Coil fabrication status at CERN

Susana Izquierdo Bermudez
on behalf of the MQXF fabrication and QA team

9th HL-LHC Collaboration Meeting
14-16 October 2019
Fermilab, Batavia, USA

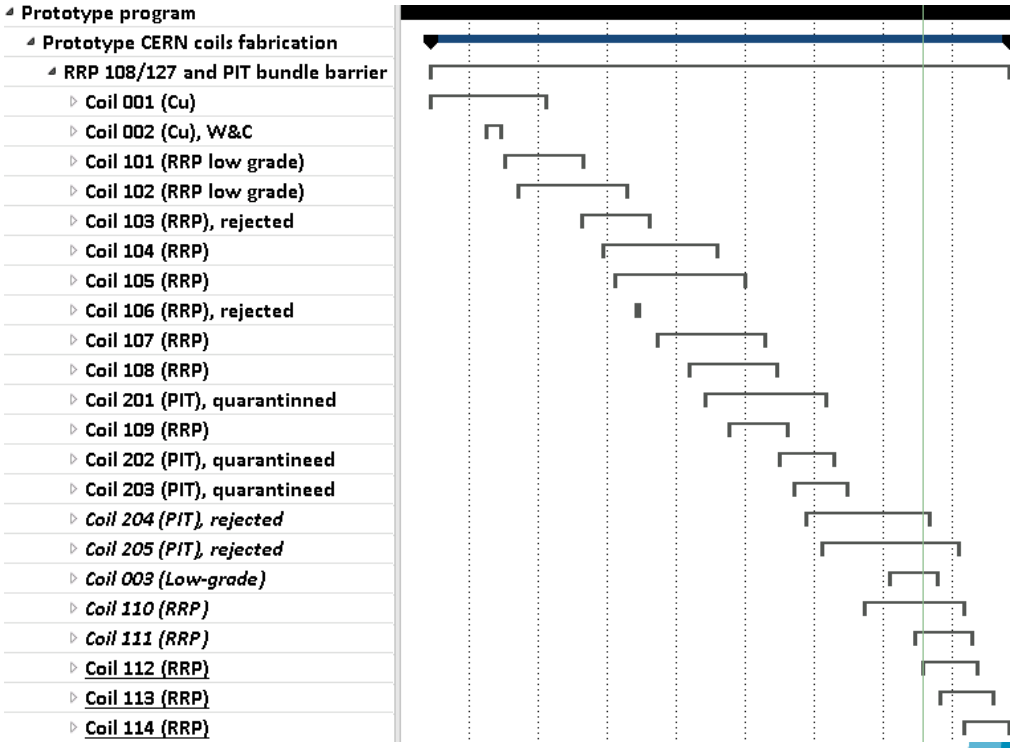
Coil Production Overview

Coil	Start fab.	End. Fab	Comment	Magnet
Coil 001	21/03/16	20/01/17	Copper	MQXFBMT1
Coil 002	15/08/16	23/09/16	Copper	Only W&C
Coil 101	03/10/16	28/04/17	Lowe grade RRP	MQXFBMT1
Coil 102	07/11/16	23/08/17	Lowe grade RRP	MQXFBMT1
Coil 103	24/04/17	20/10/17	RRP, Rejected	MQXFBMT1
Coil 104	19/06/17	16/04/18	RRP, OK	MQXFBP1
Coil 105	24/07/17	29/06/18	RRP, OK	MQXFBP1
Coil 106	18/09/17	--	RRP, Rejected	
Coil 107	13/11/17	31/08/18	RRP, OK	MQXFBP1
Coil 108	05/02/18	21/09/18	RRP, OK	MQXFBP1
Coil 201	19/03/18	01/02/19	PIT, Regrade	MQXFBMT2
Coil 109	21/05/18	19/10/18	RRP, OK	--
Coil 202	01/10/18	22/02/19	PIT, Regrade	MQXFBMT2
Coil 203	09/11/18	29/03/19	PIT, Regrade	MQXFBMT2
Coil 204	10/12/18	Ready for impreg.	PIT, Rejected	MQXFBMT2
Coil 205	21/01/19	Heat Treatment	PIT, Rejected	--
Coil 110	13/05/19	Prep for HT	RRP	--
PRODUCTION ON-HOLD: “DEBUGGING”				
Coil 003	18/07/19	Prep for impreg.	Low grade RRP	--
Coil 111	23/09/19	Cured	RRP	--
Coil 112	Not started	Not finished	RRP	--

MQXFMT: Mechanical Test Assembly

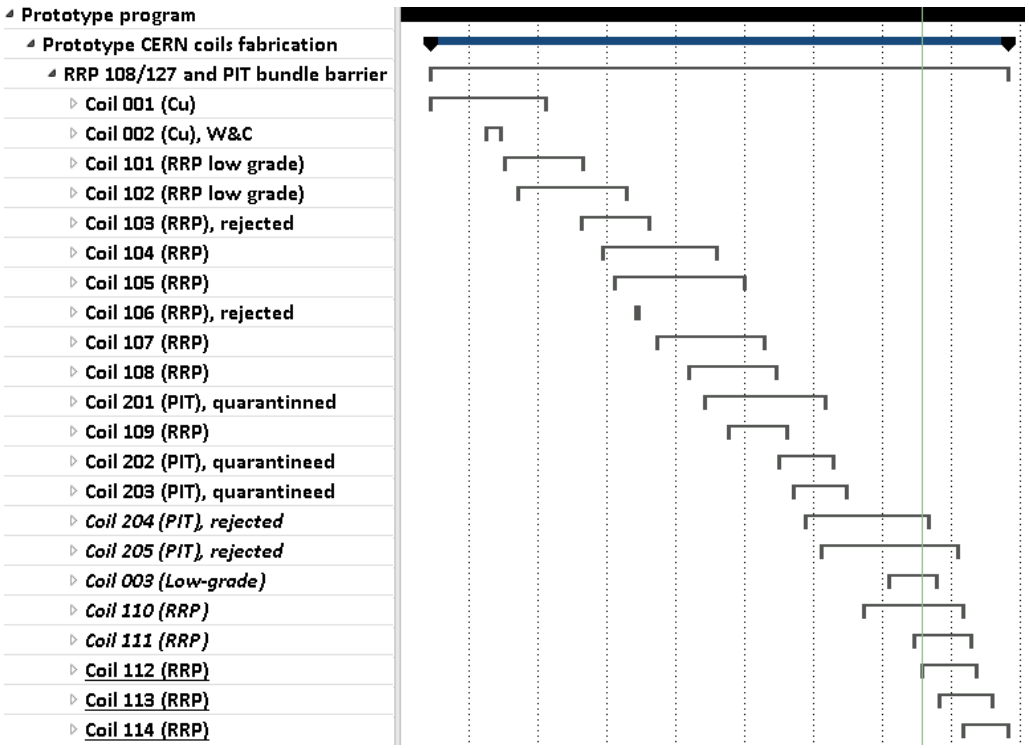
Coil Fabrication Status

- Working on
  - 204: Impregnation this week
  - 003: Preparing for impregnation
  - 205: Reaction just finished, waiting for impregnation fixture
  - 110: Preparing for reaction
  - 111: Waiting for reaction fixture
  - 112: Almost ready to start winding



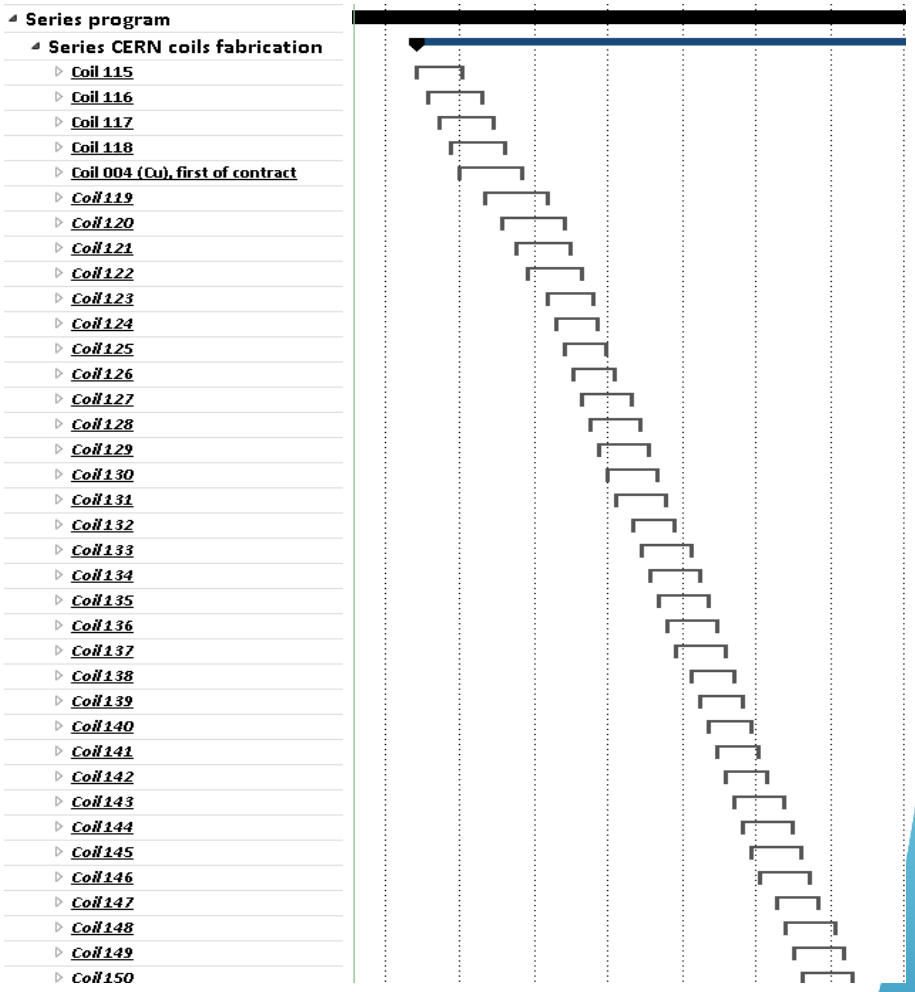
Coil Fabrication Status

- Second prototype
  - 110&111: W&C done
  - 112,113,114
- To be completed mid-2020
- 109 is kept for now as spare



Coil Fabrication Status

- First series magnet
  - Coil 115-119
  - To be completed by end of 2020
- “Contract” starting with coil 004 in mid 2020

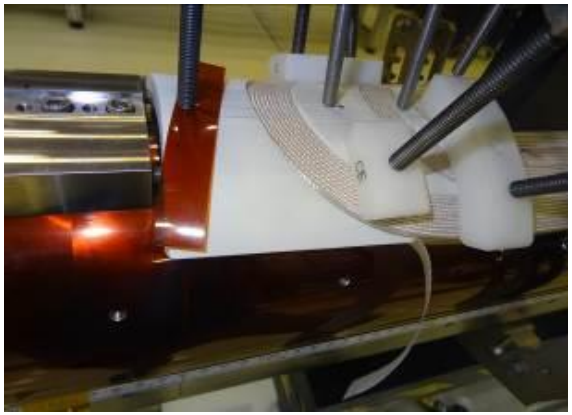
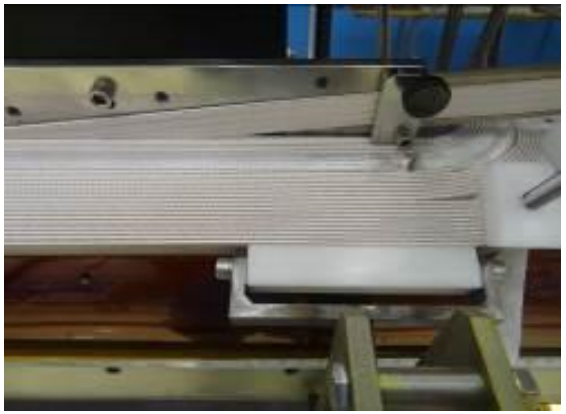


Spooling

- One critical non-conformity (coil 106)
- Interchange of the cable lengths in inner and outer layer reels → not enough cable to wound outer layer. IL unwound, OL used for short model.
  - NC report EDMS 1830153
  - Action: Checklist and cable reel measurements

Winding

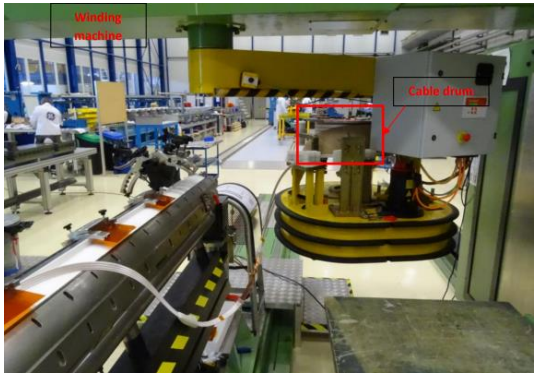
- We went through a in depth review of the procedure during the de-bugging phase, to align the experience short-long coils. The more controversial one where we did not converge:
  - Short coils: Winding tension on short models is kept constant with 25 kg
  - Long coils: 19 kg turned out to be adequate in terms of tension/instability. On the pole ends it is reduced to 7 kg while the manipulator rotates around the pole end, afterwards increased back to 19 kg.

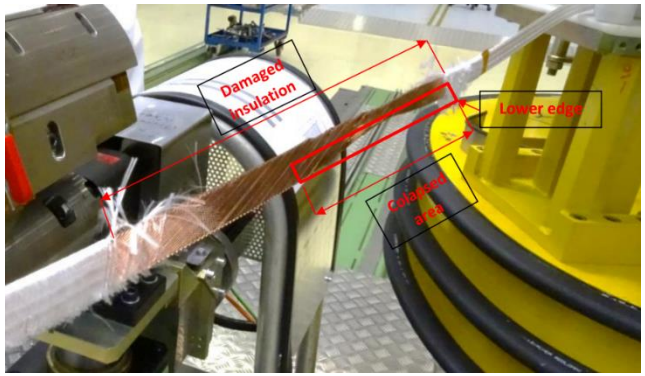



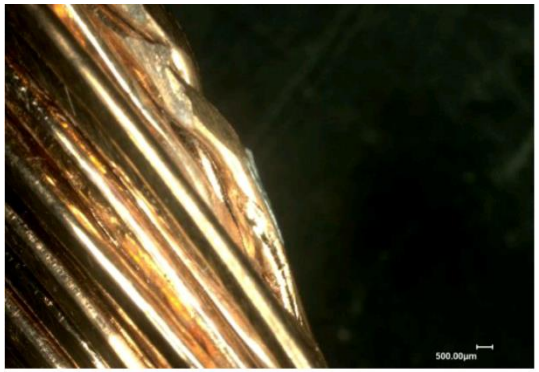

Outcome from de-bugging process: https://indico.cern.ch/event/852763/

Winding

- One critical non-conformity (coil 201)
- During winding OL (turn 1), cable collapsed. Coil was finished, and it will be used for the second mechanical assembly test (MQXFBMT2).
  - Root cause: OL cable drum not fixed on the winding arm. NC report EDMS 1964025
  - Action item: Add QC - check list of preconditions prior start of winding

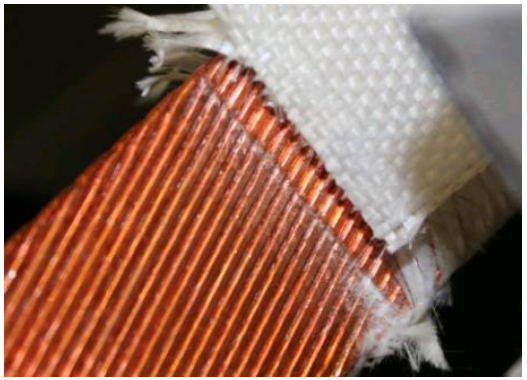


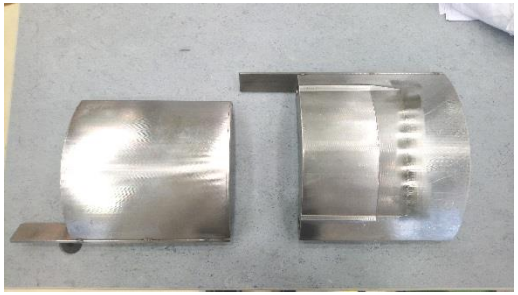




Curing

- One critical non-conformity (coil 205)
- Lead filler was blocked during curing, resulting on a damage of the
  - Root cause: Bad installation of the lead filler NC report EDMS 2087338
  - Action: Filler welded to splice block

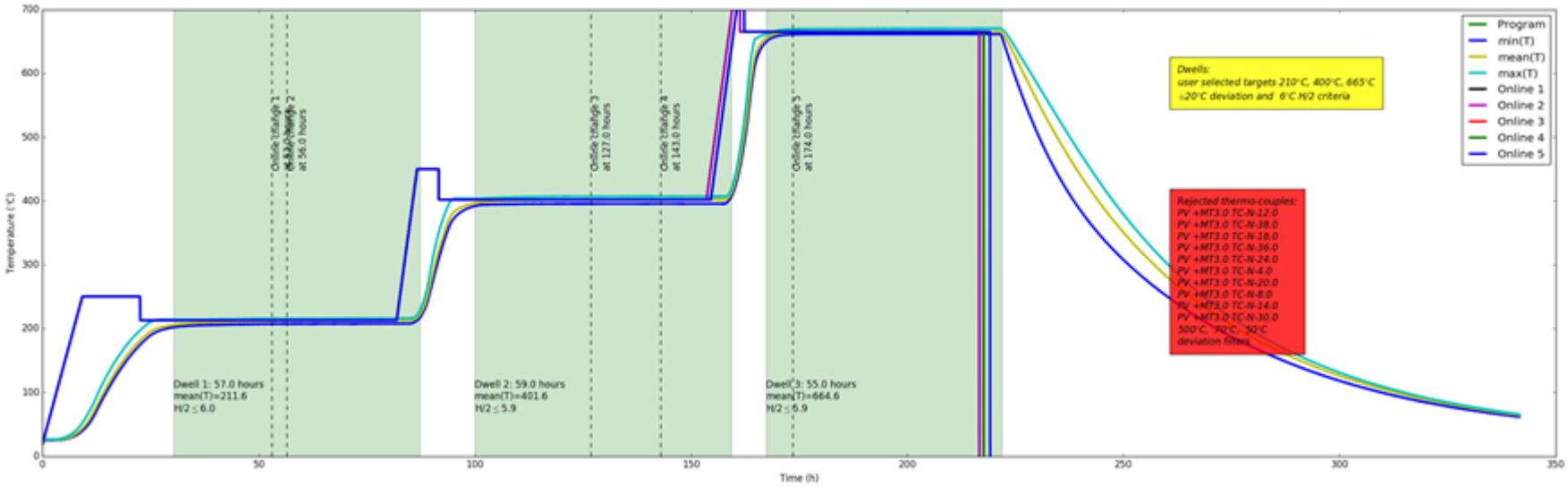




Heat treatment

- Fine tuning of the oven parameters requires on-line adjustments of the plateau lengths and temperature, including boosts.
- Practice coil 003 was used to finalize the heat treatment parameters, aiming at react coils (from coil 110) without the need of on-line adjustments.

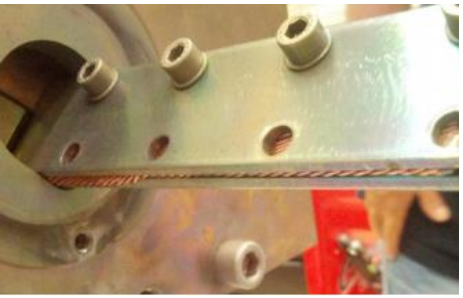
Temperature profile for coil 109



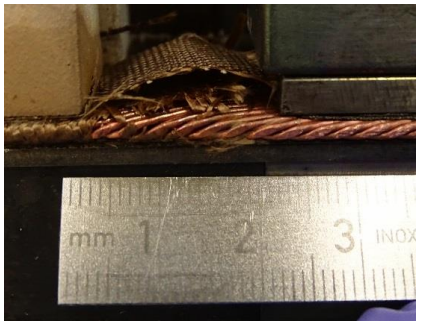
- Two critical non-conformities (coils 103 and 204)
- Electrical weakness after reaction in three coils (coils 201, 202 and 203)

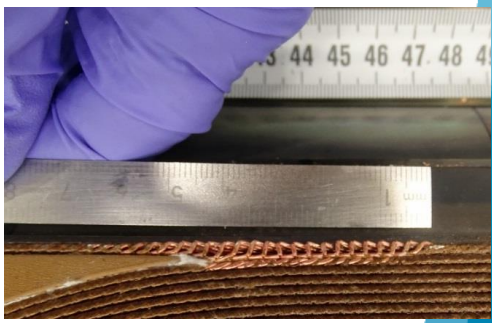
Heat treatment – NC (1/2)

- Leads got severely damaged in coil 103 during heat treatment.
  - Root cause: Non-verified tooling to support of the coil leads during heat treatment block the cables NC report EDMS 1831925
  - Action: No tooling adaptation without prior approval



- Damage of the cable in the splice region of coil 204, over a length of 600 mm.
  - Root cause: Bad installation of the lead filler → got bonded to the cable NC report EDMS 2112154.
  - Action: Lead filler welded to splice block



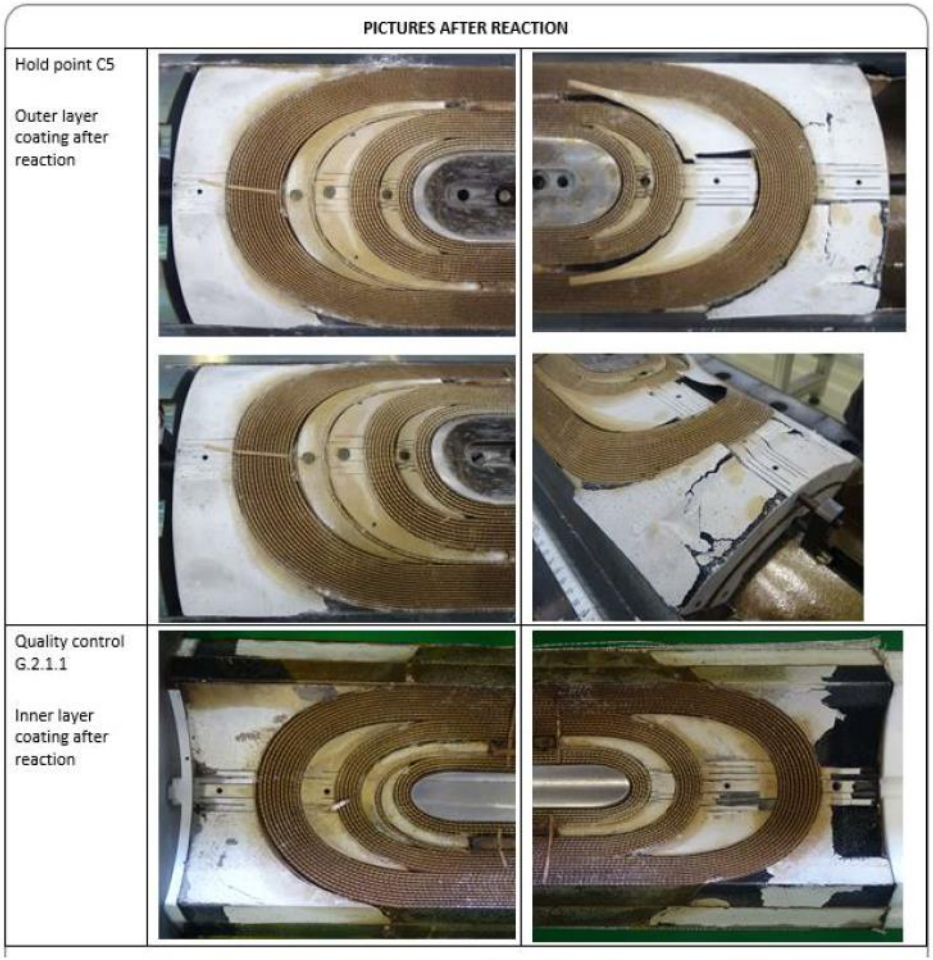


Heat treatment – NC (2/2)

- Short coil to end-shoe after impregnation in coils 201, 202 and 203.

- Root cause: Alumina coating on the end-spacers delaminates after heat treatment. NC report EDMS 2113779 & NC report EDMS 2142901
- Action:
  - End spacers will be coated by AUP supplier
  - Heat clean S2 glass table installed around spacers

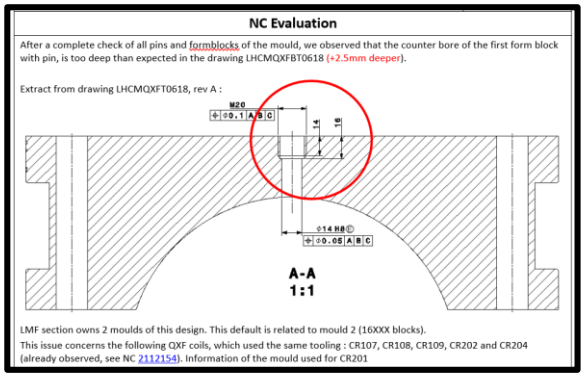
QH-to-coil (V)	Coil-to-endshoe (V)
Coil 101	1000 (R=15 GΩ)
Coil 102	1000 (R=5 GΩ)
Coil 104	1000 (R=18 GΩ)
Coil 105	1000 (R=110 GΩ)
Coil 107	1000 (R=54 GΩ)
Coil 108	1000 (R=51 GΩ)
Coil 201	Short RE outer
Coil 109	1000 (R= 1000 GΩ)
Coil 202	Short LE inner
Coil 203	Short LE inner

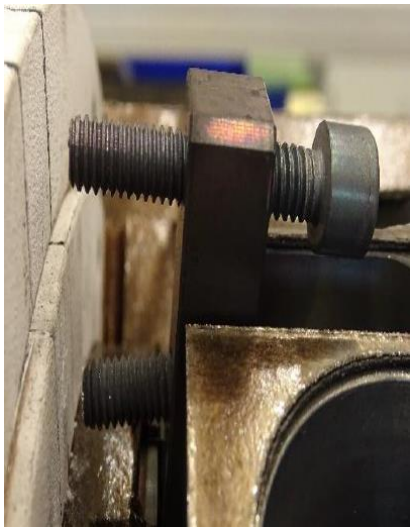


Extraction form NCR 2060087

Heat treatment – other concerns

- In coil 204, friction marks pole-centring pin were found.
- The problem re-appear in coil 003. The root cause was identified: defect on one of the reaction blocks, which allowed the engagement of the centring pin with the pole .
- The non-conformed block is discarded, and the clearance pin-pole groove has been increased by 0.05 mm since in the original design it was not sufficient to guarantee sliding in all temperature range.



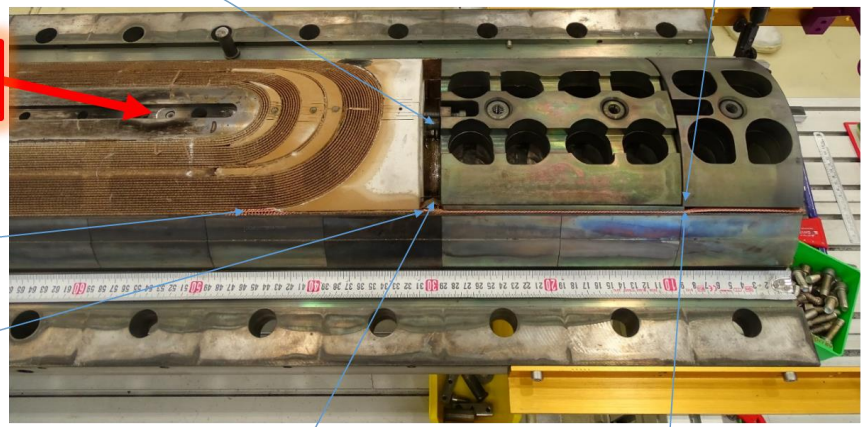


Coil 204

6. Plastic deformation: Guide screws (both extremities !), large thermal expansion and stress

5. Surface damage & cable deformation: surface damage on cable, insufficient length of mica.

7. Friction marks: pole and centring pin



1. Damage: strand/cable

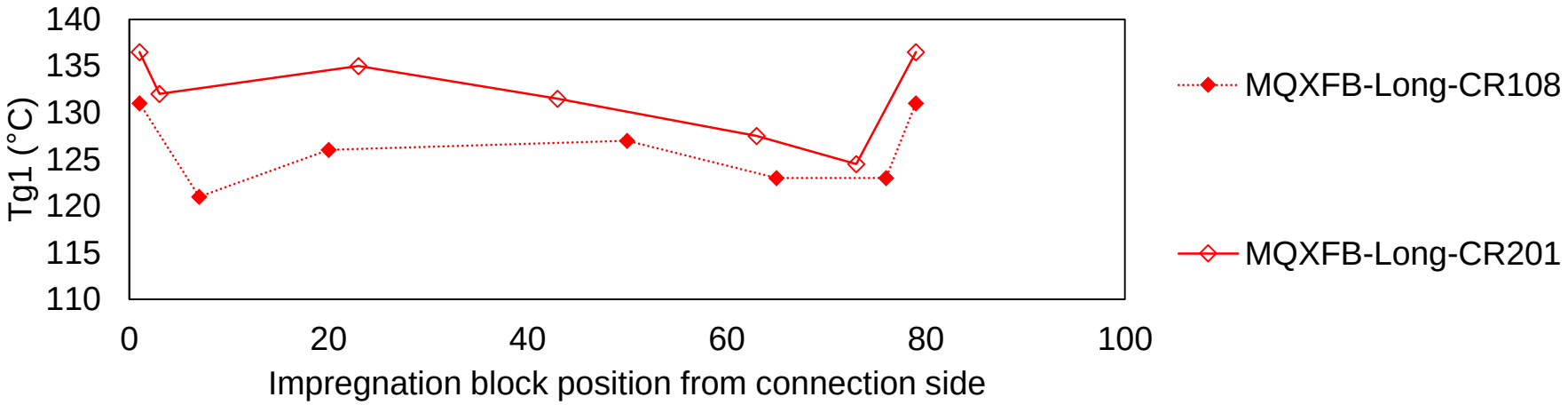
2. Damage: strand/cable

3. Unusual displacement: large gap between vamas block to end-spacer

4. Positioning error: Vamas block to filler wegde contact at pos. 100 mm

Impregnation

- We didn't have any critical non-conformities, nevertheless, we wish to further qualify the impregnation process (today we record temperatures, times and pressures, and we evaluate based on visual inspection).
- Tg was measured in coils 108 and 201 to study the impact of soaking.
- Coils 204 and 003 are planned to be used to further characterize the impregnation process:
  - Thermocouples inserted in the centring pins, very close to the coil, to better monitor the coil temperature → correlate to Tg measurements.



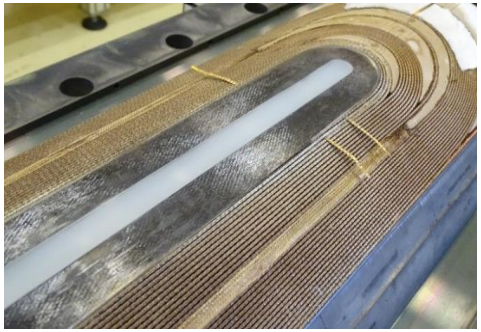
See talk from Arnaud Devred & Jose Luis Rudeiros

Open “Issues” – Electrical insulation Coil-Pole

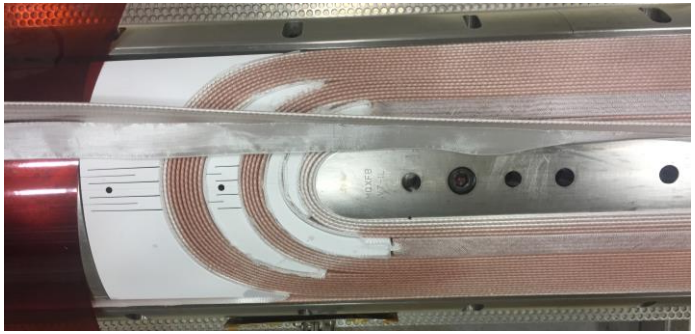
- Requirement: HiPot at 500 V
  - Pole is floating, and alignment key is made of G11
  - Max ΔV turn-turn through pole: 50 V
- <u>Corrective Actions:</u>
  - 5 instead of 4 layers of S2 glass between coil and pole starting from coil 202 (b6 correction)
  - Heat clean S2 glass tape before pole insulation (from coil 110)
  - Apply binder starting from midplane and stop at 3rd turn
    - 4 turns from coil 111, and we reduce as well the amount of binder in the turns close to the end parts.

Magnet	Coil	Coil-to-pole (V)
Practice coil	Coil 001	60GΩ
Practice coil	Coil 101	41.9GΩ
Not tested	Coil 102	37GΩ
MQXFS1	Coil 103	42GΩ
MQXFS1	Coil 104	128GΩ
Not tested	Coil 201	79GΩ
Not tested	Coil 202	77GΩ
MQXFS3a-b	Coil 105	380GΩ
MQXFS3a-b	Coil 106	139GΩ
MQXFS3a-b	Coil 107	<10GΩ
MQXFS5-MQXFS6b	Coil 203	short
MQXFS5-MQXFS6b	Coil 204	5.3GΩ
MQXFS5	Coil 205	1.23GΩ
MQXFS5	Coil 206	3.28GΩ
Not tested	Coil 207	2.41GΩ
MQXFS6a	Coil 208	0.04GΩ
MQXFS6a	Coil 209	0.92GΩ
MQXFS4	Coil 108	0.005GΩ
MQXFS4	Coil 109	0.005GΩ
MQXFS4	Coil 110	1.13GΩ
MQXFS4	Coil 111	5.4GΩ
Not tested	Coil 112	3.31GΩ
MQXFS6a-b	Coil 210	0.873GΩ
Not tested	Coil 211	short
MQXFS6a-b	Coil 212	0.204GΩ

Coil after reaction



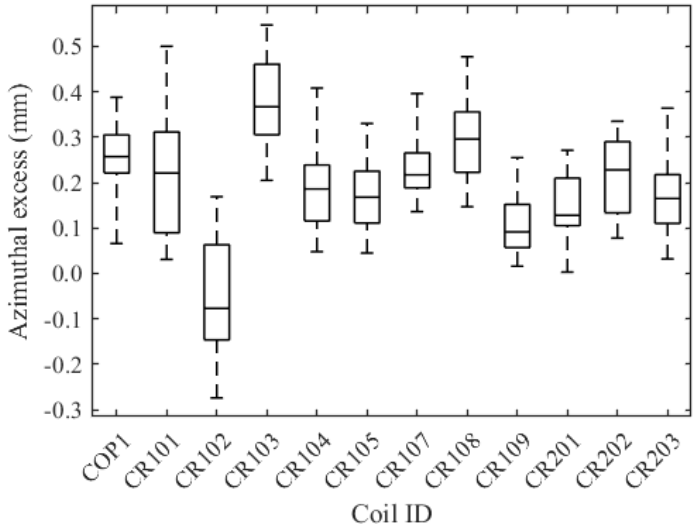
Coil 111 after applying binder



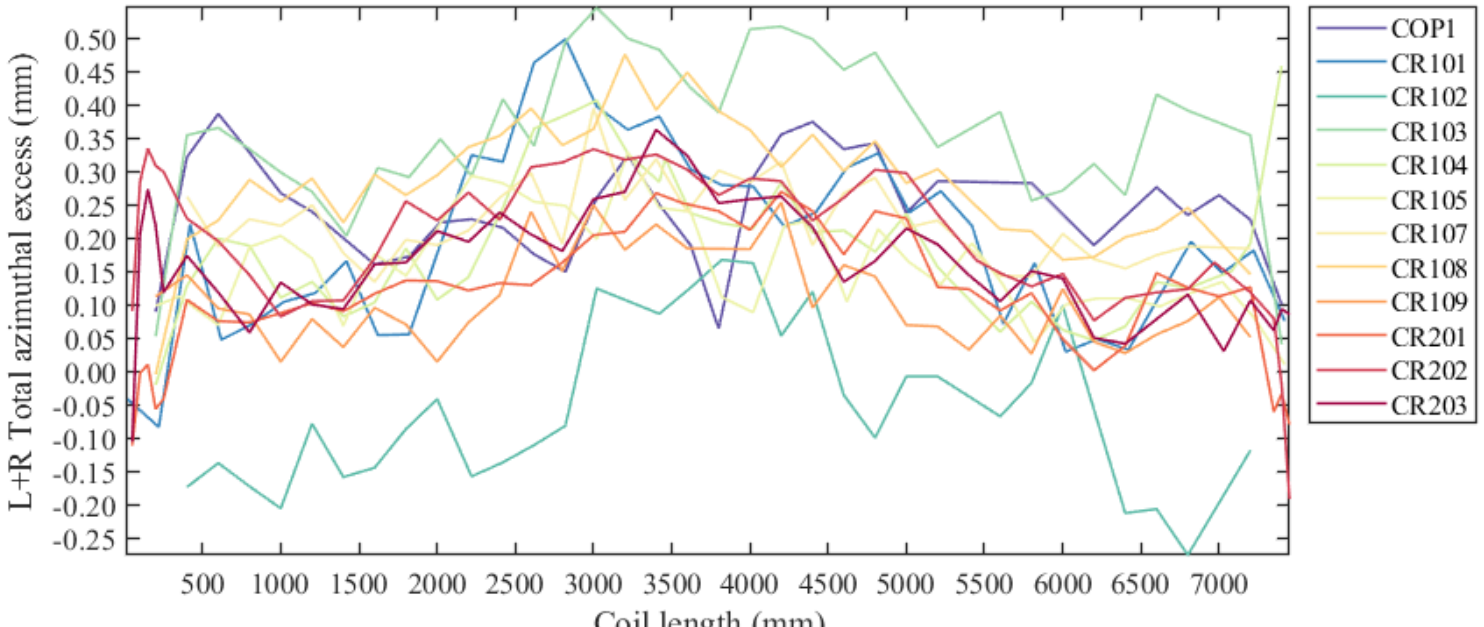
Magnet	Coil	Coil-to-pole (V)
Practice coil	Coil 001	Short coil to pole
Practice coil	Coil 002	Not performed
Practice coil	Coil 101	500 (R=0.8 GΩ)
Practice coil	Coil 102	500 (R=1.4 GΩ)
Practice coil	Coil 103	500 (R=270 MΩ)
MQXFBP1	Coil 104	500 (R=20 MΩ)
MQXFBP1	Coil 105	500 (R=30 MΩ)
NC	Coil 106	Not performed
MQXFBP1	Coil 107	500 (R=510 GΩ)
MQXFBP1	Coil 108	500 (R=338 MΩ)
NC	*Coil 201*	*500 (R=10 MΩ)*
Not tested	Coil 109	500 (R=360 MΩ)
Not tested	*Coil 202*	*500 (R=106 MΩ)*
Not tested	*Coil 203*	*500 (R=57 MΩ)*

Open “Issues” – Coil size

- Coils are systematically bigger than nominal.
- Coils are typically bigger in the centre.
- The difference of coil arc length along magnet axis is ~ 0.300 mm (i.e., 0.150 mm per side)

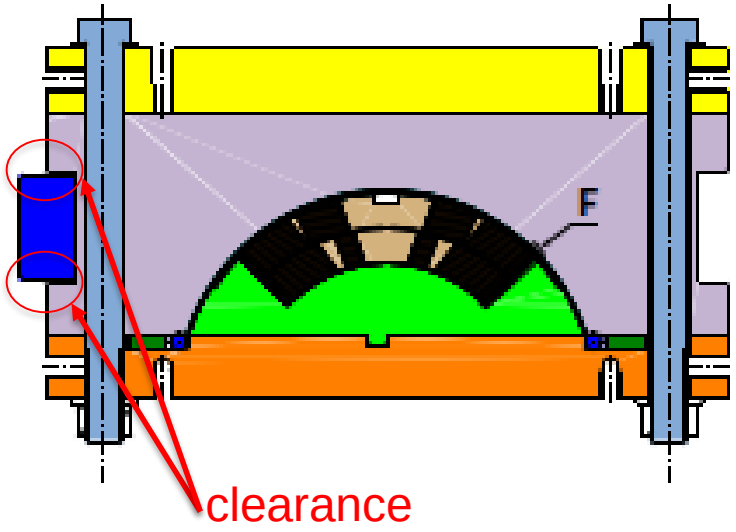


Remark: Midplane excess computation is performed with nominal OR of 113.376 mm for all coils.



Open “Issues” – Coil size

- One of the main difference founds with respect to the short coils are the side bars in the reaction and impregnation mould
  - For MQXFB coils we have the bar only in one side of the tooling
  - We have vertical clearance, so it doesn’t serve to the alignment of the blocks but provides longitudinal stiffness.



- In order to understand if the side bars have an impact on the final coil size and asymmetry:
  - Coil 203 and 003 were reacted with bars in both sides
  - We plan to impregnate Coil 204 with bars in both sides and Coil 003 without side bars

Open “issues” – Quench heaters

- Coils 204-003: External quench heaters
  - Difference on coil outer diameter compensated by introducing a 0.3 mm thick filler in between the two liners.

- Coil 205: Swap

Summary

- MQXFB coil fabrication started in 02/2016
  - 4 coils are assembled in the first prototype magnet, and we have a spare coil finished.
- A first review was carried out in 2018, bringing up the importance of a stable production team.
- Following the critical non-conformities in PIT coils, production was stopped to launch a debugging of procedures and MIP. The production of an additional practice coil was launched to validate findings and procedures improvements.
- Production re-started in 10/2019:
  - Production team and procedures have been consolidated
  - The production of the coils for the second prototype is on-going

Additional slides

Impact on difference coil size on pre-stress

TABLE I
IMPACT OF A 100 μm COIL SIZE INCREASE ON THE COIL STRESSES, MPa

	Al. Shell†	Pole†	Coil-Pole‡	Mid-Plane‡
RT Loading	5	-21	-12	-10
Cool-down	6	-20	-12	-10
Ultimate current	6	-25	-13	-10

† Strain gauge location, see Fig. 1.
‡ Mid-radius.

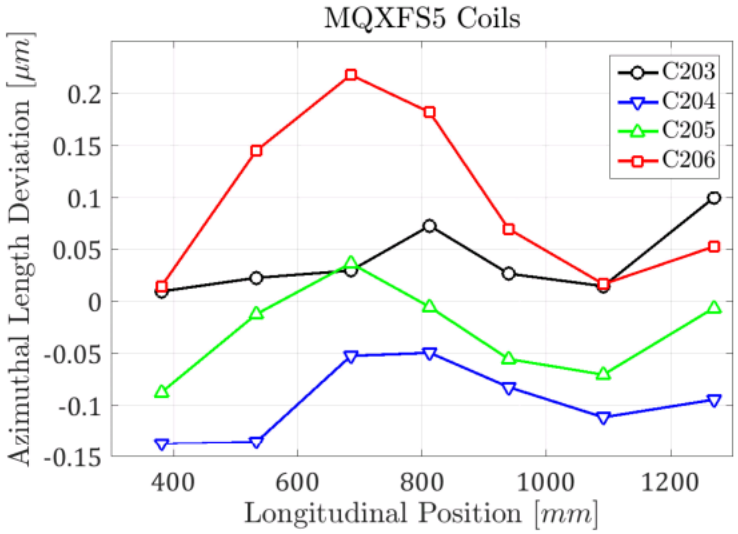


Fig. 6. MQXFS5 coil size along the length. The size deviations from the average are generally contained within ± 100 μm.

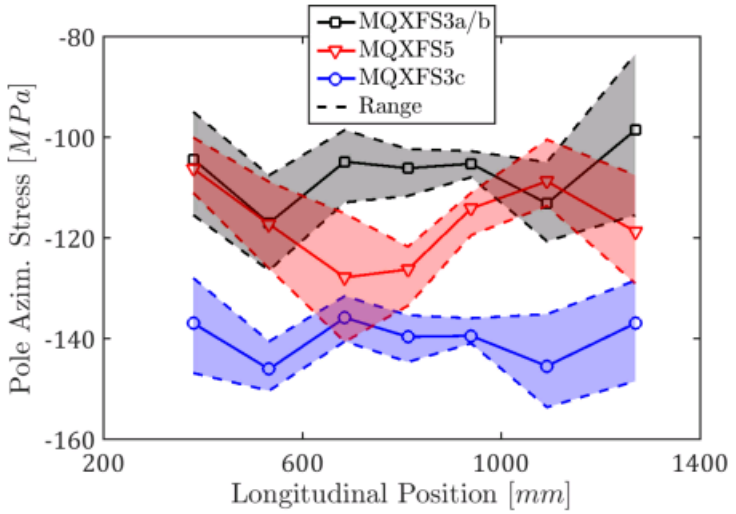
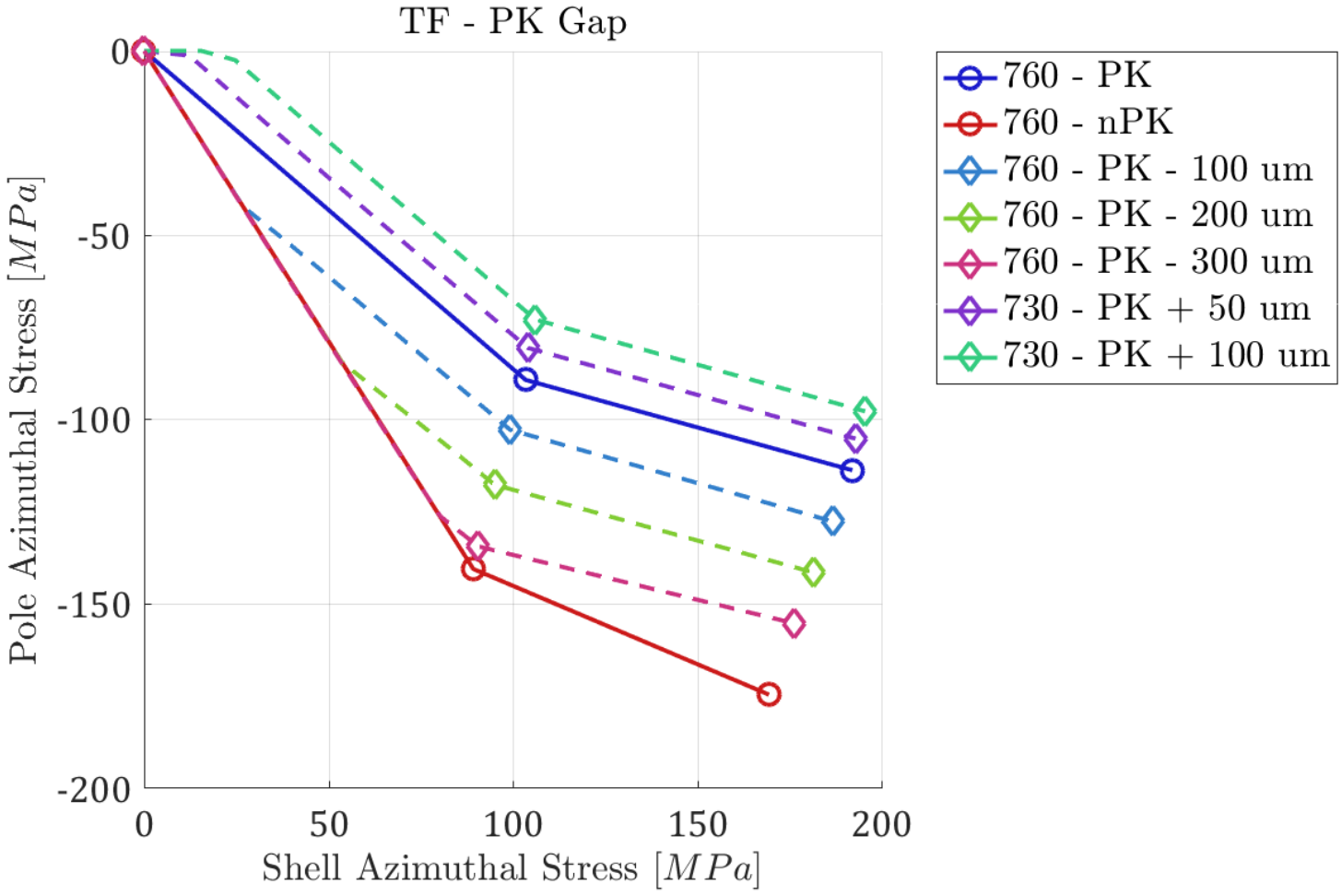


Fig. 7. Azimuthal prestress variation along the straight section. The results are computed on the basis of the measured size of the coils, using the FE approach. The computed stress variation is within ± 20 MPa in all the magnets.


TF - PK Gap
Pole Azimuthal Stress [MPa]
Shell Azimuthal Stress [MPa]
0
-50
-100
-150
-200
0
50
100
150
200
760 - PK
760 - nPK
760 - PK - 100 um
760 - PK - 200 um
760 - PK - 300 um
730 - PK + 50 um
730 - PK + 100 um