Report on Ongoing Actions for MQXFB

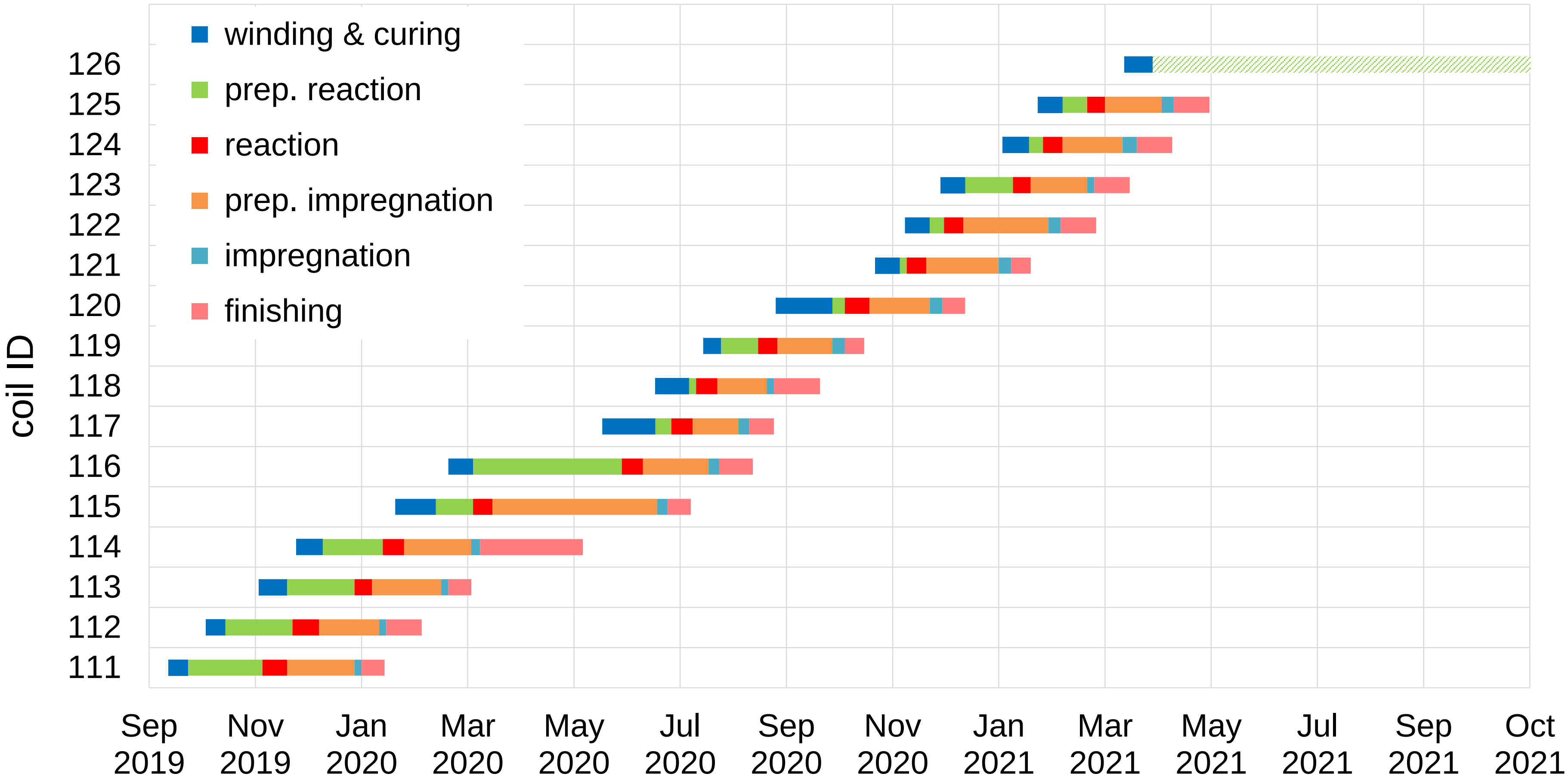
Improvements in coil manufacture

A. Milanese, on behalf of the MQXFB team

(special acknowledgements to J. Ferradas Troitino,
S. Izquierdo Bermudez and N. Lusa)

29 Apr. 2022

Making a MQXFB coil takes months, winding is only a (relatively small) phase of the production



dashboard updated
27 Oct. 2021

Since Sept. 2019, we have been continuously improving our *fabrication* and *control* procedures

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PROCEDURE DE FABRICATION
HL-LHC / WP03

POSTE 2
Procédure de bobinage des Bobines des Quadripôles Q2 Nb3Sn
Partie 1/2 - Bobinage Couche interne

ABSTRACT:

Ce document explique le mode opératoire pour le bobinage, couche interne, des bobines MQXFB de l'aimant Q2 du WP03 HL-LHC.

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Fabrication Procedure
HL-LHC / WP03

POSTE 4
Quadripôle MQXFB Nb₃Sn
PREPARATION A LA REACTION

ABSTRACT:

Ce document détaille le mode opératoire à suivre pour préparer le traitement thermique d'une bobine MQXFB.

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Fabrication Procedure
HL-LHC / WP03

POSTE 5
Quadripôle MQXFB Nb₃Sn
SPLICING

ABSTRACT:

cument détaille le mode opératoire à suivre pour préparer le joint électrique e MQXFB [5].

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Fabrication Procedure
HL-LHC / WP03

POSTE 6
Quadripôle MQXFB Nb₃Sn
IMPREGNATION
Partie 1/2 – Préparation de la bobine (avant imprégnation)

ABSTRACT:

Ce document détaille le mode opératoire à suivre pour préparer l'imprégnation d'une bobine MQXFB.

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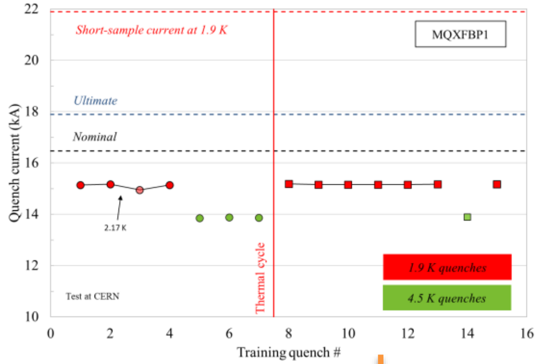
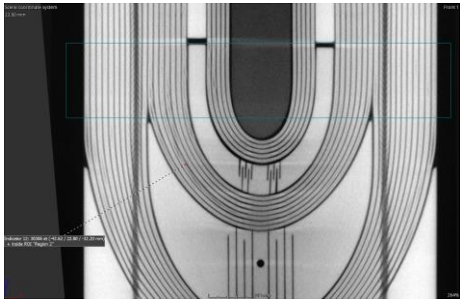
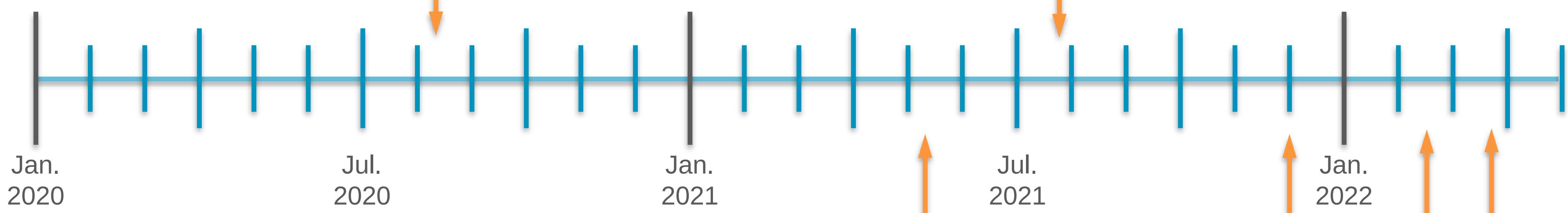
A timeline of MQXFB events puts this analysis more in context

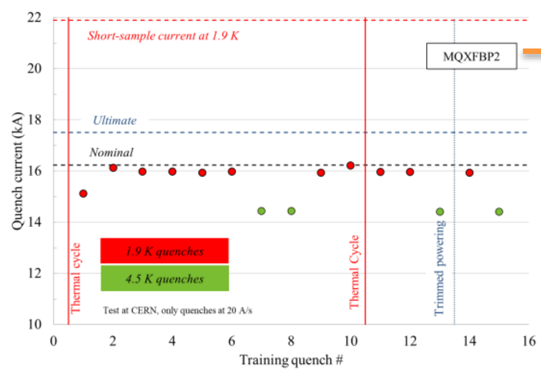




BP1

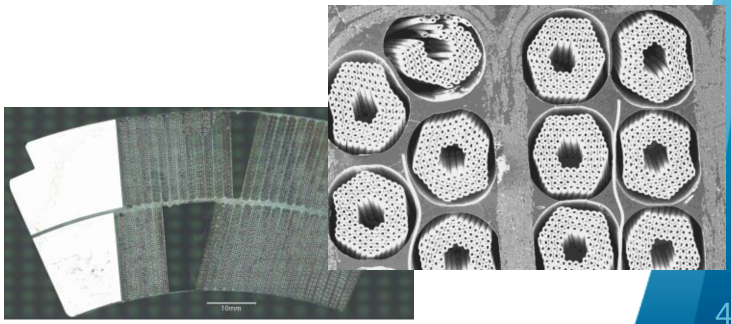
1st tomography
CR108 head





BP2

CR108 broken
strands



Main findings from review of tooling, manufacturing processes and quality control data

Selection of improvements already implemented

1. Popped strands
2. Reaction and impregnation tooling
3. Variation of coil azimuthal size
4. Elastic deflection during handling
5. Residual energy after reaction
6. Inner layer pole turn protrusion after reaction

see also
MQXF website: cern.ch\mqxf
Topical meetings on MQXF: indico.cern.ch\category\10520

1

Popped strands – as found with tomographies – are present in MQXFS / MQXFA / MQXFB coils

tomography timeline

coil	end	events IL / OL
MQXFB CR108	CS & NCS	21 / 22
MQXFS 107	CS & NCS	2 / 2
MQXFA P06	NCS	0 / 0
MQXFS 106	CS & NCS	11 / 27
MQXFB CR120	CS & NCS	2 / n.a.
MQXFA 108	CS & NCS	2 / 7
MQXFA 214	CS & NCS	4 / 8

S. Sgobba's talk

Considering MQXFB vs. MQXFA (and also MQXFS):

- the mechanical behaviour of the bare / insulated cable is similar (more in MQXF cable mechanical tests)
- some details of the winding process differ, mainly due to different architectures of the hardware (more in EDMS 2680200)
- the geometry of the end spacers is nominally the same

1

Popped strands – what did we decided to do?

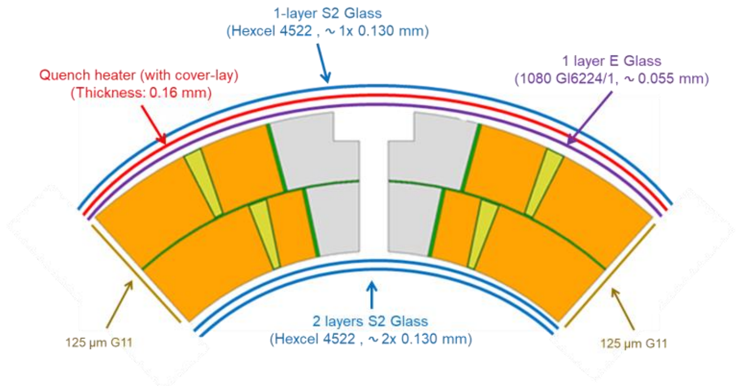
We decided not to introduce at this stage radical changes in the winding for MQXFB coils

- the LMF team recently participated in winding two MQXFS coils in B927
- our operators are aware of this effect and attentive about popped strands when winding
- we are taking additional measurements during winding / curing for the transition coils
- we improved the tooling to constrain the ends during the transfer of the cured coil to the reaction fixture baseplate

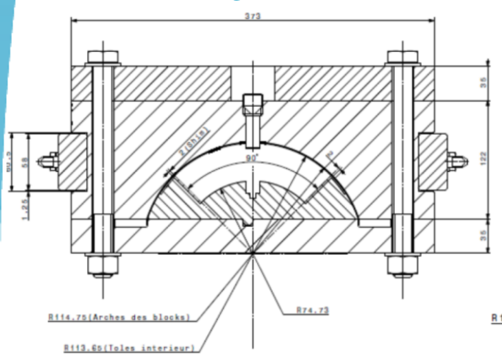
2

We report here on three main findings for the reaction and impregnation fixtures

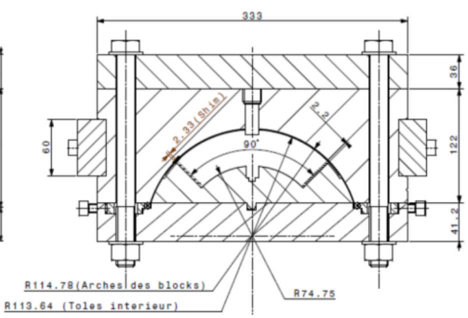
The cavity size and what we put inside for both reaction and impregnation are the same for MQXFB / MQXFA



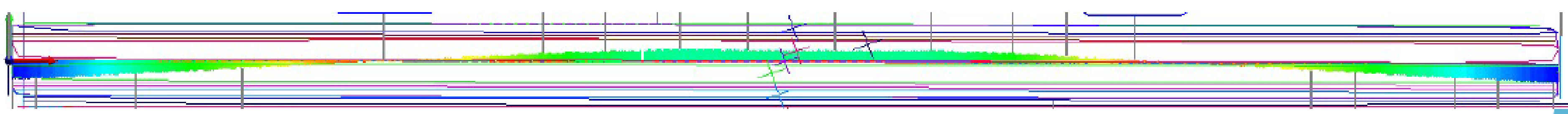
MQXFB



MQXFA



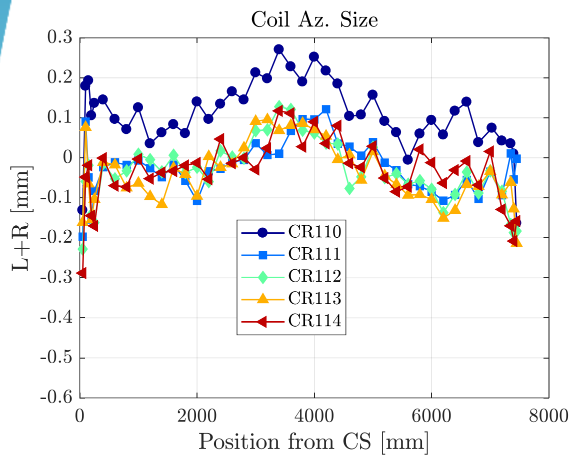
The MQXFB / MQXFA fixtures are different (in terms of transversal stiffness and longitudinal modularity) – analyses, including FE models, do not show a significant impact for the coil

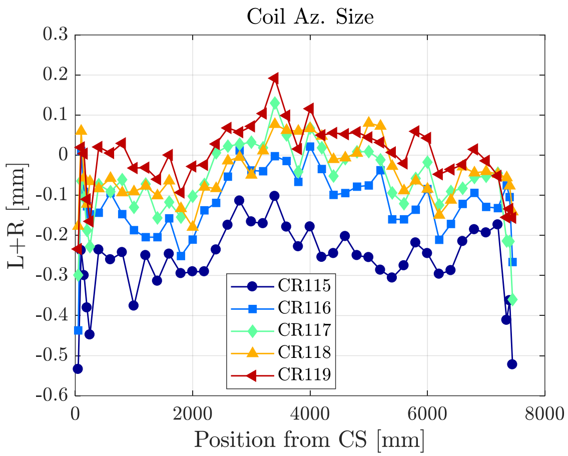


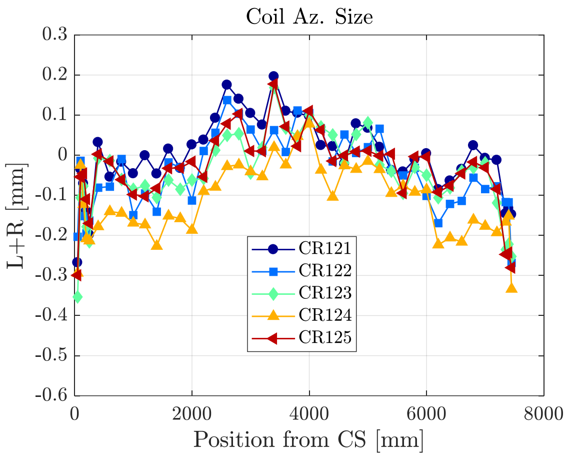
The MQXFB moulds (reaction and impregnation) are bent, with a gradual sagitta of 1.5-1.7 mm: we decided not to procure new plates – also because the root cause of the deformation is not identified – and monitor further geometrical deviations

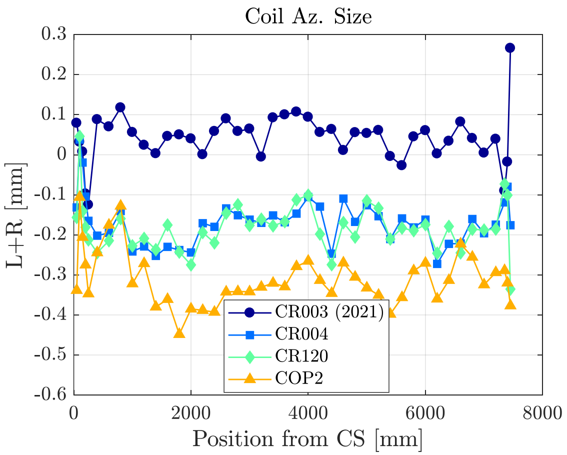
The azimuthal size of the coils tends to be larger in the central part (*big belly* effect)

3







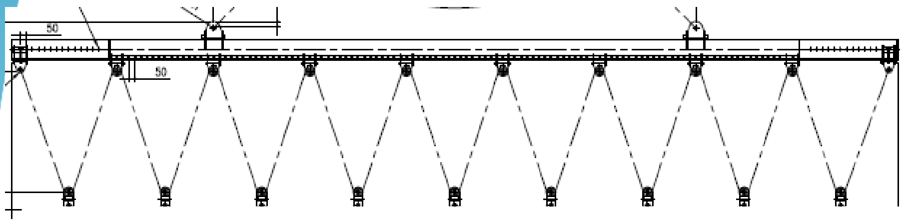


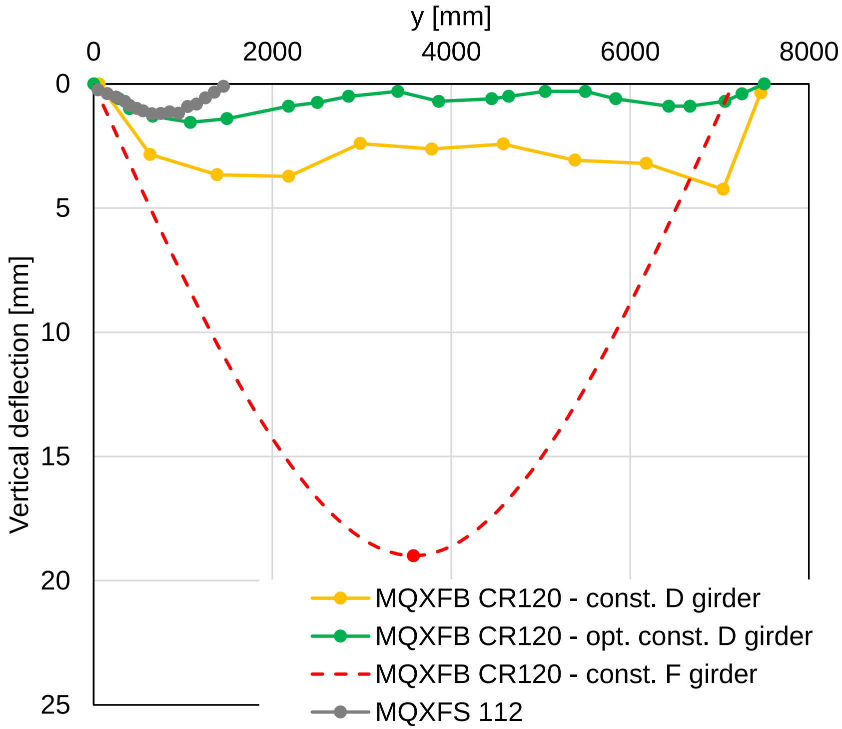
This implies a pressure difference along the length of the order of ±15 MPa

- the *big belly* might be related to the *dromedary hump* (see later) and to the insulation thickness
- we decided to shift the cable insulation thickness target towards the lowest bound, and to address the *dromedary hump*
- a mitigation is to lower the coil preload target during magnet assembly

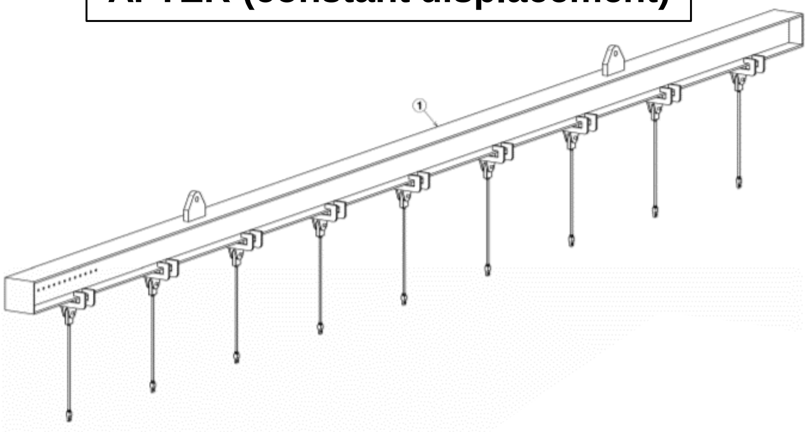
We modified the lifting girder to decrease the elastic deflection of finished coils during handling

BEFORE (constant force)





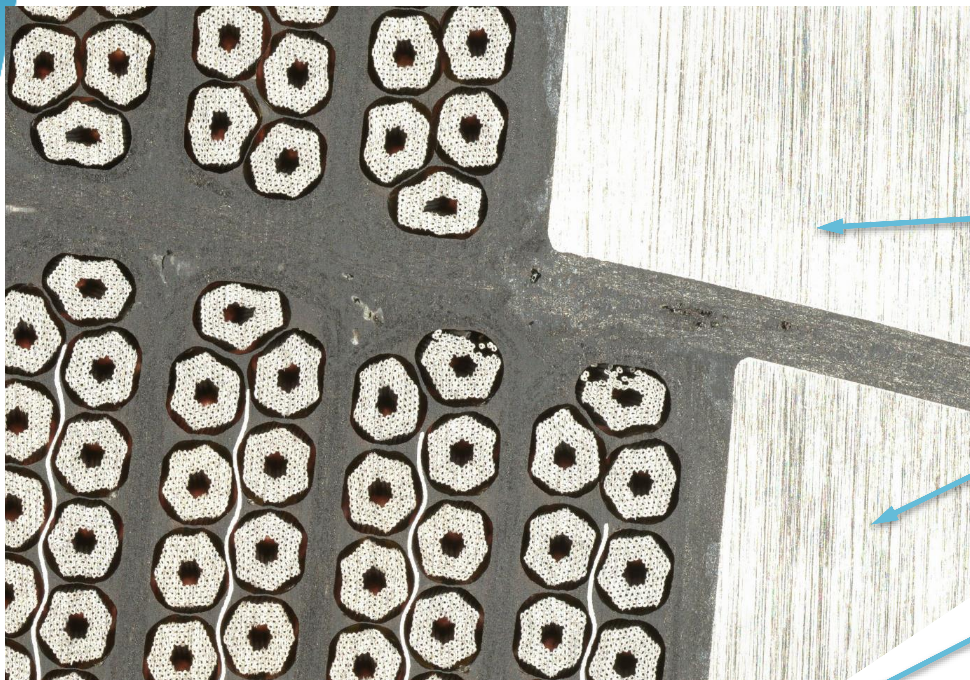
AFTER (constant displacement)



Improvement demonstrated in relative (with respect to before) and in absolute (measuring strains < 10 $\mu\varepsilon$)

The inner layer pole turn – and the poles in general – is where we focus more our attention in this moment

CR108 micrographies after Cu etching



outer layer Ti pole

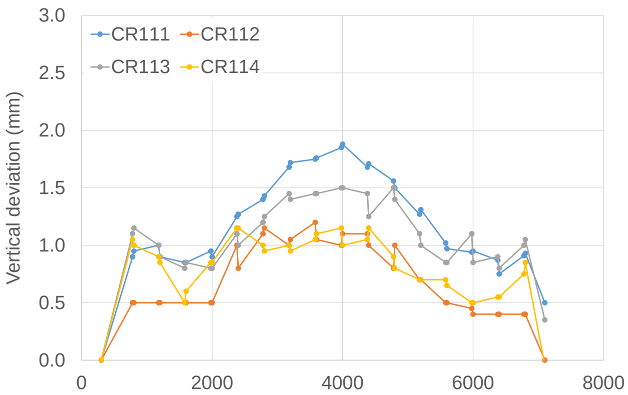
inner layer Ti pole

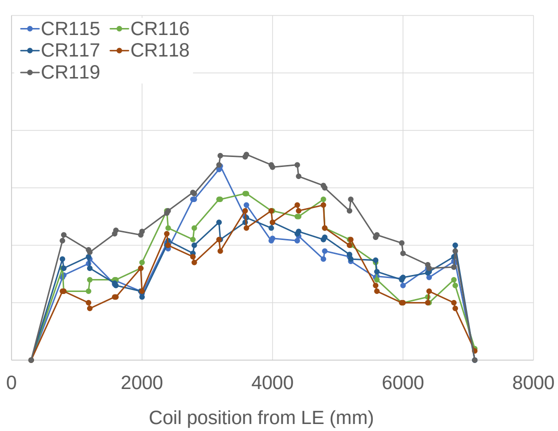
outer layer Ti pole

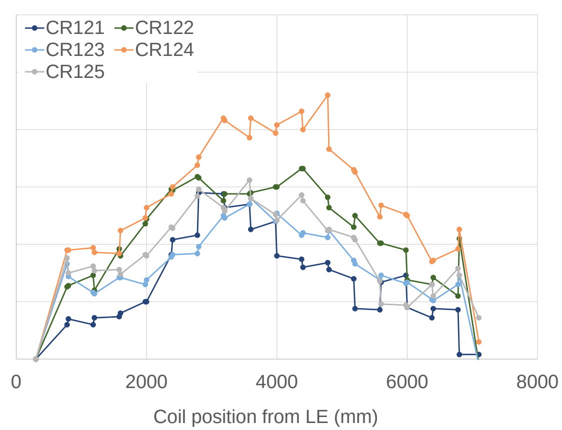
inner layer Ti pole

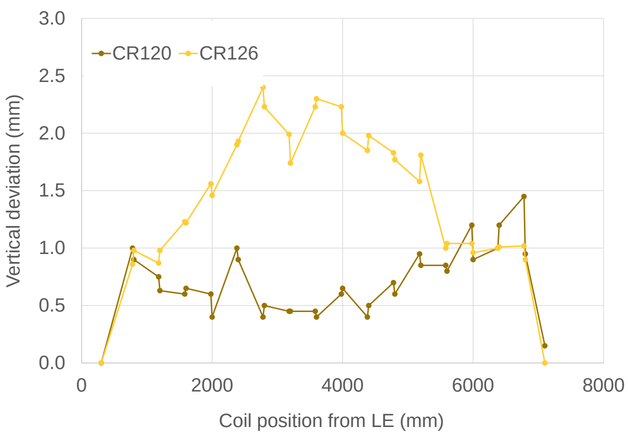
S. Sgobba's talk

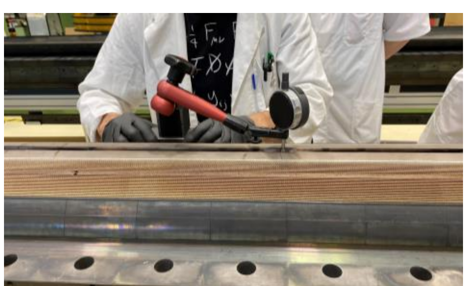
The pole (and coil) lifts up from the baseplate after reaction (*dromedary hump* effect)











This *hump* is:

- related to stored energy during reaction
- potentially inducing deleterious movements in a reacted-not-yet-impregnated coil
- possibly linked to the *big belly* effect

Similar measurements

- have been performed on MQXFS coil 116, finding 0.7-0.8 mm
- are planned for MQXFA coils

This *hump* could be caused by residual constraints in the reacted coil and to the (lack of) pole gaps

MQXFB

	total	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17
CR107	1.9	0.10	0.15	0.10	0.15	0.25	0.10	0.05	0.20	0.00	0.10	0.05	0.05	0.10	0.15	0.15	0.15
CR108	0.9	0.05	0.05	0.05	0.00	0.00	0.00	0.05	0.00	0.10	0.00	0.05	0.10	0.15	0.05	0.05	0.15
CR109	1.5	0.10	0.15	0.20	0.05	0.10	0.10	0.05	0.20	0.05	0.10	0.05	0.00	0.05	0.05	0.15	0.10
CR110	2.3	0.15	0.15	0.15	0.20	0.20	0.10	0.05	0.05	0.05	0.20	0.10	0.15	0.15	0.15	0.20	0.25
CR111	2.8	0.20	0.10	0.15	0.30	0.30	0.10	0.00	0.10	0.15	0.20	0.15	0.15	0.25	0.30	0.20	0.15
CR112	1.5	0.15	0.10	0.10	0.10	0.15	0.10	0.05	0.00	0.00	0.15	0.00	0.10	0.15	0.05	0.15	0.10
CR113	3.4	0.25	0.25	0.25	0.25	0.20	0.20	0.25	0.15	0.20	0.30	0.25	0.20	0.15	0.15	0.20	0.15
CR114	2.8	0.25	0.20	0.25	0.20	0.30	0.15	0.15	0.10	0.15	0.15	0.05	0.15	0.15	0.15	0.15	0.20
CR115	4.0	0.20	0.15	0.30	0.35	0.35	0.30	0.15	0.15	0.25	0.30	0.30	0.25	0.20	0.35	0.15	0.25
CR116	3.8	0.20	0.15	0.15	0.35	0.35	0.30	0.15	0.15	0.15	0.30	0.20	0.25	0.25	0.35	0.25	0.20
CR117	3.1	0.30	0.15	0.25	0.15	0.30	0.15	0.10	0.15	0.15	0.15	0.15	0.20	0.15	0.35	0.20	0.20
CR118	2.6	0.20	0.15	0.15	0.20	0.20	0.15	0.00	0.10	0.15	0.20	0.20	0.20	0.20	0.20	0.15	0.15
CR119	2.1	0.15	0.15	0.10	0.15	0.20	0.05	0.05	0.15	0.00	0.15	0.10	0.10	0.20	0.25	0.15	0.15
CR120	5.6	0.20	0.15	0.35	0.35	0.60	0.50	0.35	0.50	0.45	0.45	0.50	0.50	0.35	0.15	0.00	0.15
CR121	3.5	0.20	0.25	0.20	0.40	0.35	0.35	0.20	0.25	0.10	0.10	0.25	0.35	0.10	0.10	0.15	0.10
CR122	3.8	0.15	0.10	0.10	0.40	0.15	0.25	0.05	0.00	0.10	0.45	0.15	0.40	0.60	0.50	0.15	0.20
CR123	3.0	0.20	0.10	0.10	0.25	0.40	0.20	0.00	0.10	0.15	0.00	0.35	0.30	0.20	0.30	0.20	0.15
CR124	3.3	0.20	0.15	0.20	0.25	0.25	0.35	0.10	0.15	0.15	0.10	0.25	0.20	0.20	0.35	0.15	0.25
CR125	2.7	0.25	0.10	0.20	0.20	0.30	0.30	0.00	0.00	0.10	0.25	0.15	0.20	0.20	0.10	0.10	0.20
CR126	1.9	0.30	0.14	0.23	0.19	0.15	0.13	0.02	0.03	0.00	0.00	0.00	0.10	0.17	0.14	0.12	0.22

MQXFA FNAL

	total	1	2	3	4	5	6	7	8	9	10
101	2.7	0.06	0.31	0.38	0.36	0.51	0.33	0.31	0.13	0.33	0.00
104	2.3	0.10	0.20	0.13	0.20	0.30	0.38	0.46	0.28	0.23	0.00
106	3.2	0.18	0.43	0.33	0.36	0.56	0.36	0.46	0.25	0.25	0.04
107	2.8	0.04	0.10	0.18	0.46	0.50	0.51	0.33	0.53	0.15	0.04
108	2.0	0.15	0.08	0.25	0.08	0.20	0.36	0.25	0.41	0.13	0.08
109	3.3	0.15	0.36	0.36	0.31	0.43	0.56	0.36	0.48	0.18	0.15
110	2.8	0.19	0.15	0.23	0.28	0.25	0.42	0.32	0.50	0.26	0.18
111	2.5	0.08	0.00	0.18	0.31	0.51	0.66	0.46	0.31	0.05	0.00
112	1.8	0.00	0.00	0.28	0.23	0.28	0.31	0.28	0.25	0.13	0.08
113	1.9	0.04	0.00	0.13	0.36	0.18	0.31	0.36	0.08	0.38	0.10
114	1.9	0.13	0.00	0.05	0.13	0.64	0.04	0.51	0.04	0.23	0.13
115	1.2	0.10	0.36	0.10	0.04	0.00	0.08	0.46	0.00	0.00	0.08
116	1.6	0.10	0.00	0.08	0.20	0.31	0.20	0.18	0.36	0.00	0.13
117	1.4	0.00	0.00	0.13	0.23	0.15	0.31	0.36	0.09	0.13	0.06
119	2.6	0.10	0.00	0.00	0.60	0.45	0.46	0.42	0.45	0.00	0.10
121	1.1	0.05	0.00	0.05	0.00	0.05	0.13	0.13	0.13	0.50	0.05
122	1.3	0.10	0.00	0.00	0.09	0.25	0.20	0.15	0.40	0.00	0.10
123	1.3	0.00	0.08	0.00	0.00	0.33	0.00	0.61	0.00	0.23	0.08
124	1.4	0.00	0.04	0.05	0.50	0.15	0.45	0.15	0.03	0.00	0.06
125	1.7	0.00	0.00	0.07	0.20	0.25	0.27	0.12	0.07	0.00	0.76
126	0.9	0.08	0.08	0.08	0.06	0.18	0.08	0.20	0.06	0.02	0.08
127	1.2	0.00	0.00	0.20	0.13	0.51	0.00	0.15	0.25	0.00	0.00
128	4.1	0.09	0.08	0.10	1.16	1.25	0.15	0.66	0.41	0.15	0.00
129	2.6	0.15	0.10	0.25	0.15	0.55	0.30	0.50	0.30	0.15	0.10
130	1.4	0.05	0.04	0.08	0.28	0.08	0.18	0.33	0.13	0.20	0.08
131	2.2	0.00	0.08	0.25	0.04	0.20	0.58	0.42	0.51	0.05	0.08
132	2.7	0.13	0.00	0.00	0.23	0.61	0.56	0.38	0.51	0.13	0.13
133	2.9	0.08	0.06	0.21	0.38	0.28	0.31	0.46	0.36	0.48	0.25
134	2.1	0.05	0.06	0.48	0.05	0.08	0.51	0.18	0.50	0.10	0.05
135	1.8	0.13	0.05	0.38	0.23	0.10	0.33	0.25	0.18	0.05	0.13
136	2.7	0.08	0.05	0.31	0.46	0.23	0.81	0.41	0.13	0.10	0.13
137	1.7	0.04	0.00	0.00	0.53	0.15	0.20	0.43	0.15	0.08	0.10
138	2.3	0.08	0.18	0.00	0.41	0.23	0.64	0.33	0.33	0.15	0.00
139	2.7	0.09	0.08	0.20	0.50	0.50	0.45	0.40	0.30	0.15	0.05
140	1.9	0.09	0.00	0.15	0.20	0.20	0.55	0.20	0.29	0.14	0.09
141	3.0	0.00	0.28	0.30	0.31	0.31	0.41	0.46	0.52	0.19	0.23
142	4.4	0.08	0.05	0.10	0.23	0.20	0.64	1.27	0.20	1.52	0.10

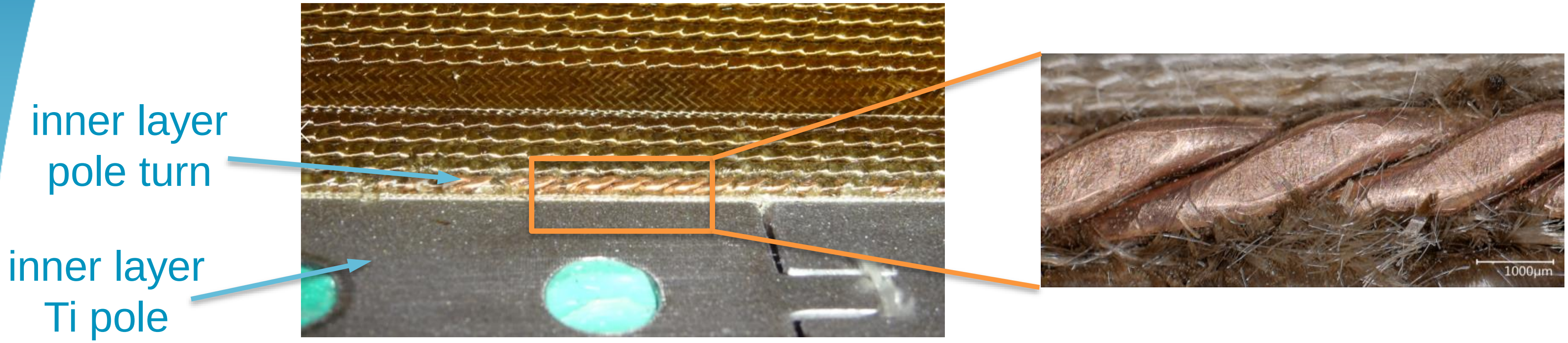
MQXFA BNL

	total	1	2	3	4	5	6	7	8	9	10
202	2.2	0.00	0.18	0.33	0.28	0.36	0.28	0.28	0.38	0.10	0.00
203	1.0	0.00	0.05	0.08	0.05	0.23	0.13	0.20	0.23	0.08	0.00
204	1.4	0.08	0.08	0.18	0.13	0.18	0.20	0.25	0.20	0.00	0.10
206	0.6	0.00	0.36	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00
207	2.4	0.00	0.00	0.00	0.71	0.38	0.69	0.64	0.00	0.00	0.00
209	1.7	0.00	0.00	0.20	0.58	0.28	0.18	0.20	0.23	0.00	0.00
210	1.9	0.00	0.00	0.15	0.20	0.30	0.28	0.30	0.18	0.36	0.10
211	2.0	0.00	0.08	0.30	0.28	0.23	0.30	0.20	0.18	0.41	0.00
212	1.9	0.00	0.00	0.41	0.30	0.00	0.43	0.56	0.05	0.10	0.00
213	0.9	0.08	0.00	0.13	0.05	0.23	0.33	0.00	0.00	0.05	0.00
214	0.6	0.00	0.00	0.00	0.10	0.13	0.23	0.18	0.00	0.00	0.00
215	1.0	0.10	0.05	0.08	0.08	0.13	0.15	0.05	0.10	0.28	0.00
216	1.3	0.00	0.15	0.00	0.36	0.10	0.00	0.30	0.41	0.00	0.00
217	1.5	0.00	0.00	0.30	0.23	0.15	0.36	0.28	0.15	0.00	0.00
218	1.8	0.00	0.08	0.00	0.41	0.30	0.23	0.23	0.46	0.05	0.00
219	2.8	0.13	0.15	0.53	0.36	0.56	0.66	0.18	0.25	0.03	0.00
220	2.1	0.69	0.05	0.15	0.13	0.10	0.30	0.15	0.41	0.08	0.05
221	2.1	0.10	0.10	0.38	0.41	0.28	0.36	0.30	0.05	0.08	0.00
222	1.4	0.00	0.08	0.08	0.08	0.20	0.23	0.08	0.64	0.00	0.00
223	2.0	0.00	0.03	0.41	0.28	0.30	0.36	0.13	0.36	0.18	0.00
224	2.2	0.05	0.25	0.08	0.36	0.33	0.23	0.36	0.36	0.10	0.05
225	2.3	0.25	0.05	0.41	0.23	0.38	0.36	0.20	0.08	0.28	0.05
226	2.1	0.05	0.20	0.30	0.36	0.15	0.28	0.15	0.33	0.15	0.10
227	1.3	0.00	0.05	0.20	0.25	0.25	0.08	0.05	0.23	0.10	0.08
228	2.2	0.00	0.05	0.36	0.30	0.36	0.28	0.30	0.46	0.10	0.00
229	1.6	0.13	0.00	0.05	0.30	0.25	0.25	0.30	0.25	0.03	0.00
230	2.0	0.10	0.10	0.00	0.28	0.00	0.20	0.20	0.36	0.20	0.51
231	2.0	0.00	0.10	0.30	0.30	0.43	0.43	0.15	0.00	0.25	0.00

The pole gap after reaction, for MQXFA and MQXFB coils

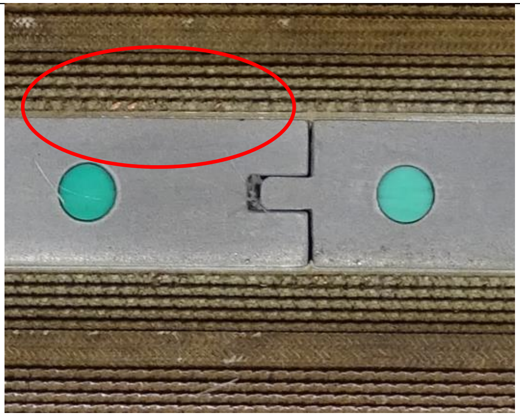
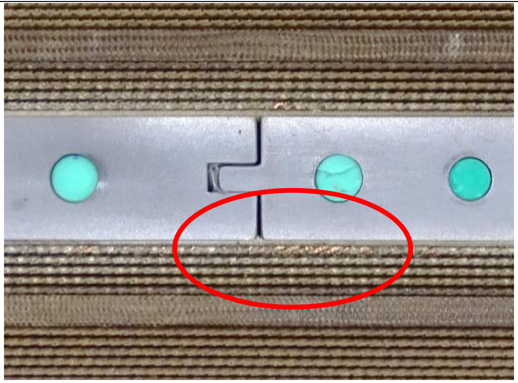
- is similar for the total, at 2-4 mm
- is different for the longitudinal distribution
  - MQXFA gaps are larger in the center
  - MQXFB gaps are larger at the extremities

On coil CR122, we observed an inner layer pole turn protrusion (towards the aperture)

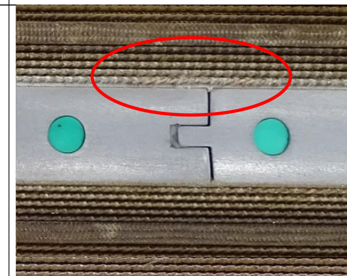
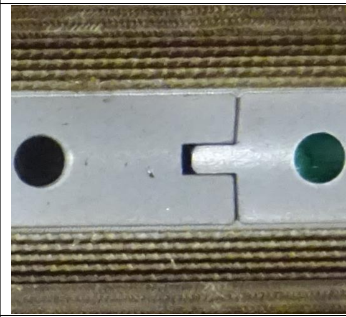
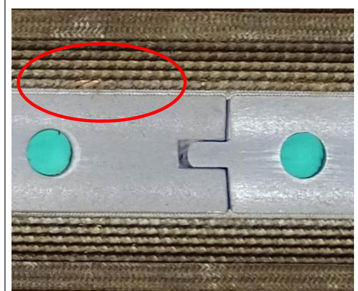
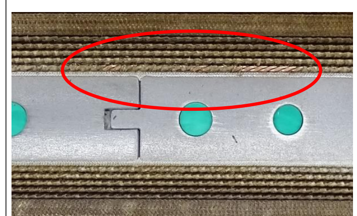
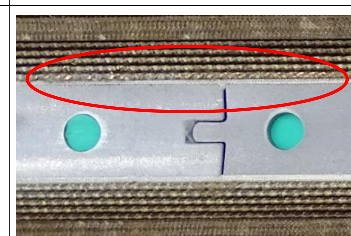


- 0.8 – 1 mm protrusion of the pole turn with respect to the pole piece observed after reaction, at 5200 mm
  - NCR EDMS 2469659 (including Fuji paper analysis)
  - inspection with the microscope did not reveal any specific deformation or degradation on the cable
  - this coil will not be assembled in next magnet
- dedicated inspection added on all coils afterwards
- for previous coils, visual inspection based on pictures
- when we observe something, this is always at the segmented Ti pole junctions (pole length is 400 mm)

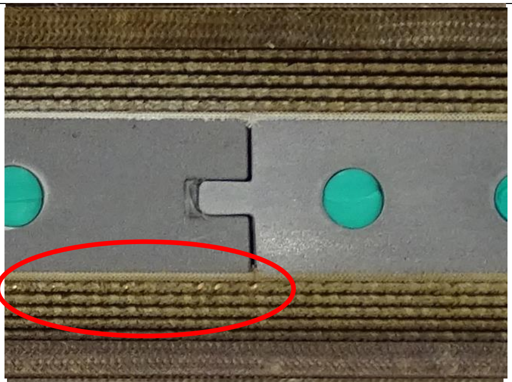
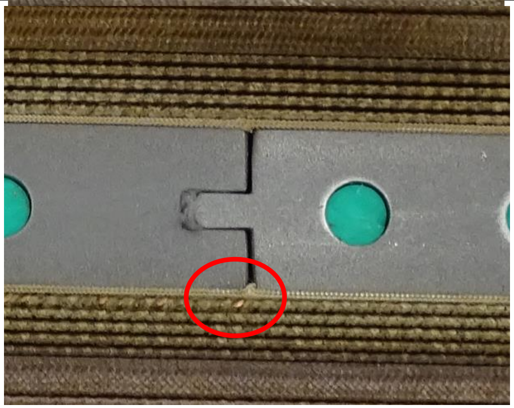
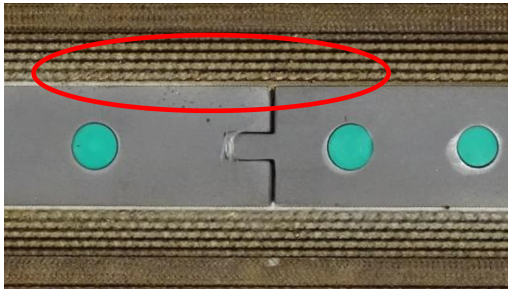
Inner layer pole turn inspection in CR121 and CR122

Coil	Observations on the pictures (Distance from the splice blox)	after the RHT mould opening	At the end of the inner layer preparation for impregnation	Comments
CR121	3600 mm			Bare cable partially visible, closed to the pole junction
CR122	5200 mm			IL turn 1 higher than expected NCR 2469659

Inner layer pole turn inspection in CR123

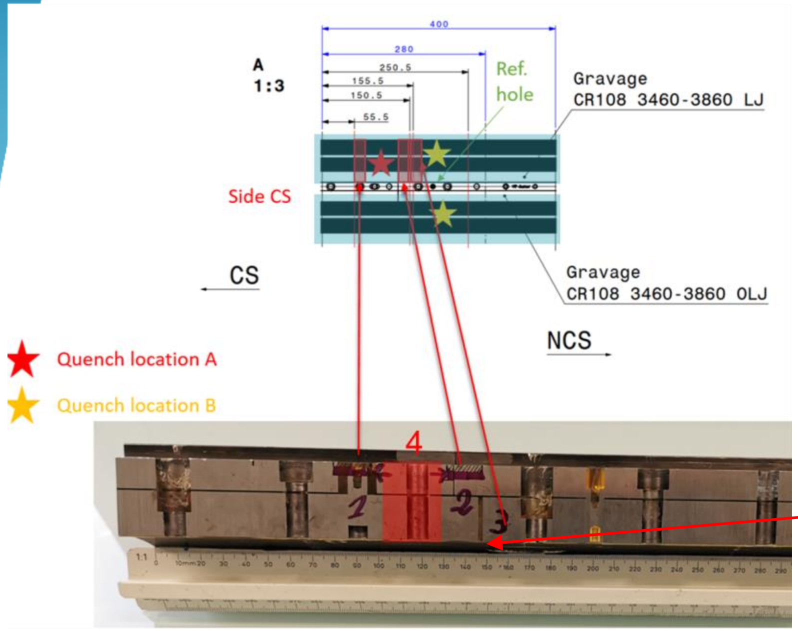
Coil	Observations on the pictures (Distance from the splice blox)	after the RHT mould opening	At the end of the inner layer preparation for impregnation	Comments
CR123	2400 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself
	3600 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself
	4020 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself
	4800 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself

6 Inner layer pole turn inspection in CR124 and CR125

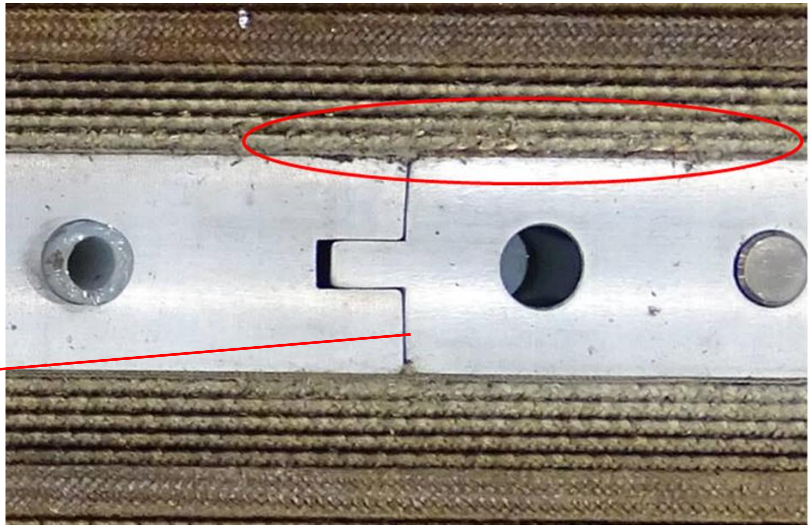
Coil	Observations on the pictures (Distance from the splice blox)	after the RHT mould opening	At the end of the inner layer preparation for impregnation	Comments
CR124	2800 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself
	6000 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself
CR125	4400 mm			- Bare cable partially visible, closed to the pole junction. - No defect observed on the cable position itself

6

Inner layer pole turn inspection in CR108



defect at 3680 mm



- Metallography inspections in the quench location show a defect in the region 3560-3800 mm
- Visual inspection shows degradation of the pole turn insulation at 3680 mm
- For coil CR108, we have a correlation between quench location, broken strands and insulation damage
  - though the insulation damage is only on one side of the pole

Short term plan for further improvements

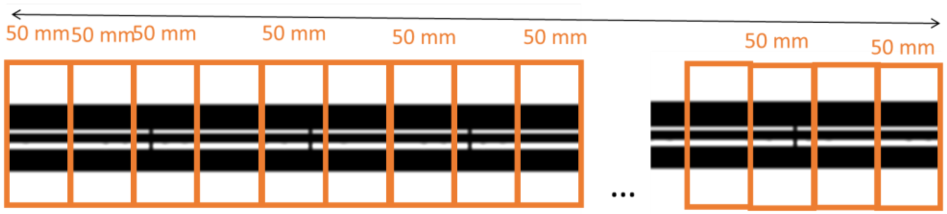
CR126
(prep. impregnation)

CR127
(winding
and curing)

CR128
(not yet
started)

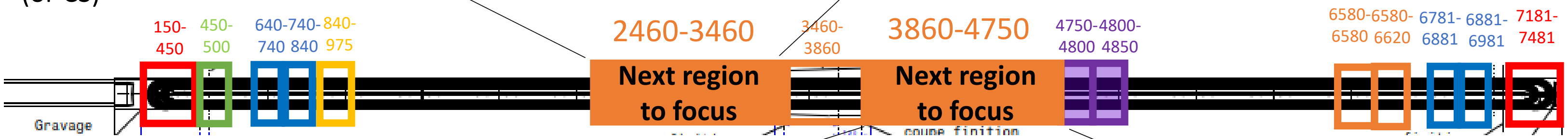
We keep slicing up CR108, to check in particular whether the broken strands are local or distributed

Sketches not in scale



≈ 1 m (i.e, ≈ 20 slices 50 mm length, 20 slices to be inspected (one face))

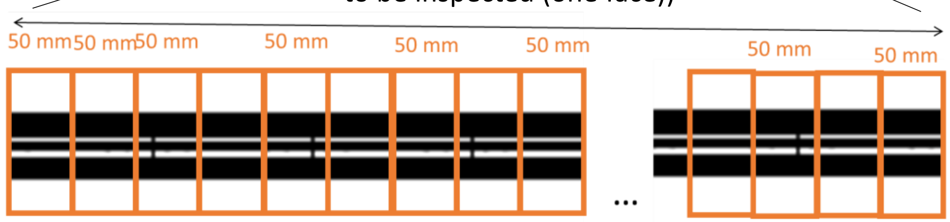
CC
(or CS)



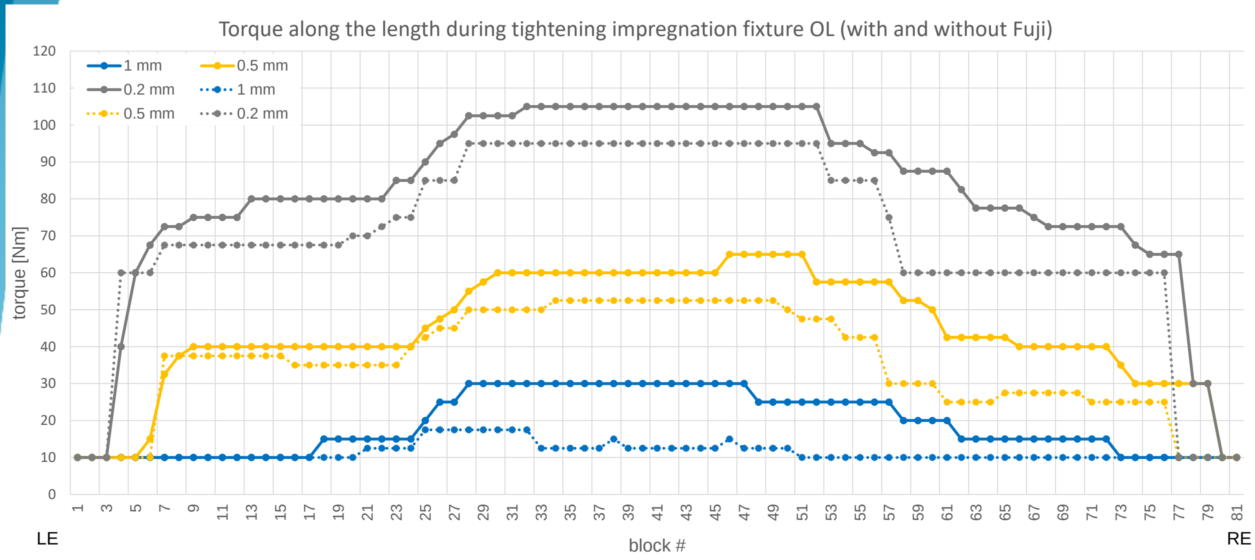
COC
(or NCS)

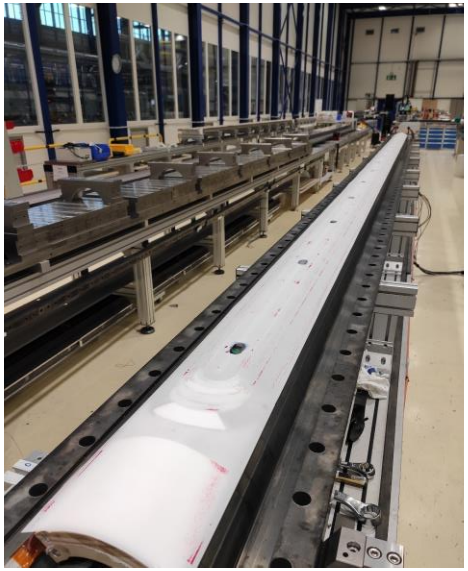
z=0

≈ 1 m (i.e, ≈ 20 slices 50 mm length, 20 slices to be inspected (one face))

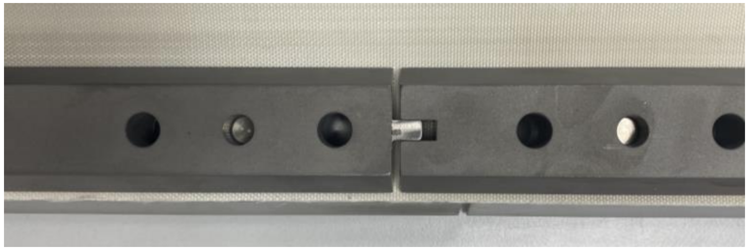
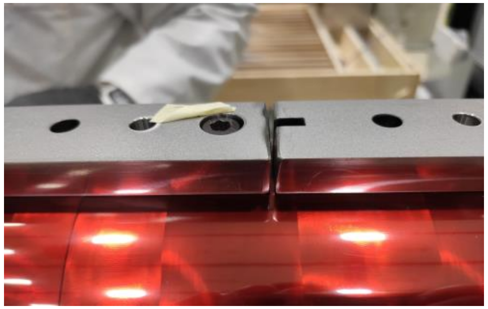
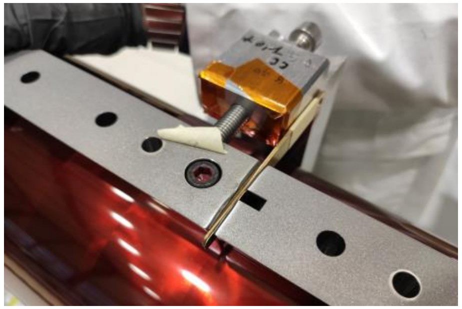


CR126 – extra measurements taken when closing / opening the reaction / impregnation fixtures





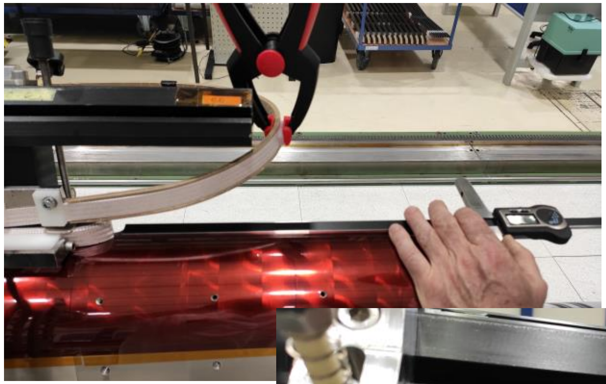
CR127 – Several actions to give more room to the coil during heat treatment and decrease the stored energy

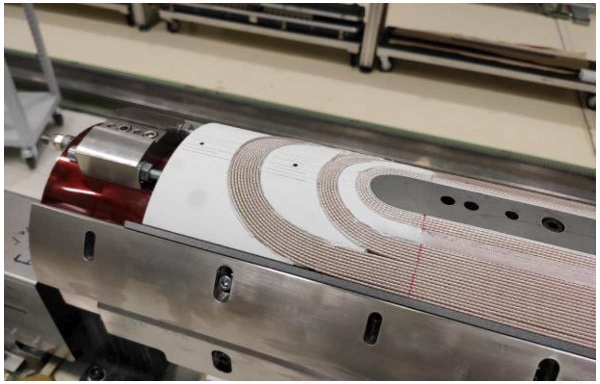




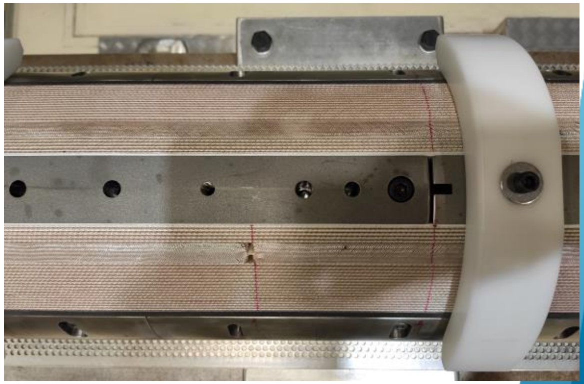
- Pole gaps increase from 0.9 mm to 1.5 mm
- Removal of T-slot in poles
  - to avoid any possible lack of longitudinal sliding
- Rounding of all edges of the poles
  - to address effect of pinching of fiberglass
- Removal of one layer of fiberglass on OL during reaction
- Reduction of winding tension in the OL
  - scaled with the ratio of IL / OL turns (28 / 22)


Residual gaps are filled before impregnation

CR127 – additional measurements during winding and curing, also related to the popped strand analysis







The plan for the coils is part of a more general strategy (see E. Todesco's talk)

- CR126
  - continue the fabrication with the standard procedure and additional measurements (ex. displacements, torques on bolts, geometry with laser tracker, intermediate closures of mould with Fuji paper)
- CR127
  - implement selected changes in the procedures, checking in particular the impact on the *dromedary hump*, the *pole turn protrusion* and the *big belly*
  - candidate for destructive analyses, focussed on broken strand issue
- CR128
  - winding on hold till CR127 is reacted
  - candidate for fast-track testing in a magnet (MQXFBP1b or similar), to confirm performance
- Continue the destructive analyses in CR108
- Keep alert, keep sharing and discussing with colleagues, including AUP

Thank you