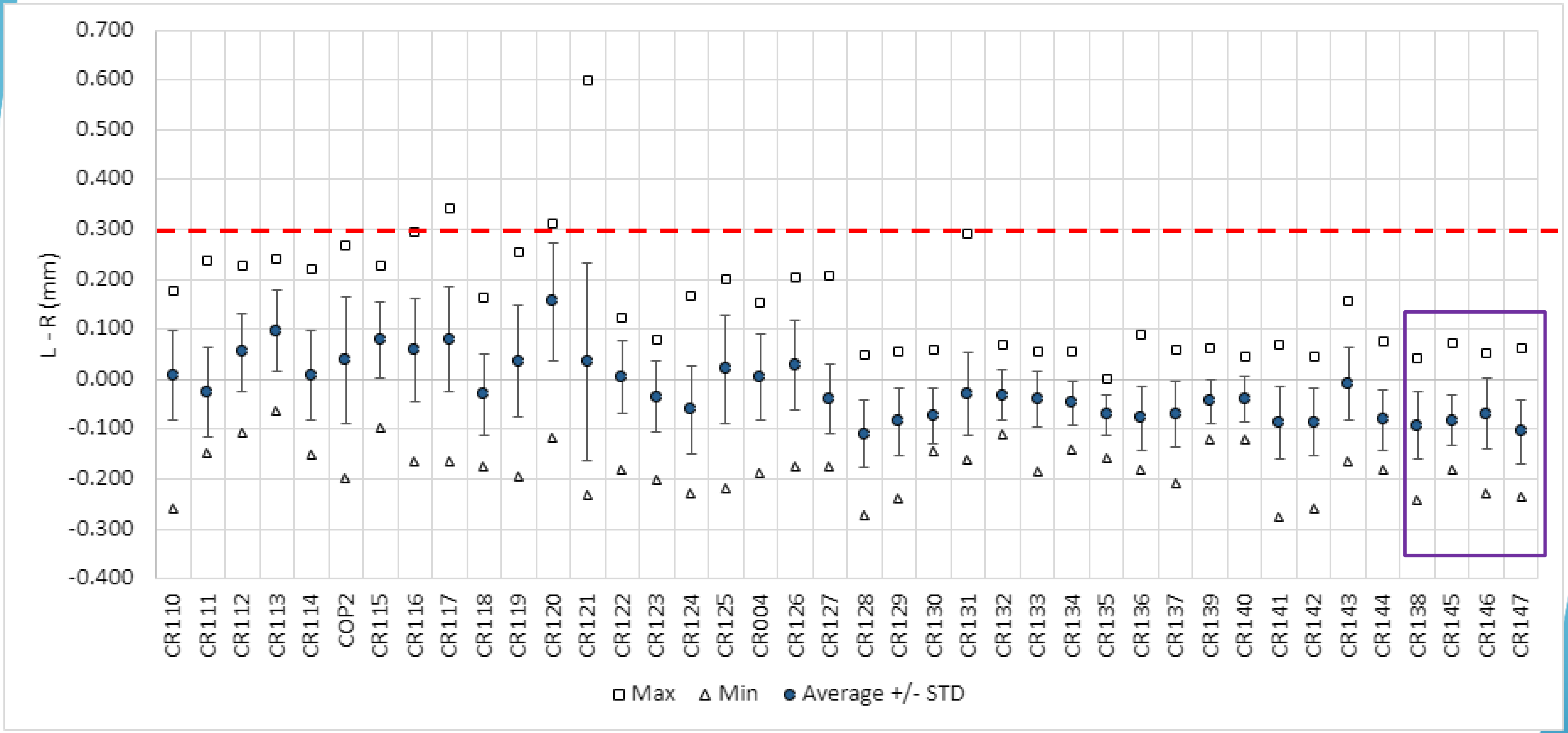
Impregnated coil geometry (Faro arm) - L+R

- The coils do not have 'belly'



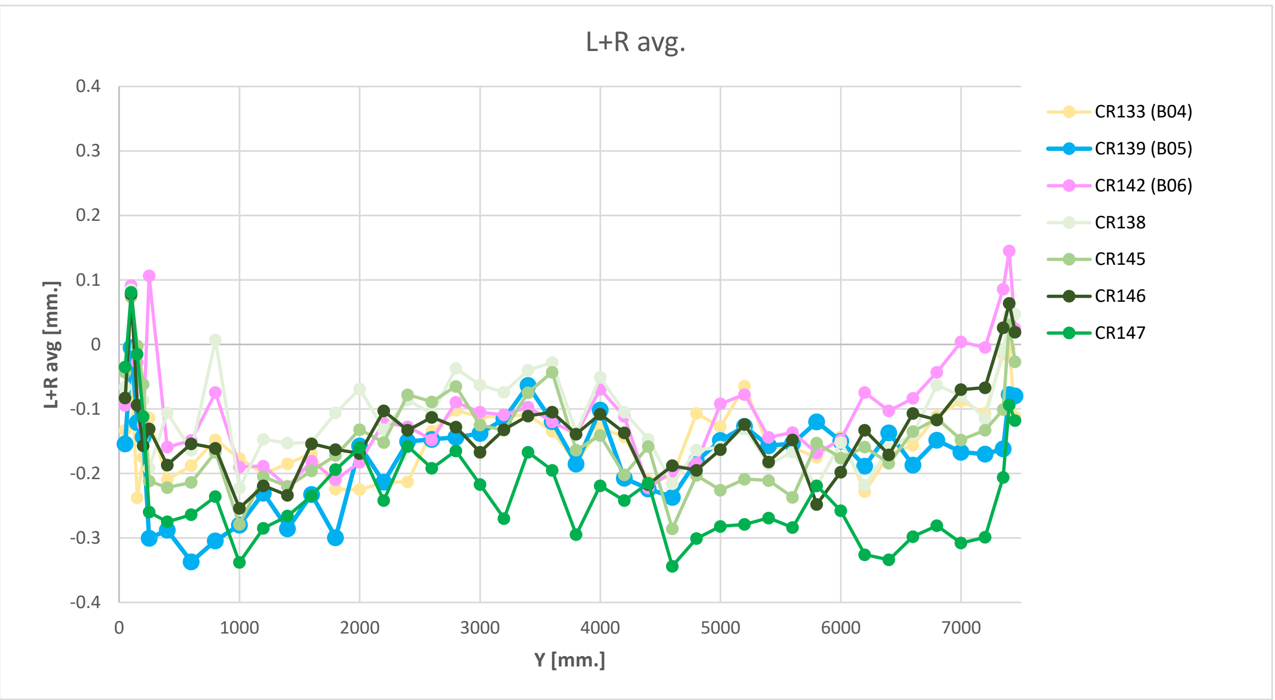
Impregnated coil geometry (Faro arm) – L-R

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

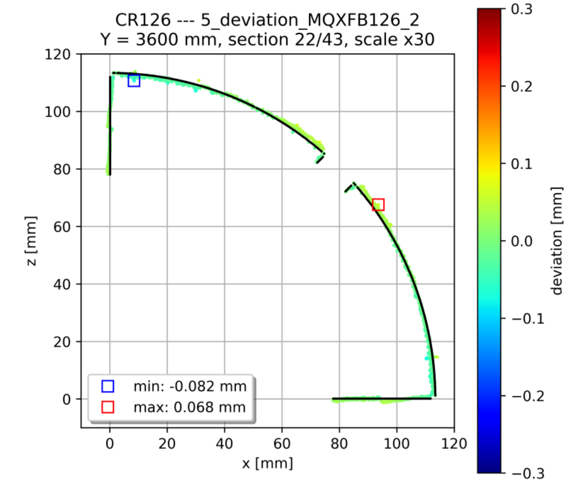


Impregnated coil geometry (Faro arm)

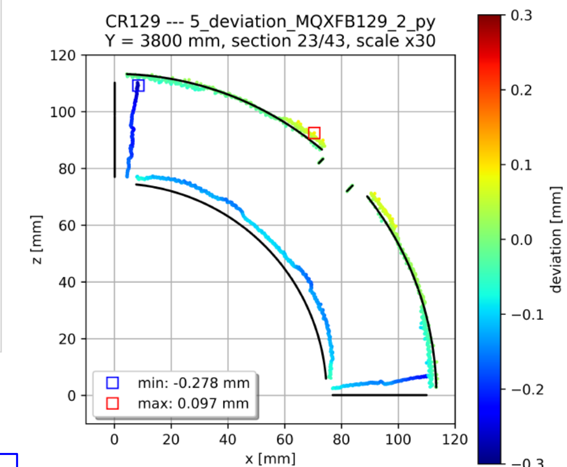
- Systematic behavior in terms of coil shape to previous coils without binder: mid-plane has a little 'wedge' (the coil covers 89.6 degrees instead of 90 degrees)
- Based on FEM we expect ≈ 15 MPa increase in the mid-plane stress (inner edge) under conservative assumptions, confirmed with a mock-up test,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



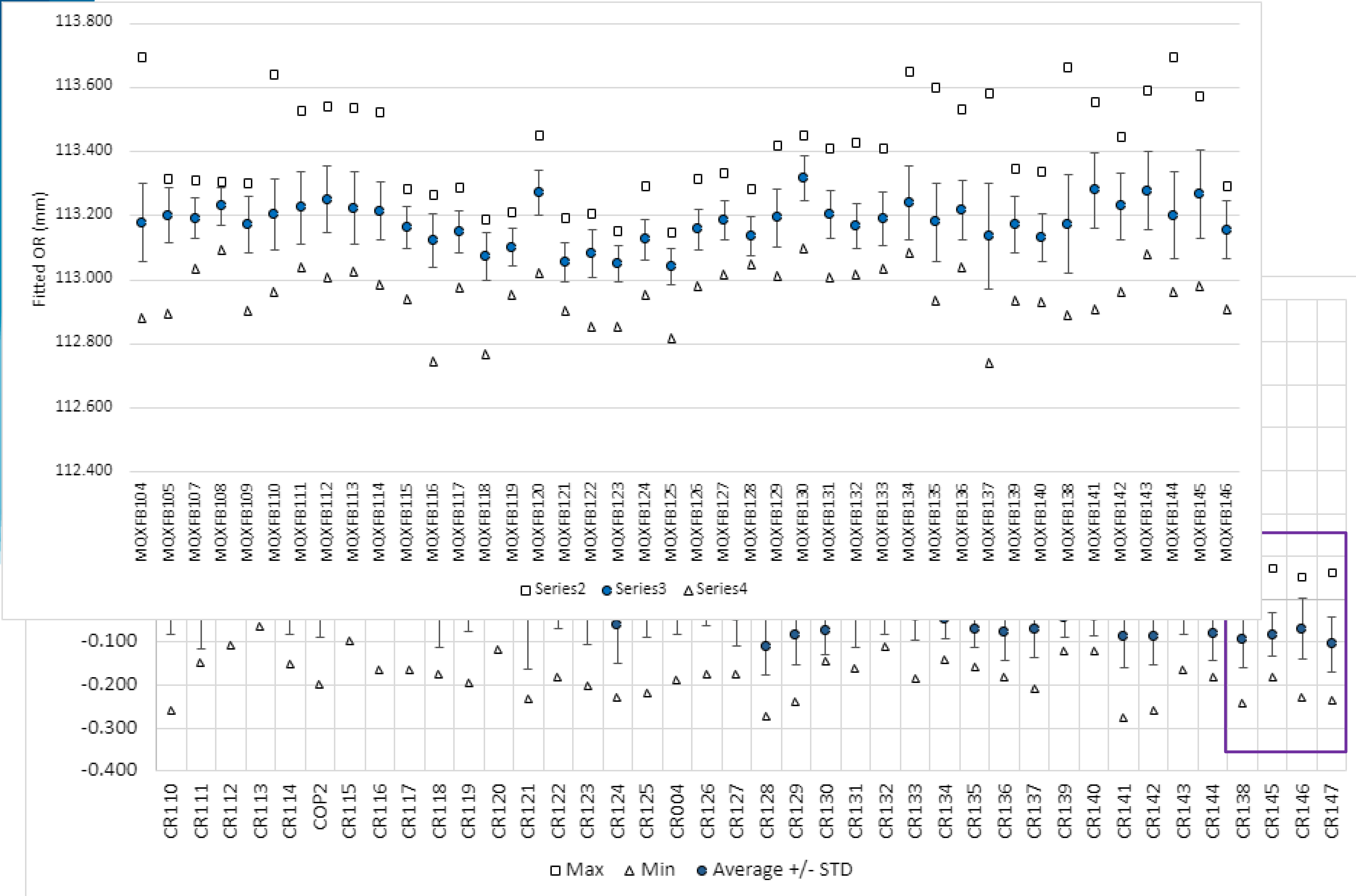
Typical cross-section standard coil



Typical cross-section coil without binder in the OL



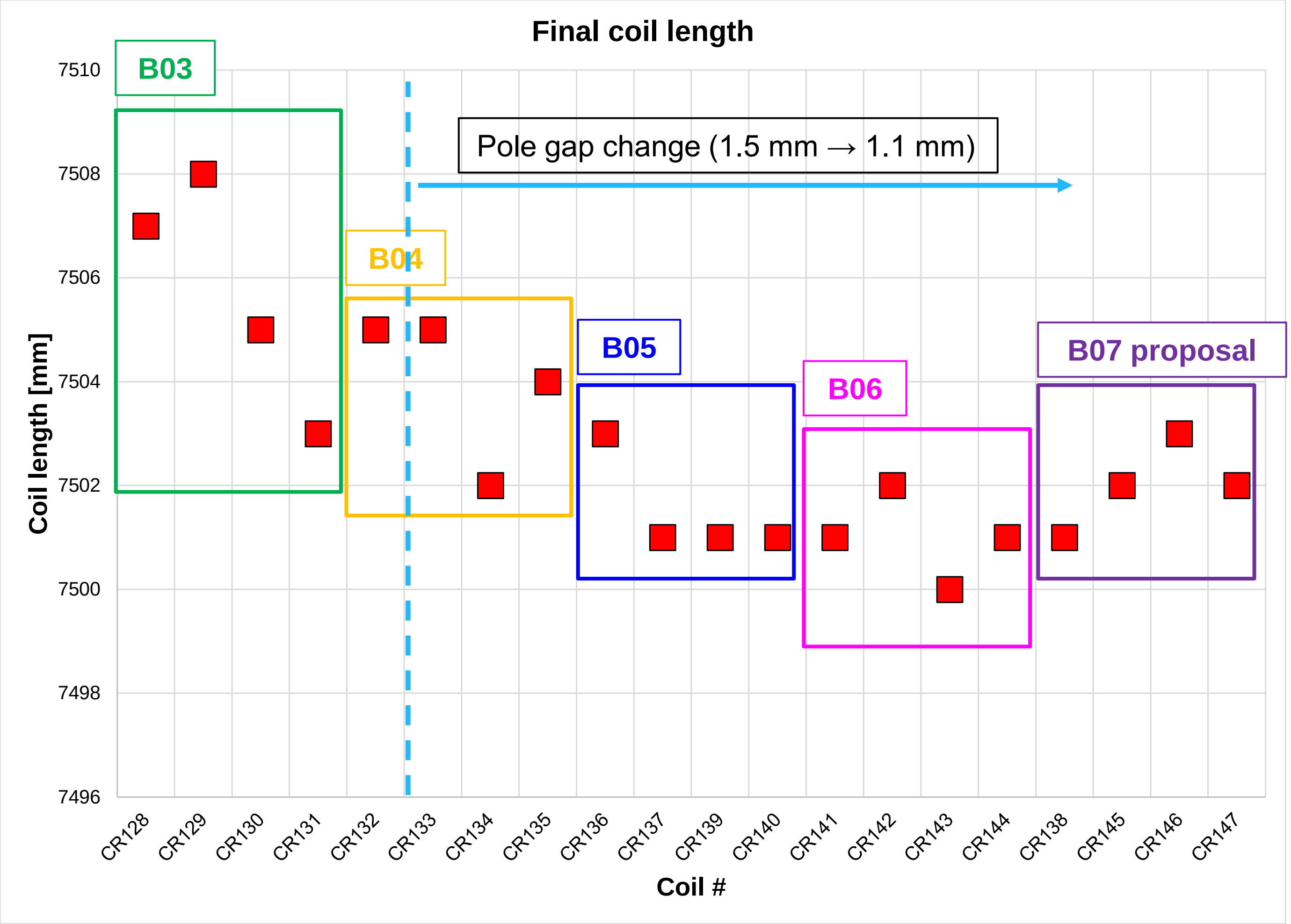
Further detail about coil metrology in Penelope's presentation



113.800
113.600
113.400
113.200
113.000
112.800
112.600
112.400
Fitted OR (mm)
MOXFB104 MOXFB105 MOXFB107 MOXFB108 MOXFB109 MOXFB110 MOXFB111 MOXFB112 MOXFB113 MOXFB114 MOXFB115 MOXFB116 MOXFB117 MOXFB118 MOXFB119 MOXFB120 MOXFB121 MOXFB122 MOXFB123 MOXFB124 MOXFB125 MOXFB126 MOXFB127 MOXFB128 MOXFB129 MOXFB130 MOXFB131 MOXFB132 MOXFB133 MOXFB134 MOXFB135 MOXFB136 MOXFB137 MOXFB139 MOXFB140 MOXFB138 MOXFB141 MOXFB142 MOXFB143 MOXFB144 MOXFB145 MOXFB146
Series2 Series3 Series4
-0.100
-0.200
-0.300
-0.400
CR110 CR111 CR112 CR113 CR114 COP2 CR115 CR116 CR117 CR118 CR119 CR120 CR121 CR122 CR123 CR124 CR125 CR004 CR126 CR127 CR128 CR129 CR130 CR131 CR132 CR133 CR134 CR135 CR136 CR137 CR139 CR140 CR141 CR142 CR143 CR144 CR138 CR145 CR146 CR147
Max Min Average +/- STD

Final coil length

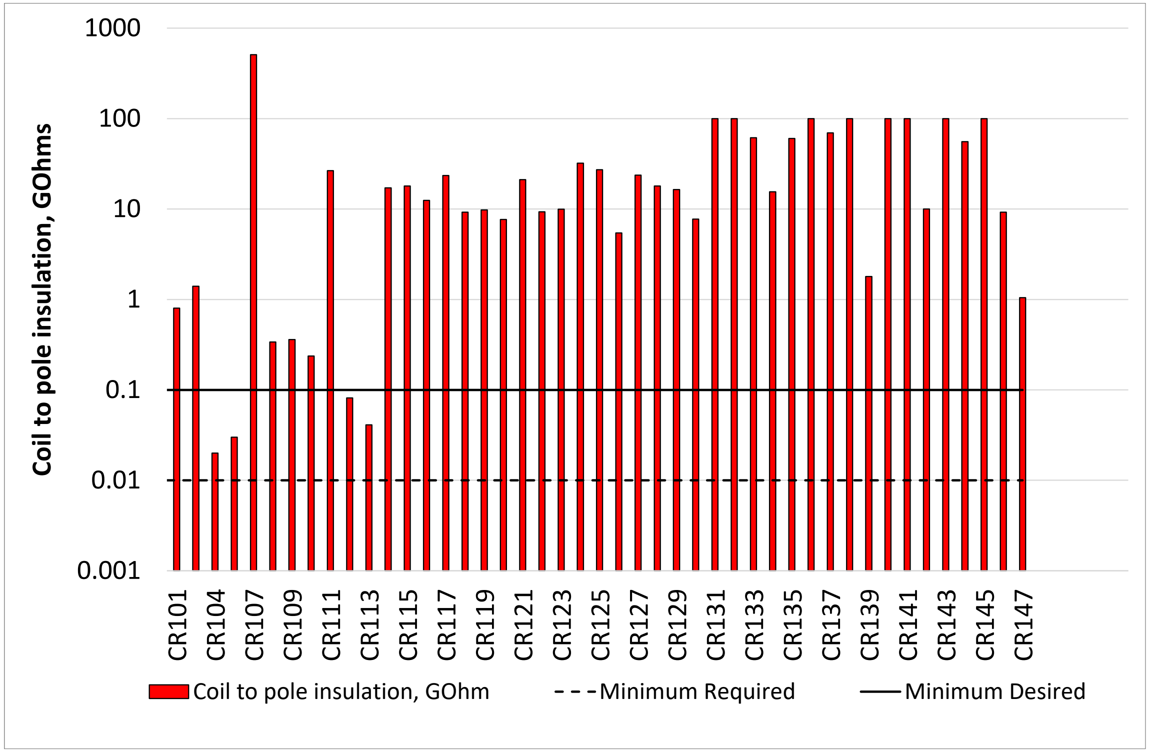
- The total pole gap starting from coil 133 is 6.2 mm smaller



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

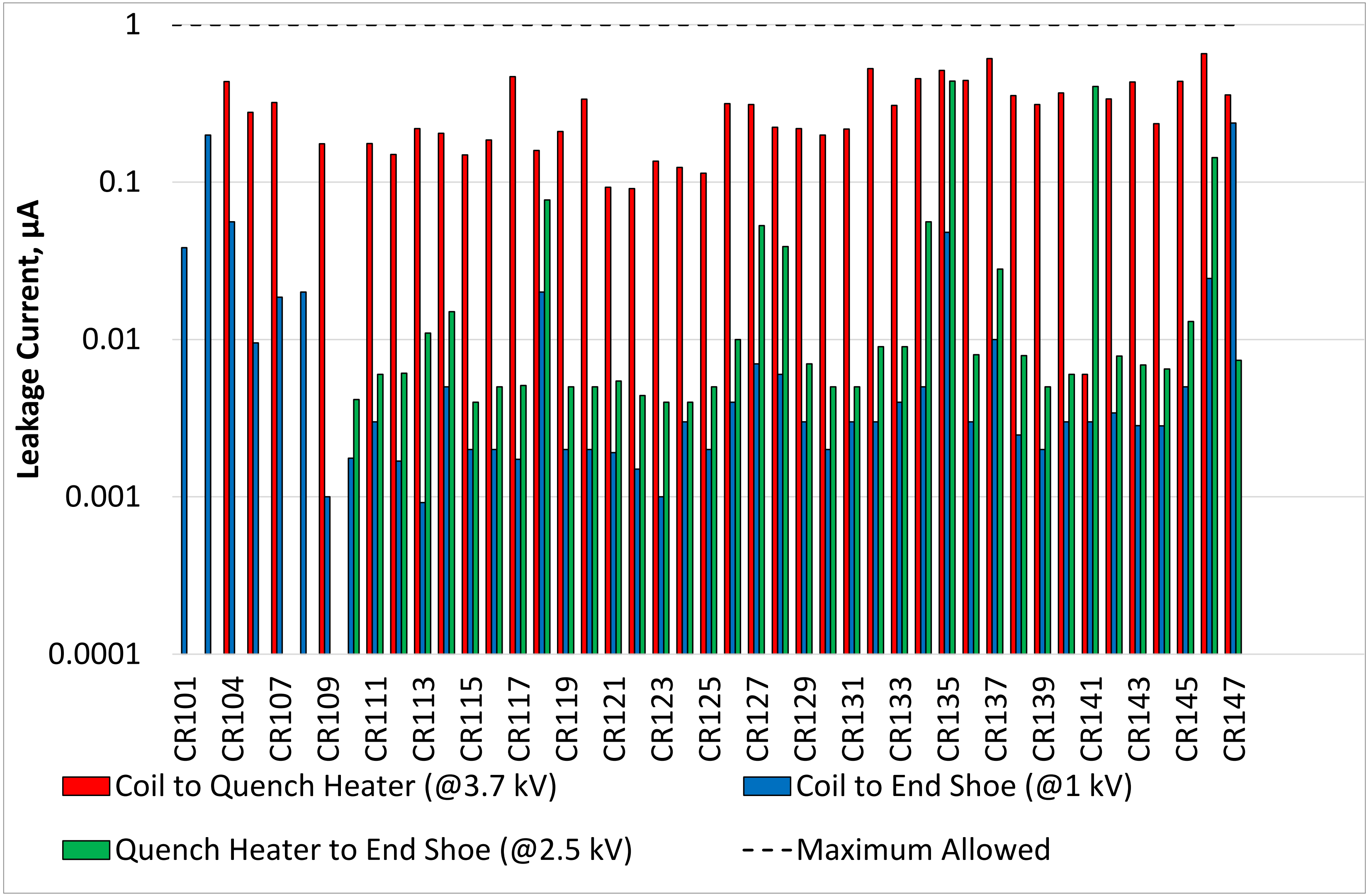


From production performance monitoring plots [EDMS 2374351]

QH to coil

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

Dielectric strength



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- Non-conformities
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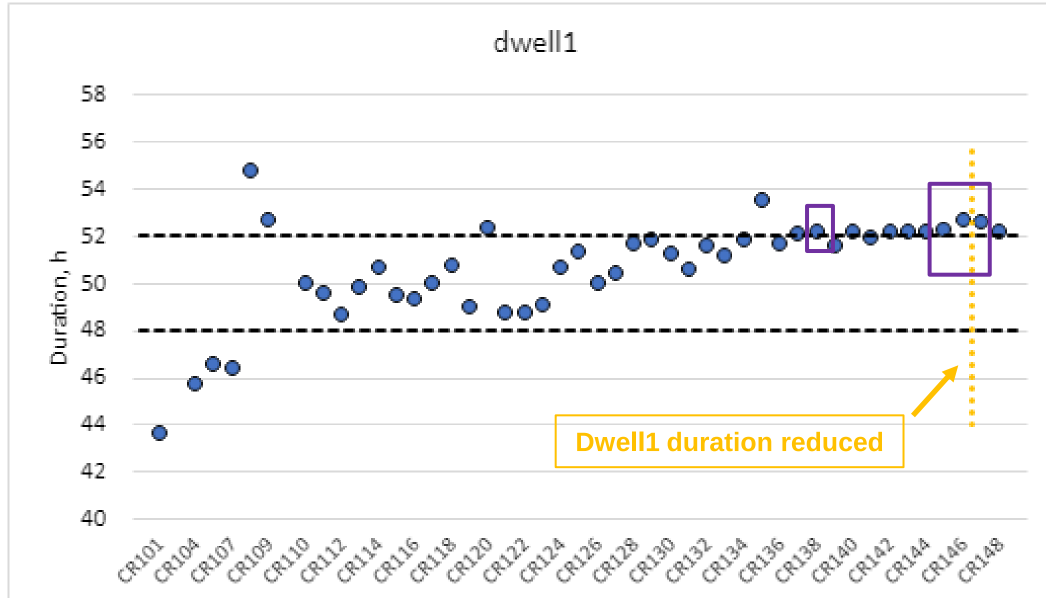
Analysis of non-conformities

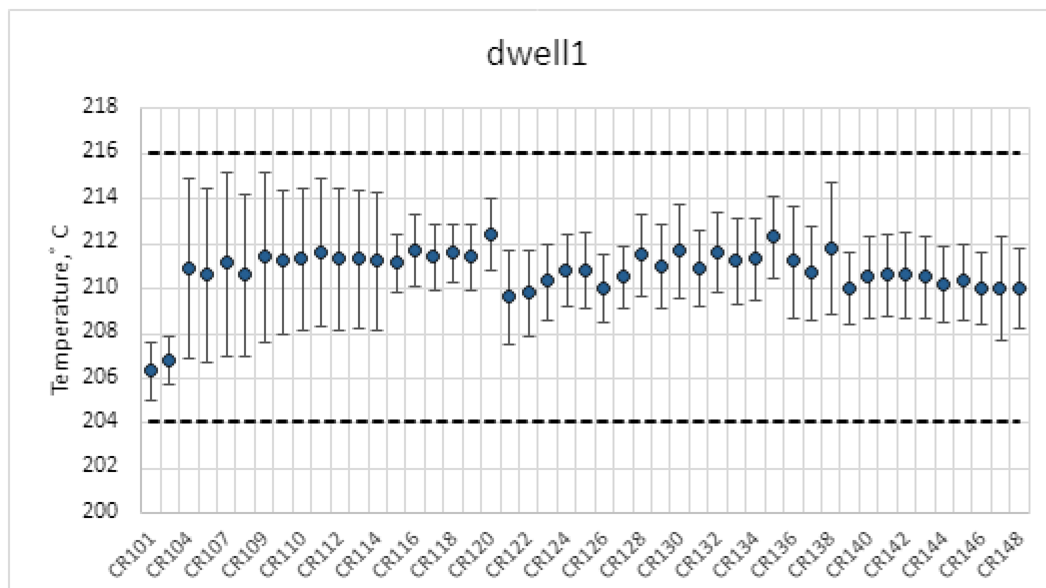
CR138	2962606	Issue during RHT cycle	Non-critical level 2
	2961736	RHT parameters out of specification	Non-critical level 2
	3011012	Lower temperature locally during heating up to 110°C (impregnation cycle)	Non-critical level 1
	2974448	Over-heating during impregnation cycle	**Critical level 3**
	3128109	Cable insulation damaged	Non-critical level 1
CR145	3073728	Dwell1 and dwell2 durations out of specifications	Non-critical level 1
	2884016	Dwell3 homogeneity out of range	Non-critical level 1
CR146	3083049	Inner layer connection cable damaged during core removal	Non-critical level 2
	3088822	Dwell1 and dwell2 durations out of specifications	Non-critical level 1
CR147	3088717	IR1 end part coating damaged after IL curing	Non-critical level 1
	3101915	Dwell1 and dwell2 durations out of specifications	Non-critical level 1
	2884016	Dwell3 homogeneity out of range	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

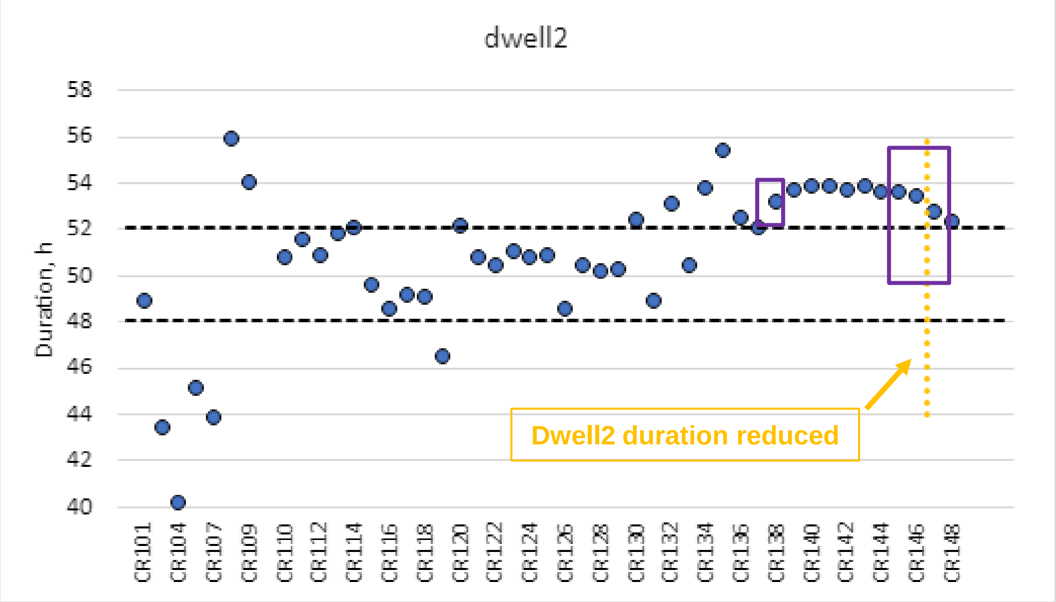
- The duration of dwell1 is out of specification in all the 4 coils:
  - CR138: 52.09 h
  - CR145: 52.17 h
  - CR146: 52.61 h
  - CR147: 52.53 h
  - Spec. 52 h maximum allowed
- Temperature homogeneity within specification

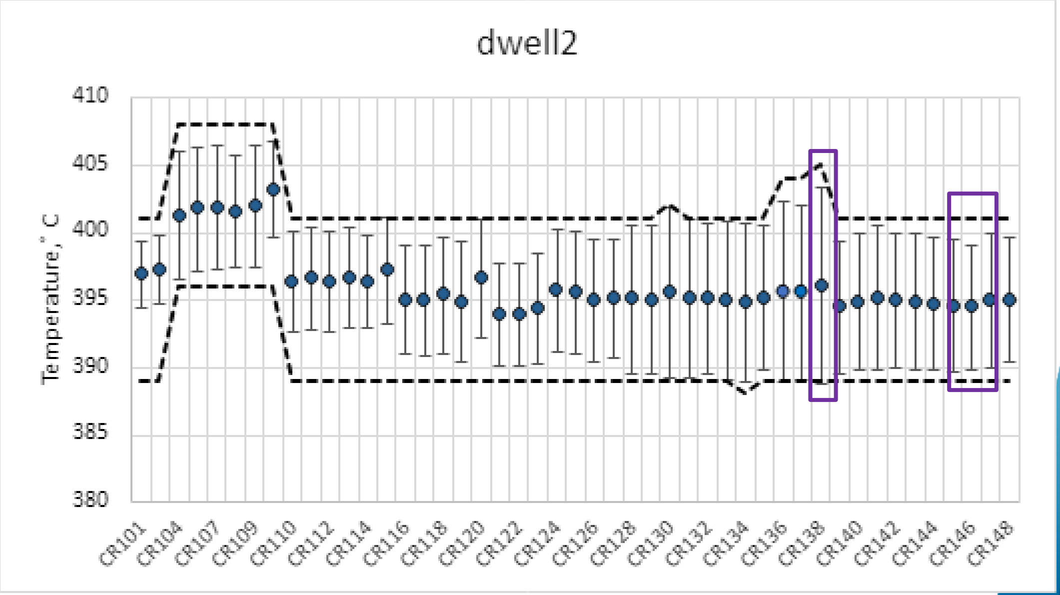




RHT NCR – dwell2

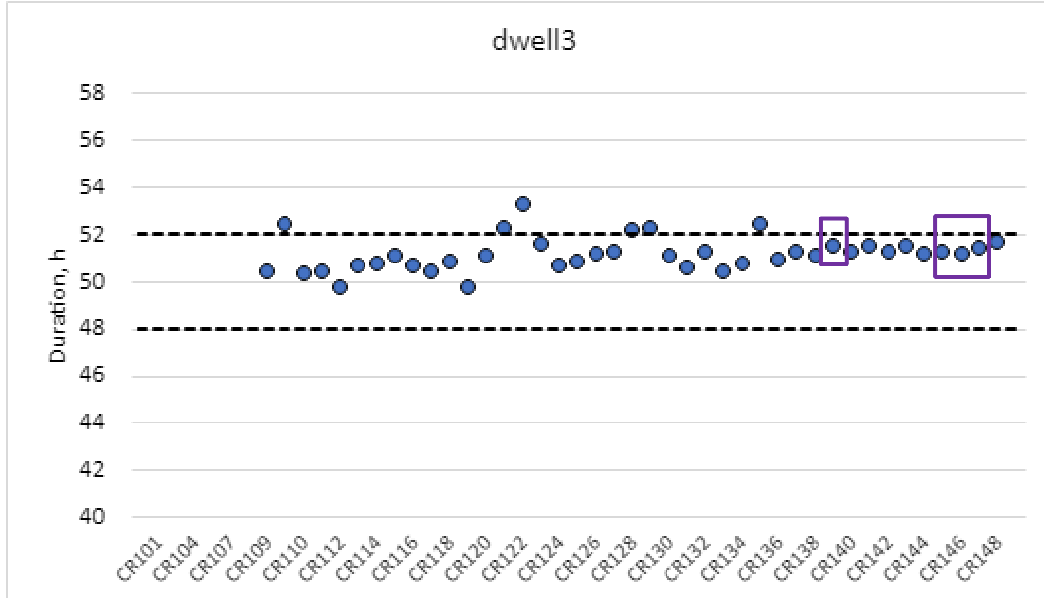
- The duration of dwell2 is out of specification in all the 4 coils:
  - CR138: 53.09 h
  - CR145: 53.54 h
  - CR146: 53.38 h
  - CR147: 52.67 h
  - Spec. 52 h maximum allowed
- In coil CR138 (previously in CR136 and CR137) the upper band of the plateau had to be increased from 401°C to 404°C
  - TCs close to the RE of the mould were warmer
  - Furnace intervention after CR138 RHT (see next slides)

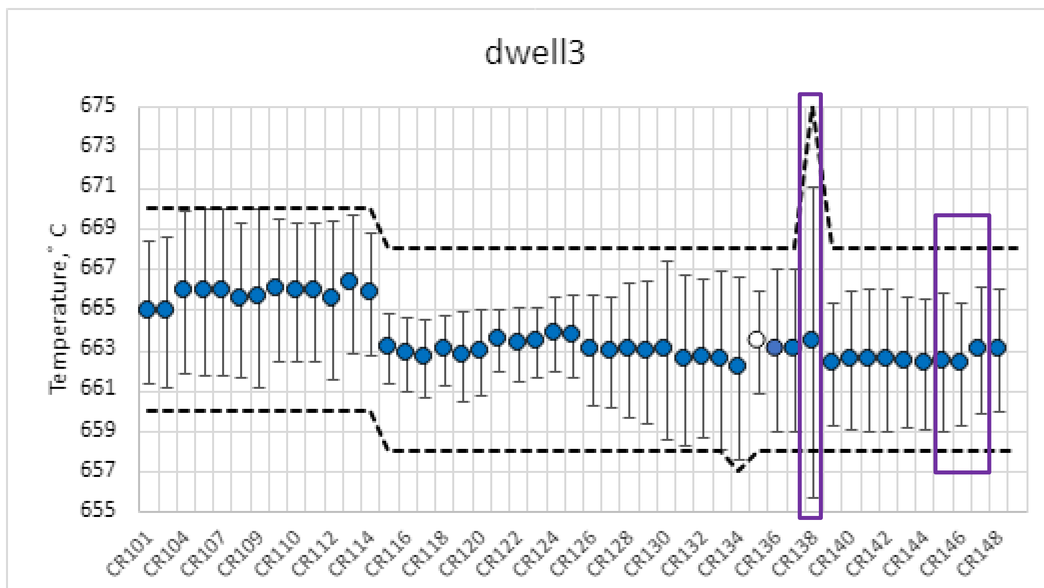




RHT NCR – dwell3

- The duration of dwell3 is within specification for the 4 coils (52 h max. allowed)
- In CR138, 3 TCs were out of range (TT17, TT19 and TT37)
  - Max. temperature measured: 675°C
  - Max. temperature allowed: 668°C
  - Root cause analysis pointed to the melting of the fuse 3F6
  - NCR 2962606 and NCR 2961736
- Dwell3 mean H/2 out of spec
  - CR138: 7.7°C
  - CR145: 3.4°C
  - CR146: 3°C
  - CR147: 3.1°C
  - Spec. 3°C maximum allowed

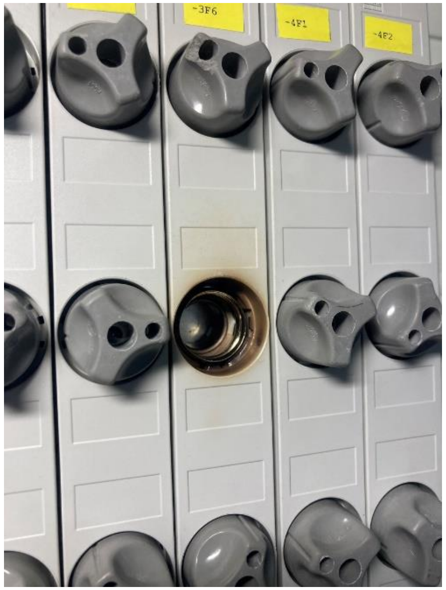




CR138 (NCR 2962606) → Furnace intervention

- The furnace has several heating zones along the length
  - A1-B1: LE of the mould (door)
  - A8-B8: RE of the mould

- During the 3rd plateau, issue in B7 zone which was not regulating correctly the temperature
  - Adjacent heating zones B6 and B8 provide more heat flow so the temperature increased above the target
- Root cause analysis showed a B7 zone fuse heavily damaged which was then replaced
  - Electrical check of the heating resistances of the furnace and of the elctrical circuit → ok

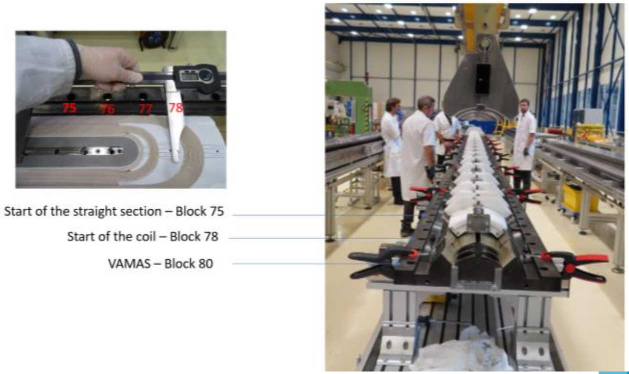


Preventive action:

- Check of the fuses every 3 months in the preventive maintenance planning
- Implementation of phase controller on each of the static relays to monitor any missing phase

CR138 (NCR 2961736) → RHT parameters out of spec

- The impact of the NCR 2962606 on the coil is translated in several parameters out of spec
  - $T_{max\ dwell2}$: 416°C (max. allowed 401°C)
  - $T_{max\ dwell3}$: 675°C (max. allowed 668°C)
  - Dwell2 $_{H/2\ homogeneity}$: 7.3°C (max. allowed 5°C)
  - Dwell3 $_{H/2\ homogeneity}$: 7.7°C (max. allowed 3°C)
- Anomalous heating in the rear part of the oven (TCs17, 19, 37) located in block #75 reached the higher temperature, i.e. 675°C
  - Assess the impact of the over temperature on Ic and RRR in that location
  - VAMAS samples placed in RE of the mould allow for conservative assessment
- As explained by S. Hopkins (EDMS 3012883)
  - RRR in RE of the coil is reduced w.r.t. standard coils, minimum measured 173 (minimum required 100) → RRR in specification
  - Ic test samples heavily oxidised in RE of the mould but measurement within specification
    - CC sample: Ic increase of 2.2% / 7.4% at 12 T/15 T (at 4.3 K)
    - COC sample: Ic increase of 2.4% / 7.6% at 12 T/15 T (at 4.3 K)

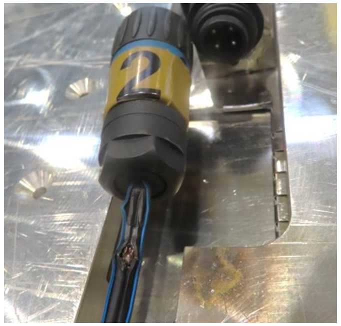


CR138 (NCR 2974448) → Over heating during impregnation cycle

- NCR deeply discussed during CW group meeting on December the 6th (indico 1355007)
- During the tests performed prior to inject the epoxy resin into the mould, an issue caused the stop of the operations and the opening of the mould
- Instead of degassing at 110°C, the mould was heated up to 250/300°C for 24 hours (best guess based on findings)

What did it happen?

- In the impregnation machine there are 2 sets of TCs (for MQXFB and 11T coils)
- The correct TCs were installed in the mould but the wrong connector was plugged in the impregnation machine (11T connector)
  - Monitoring of the 11T TCs which were in contact with the impregnation machine table so "in the air"
  - We were blind at the level of the mould temperature
- When 110°C were set for the degassing cycle, the heating plates ran at maximum power
  - Short circuit between power connector and heating plate #2 appeared, causing tripping of the circuit breaker and stop of all heaters
  - Investigation of the root causes

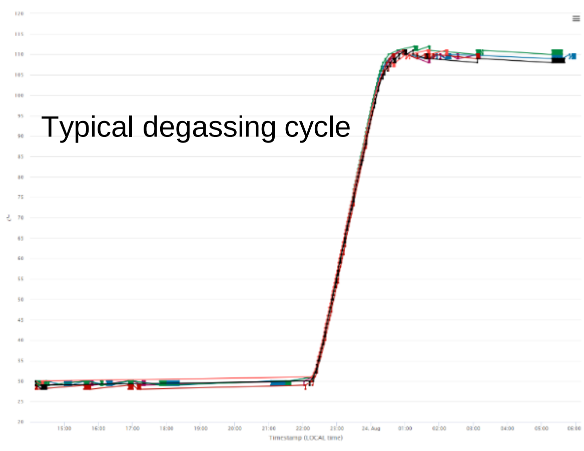


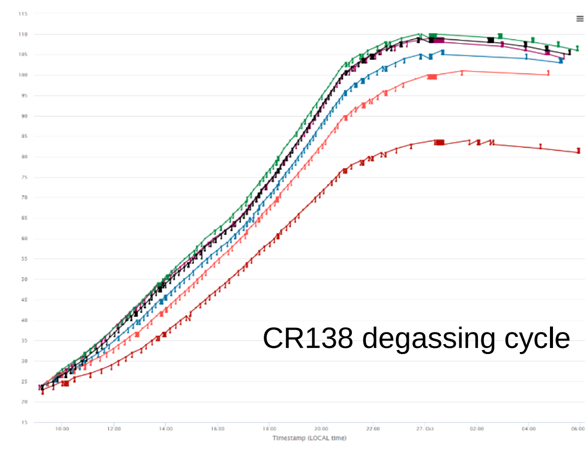
Why did it happen? → Human errors

1. The wrong connector was plugged by the operator (procedure not followed)

8.10.1	**Raccordement des thermocouples** Brancher le connecteur « MQXF » des thermocouples. Vérifier la cohérence des valeurs de températures sur l'interface. **Renseigner l'étape 13 de l'onglet «Suivi Imprégnation machine » de la fiche de suivi MQXFB [2]).**	 

2. Parallel activities on another mould were 11T TCs were installed during the days preeceding the MQXFB coil
   - Reason why the 11T TCs and plug were not hidden as usual
3. Direct monitoring of the degassing cycle not done
   - Unusual behavior could have been detected





Action plan and results

- Opening of the impregnation mould to further investigate
- Perform 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 Ic 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
- Replace all the polyimide parts (splice insulation and QH)
- Visual inspect the coil
- Replace all damaged parts and install fresh S2 glass → NCR 3128109
- Consolidation of the impregnation machine, replace the wiring and implementation of plugs with oriented slots to avoid any connection error

- **Preventive action:**
  - Regular reminders to the impregnation machine operators to strictly follow the procedures and check lists

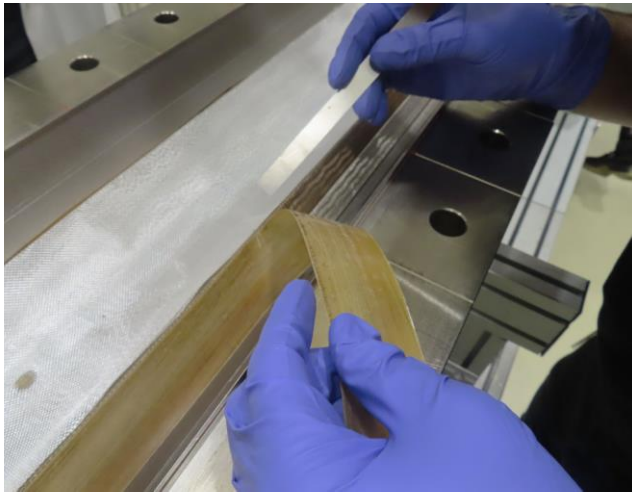
Last updates

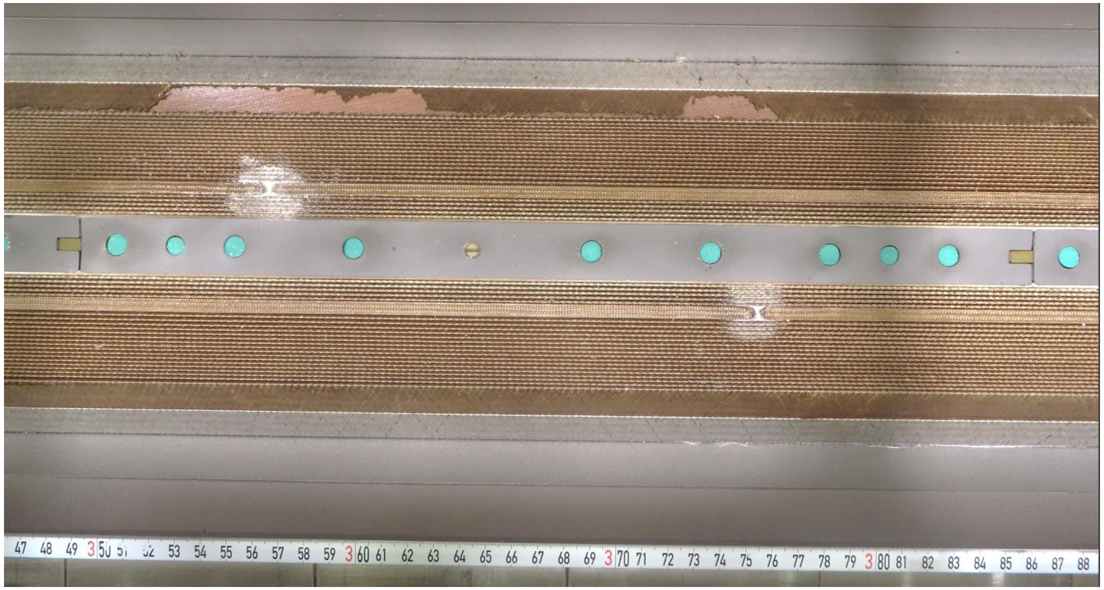
- Magnet MQXFA17 experienced a similar NCR where the NbTi leads were overheated during splicing (EDMS 3119668)
- The magnet was cold tested and did not show any limitation at the level of the splice region
- Moreover the splice resistance was measured and within specifications

For all those reasons, we propose to use CR138 for MQXFB07

CR138 (NCR 3128109) → Cable insulation damaged

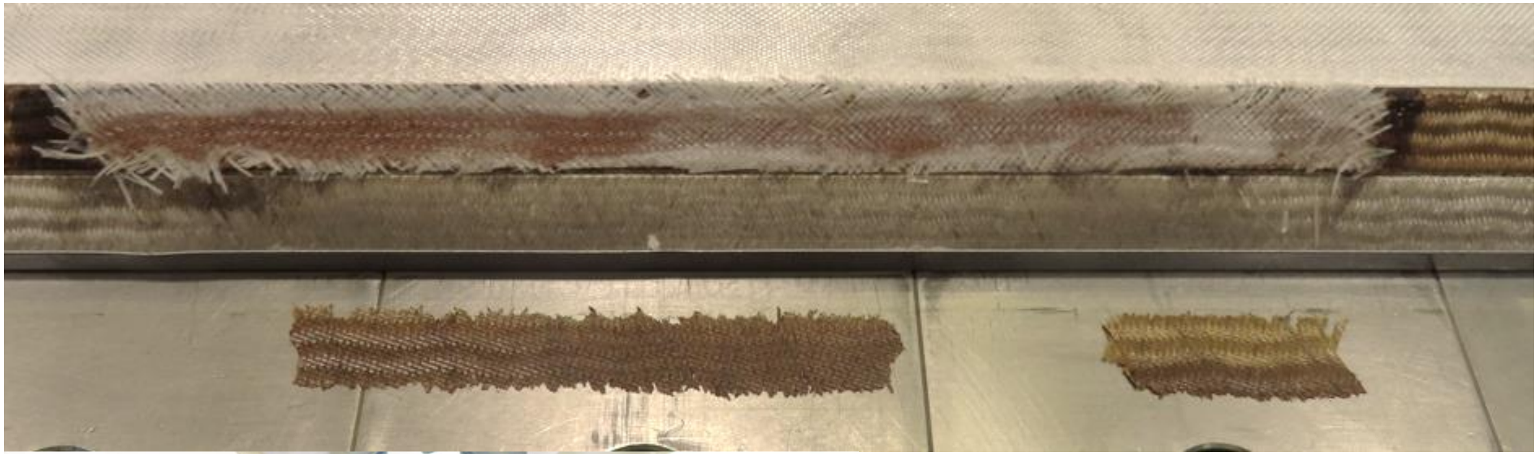
- After the NCR 2974448 the mould was opened to inspect the coil and replace the damaged parts
- The G11 midplane shim was partially glued to the midplane of the coil (opposite layer jump)
  - During its removal, parts of the S2 glass insulation were stuck to the G11
  - Removal of the fragile S2 glass over about 200 mm
  - Local installation of fresh S2 glass to repair and new G11 shims

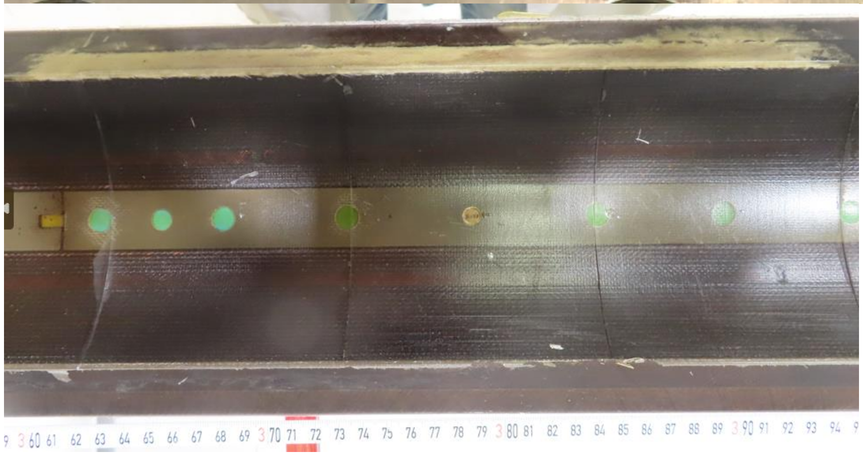


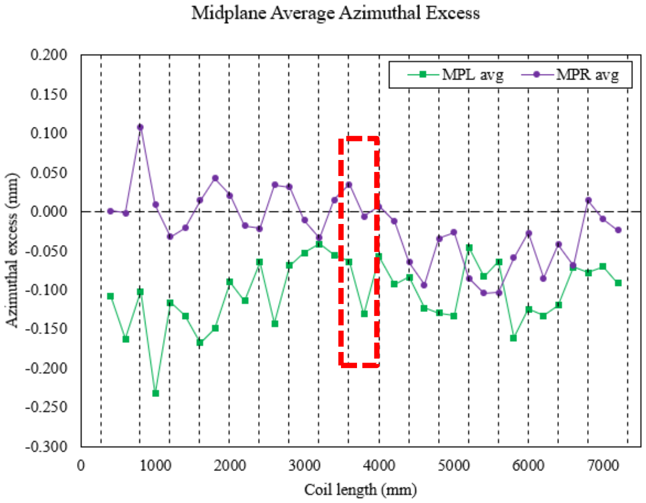


CR138 (NCR 3128109) → Cable insulation damaged

- The geometrical measurement showed no over thickness in the repair location EDMS 3057190

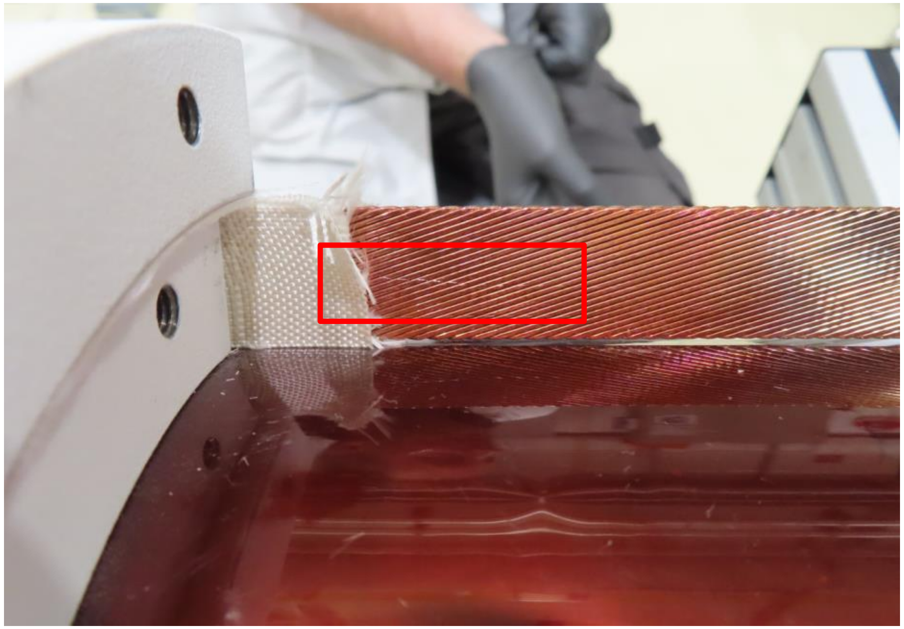


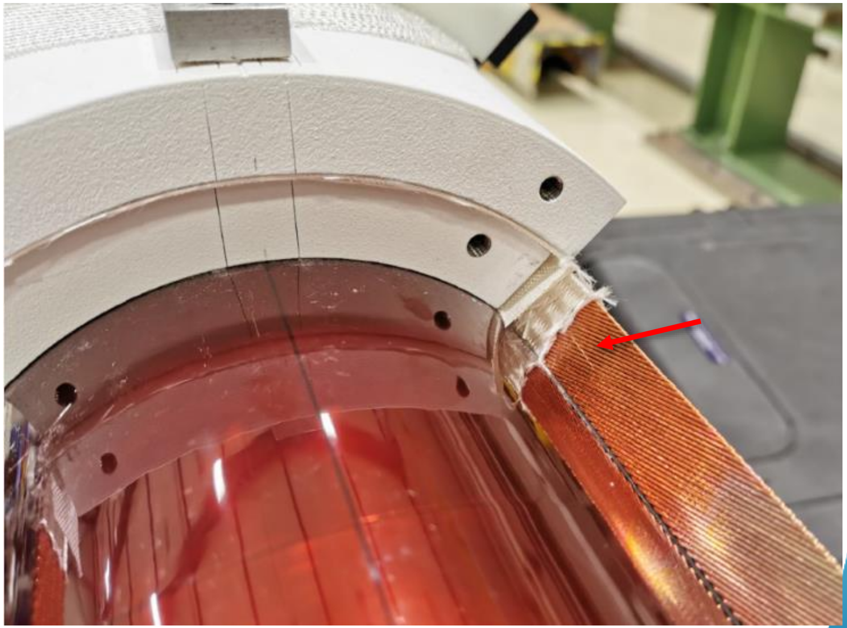




CR146 (NCR3083049) – Inner layer connection cable damaged

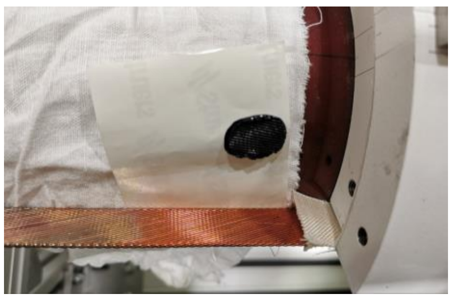
- The inner layer cable exiting from the coil was damaged during the removal of the S2 glass insulation, prior to remove the core
- Normally a 0.05 mm thick shim is inserted between the cable and the S2 glass then the fiberglass is cut
- During the cut of the S2 glass with a blade, the shim was not correctly kept by the operator, so it slipped away and the cable underneath was superficially damaged





CR146 (NCR3083049) – Inner layer connection cable damaged

- **Action plan:**
  - Optical inspection of the cable before/after RHT
  - Replica of the damage to measure the depth of the cut

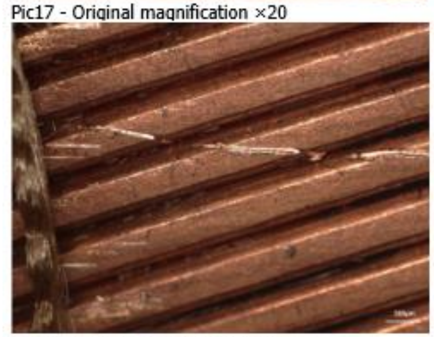


- **Result of the analysis:**
  - The optical inspection showed that only the copper was affected by the scratch
  - The measurement of the replica showed a maximum depth of the cut of 21.6 µm (more details in M. Crouvizier report EDMS 3083153)
  - The optical inspection of the cable after RHT did not reveal any tin leak

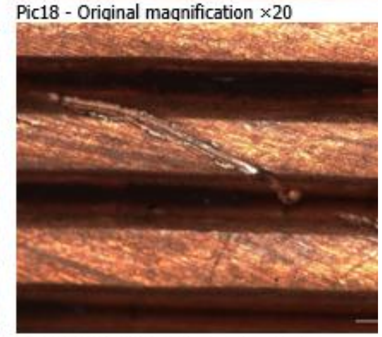
Pictures of the cable after RHT

Pic17 - Original magnification ×20

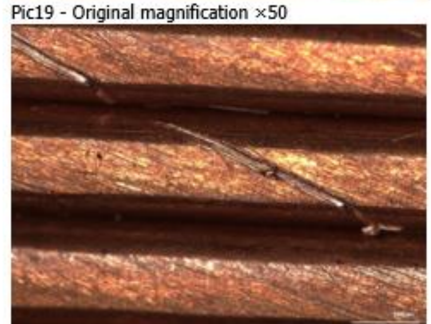
Pic18 - Original magnification ×20



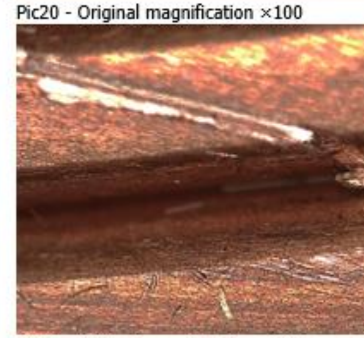
Pic19 - Original magnification ×50



Pic20 - Original magnification ×100



Pic21 - Original magnification ×100



Pic22 - Original magnification ×200

HiLumi HL-LHC PROJECT CERN

Outline

- Manufacturing data
- Non-conformities
- Conclusion/Proposal

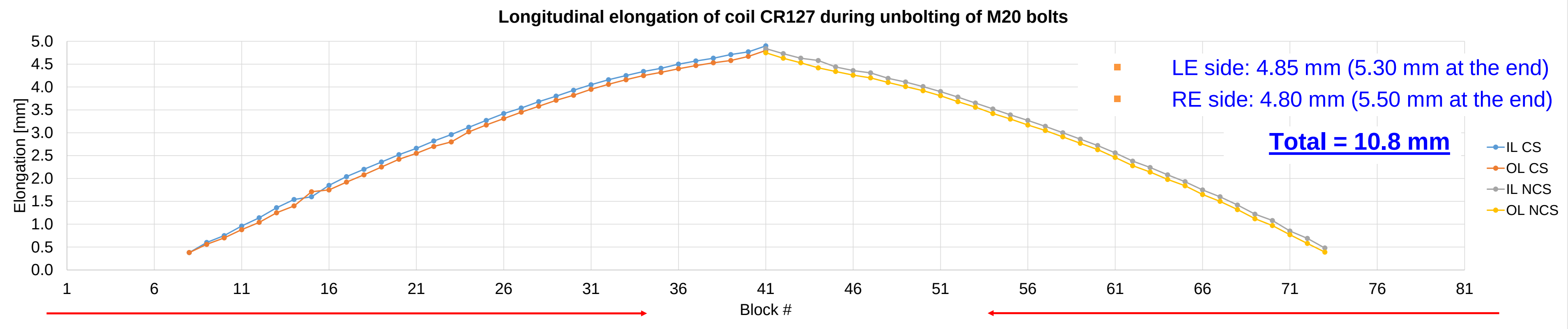
Conclusion/Proposal

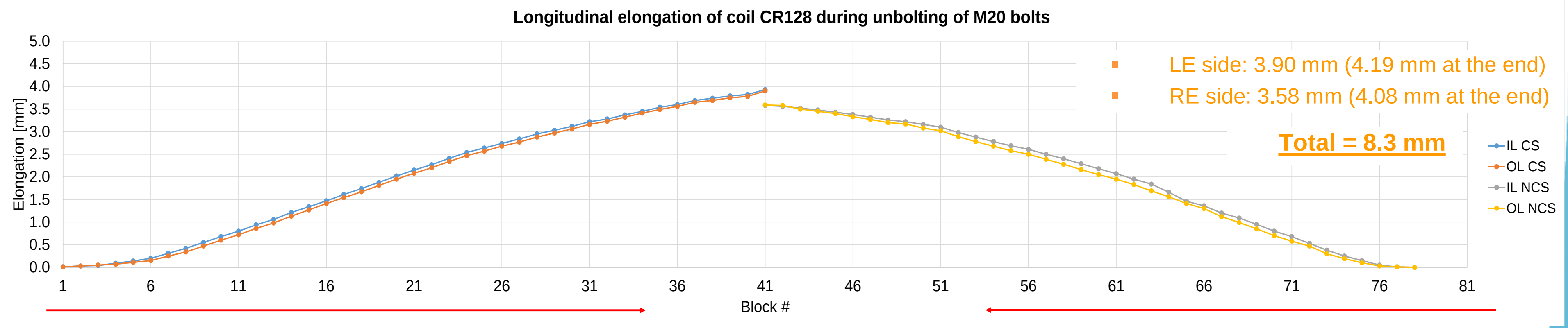
- Use CR138 - CR145 - CR146 - CR147 for MQXFB07 assembly
- The coil instrumentation will start in 2 weeks and the magnet loading is planned for end of September/beginning of October

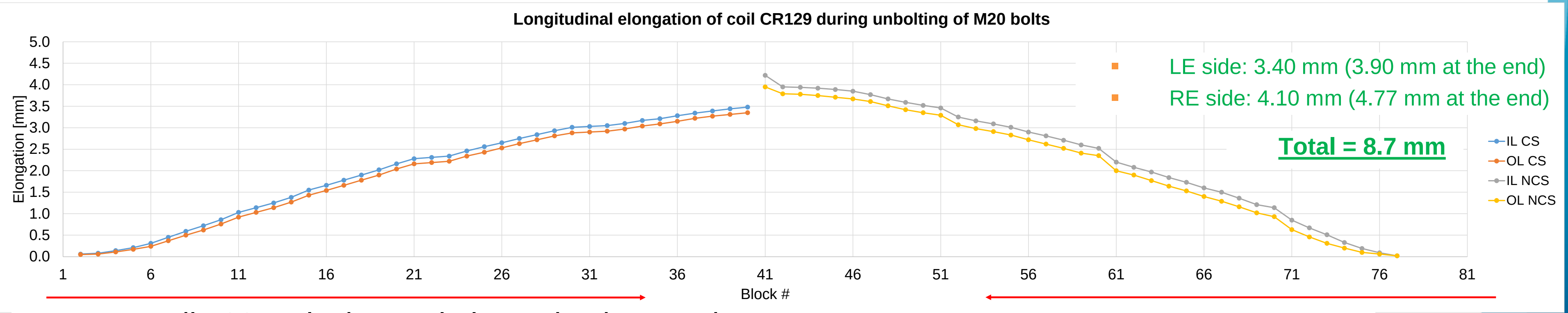
Thank you!

Additional slides

Coil elongation when opening the reaction fixture



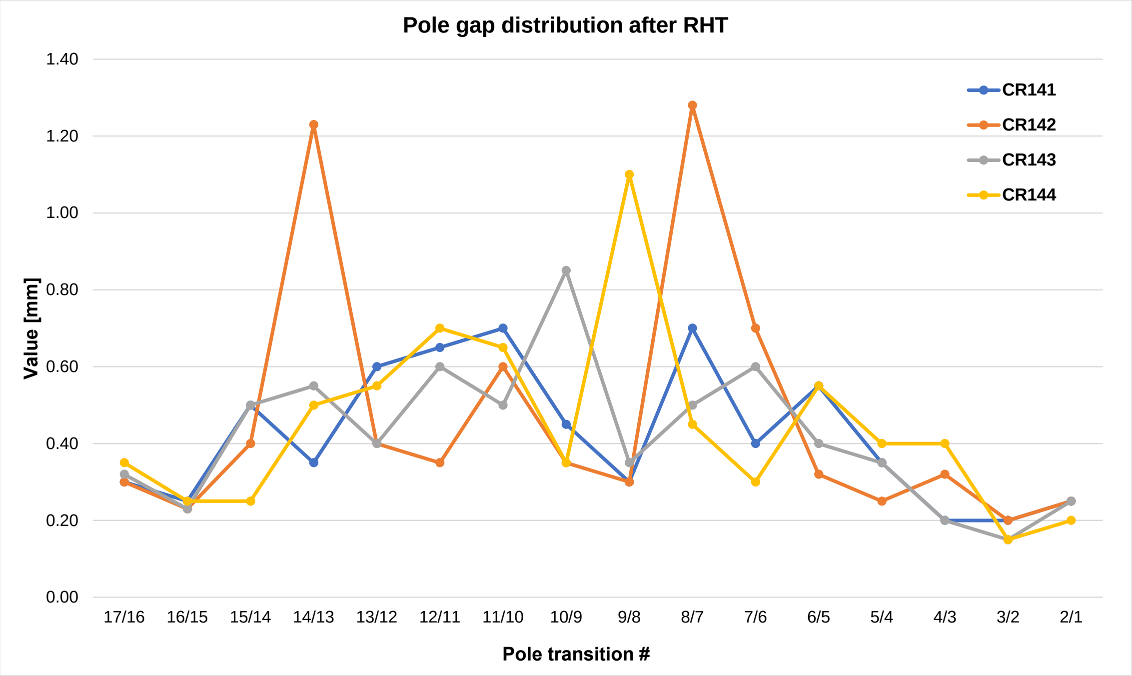




- From coil 130, only the total elongation is traced

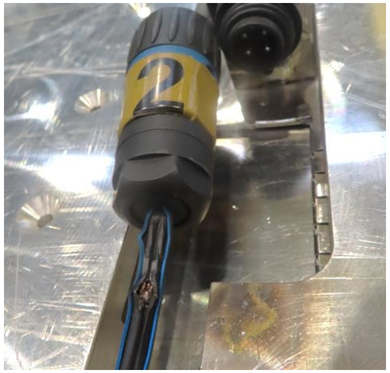
Pole gaps

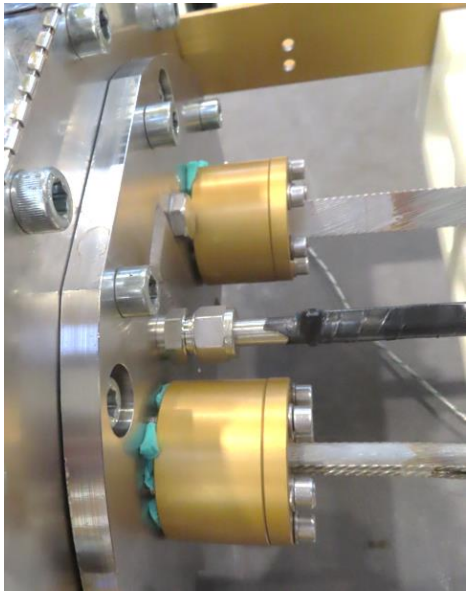
- In transition coils the pole gaps was increased: 0.9 mm → 1.5 mm
- The absence of binder on the OL has an impact on the gap change after reaction
  - Fully binder cured coils: ~ 1 mm/m
  - Partially binder cured coils: ~ 0.8 mm/m
- Comparing to AUP, coils with binder in both layers have a similar relaxation due to the heat treatment (1.1 mm/m AUP vs 1 mm/m CERN) and about half of the relaxation after winding (due to the lower winding tension at CERN)
- In the latest coils (CR127-CR144), poles gaps in the middle of the coil are not closed after reaction, as it is the case for AUP coils



CR138 (NCR 2974448) → Over heating during impregnation cycle

- Some plastic parts were partially melted and damaged:
  - Plug covers 3D printed in TPU95 at around 245°C
  - Power cable sheats damaged (melting temperature around 300°C)
  - Leads silicon joints damaged





- No tin-silver leakage have been observed at the level of the leads existing the mould (T_m = 227°C)

→ <u>Temperature estimation: 250/300°C</u>

Action plan

- Opening of the impregnation mould to further investigate
- Perform splice analyses:
  - Splice resistance measurement at RT
  - Visual inspection
  - X-rays to check the quality of the joint compared to a conform splice Nb_3Sn-NbTi sample
- Assess the performance degradation of the NbTi cable
- Assess potential damage of the Nb_3Sn reacted cable
- Replace all the polyimide parts (splice insulation and QH)
- Visual inspect the coil
- Replace all damaged parts and install fresh S2 glass
- Replace the impregnation machine wiring and implementation of plugs with oriented slots to avoid any connection error

- **Preventive action:**
  - Regular reminders to the impregnation machine operators to strictly follow the procedures and check lists

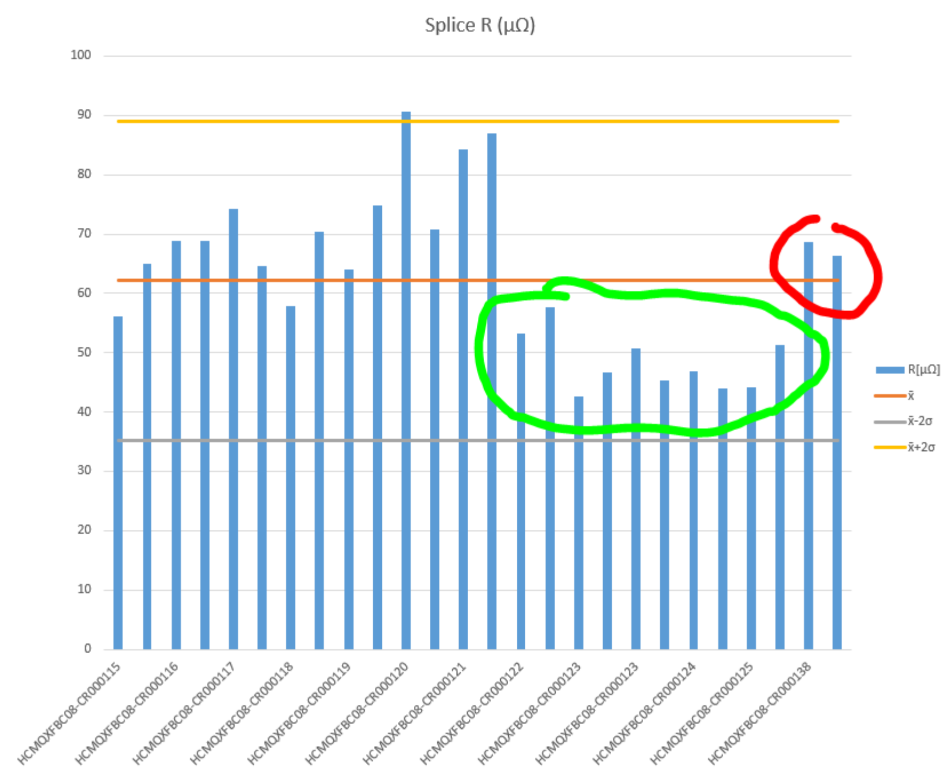
Splice analyses

- **<u>Splice resistance at RT</u>** (test results on *EDMS 2975146*)
  - Acceptance range: 15 – 100 μΩ
  - Measured range: 66 – 69 μΩ

Test Name	Current [A]	Test Object 1	Test Object 2	I+	I-	V+	V-	FILL HERE Measure	R[μΩ]	Test Units	Min. Limit	Max. Limit	PASSED	Comments
R[dc]	10	Outer coil splice	Outer coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#1	67.9	[μΩ]	15	100	YES	
R[dc]	10	Outer coil splice	Outer coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#2	67.8	[μΩ]	15	100	YES	
R[dc]	10	Outer coil splice	Outer coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#3	70.3	[μΩ]	15	100	YES	
R[dc]	10	Outer coil splice	Outer coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	Test Result	68.7	[μΩ]	15	100	YES	

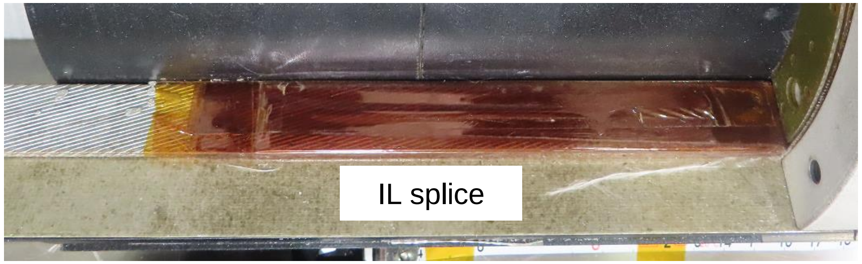
Test Name	Current [A]	Test Object 1	Test Object 2	I+	I-	V+	V-	FILL HERE Measure	R[μΩ]	Test Units	Min. Limit	Max. Limit	PASSED	Comments
R[dc]	10	Inner coil splice	Inner coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#1	68.0	[μΩ]	15	100	YES	
R[dc]	10	Inner coil splice	Inner coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#2	66.4	[μΩ]	15	100	YES	
R[dc]	10	Inner coil splice	Inner coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	#3	64.6	[μΩ]	15	100	YES	
R[dc]	10	Inner coil splice	Inner coil splice	BbS 15mm to Sp	CoS 15mm to Sp	BbS 5mm to Sp	CoS 5mm to Sp	Test Result	66.3	[μΩ]	15	100	YES	

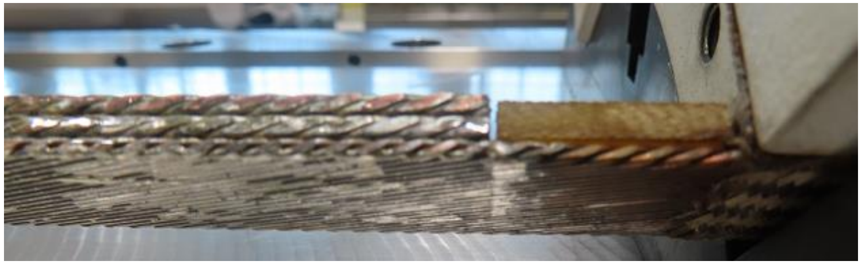
This result does not tell us the splice is good but at least it tells it is not bad

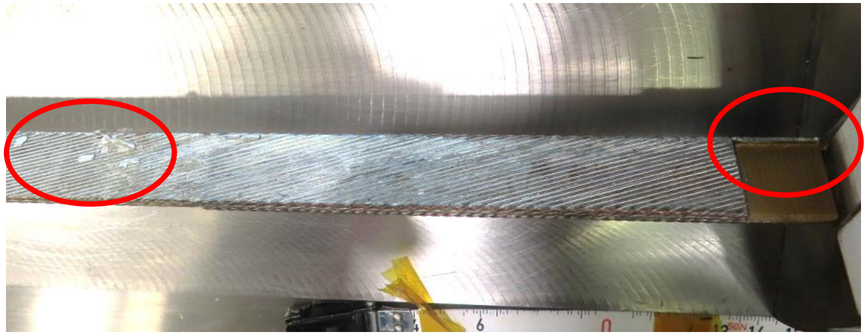


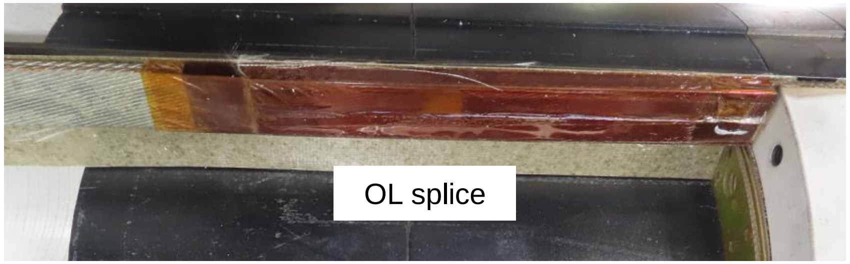
Splice analyses

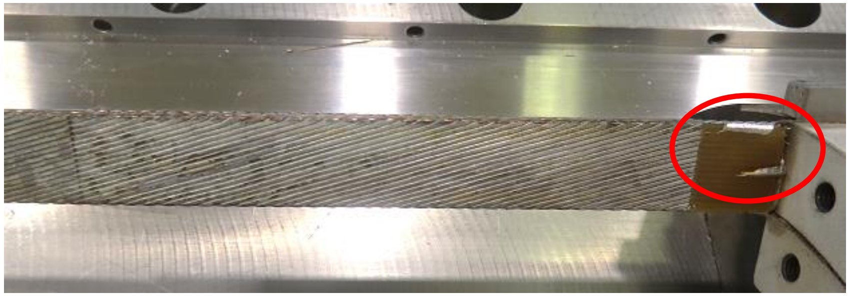
- **<u>Splice visual inspection</u>** (all pictures available on *EDMS 2975146*)
  - Tin-silver drops at the extremities of the splice insulation
  - Once the insulation removed, more SnAg was observed at the extremities of the splice region (towards the coil ends and towards mould end for the IL splice)
  - " Leopard skin" effect observed on both NbTi cables

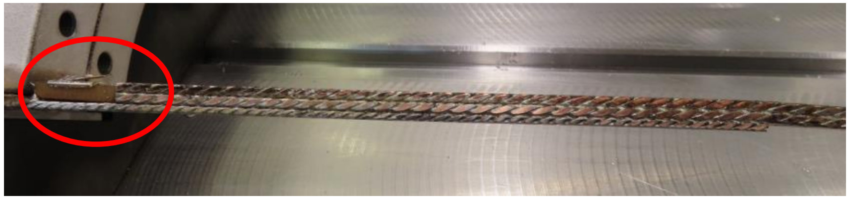












The splices have been impacted by the impregnation mould overheating

Splice analyses

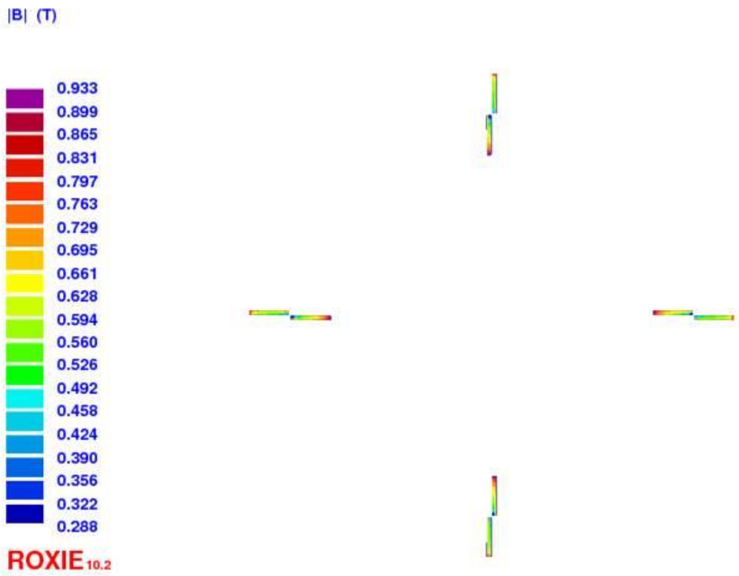
- **Splice x-rays** (report available on *EDMS 2975595*)
  - LMF production team provided the following samples to EN-MME-MM team:
    - Extracted splice from impregnated coil CR120
    - 2 Nb_3Sn-NbTi splice mock-ups manufactured on-purpose
    - 1 Nb_3Sn reacted cable and 2 NbTi cables fixed together with tape
  - Those samples were used to figure out the reference situation and could make comparisons
  - The interpretation of the images is not easy
    - **RESULT: The penetration of the solder is worse with respect to the reference sample by 20%**

What to do with the splices?

- The typical resistance at cold is 0.2 – 0.3 nΩ (requirement < 1nΩ)
- High risk of damaging Nb_3Sn cable when improving the quality of the joint

NbTi performance degradation

- TE-MSC-LSC team carried out Ic measurements on NbTi wires heated at 300°C for 24 hours
  - NbTi strands showed a degradation of the Ic of 27% at 8T and 1.8K (Ic measurements)
  - From magnetization measurements, the treatment: magnetization ratio suggests a Jc degradation of around 31% at 8T (comparable to the value from transport measurements) and around 6% at 0.5-2T
- Susana computed the magnetic field in the splice region for assessment of the NbTi:
  - At nominal operation conditions, it is less than 1T
  - If we assume that current goes through the 2 leads homogeneously, the current density is 1400A/mm^2



Based on those results, we have margin for operation

Impregnation machine consolidation

- Heating plates power wiring were replaced
- Implementation of two new plugs of MQXFB and 11T TCs with oriented keys and painted differently