Improvements in MQXFB coil fabrication

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12th HL-LHC Collaboration Meeting
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Outline

- Coil fabrication status
  - Dashboard
  - General context
- Improvements and lessons learnt
  - Coil CR126
    - New features
    - Measurements during coil fabrication
    - Fuji paper test
  - Coil CR127
    - New features
    - Measurements during coil fabrication
    - Dimensional scanning after heat treatment
  - Metrology CR126 and CR127
- Conclusions

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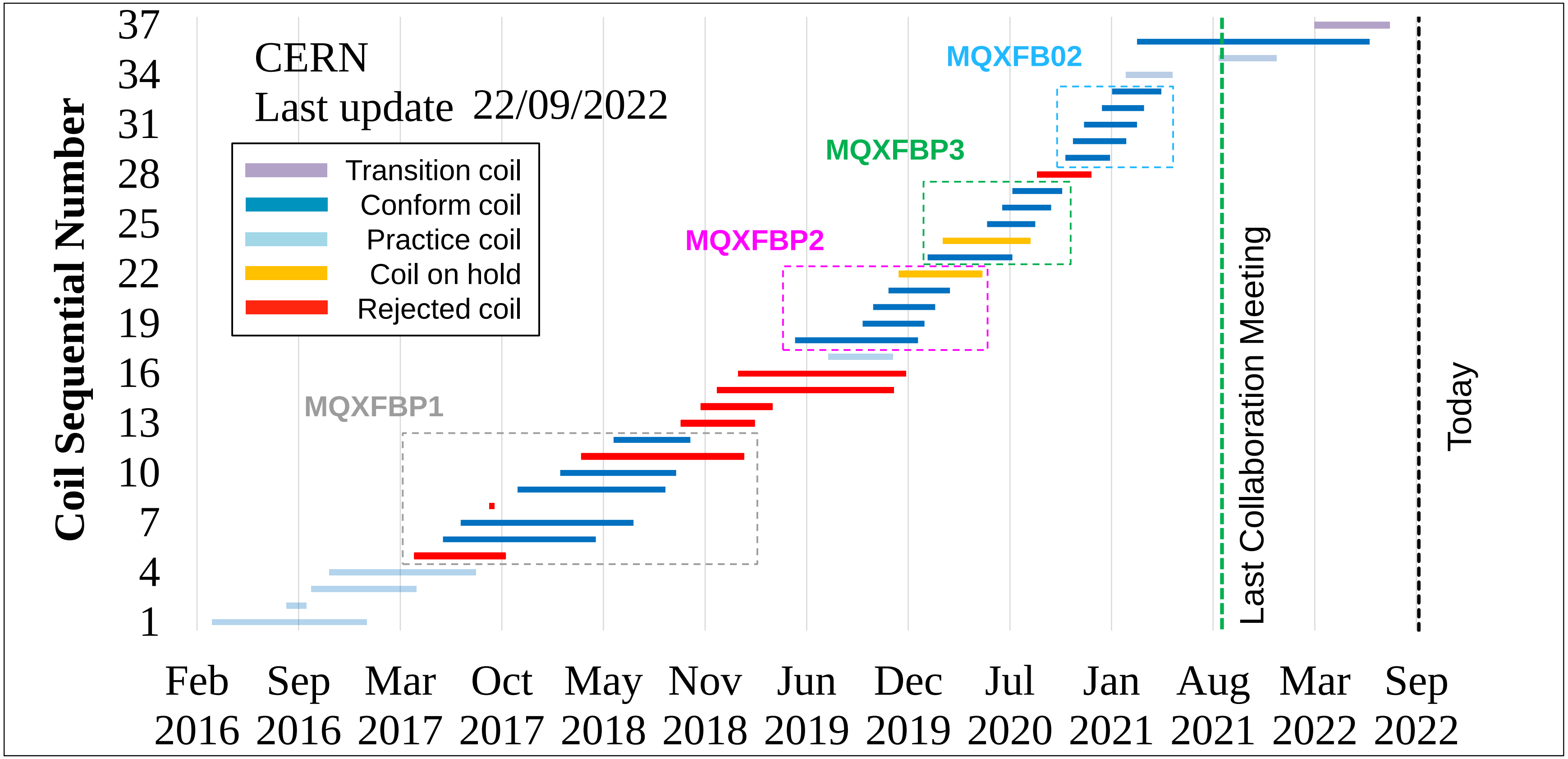
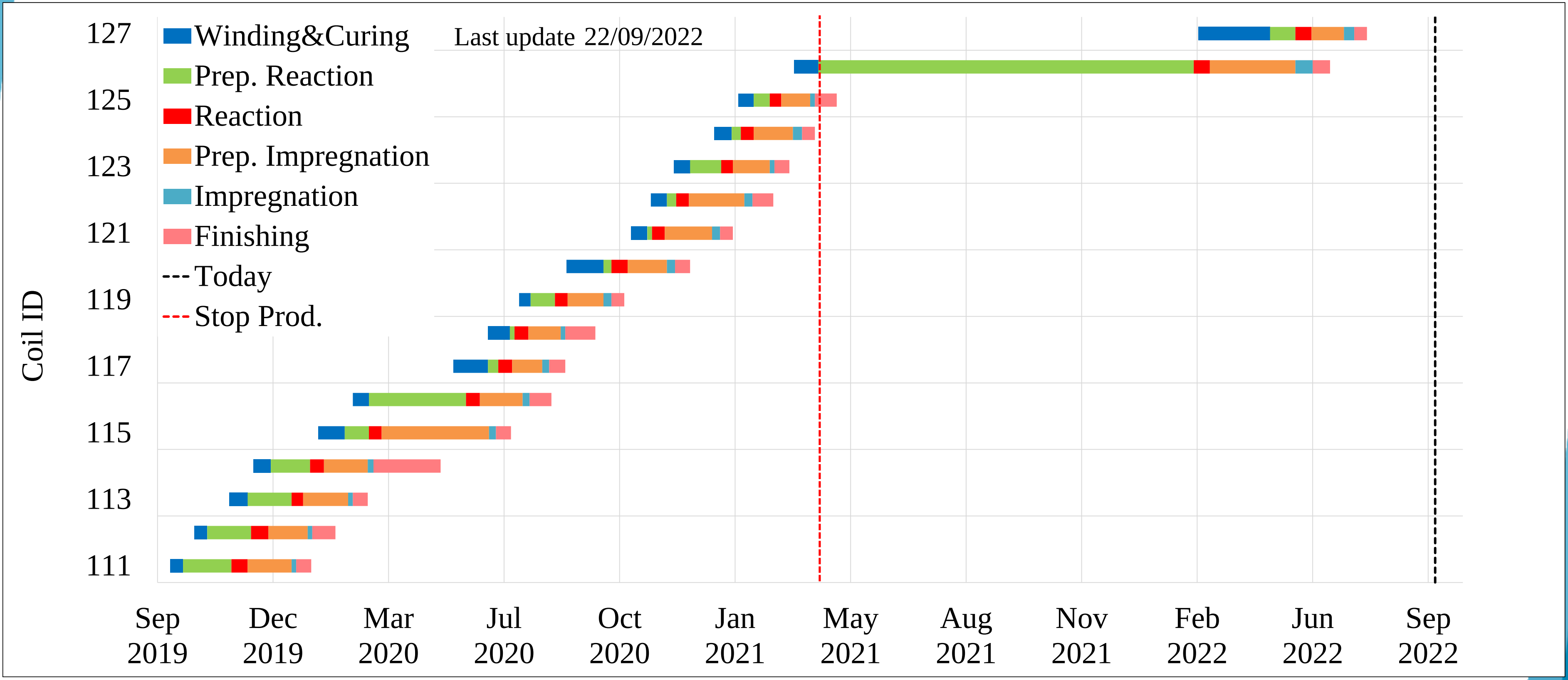
Dashboard

- Since the beginning of the production, *36* MQXFB coils have been manufactured



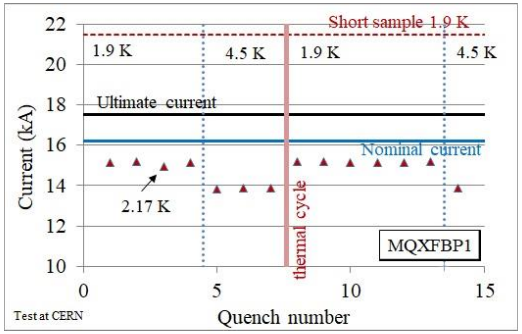
Dashboard

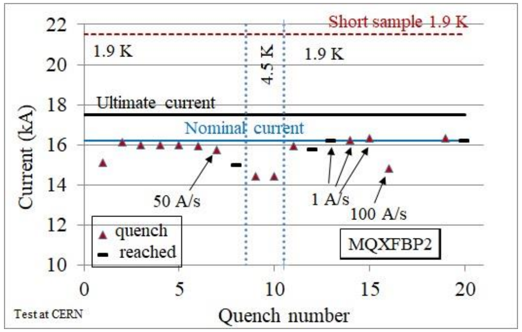
- From last Collaboration Meeting ([indico 1079026]) 2 SC coils were manufactured:
  - Production on hold following cold tests of MQXFBP2

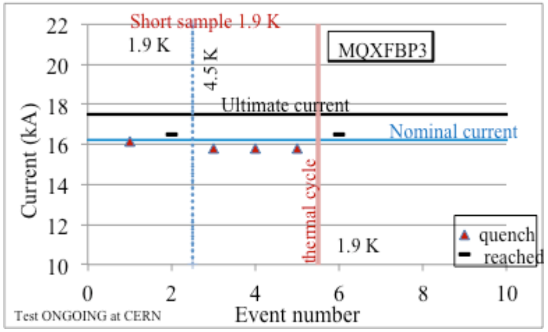


General context

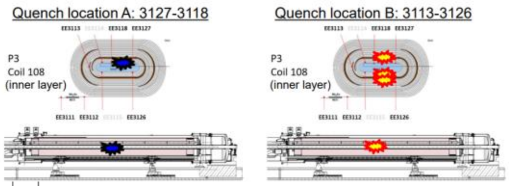
- MQXFBP1 had a performance limitation in one coil at 15kA (6.5 TeV equiv.), [EDMS 2402009]
  - Very reproducible quench in one coil, performance loss at 4.5K consistent with 1.9K behaviour (reproducible after thermal cycle)
  - The limiting coil was CR108 (~ in the longitudinal center)
- MQXFBP2 had a performance limitation at 16kA [EDMS 2469619]
  - Very reproducible quench in one coil also close to the magnet center, similar to MQXFBP1 but with 1kA more
  - Trimmed powering showed similar limitations in two other coils
- MQXFBP3 reached nominal current + 300A at 1.9K but not at 4.5K (15.8kA all quenches in the same coil close to the middle) *see F. J. Mangiarotti talk* [indico 1161569]

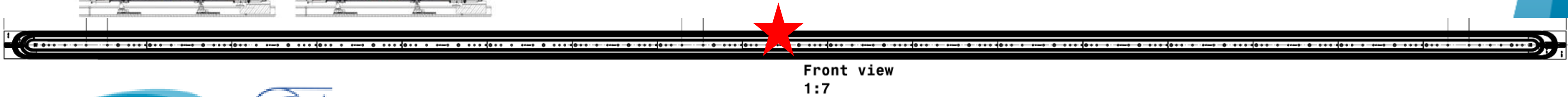






Test still ongoing

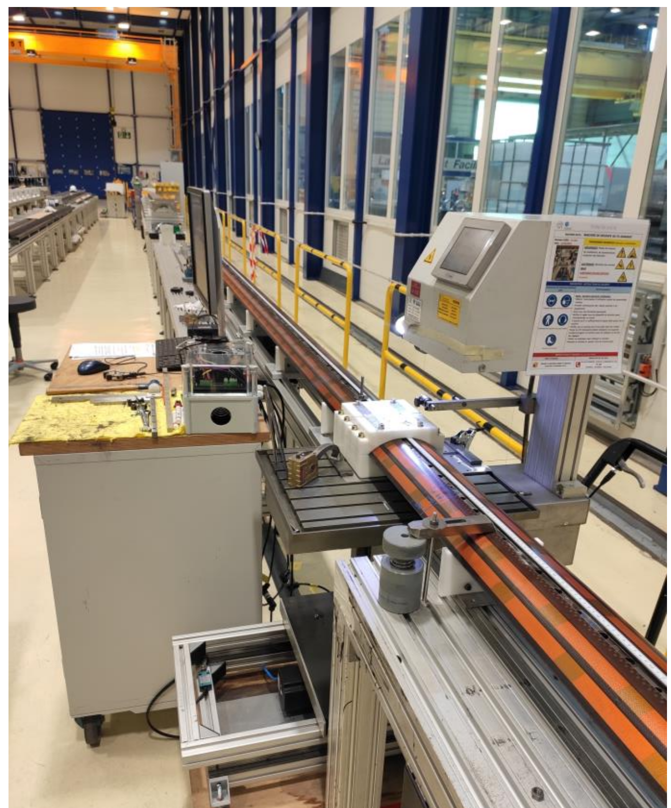




Metallography inspection

- Systematic inspection of selected MQXFB coils focusing in the pole-to-pole transitions as consequence of the coil CR108 inspection campaign:
  - Diamond wire saw cutting and slicing
  - Deep copper etching and micrographies (*see A. Moros talk* indico 1161569)

It required → Improved set-up and on-purpose developed system to cut in better conditions long coils



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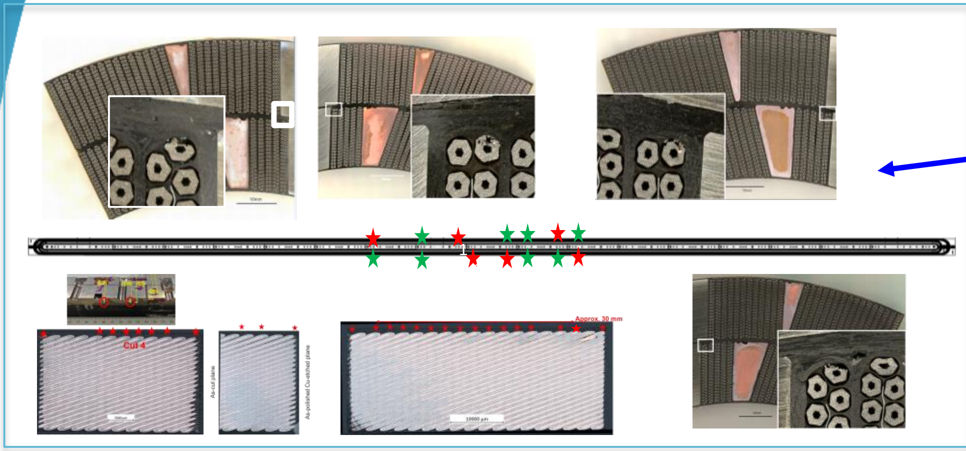
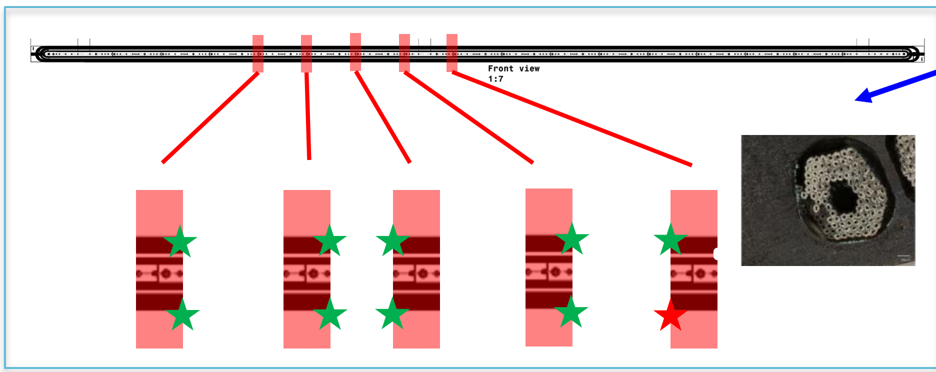
Metallography inspections

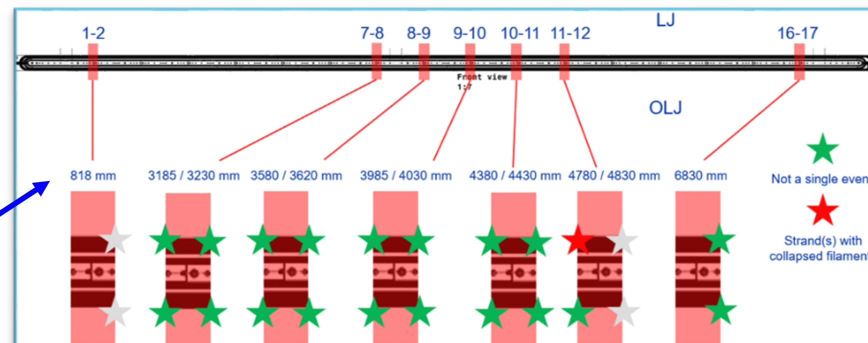
see A. Moros talk (indico 1161569)



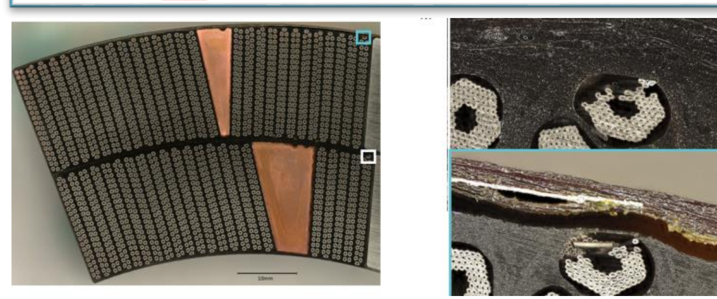
CR108 – many broken filaments in same cross section location (IL pole turn, towards the OL pole), in several longitudinal locations, at the pole transitions



CR120 (EDMS 2419556) – one damaged strand, IL pole turn, towards the inner radius (mandrel) → pole transition #8-9

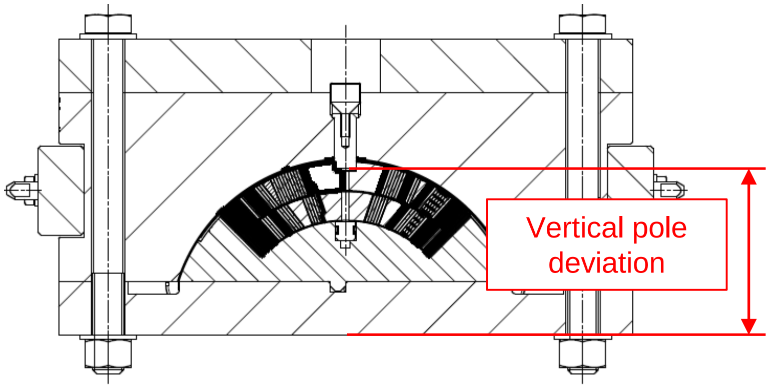


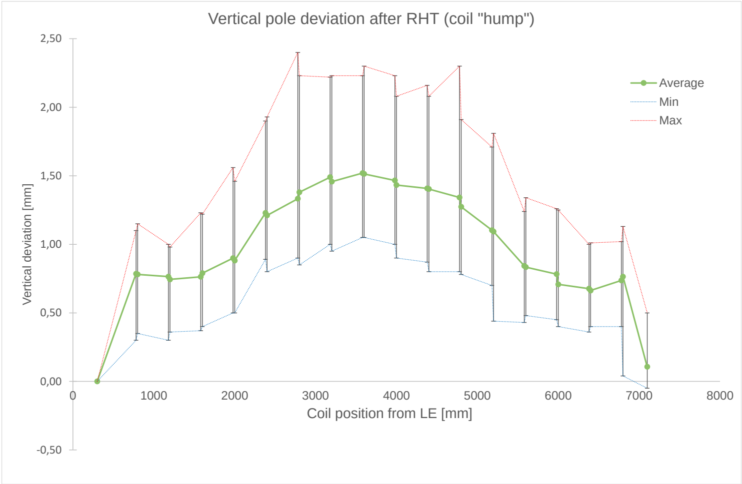
CR126 – two damaged strands, IL pole turn towards the OL pole (as in CR108) and OL pole turn towards the OD of the coil – in one longitudinal location at the pole transition → pole transition #11-12

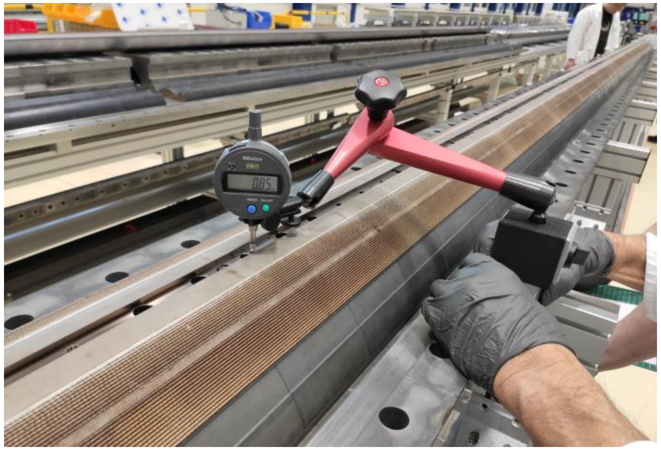


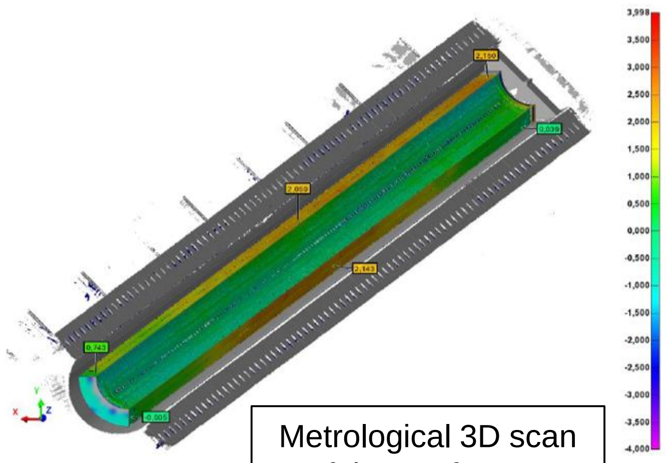
Vertical deflection of the pole with respect to the baseplate after reaction (“hump”)

- After reaction, a vertical deflection of the outer layer pole with respect to the base plate of 1-2 mm is typically observed (EDMS 2636108)









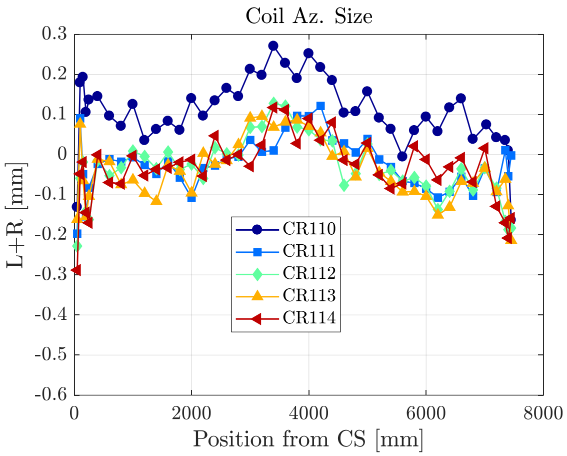
Metrological 3D scan of the IL after HT

Azimuthal arc length of impregnated coils

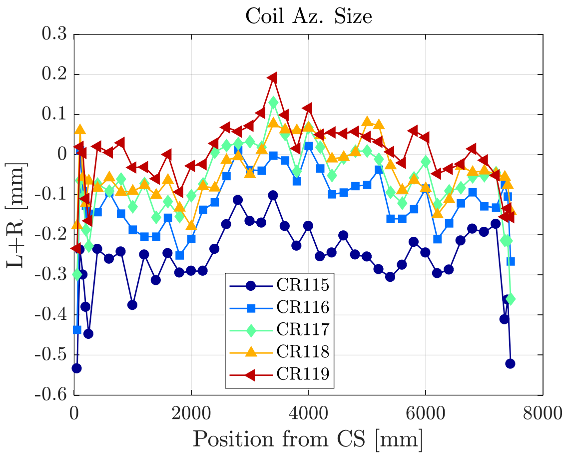
- After impregnation, coils are azimuthally larger in the middle, there is a systematic 'belly' shape in our coils:
  - L+R arc excess typically 0.150 mm larger in the middle

indico 1075064

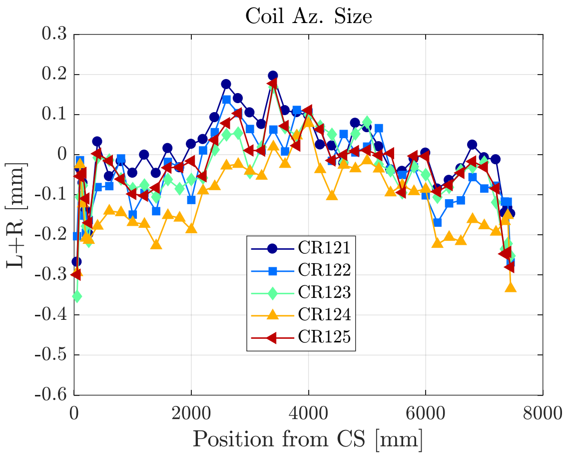
MQXFBP2 coils



MQXFP3 coils



MQXFB02 coils



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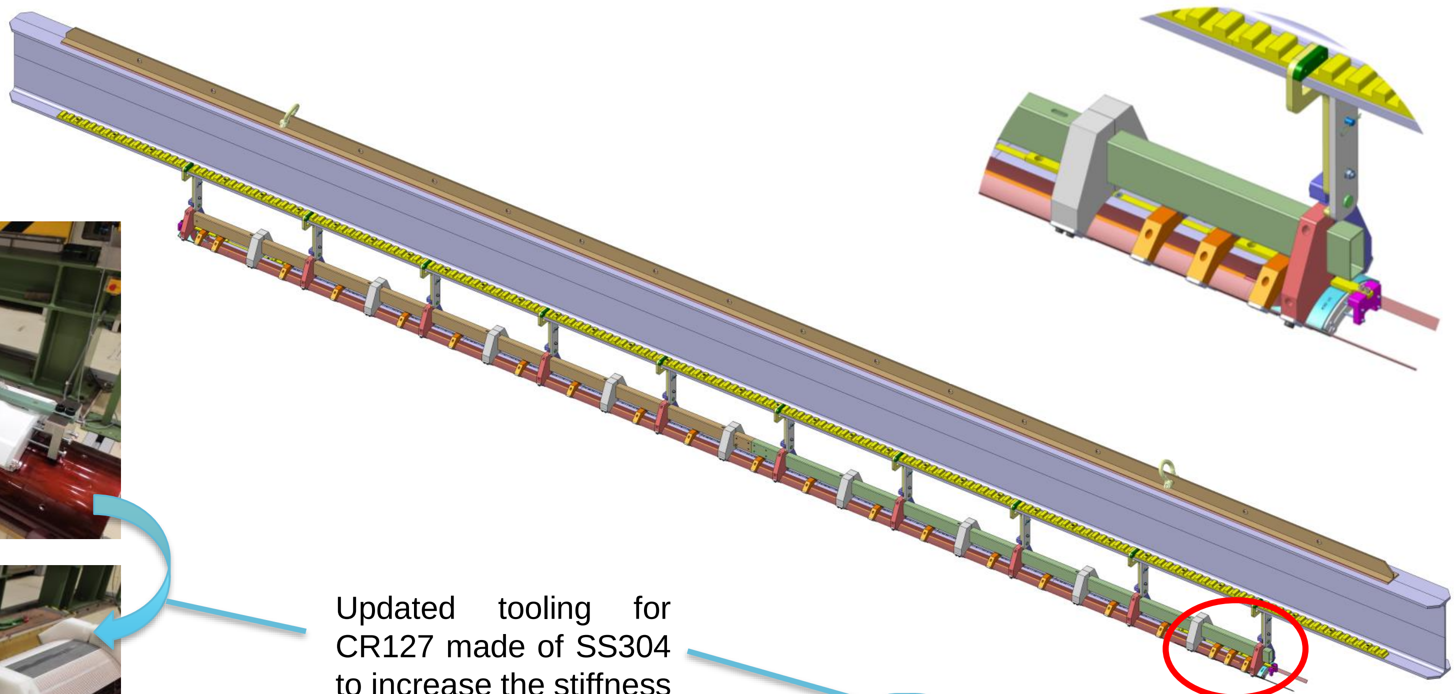
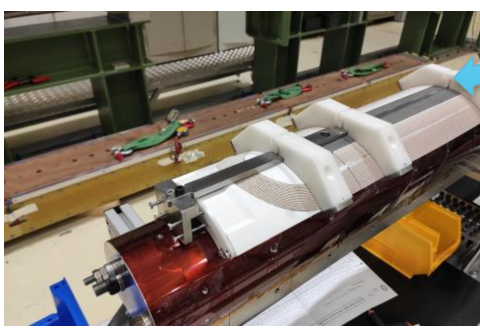
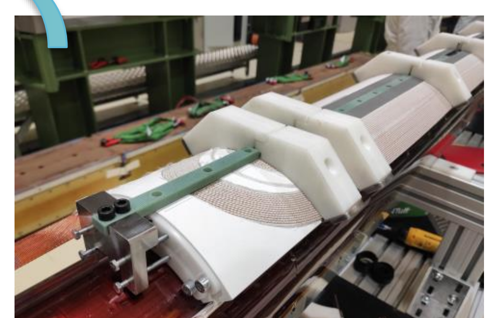
CR126: new features (all kept also for CR127)

- Improved tooling to better support the extremities during handling from the winding mandrel to the reaction fixture





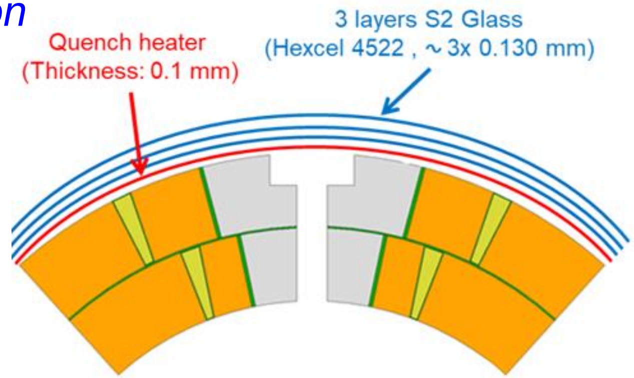
Updated tooling for CR127 made of SS304 to increase the stiffness



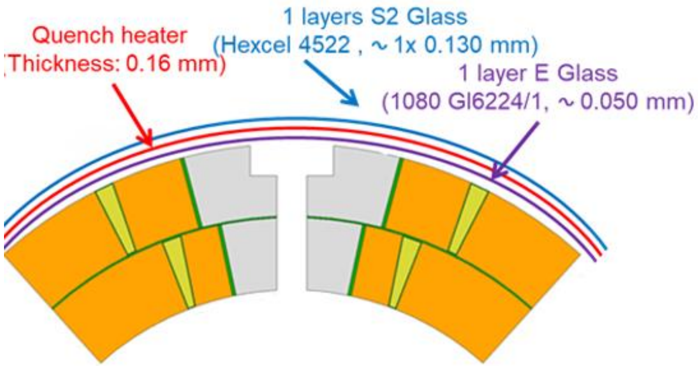
CR126: new features (all kept also for CR127)

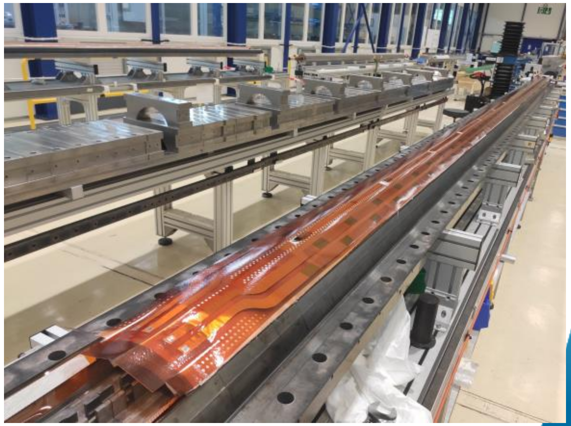
- Improved lifting tooling for impregnated coil
- Mini-swap and new QH design, removing one layer of S2-glass in the OD

Previous OL configuration (old QH design)



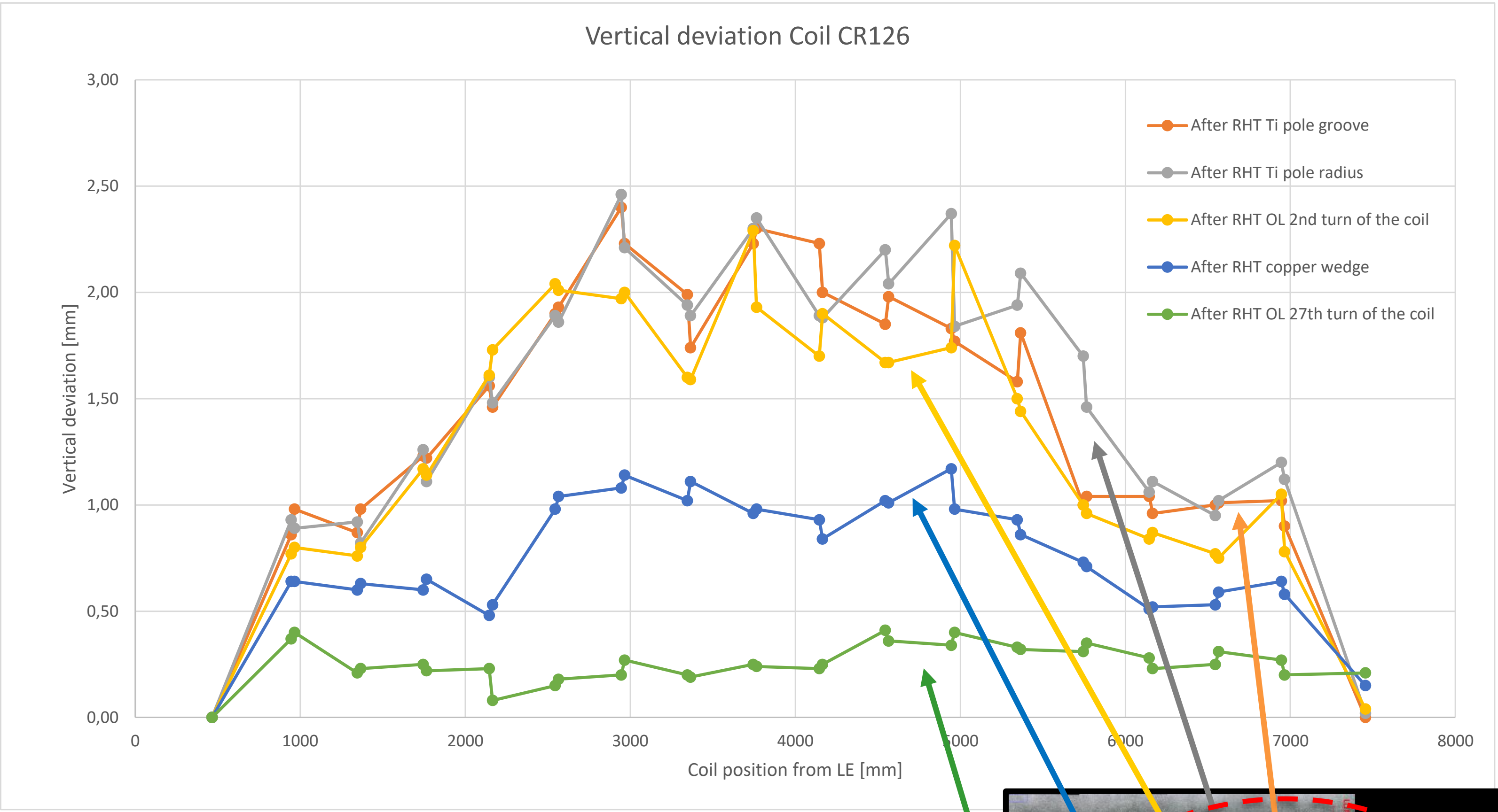
New OL configuration with mini-swap (new QH design, with coverlay)

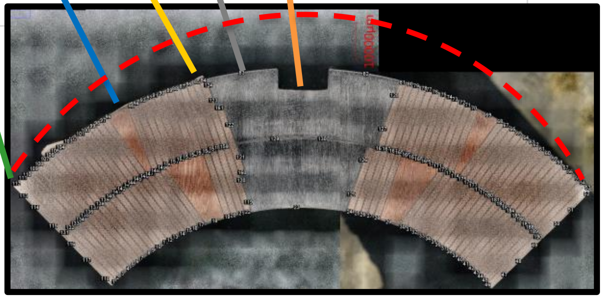




CR126: opening of the reaction fixture

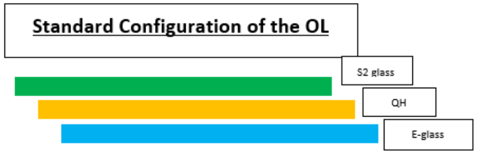
- The pole turn follows the pole, the mid-plane stays in place



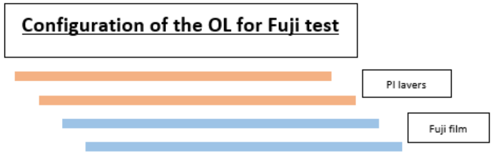


CR126: Fuji paper test

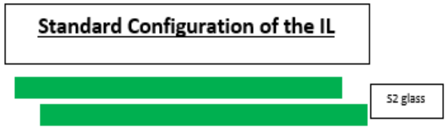
- Fuji paper assemblies in coil CR126:
  - <u>Fuji paper LW</u> (2.5 – 10 MPa)
  - Preparation for impregnation of the OL (QH and S2 glass replaced by Fuji LW and polyimide) → tightening to 0.2 mm gap
  - Opening of the fixture, close again with the OL facing up, standard process (QH + S2 glass, fixture closed to 0.2 mm gap)
  - Preparation for impregnation of the IL and mid-plane (S2 glass replaced by Fuji LW and polyimide) → fixture fully closed
  - Open the fixture, close again with the IL facing up, standard process (S2 glass, fixture fully closed)



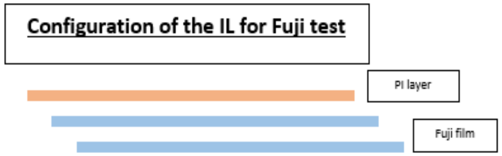
Thicknesses:
- E-glass = 0.055 mm
- QH coverlay = 0.160 mm
- S2 glass = 0.130 mm
- **Total = 0.345 mm**



Thicknesses:
- Fuji LW = 0.100 x 2 = 0.200 mm
- PI layers = 0.075 x 2 = 0.150 mm
- **Total = 0.350 mm**



Thicknesses:
- S2 glass = 0.130 x 2 = 0.260 mm
- **Total = 0.260 mm**



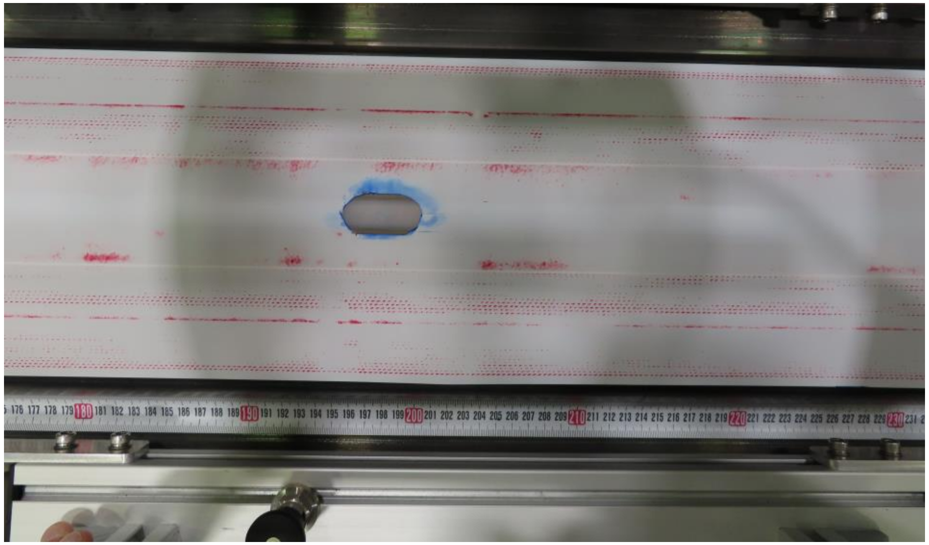
Thicknesses:
- Fuji LW = 0.100 x 2 = 0.200 mm
- PI layers = 0.050 mm
- **Total = 0.250 mm**

CR126: Fuji paper test

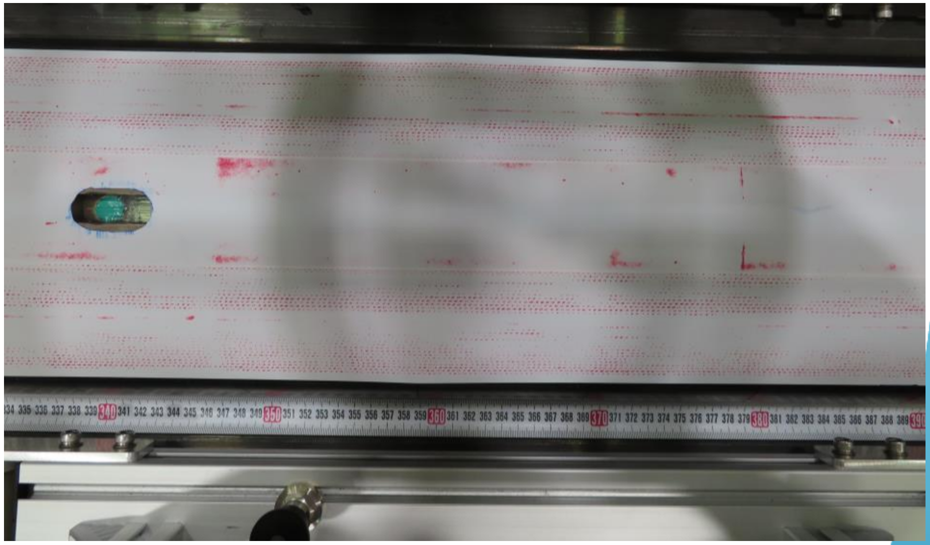
- OL results rather good → pressure applied on the coil turns with no significant concentration close to the transitions
- Towards the middle, where the coil is azimuthally bigger, Fuji paper reveals more turns

EDMS 2739168

1.5 m from coil end CS



Middle



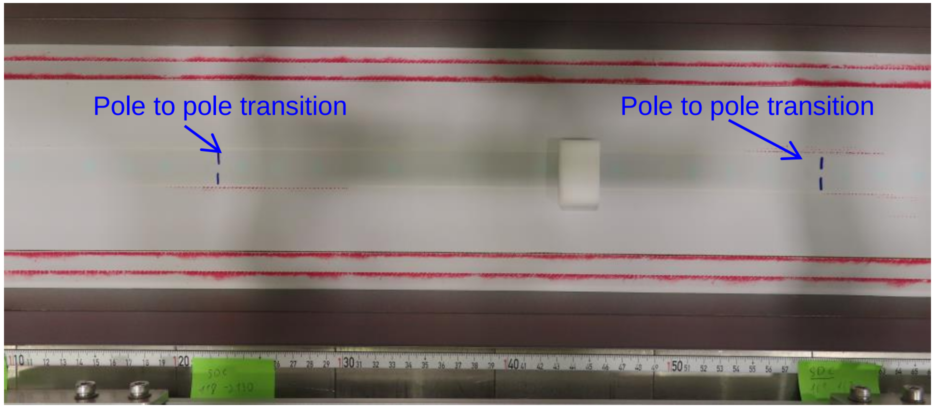
Fuji paper LW (2.5 – 10 MPa)

CR126: Fuji paper test

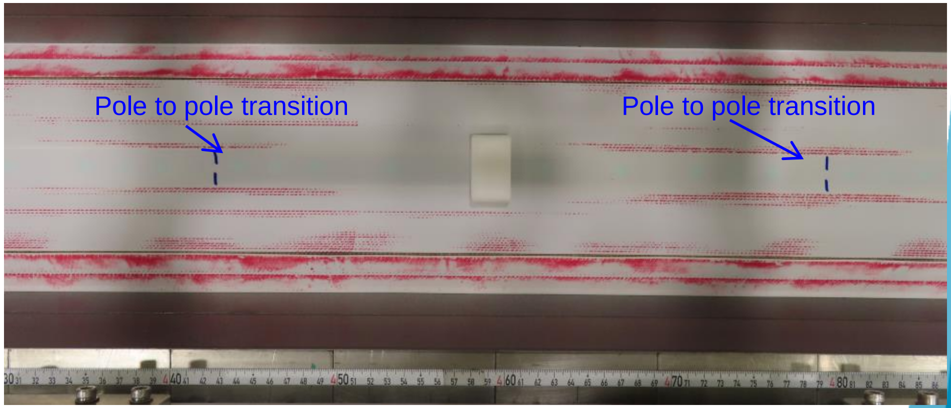
- The Fuji paper in the IL showed a stress concentration in the first turn pole-to-pole transitions, even for the transitions close to the coil end
- Towards the middle, where the coil is azimuthally bigger, more turns are revealed

[EDMS 2739168]

1.5 m from coil end CS



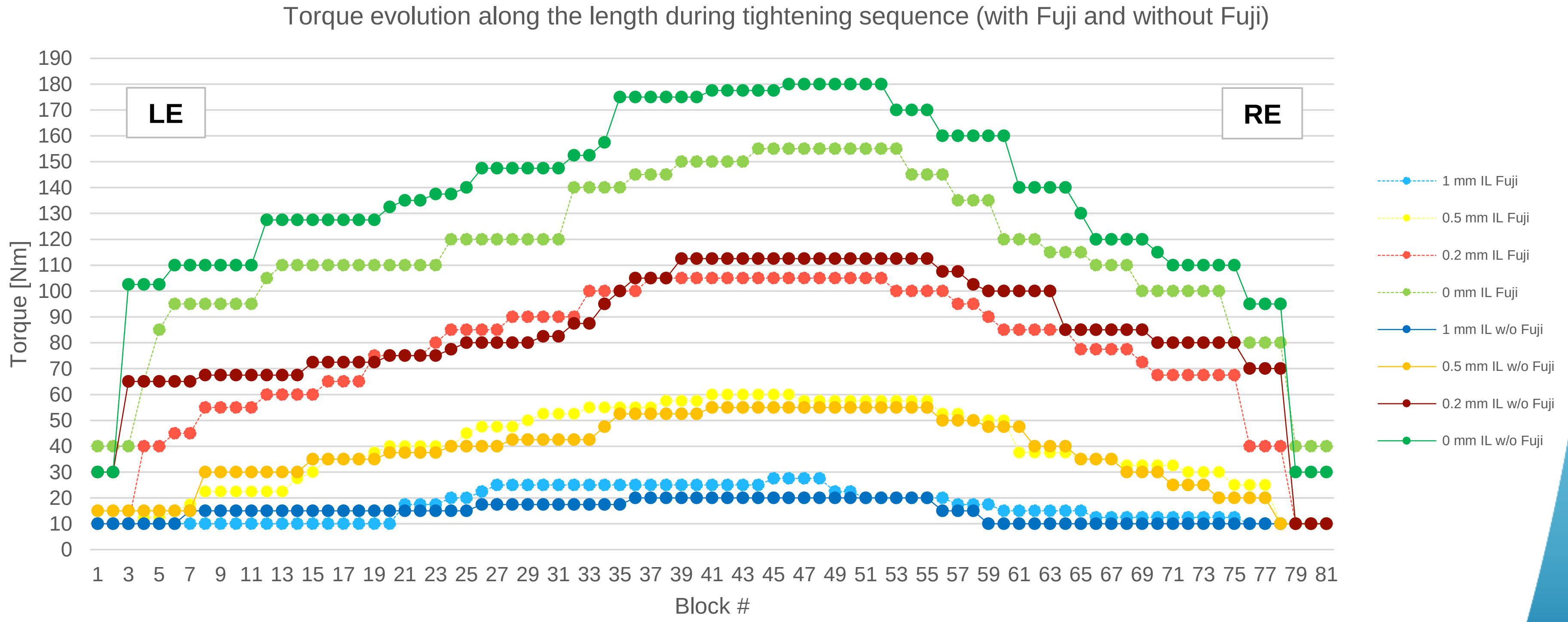
Middle



Fuji paper LW (2.5 – 10 MPa)

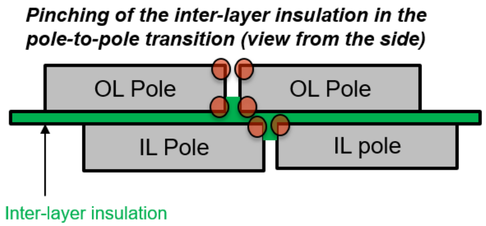
CR126: Fuji paper test

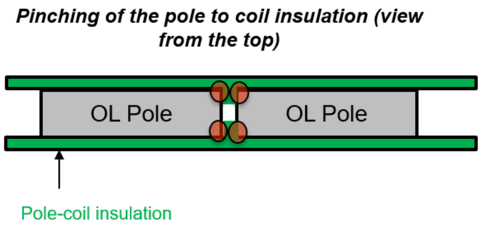
- Impregnation fixture closed in steps
  - 1 mm, 0.5 mm, 0.2 mm and 0 mm gap between formblocks and base plate
- In this case, torque at each step was monitored during the tightening
  - Towards the middle of the coil a higher torque is needed for a fixed gap → coil is tighter in the middle
  - Torque needed to close the fixture with and without Fuji paper are comparable for higher gap, then the difference becomes more relevant
  - This effect is not present in copper coil CR005

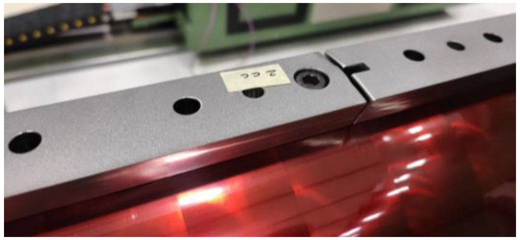


CR127: new features

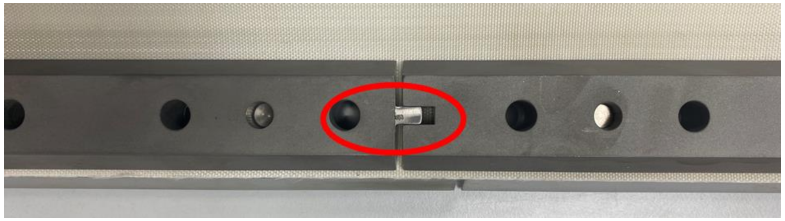
- <u>Purpose:</u> trying to address the "hump" after RHT which could be linked to the broken filaments mechanism
- <u>Winding</u>
  - Slight rounding the edges of pole-to-pole transition to reduce the insulation pinching effect



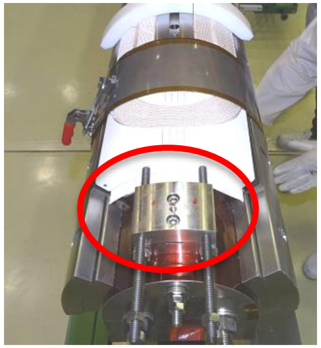




  - Increase of the initial pole-to-pole gap 0.9 mm → 1.5 mm (wedge gap is increased accordingly)
  - Remove the alignement feature for IL poles



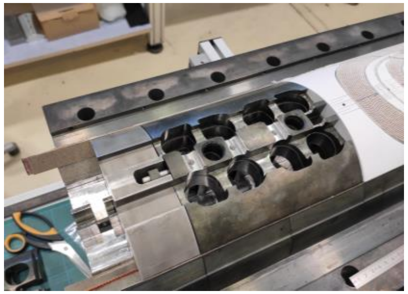
  - Decrease the winding tension in the OL (19 kg → 14 kg) to have the same " Tension*Nturns" in the IL and OL
- <u>Curing</u>
  - Remove the saddle stopper during curing cycle to not longitudinally constrain the coil



CR127: new features

- <u>Preparation for reaction</u>
  - Change of the aligning plates material from stainless steel to titanium → the goal was to be sure that the poles can slide at all temperature ranges as the thermal coefficient is the same

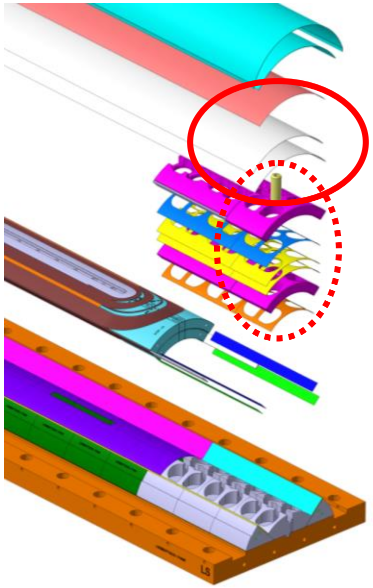
  - During heat treatment, the coil had space to move in both ends (untill coil CR126, the connection end was fixed)



  - Decrease the radial insulation in the reaction fixture by 0.125mm (consistent with the impregnation fixture)

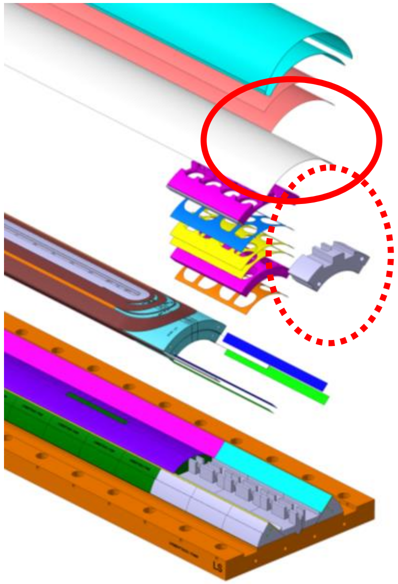
Previous configuration:

Material	Thickness [mm]
S2 glass	2 x 0.250
Mica	0.200
Total thickness: 0.700 mm	



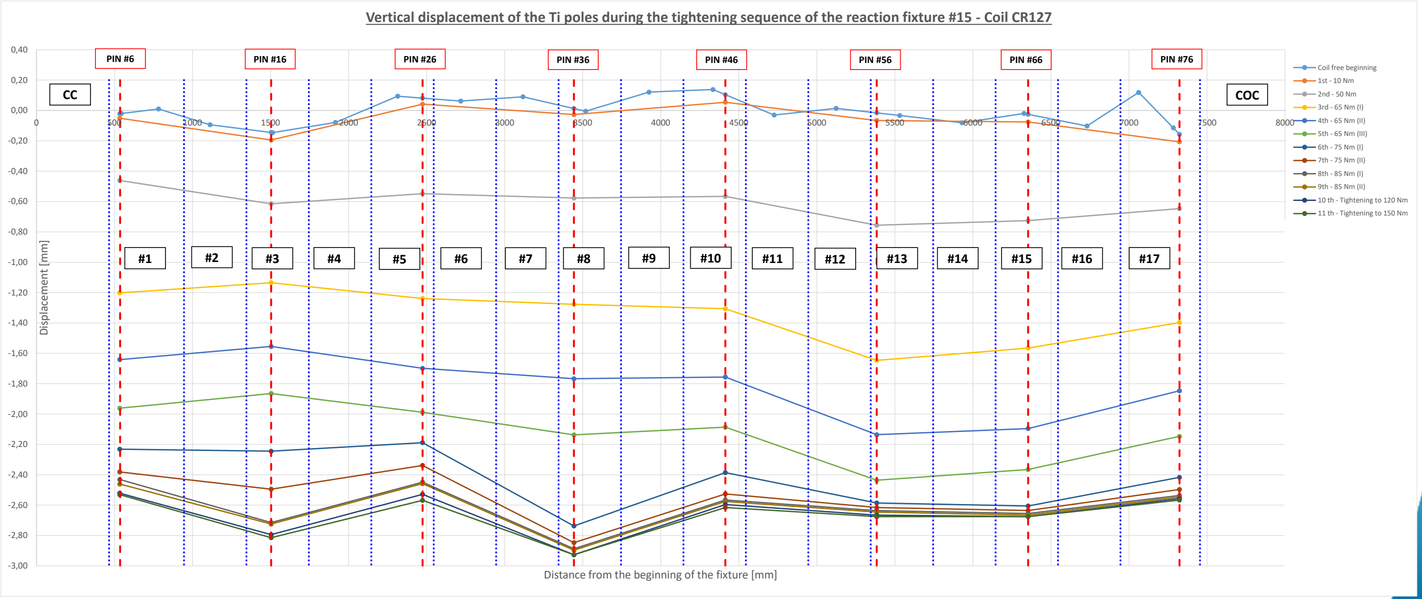
New configuration:

Material	Thickness [mm]
S2 glass	0.250
Mica	0.200 + 0.125
Total thickness: 0.575 mm	



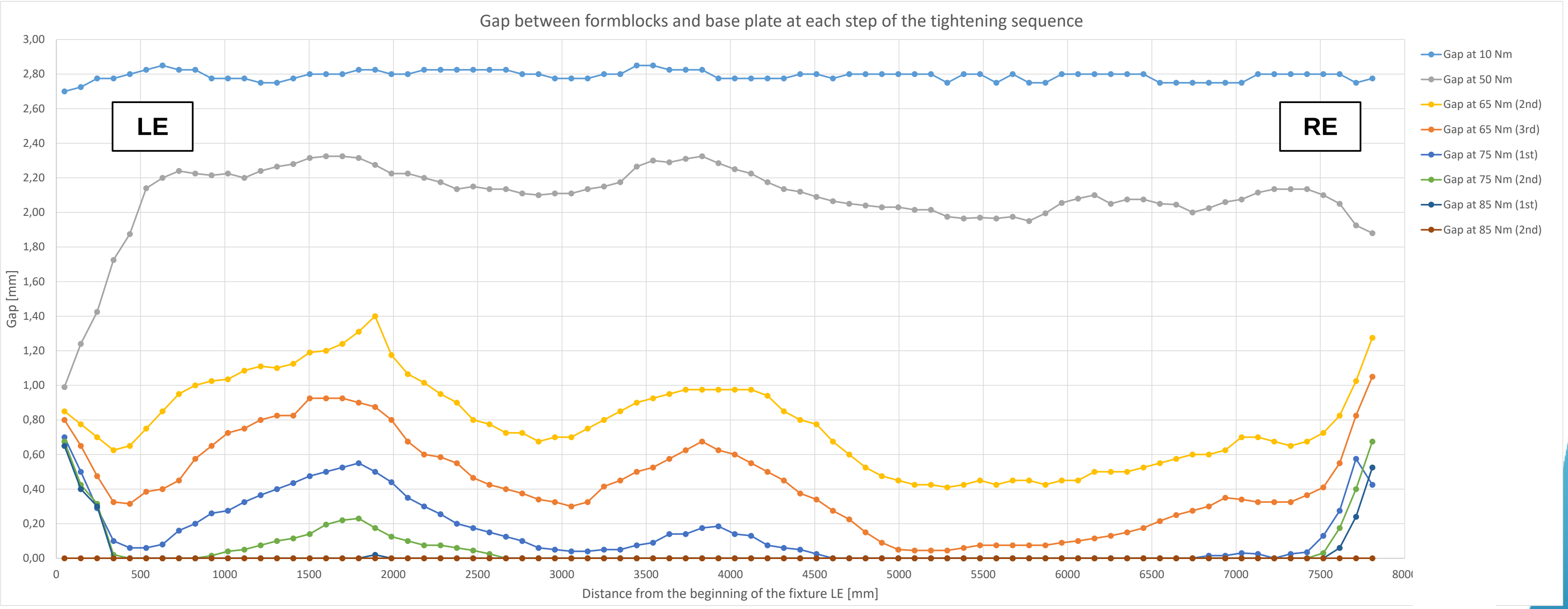
CR127: new features

- Preparation for reaction
  - The sequence to close and open the fixture was modified
    - Closure: start in the middle, moving towards the ends in a symmetric way (before it was from the CS to the NCS)
    - Opening: start in the extremities, moving towards the middle in a symmetric way (before it was from NCS to the CS)
  - Installation of dial gauges along the length to monitor the displacement of the poles during the closure of the fixture → modification of the Ti pins



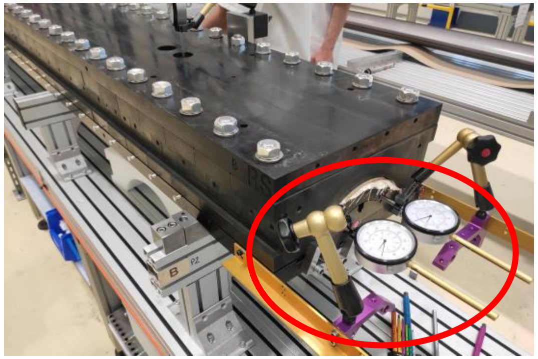
CR127: closure of the reaction fixture – Torque/Gap

- During the closure of the reaction fixture, no sign of a larger coil in the longitudinal middle
  - Closure by step at a given torque
- Fixture tightened at a relatively low torque 85 Nm → increased up to 150 Nm to assure tight closure during HT



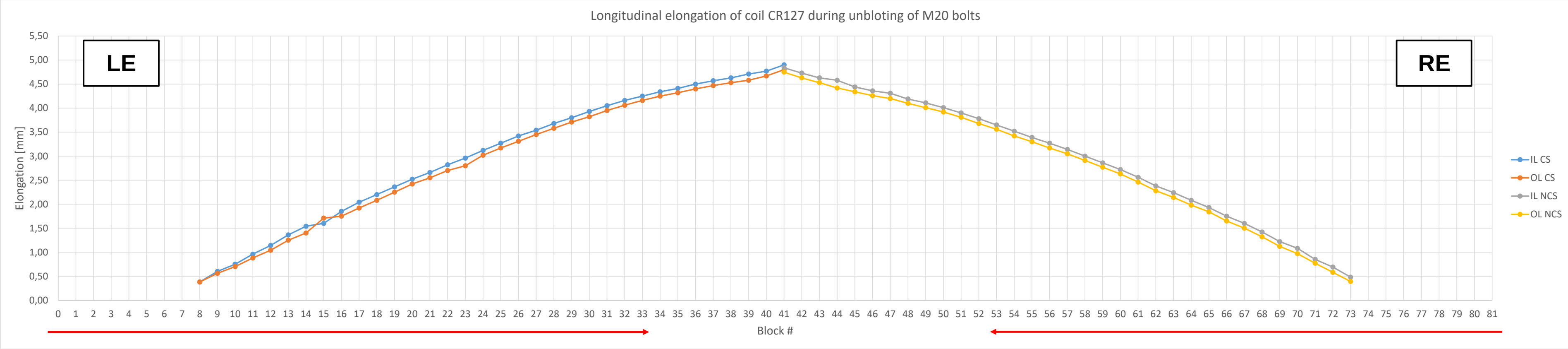
CR127: opening of the reaction fixture

- For the first time, measurement of the longitudinal displacement of the coil during the opening of the fixture (additional set-up required)
- The coil gradually moves outwards by about 5 mm per side (most of the movement was during the unbolting of the M20 bolts)



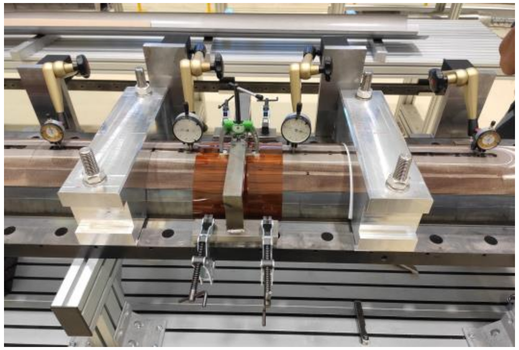
Longitudinal elongation of coil CR127 during opening of the reaction fixture [mm]

	Unbolting M20	Removal top plate	Removal formblocks	Unscrewing M6	Day after
IL CS	4,90	5,02	5,09	5,24	5,31
OL CS	4,80	4,90	5,02	5,22	5,28
IL NCS	4,84	4,96	5,39	5,54	5,58
OL NCS	4,75	4,86	5,23	5,38	5,43

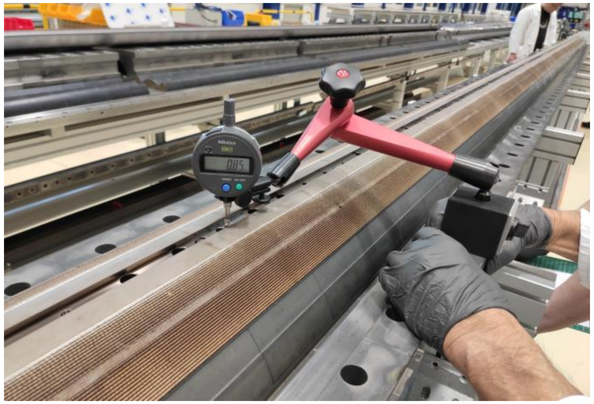


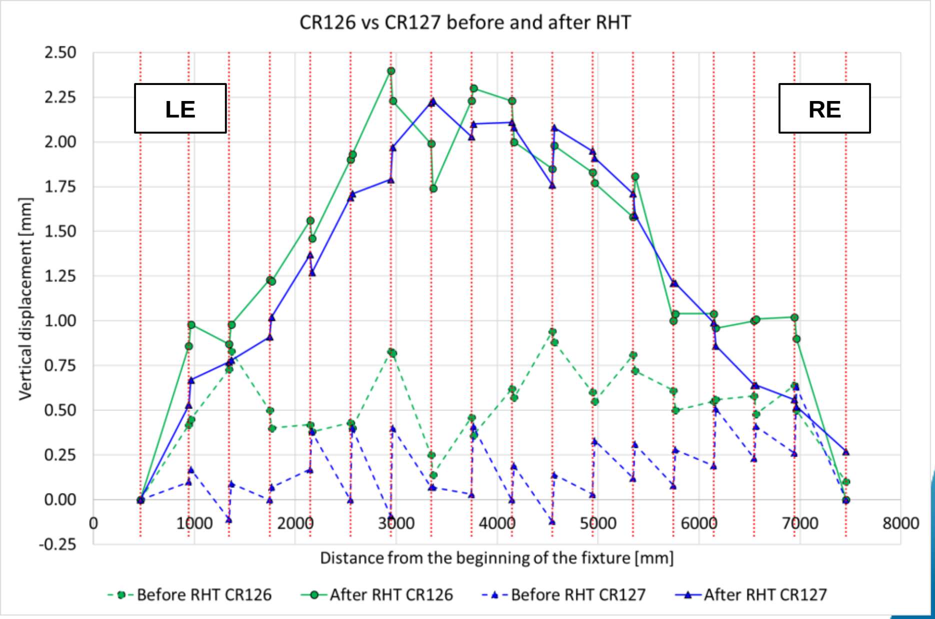
CR127: the "hump" after RHT

- The Ti pieces to join the OL poles were stuck after reaction:
  - A tooling was developed to remove them and the pole gaps did not change (probably they were not holding much force)
  - The pole gap closed almost 10 mm with respect to the value measured before HT
  - The plate width increased by around 0.05 mm during HT



- Once the fixture opened, the same "hump" at the level of the poles was observed:
  - Assuming that the plates did not have a significant impact in the system behaviour, more longitudinal space does not prevent vertical displacement
  - CR127 very similar to CR126 and previous coils





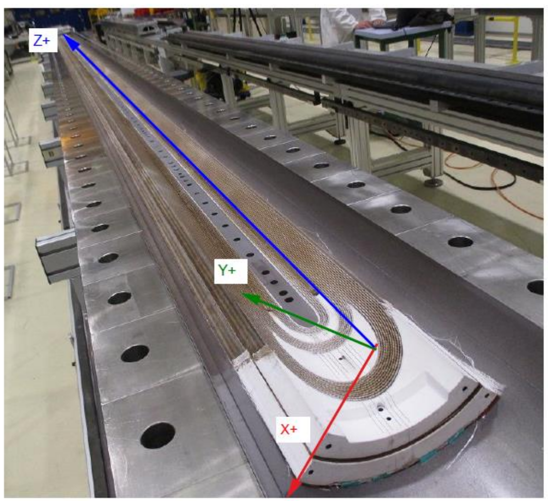
CR127: dimensional scanning after RHT

- For the first time, a non-invasive dimensional scan of the coil in the free state (IL upwards) was performed on a MQXFB coil after reaction
  - Instrument: MetraSCAN 3D optical CMM scanner (Creaform), precision ≈ 0.025 mm
  - **<u>Result</u>:** the mid-plane in the middle of the coil is shifted upwards by around 2 mm per side (<u>consistent with the "hump" and "belly" shape</u>)

RAPPORT DE CONTRÔLE

N°EDMS: 2752596

Contrôleur:	RIGAUD J.Ph.	Demandeur:	
N°JOB:	J......	Projet:	bobine MQXF
Date:	28.06.2022	Désignation:	métrologie bobine bât.180
Machine:	SCAN CREAFORM	N°plan/indice:	--- ind. --



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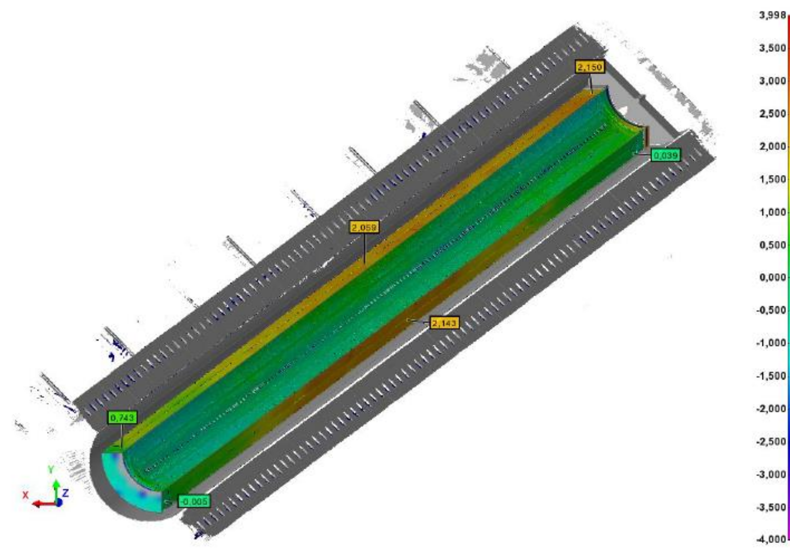
comparaison avec modèle CAO 1/4 de tube Øext. 230mm et Øint 149mm longueur 7400 mm pour écarts à surface



CR127: dimensional scanning after RHT

RAPPORT DE CONTRÔLE

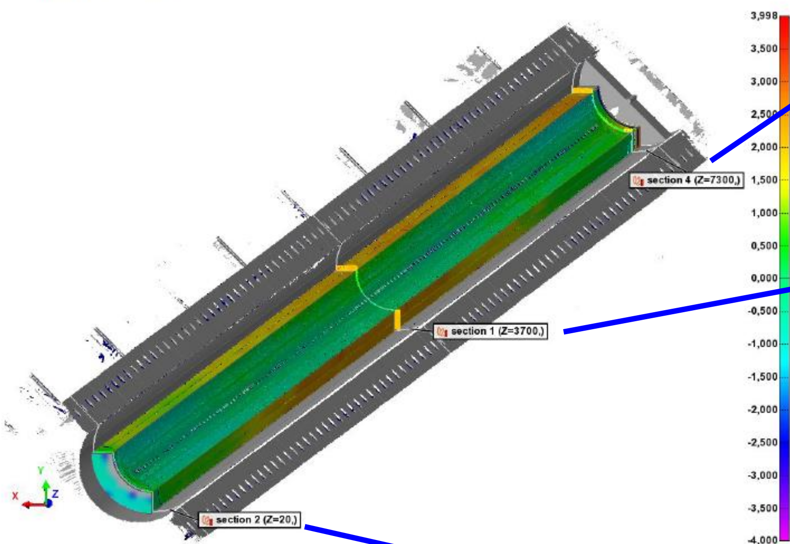
N°EDMS: 2752596

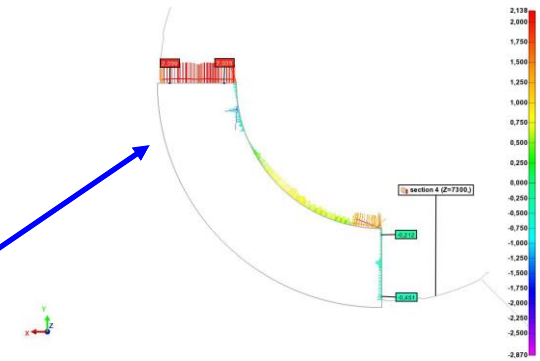
MATERIALS & METROLOGY

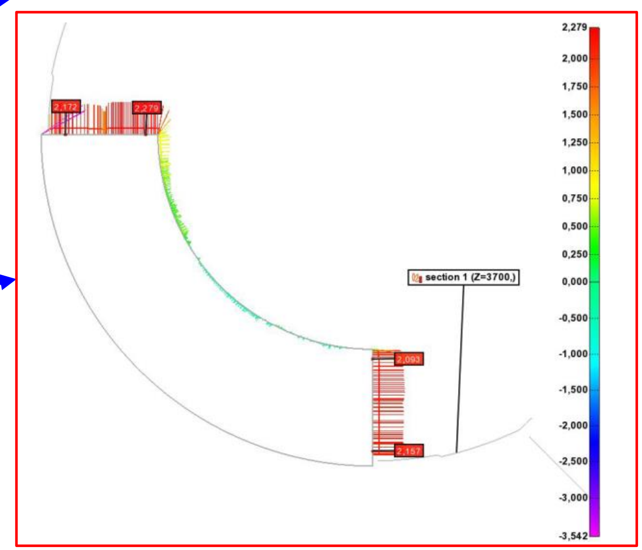
Contrôleur:	RIGAUD J.Ph.	Demandeur:	
N°JOB:	J......	Projet:	bobine MQXF
Date:	28.06.2022	Désignation:	métrologie bobine bât.180
Machine:	SCAN CREAFORM	N°plan/indice:	--- ind. --

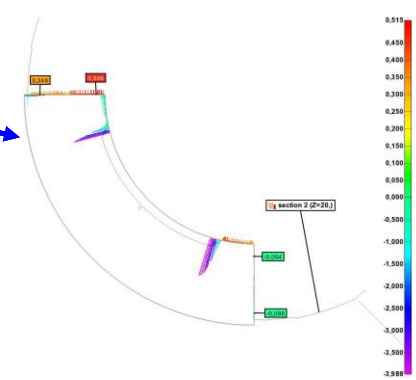
comparaison avec modèle CAO 1/4 de tube Øext. 230mm et Øint 149mm longueur 7400 mm
pour écarts à surface

position des sections





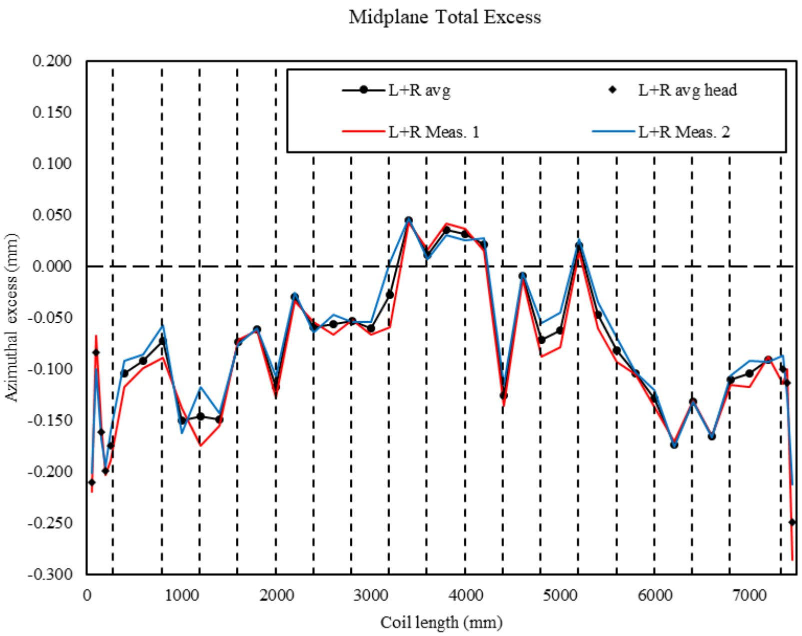




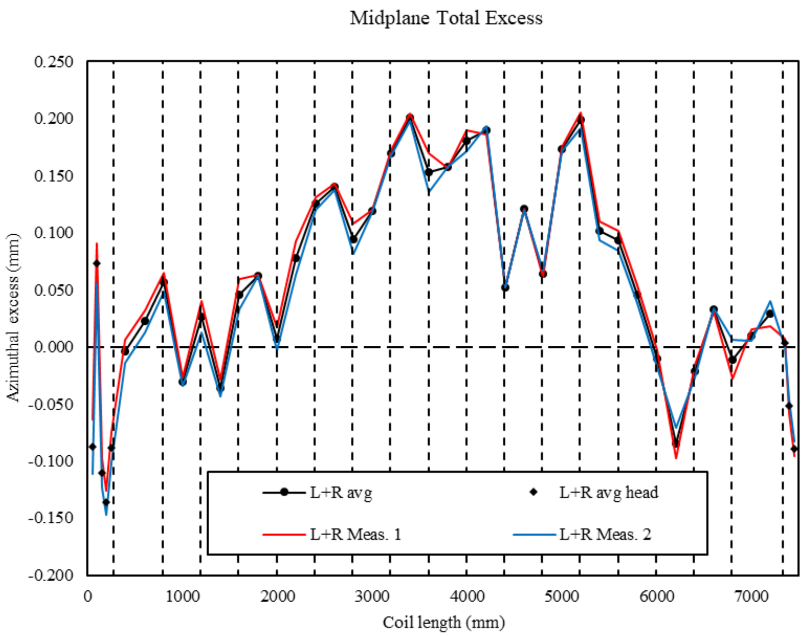
Metrology: CR126 and CR127

- Usual "belly" shape
  - Coil CR126 is a bit smaller than CR127 due to the double closure of the impregnation fixture (Fuji paper tests), a similar effect was already observed in another coil

CR126



CR127



Outline

- Coil fabrication status
  - Dashboard
  - General context
- Improvements and lessons learnt
  - Coil CR126
    - New features
    - Measurements during coil fabrication
    - Fuji paper test
  - Coil CR127
    - New features
    - Measurements during coil fabrication
    - Dimensional scanning after heat treatment
  - Metrology CR126 and CR127
- **Conclusions**

Conclusions

- Performance limitation of MQXFBP1 and MQXFBP2 pointed to the central region of the coils → main drive of the analyses
- Focus on
  - Coil cut for post-mortem inspections (metallography and deep copper etching)
    - Broken filaments in several pole-to-pole transitions in coil CR108 (limiting coil in MQXFBP1)
    - Broken filaments in one pole-to-pole transition in virgin coil CR126
  - Manufacturing data → systematic behaviour
    - Coil "hump" towards the middle of the coil after RHT
    - Higher torque to close the impregnation fixture towards the longitudinal center
    - Azimuthal coil size systematically larger in the longitudinal center (0.150 mm per side)
- Pre-transition coil CR126
  - Improved tooling for handling and QH mini-swap
  - Used to better understand a possible mechanism linked to the broken filaments
  - Standard manufacturing procedure, with additional Fuji paper tests during impregnation fixture closure
  - High stress concentrations in the IL pole block close to the pole-to-pole transitions

Conclusions

- 1st transition coil CR127
  - New features to avoid/reduce constrains in the reacted coil
  - Additional measurements during the closure/opening of the fixtures → reacted coil elongates during the opening of the reaction fixture by ~10 mm
  - MetraSCAN of the IL of the coil after RHT → correlation between IL and OL of the coil
- Modifications in CR127 did not play a significant role → usual behaviour after RHT
- The 2nd transition coil CR128 is in preparation
  - Features from coil CR127 will be kept
  - Changes will be introduced at the level of the curing

Thank you!

A special thank you to the MQXFB coil fabrication team for the dedication and attitude shown during this not easy period!

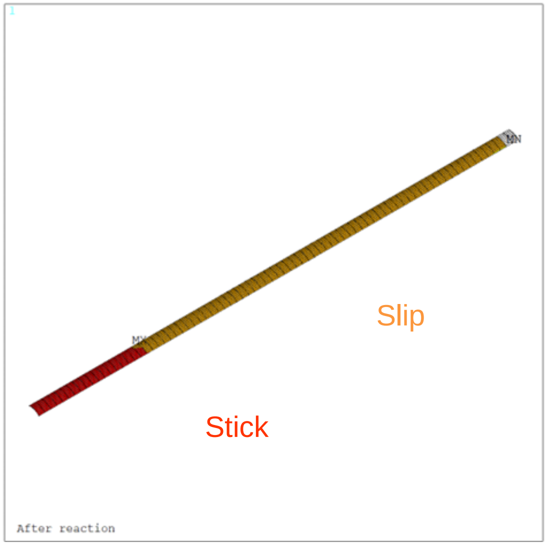
Spare slides

Possible mechanism

- MQXF reaction fixture assumes 4.5 % (1.2 %) azimuthal (radial) expansion of the conductor during heat treatment
  - The expected expansion is ≈ 3 % azimuthally, < 1 % radial, but the design approach was to be conservative in terms of free space in the reaction cavity
- Experiments on strands, cables and coils (insulated/non-insulated) have shown that the volumetric expansion of the conductor is ≈ 3 %, but the azimuthal, radial and axial expansion depends on the way the cable is constrained (see [1])
- Due to the friction of the coil to the tooling, the constrain seen by the coil is different in the middle and close to the ends: the middle of the coil might be locked by friction whereas closer to the ends the coil can slide
  - This mechanism gets more important when increasing the coil length, MQXFB are the longest Nb_3Sn coils ever built
  - Due to the different constrains seen by the coil, larger azimuthal increase of the conductor size in the middle than close to the ends, resulting in a bigger coil in the middle after heat treatment (by ≈ 2 mm per side in free state).
  - The coil is rigid enough to deform the impregnation tooling and keep the signature after reaction, with an excess of arc length of ≈ 0.1 mm per side

TABLE V
SUMMARY OF AVERAGE DIMENSIONAL CHANGES FOR CABLES AND COILS

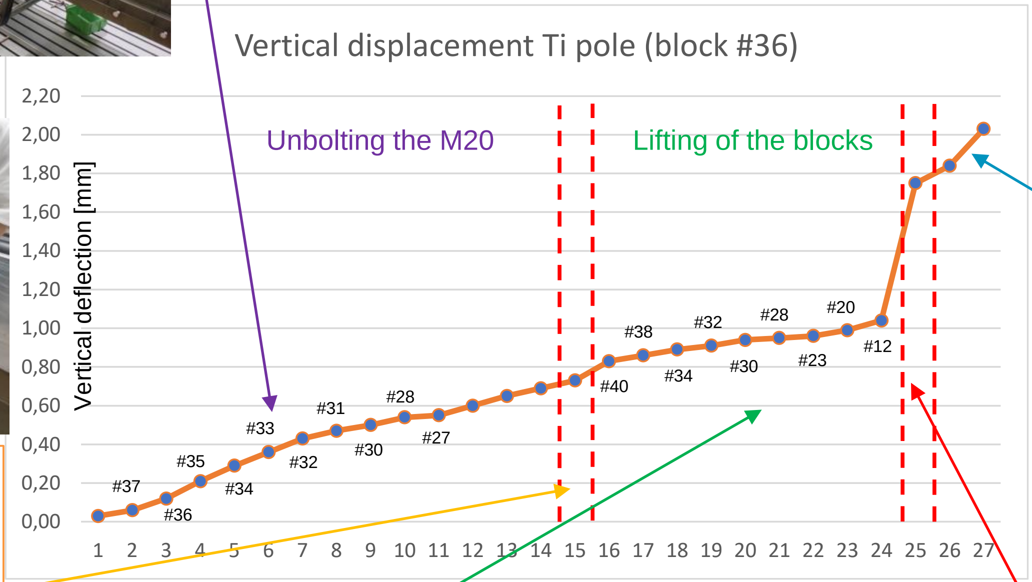
Conductor	Insula -tion	Thick. [%]	Width [%]	Length [%]	Area [%]	Vol. [%]
MQXF cable	Sleeve	2.8	1.1	-0.4	3.9	3.5
	Braid	3.2	0.0	-0.1	3.2	3.1
CERN 101	Braid	3.0	0.1	-0.04	3.1	3.0
LARP 1	Braid	3.1	0.5	-0.2	3.6	3.4



[1] E. Rochepault et al., "Dimensional Changes of Nb3Sn Rutherford Cables During Heat Treatment," in IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-5, June 2016, Art no. 4802605, doi: 10.1109/TASC.2016.2539156.

CR126: opening of the reaction fixture

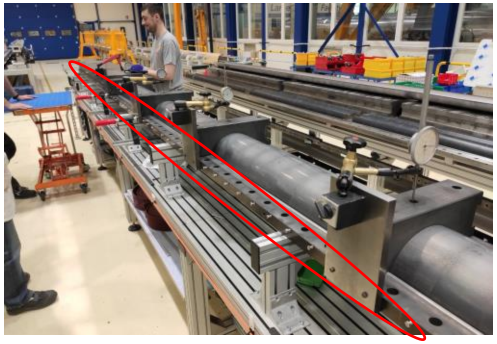
Unbolting the M20
Gradual lifting of the pole, starting 2 blocks before the unbolting of the concerned block. The vertical displacement stabilizes after unbolting 6-7 blocks



Coil in free state
The pole moved by 0.1 mm in 4-5 hours; 0.1 mm more 24 hours later

Lifting the top plate
0.05 mm vertical displacement when the top plate is lifted

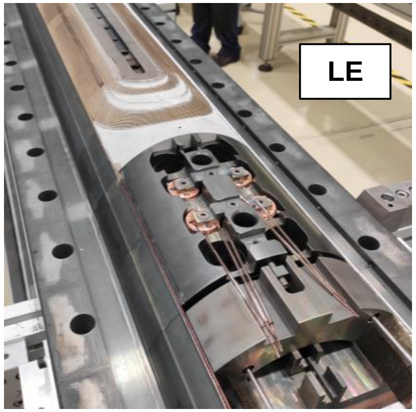
Lifting of the blocks
Gradual lifting of the pole, the 4 blocks before and after the concerned location have an impact on the vertical displacement

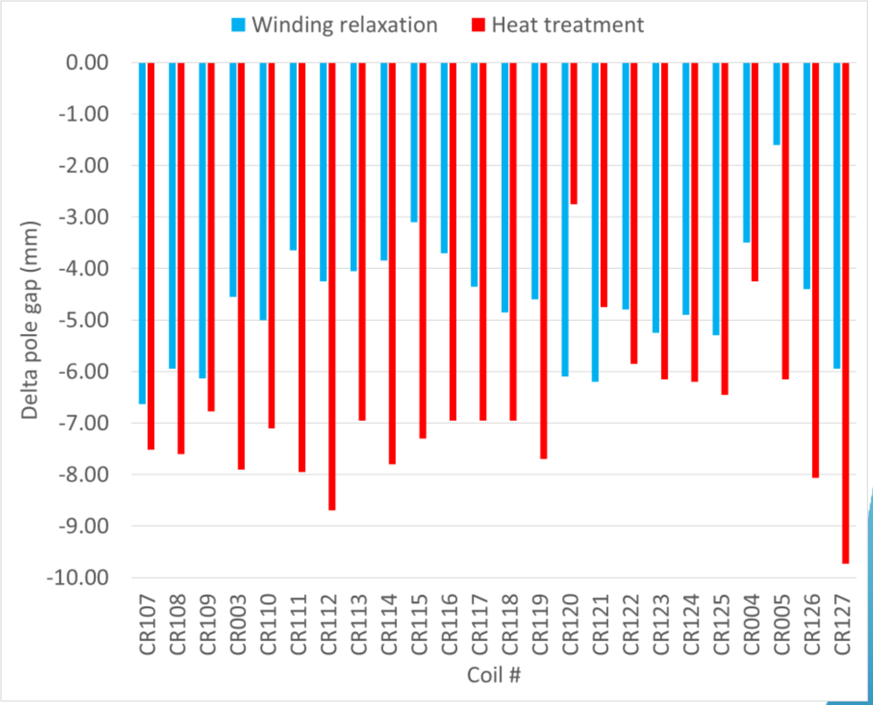


Unbolting the M6 (liner & filler)

CR127: pole gaps

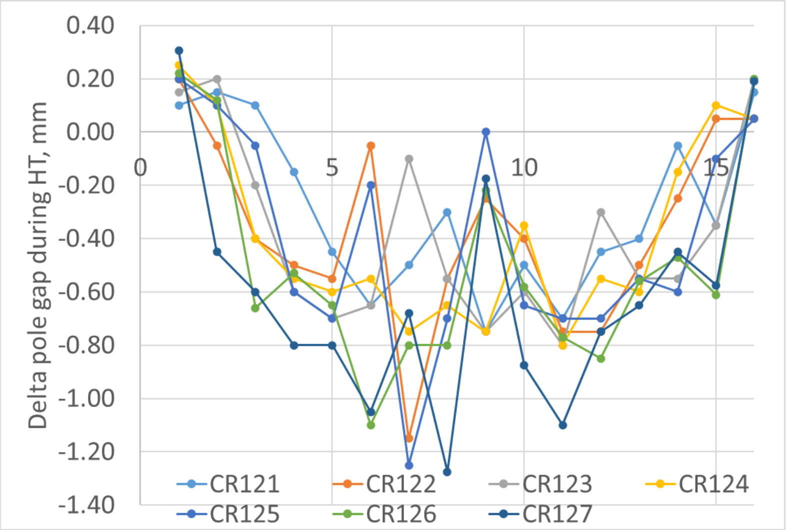
- Pole gaps were not closed after RHT once the reaction fixture was opened
- The pole gap closed almost 10 mm with respect to the value measured before HT





Pole gaps in CR126/127: longitudinal distribution

- The gap in the middle of coil CR127 is closed after heat treatment, but it was already almost closed before reaction when the coil was placed in the reaction fixture
- 0.3-1 mm gap left after heat treatment



CR126	total	17/16	16/15	15/14	14/13	13/12	12/11	11/10	10/9	9/8	8/7	7/6	6/5	5/4	4/3	3/2	2/1
avant bobinage	14.40	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
avant curing couche interne	14.40	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
après curing couche interne	14.90	0.70	0.90	1.15	0.80	0.90	1.00	0.95	0.90	1.05	0.80	1.05	1.05	0.95	0.90	1.00	0.80
avant curing couche externe	14.05	0.60	0.80	1.10	0.80	0.90	1.00	0.95	0.85	0.95	0.75	0.95	1.00	0.90	0.85	0.90	0.75
après curing couche externe (before stop)	12.85	0.00	0.75	1.10	0.85	0.90	1.10	0.85	0.80	1.00	0.65	0.95	1.05	0.90	0.75	0.95	0.25
après curing couche externe (after stop)	12.55	0.00	0.70	1.05	0.80	0.85	1.10	0.85	0.80	1.00	0.60	0.90	1.05	0.90	0.80	0.95	0.20
avant réaction	10.00	0.00	0.00	0.80	0.70	0.75	1.10	0.80	0.80	0.25	0.60	0.90	1.00	0.75	0.70	0.75	0.10
après réaction	1.94	0.22	0.12	0.14	0.17	0.10	0.00	0.00	0.00	0.03	0.02	0.13	0.15	0.19	0.23	0.14	0.30
CR127	total	17/16	16/15	15/14	14/13	13/12	12/11	11/10	10/9	9/8	8/7	7/6	6/5	5/4	4/3	3/2	2/1
avant bobinage	24.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
avant curing couche interne	23.65	1.45	1.45	1.50	1.50	1.50	1.50	1.50	1.50	1.45	1.55	1.45	1.45	1.45	1.45	1.45	1.50
après curing couche interne	24.10	1.30	1.50	1.70	1.40	1.55	1.50	1.55	1.45	1.55	1.60	1.60	1.45	1.50	1.50	1.60	1.35
avant curing couche externe	22.30	1.10	1.40	1.50	1.30	1.40	1.40	1.40	1.40	1.40	1.40	1.55	1.50	1.45	1.40	1.45	1.25
après curing couche externe	22.85	0.30	1.50	1.70	1.45	1.55	1.50	1.60	1.45	1.55	1.60	1.65	1.45	1.55	1.45	1.55	1.00
avant réaction	18.05	0.03	0.90	1.60	1.30	1.30	1.60	1.00	1.95	0.23	1.55	1.55	1.35	1.30	1.20	1.15	0.04
après réaction	8.32	0.34	0.45	1.00	0.50	0.50	0.55	0.32	0.68	0.06	0.68	0.45	0.60	0.65	0.75	0.58	0.23

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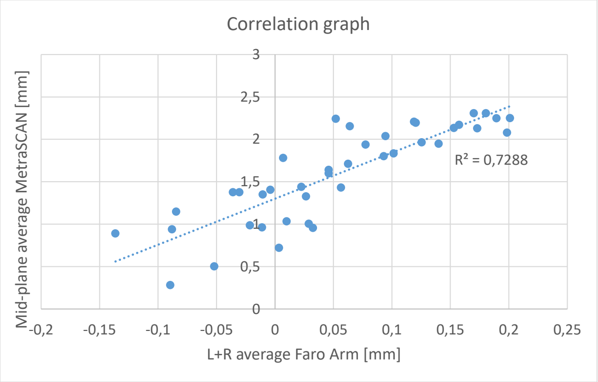
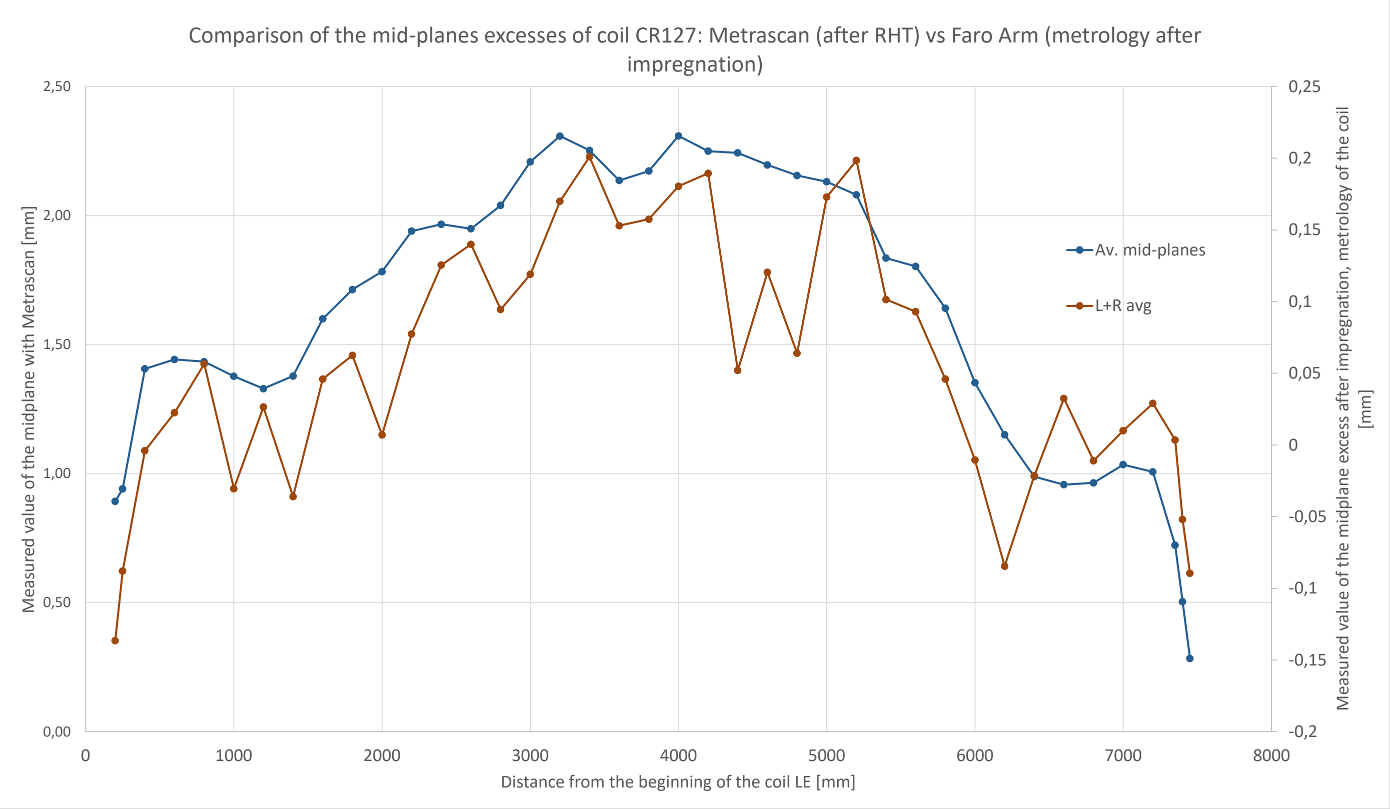
Metrology: CR127

- Comparison of the midplane excesses given by
  - The metrology done with the Faro Arm on the impregnated coil
  - The scan done with Metrascan of the same coil after RHT
- Overall good correlation

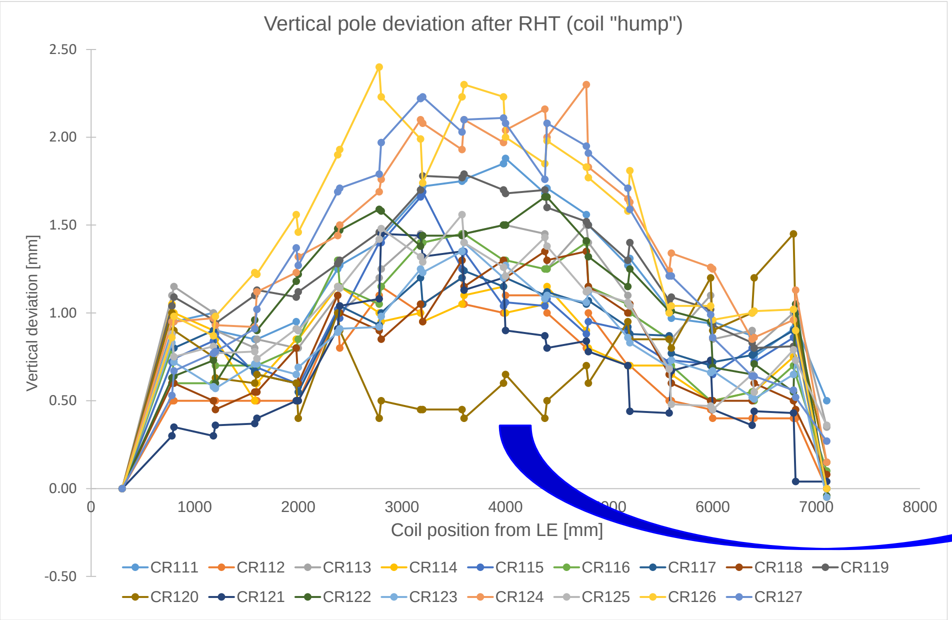


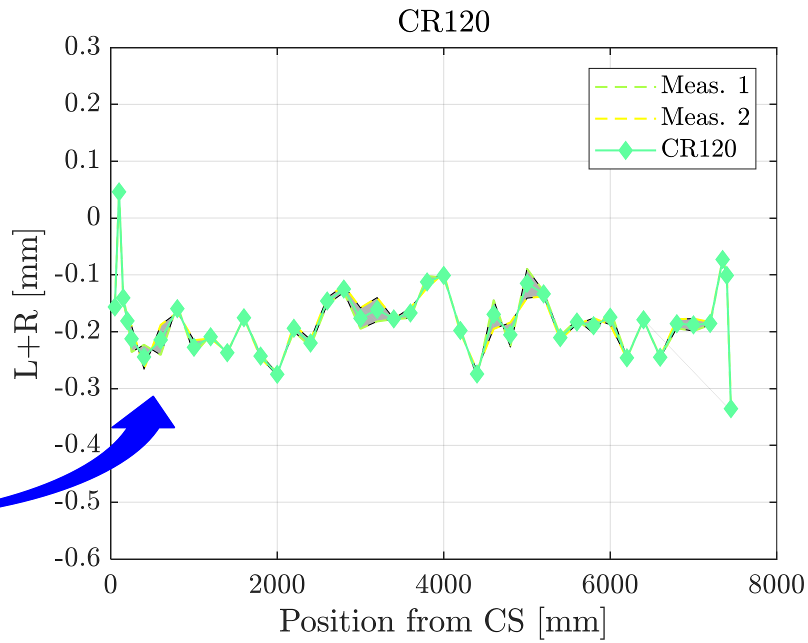


Vertical deflection of the coil after reaction and azimuthal excess of the impregnated coil

- In coil CR120 and in the copper coils, no “hump” is observed in the middle of the coil after HT
- The coil azimuthal excess after impregnation is uniform along the length

the two effects could be correlated!





[NCR EDMS 2419556]

[Technical Note EDMS 2670844]