Towards MQXFB series coils

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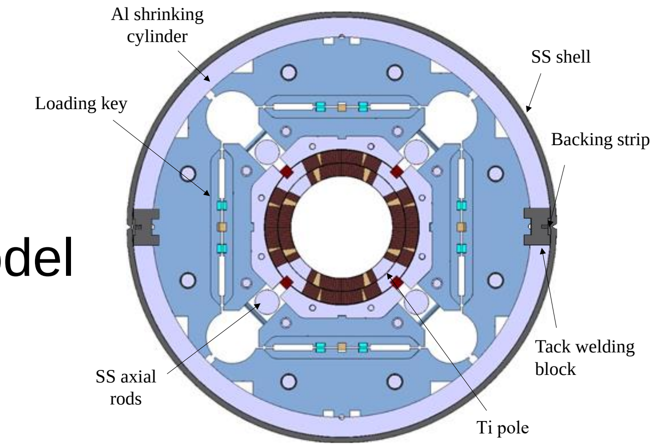
Outline

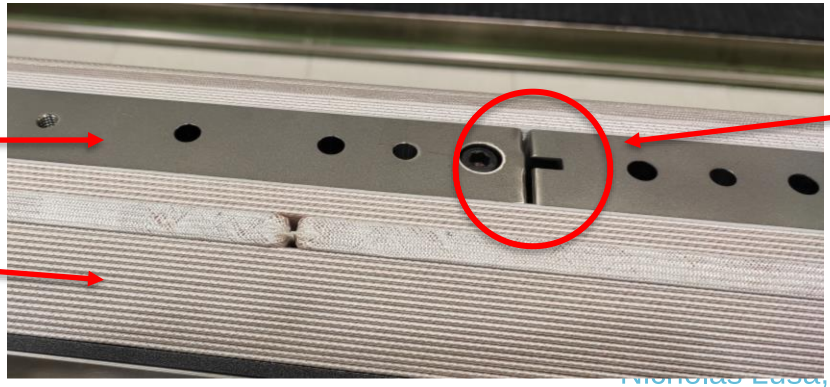
- **Introduction**
- Coil manufacturing observables
- New generation MQXFB coils
- Conclusions

Introduction

- MQXF magnets are the new inner triplets Nb_3Sn based for HL-LHC
  - Nominal operation (7 TeV): 16.23 kA, 132.2 T/m; **11.3 T B_{peak}**
  - **MQXFA** (by US-AUP) with 4.2 m L_m
  - **MQXFB** (by CERN) with 7.2 m L_m
  - MQXFA and MQXFB share the same cross-section (joint short model development program '**MQXFS**' to validate the design)

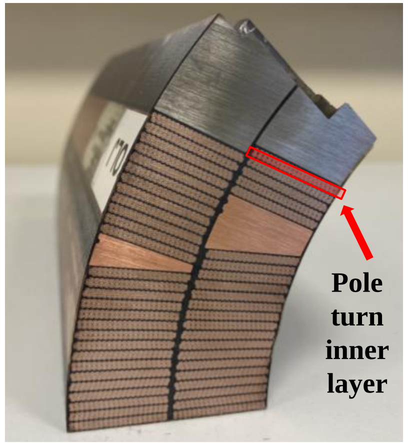


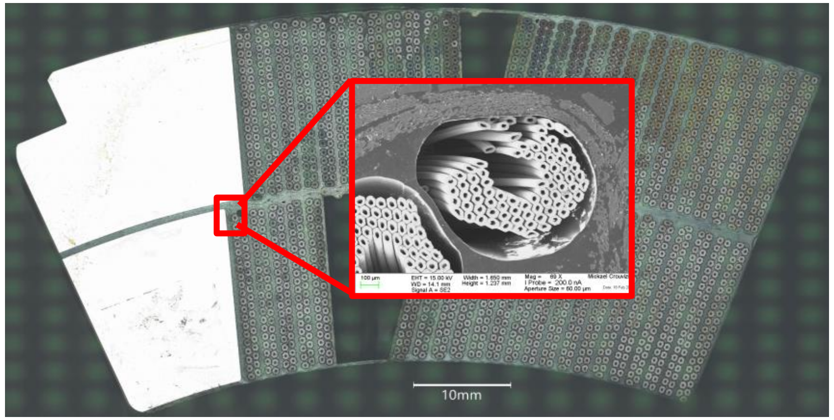
- MQXF coils are composed of 50 turns in two layers using a single unit length of S2 glass insulated cable.
- The cable is wound around several segmented Ti poles (heat treated and impregnated with the coil)



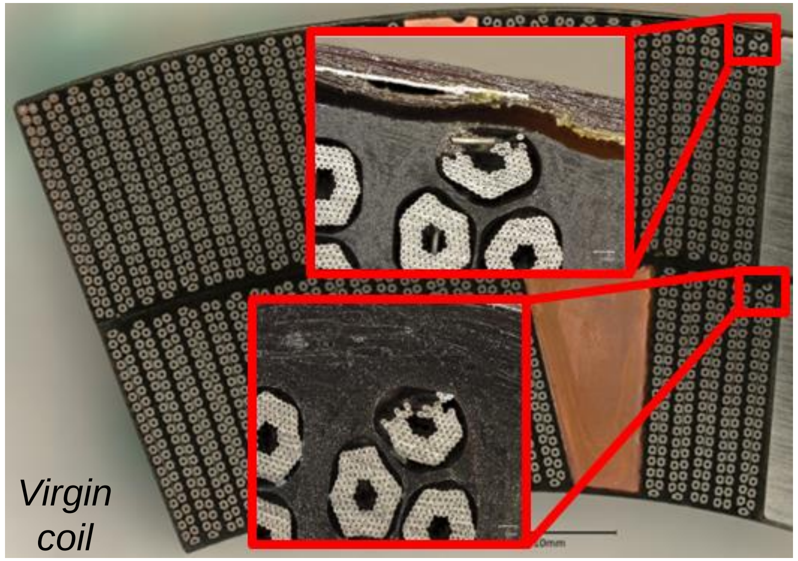
Introduction

- **MQXFBP1/BP2** were limited at 93% and 98% of the nominal current at 1.9 K (quench location in the IL pole turns near the magnet mechanical center)
- **MQXFBP3** and **MQXFB02** reached I_{nom} + 300 A at 1.9 K but showed similar limitations at 4.5 K
- Post-mortem inspections of MQXFBP1 limiting coil showed recurrent broken Nb_3Sn sub-elements in the IL pole turn close to pole-to-pole transitions
- Post-mortem inspections were performed also in virgin coil CR126 showing similar defects





MQXFBP1 limiting coil CR108



Virgin coil CR126

Introduction

- **MQXFBP1/BP2** performance limitation prompted stopping the coil fabrication
    - Analysis of the possible root causes:
        - Cold mass assembly
        - Magnet assembly
        - *Coil fabrication*

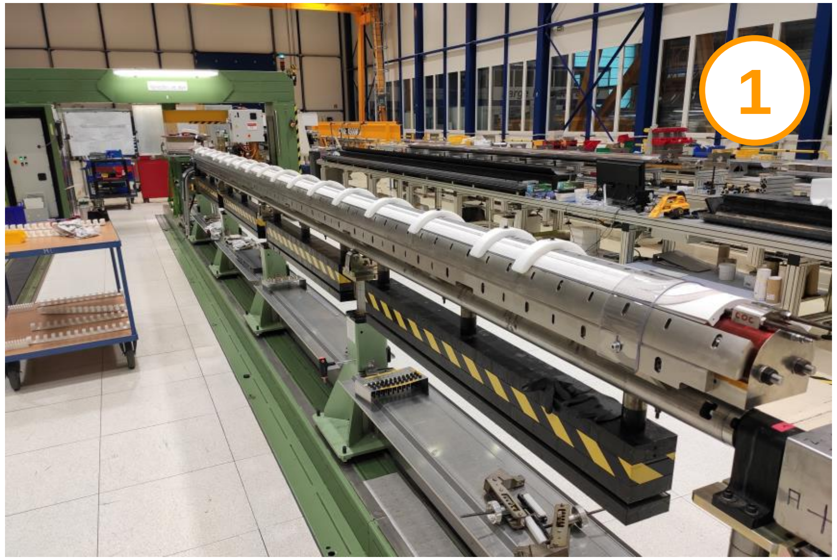
- **MQXFBP3** → *meets HL-LHC requirements* (I_{nom} + 300 A at 1.9 K with ≈ 2 K of temperature margin)
    - Implemented improvements from cold mass assembly
- **MQXFB02** → *meets HL-LHC requirements* (I_{nom} + 300 A at 1.9 K with ≈ 2.8 K of temperature margin)
    - Implemented also improvements from magnet assembly

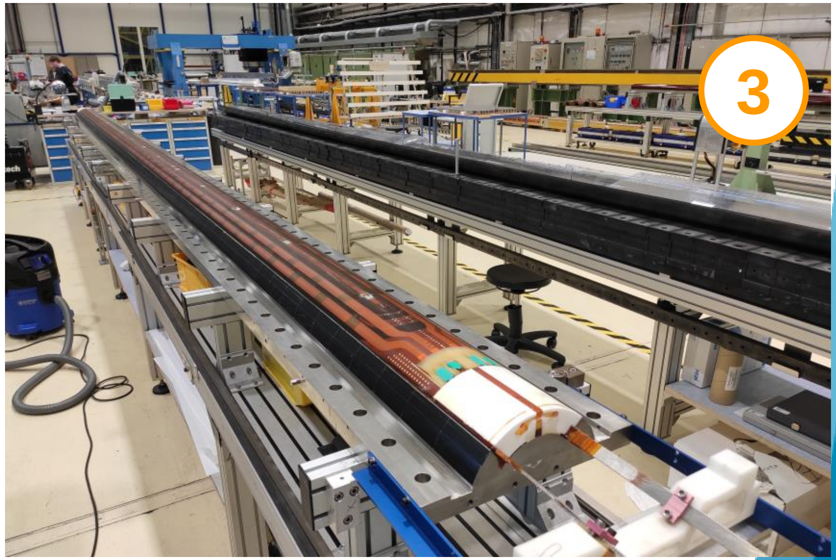
Outline

- Introduction
- **Coil manufacturing observables**
- New generation MQXFB coils
- Conclusions

Coil manufacturing process

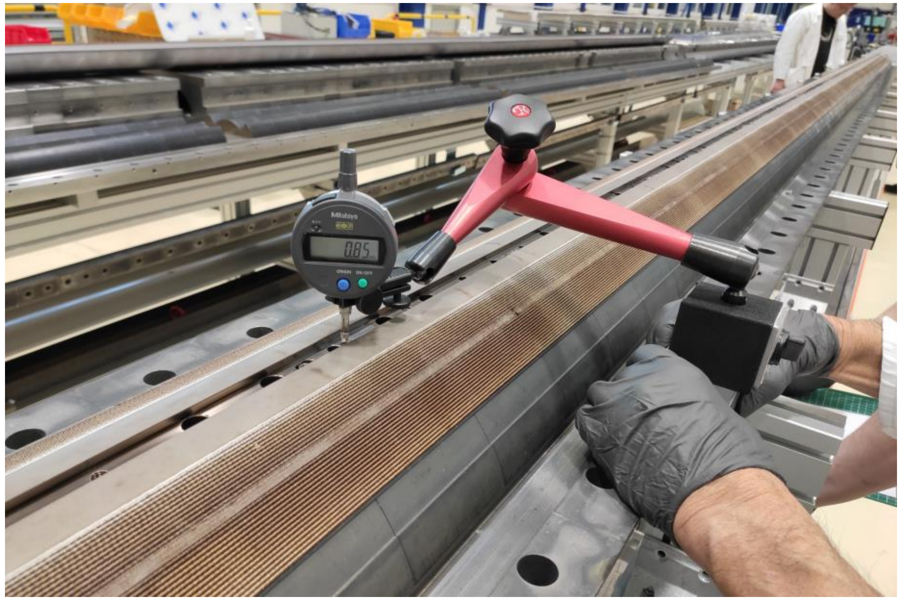
- Manufacturing process divided in three main steps:
  1. Winding and curing
     - IL winding and curing (with ceramic binder)
     - OL winding and curing (with ceramic binder)
  2. Reaction heat treatment
  3. Vacuum pressure impregnation



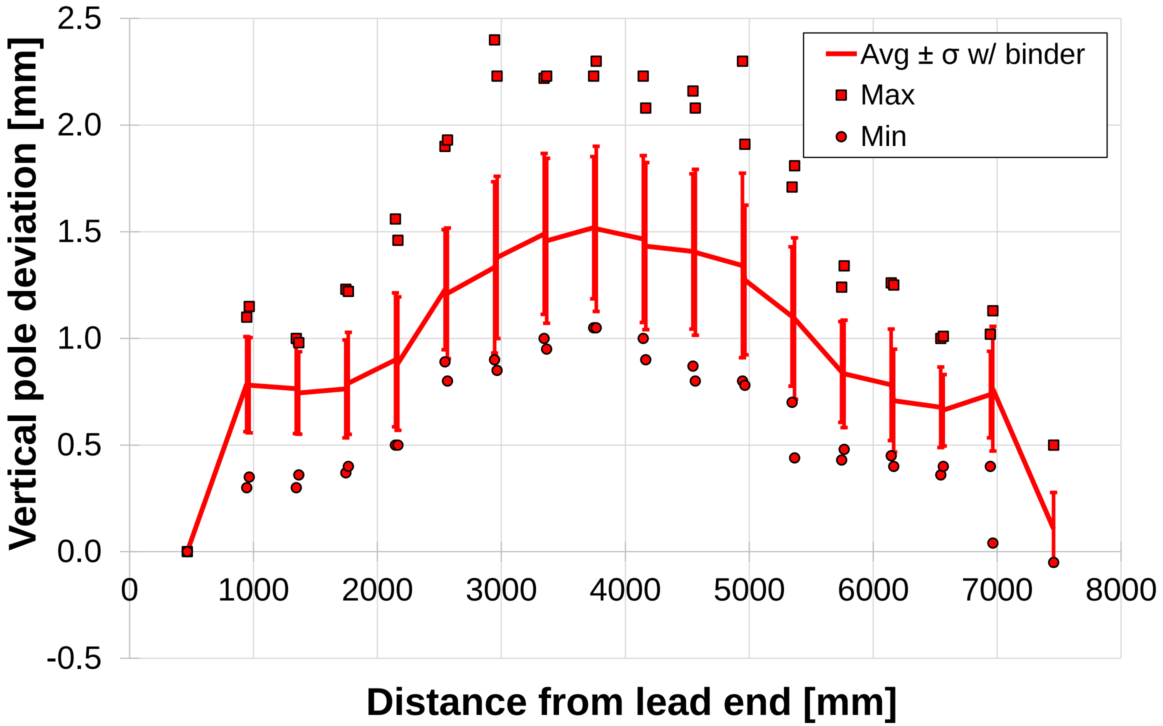


Coil manufacturing observables

- **Coil 'hump' after reaction**
  - Vertical deviation of the outer layer poles with respect to the base plate of about 1.5 mm observed after the opening of the reaction fixture

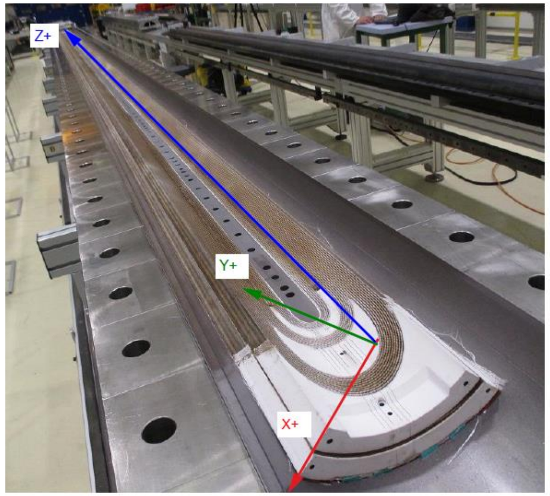


Vertical pole deviation along the length (reacted coil)

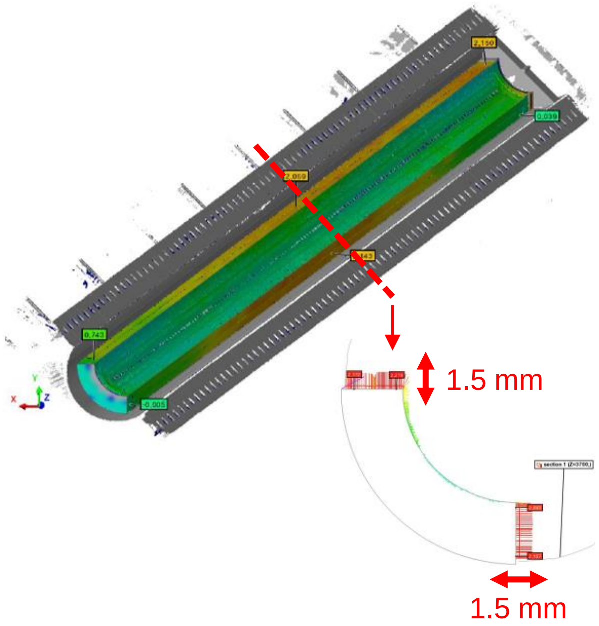


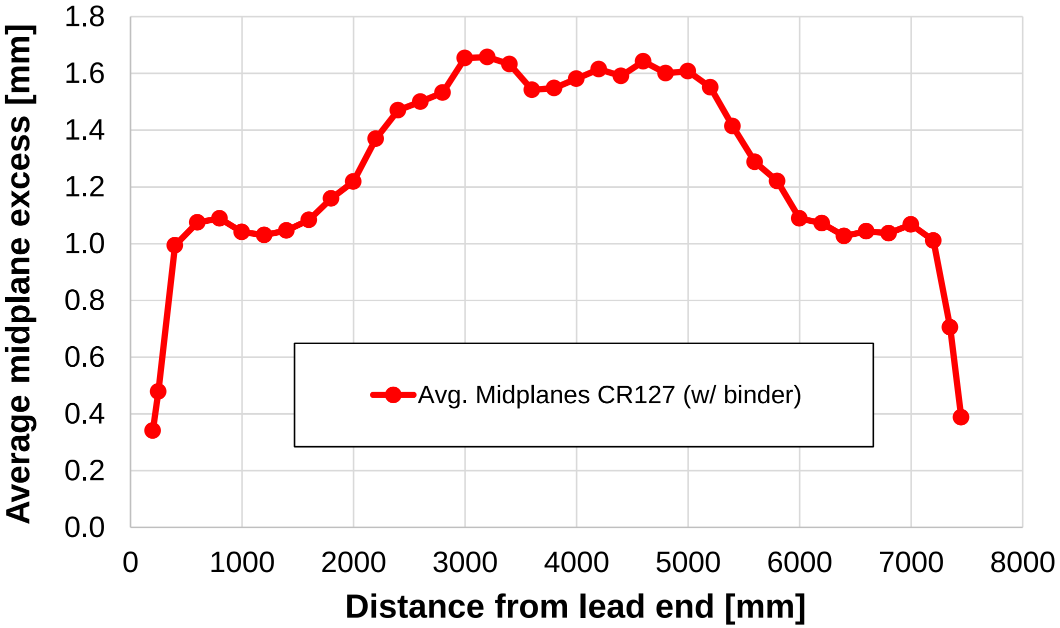
Coil manufacturing observables

- **Coil ‘hump’ after reaction**
  - When the coil is with the inner layer upwards in free state, an excess of about 1.5 mm is observed in the midplanes towards the longitudinal center
  - Measurement done using MetraSCAN® 3D optical CMM scanner



Metrological 3D scan of the inner radius and midplanes after HT (reacted coil)



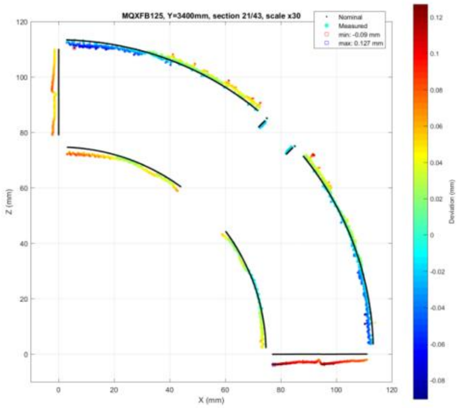


Coil manufacturing observables

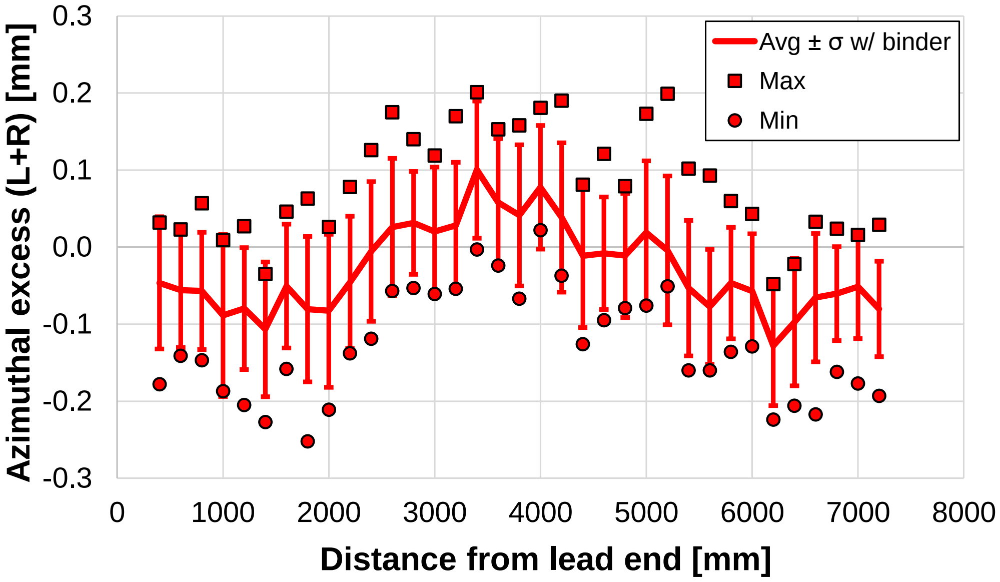
- **Coil azimuthal size after impregnation**
  - The coil is azimuthally bigger in the middle of about 0.1 mm per midplane
  - The coil is rigid enough to slightly deform the impregnation fixture, keeping the signature of a ‘fat’ coil towards the longitudinal center

Coil closed in the impregnation fixture

Metrology measurements of the impregnated coil



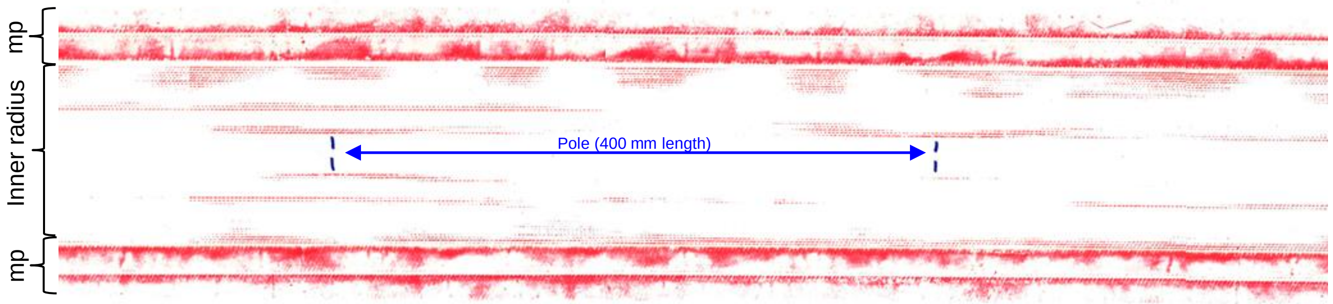
Azimuthal coil arc excess (impregnated coils)



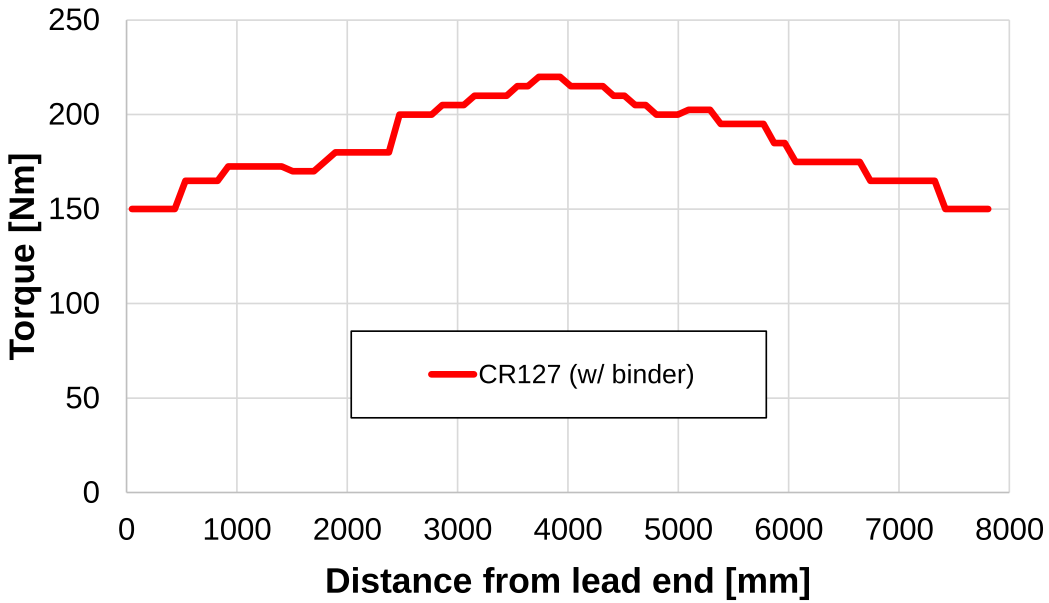
Coil manufacturing observables

- **Torque monitoring during impregnation fixture closure**
  - The torque needed to close the impregnation fixture gradually increased towards the longitudinal center of the coil
- **Stress regions in the vicinity of the pole-to-pole transitions**
  - Pressure sensitive film installed in the inner radius and midplanes of coil CR126 when preparing the coil for impregnation revealed stress concentrations close to the pole-to-pole transitions

Pressure sensitive film imprints (2.5 – 10 MPa) of the inner coil radius and midplanes during the closure of the impregnation fixture



Torque required to close the impregnation fixture (reacted coil)



Outline

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- Coil manufacturing observables
- **New generation MQXFB coils**
- Conclusions

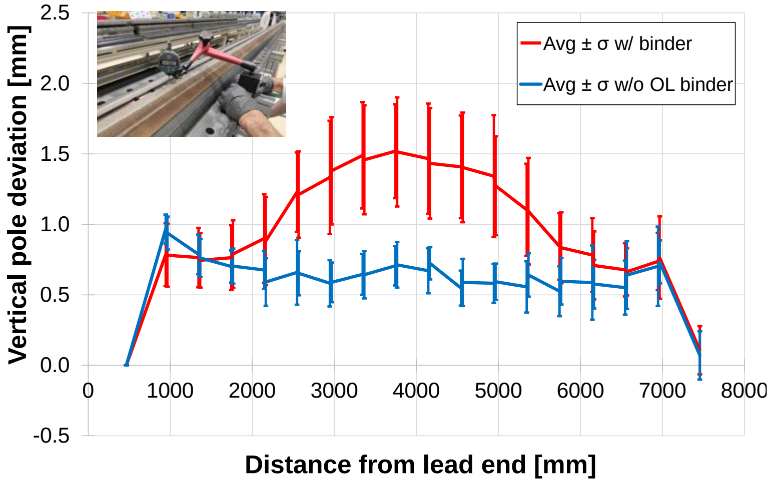
New generation coils: modifications implemented

- Possible mechanism
  - The coil is a constrained state after RHT due to friction between coil and mold, the energy is released during the mold opening
  - Effect length dependent (not observed in MQXFA and MQXFS coils)
- Purpose → reducing the longitudinal, azimuthal and radial friction between coil and the reaction mold
  - Modifications implemented in the manufacturing steps preceeding the RHT
- The major modifications are:
  - Pole gap increase from 2.0 mm/m to 3.4 mm/m (then optimised to 2.5 mm/m)
  - Partial compensation of the curing cavity → reducing the azimuthal size of the unreacted coil
  - Removal of the ceramic binder from the outer layer of the coil

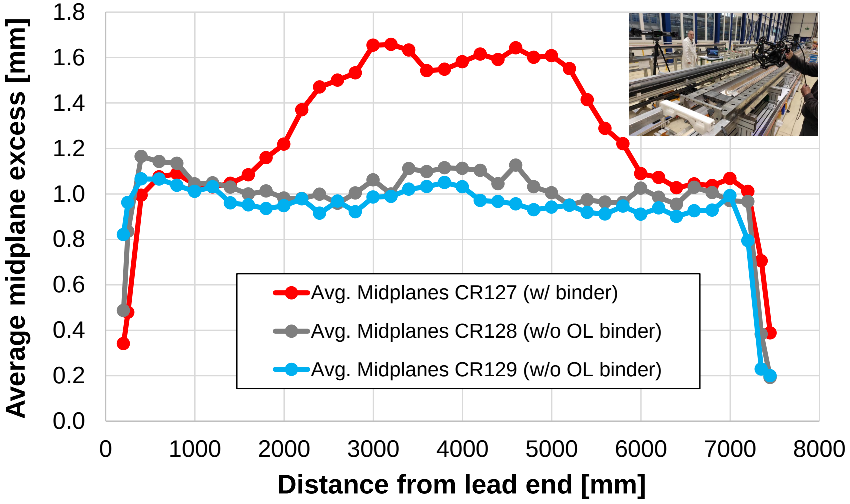
New generation coils: results and measurables

- **Coil ‘hump’ after reaction and coil azimuthal size after impregnation**
  - New generation coils do not show any ‘hump’ from the OL (ends raise up to about 1 mm and straight part flat at about 0.7 mm) → similar to MQXFA
  - 3D scan of the inner layer of the coil in free state confirmed a more homogeneous geometry of the coil in the longitudinal direction
  - New generation coils are more uniform along the length, azimuthally smaller and do not present any sign of a ‘fatter’ coil towards the longitudinal center

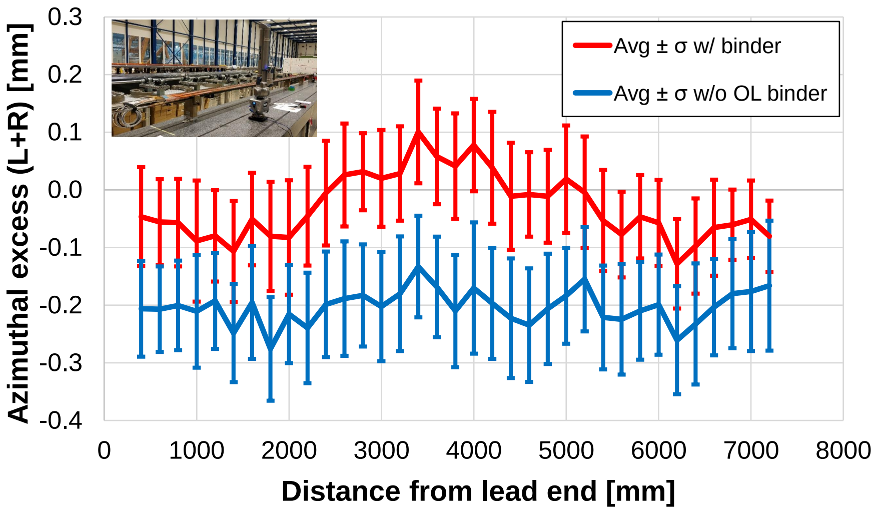
Vertical pole deviation along the length (reacted coil)



Metrological 3D scan of the inner radius and midplanes after HT (reacted coil)

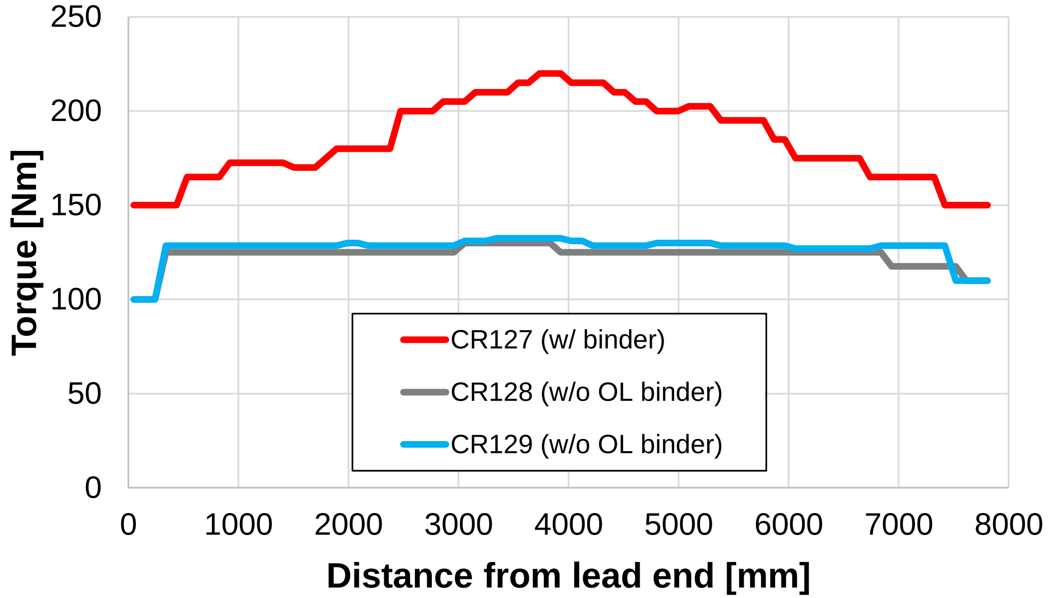


Azimuthal coil arc excess (impregnated coils)



New generation coils: results and measurables

- **Torque monitoring during impregnation fixture closure**
  - The torque needed to close the impregnation fixture for new genration coils is uniform along the length and almost half w.r.t. coils cured with binder on both layers



- **Additional measurements:**
  - New generation coils exhibit lower pole gap reduction after reaction (0.74 mm/m in coils w/o OL binder vs 1 mm/m)
  - New generation coils exhibit less elongation during the opening of the reaction fixture (0.9 mm/m in coils w/o OL binder vs 1.5 mm/m)

Outline

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- **Conclusions**

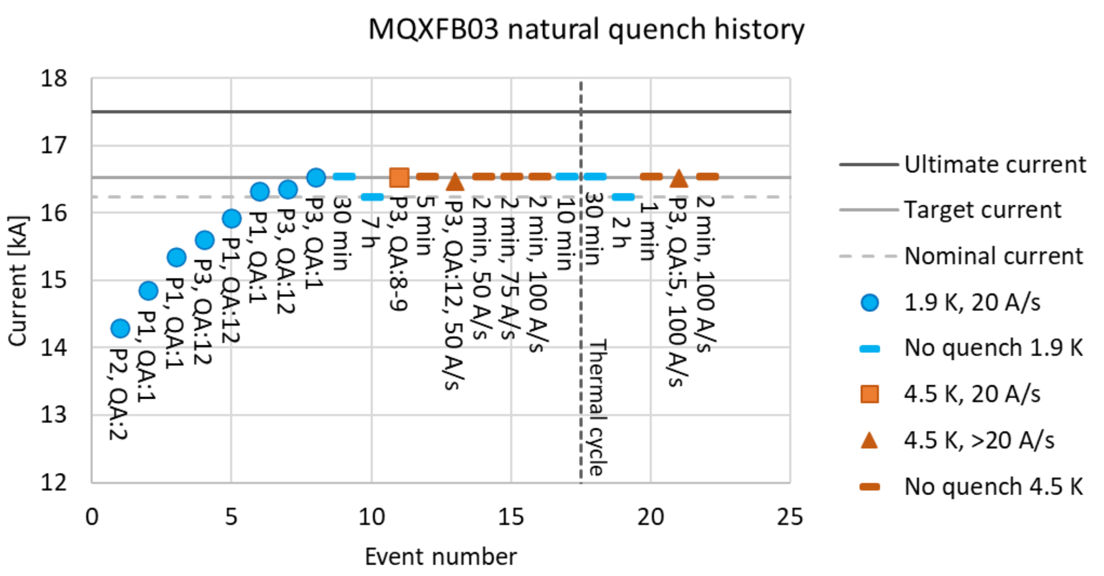
Conclusions

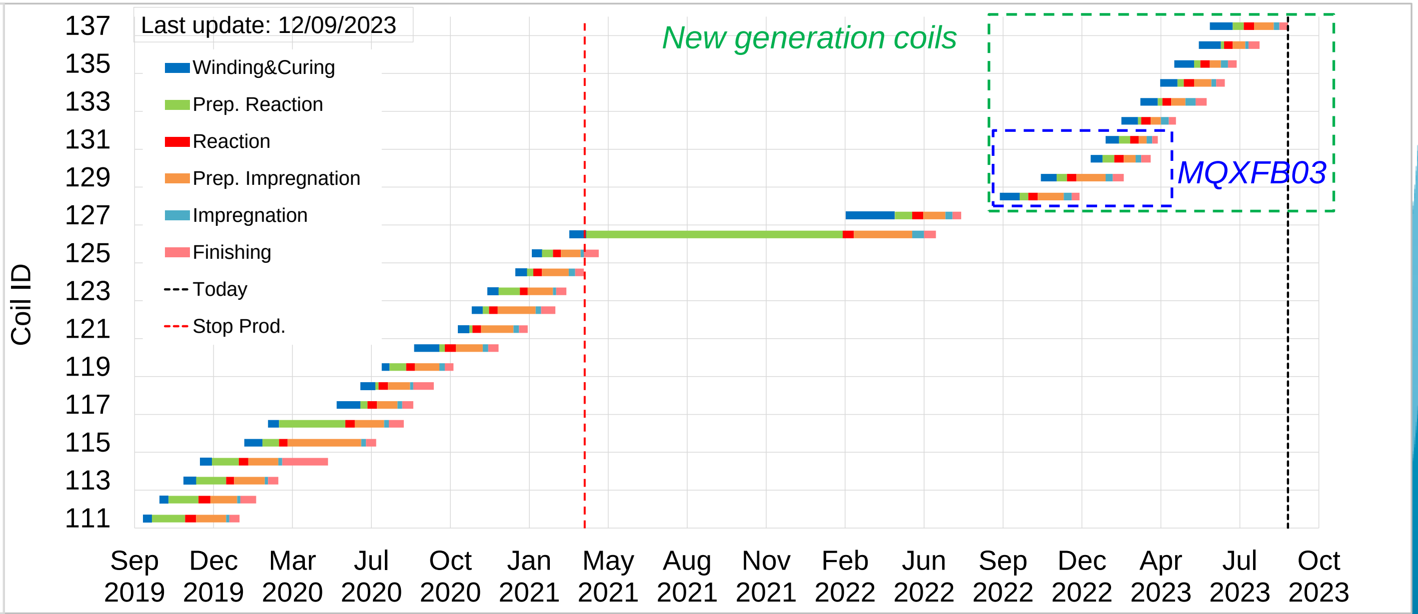
- MQXFB coils are the longest Nb_3Sn coils for accelerator magnets ever built
- Coil manufacturing process was reviewed to improve MQXFB magnet performance
- Evidences pointing to a constrained state of the coil after RHT
  - Not observed in MQXFA and MQXFS coils
- Modifications aimed at reducing longitudinal, azimuthal and radial friction between coil and reaction mold
  - Pole gap increase
  - Partial compensation of the curing cavity
  - **Removal of the ceramic binder from the outer layer of the coil**
- New generation coil measurables point to a coil which is more ‘relaxed’ after RHT
  - No coil ‘hump’ after reaction
  - No bigger coil azimuthal size towards the middle after impregnation
  - More homogeneous torque required to close the impregnation fixture

More uniform coil size along the length

Conclusions

- 10 new generation coils have been manufactured 4 of which have been assembled in magnet MQXFB03
- Test of MQXFB03 is ongoing:
  - Reached target current (I_{nom} + 300 A) both at 1.9 K and 4.5 K
  - No signs of degradation in the pole-to-pole transitions





Courtesy of F. Mangiarotti

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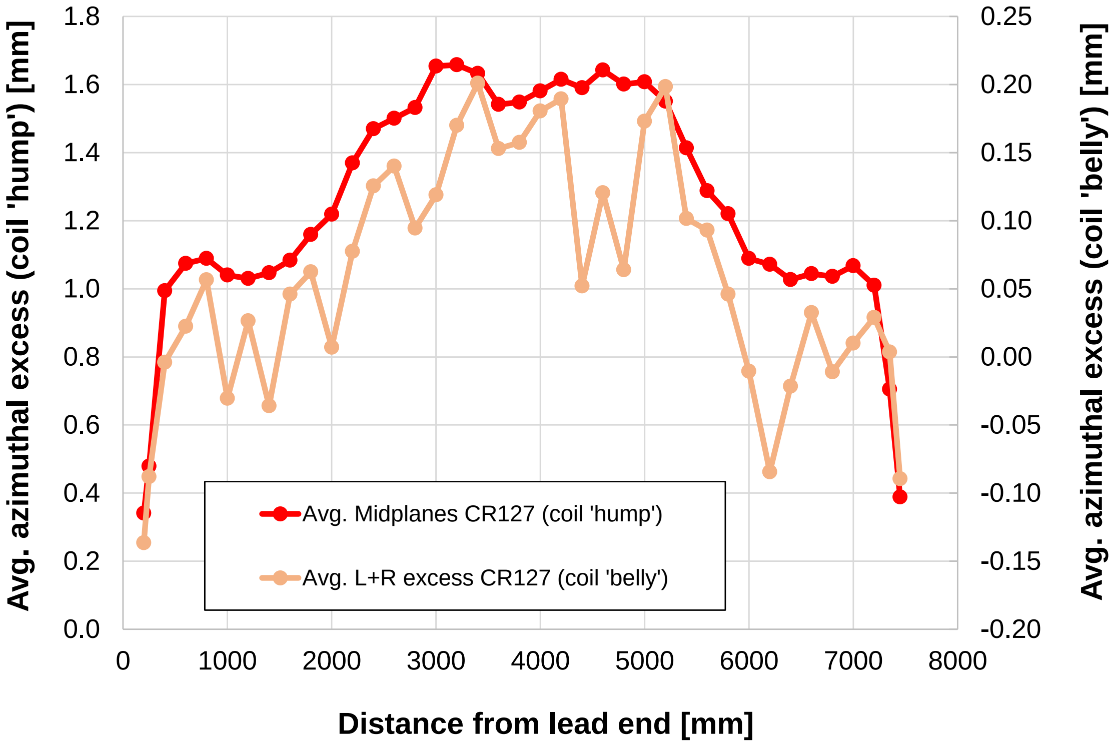
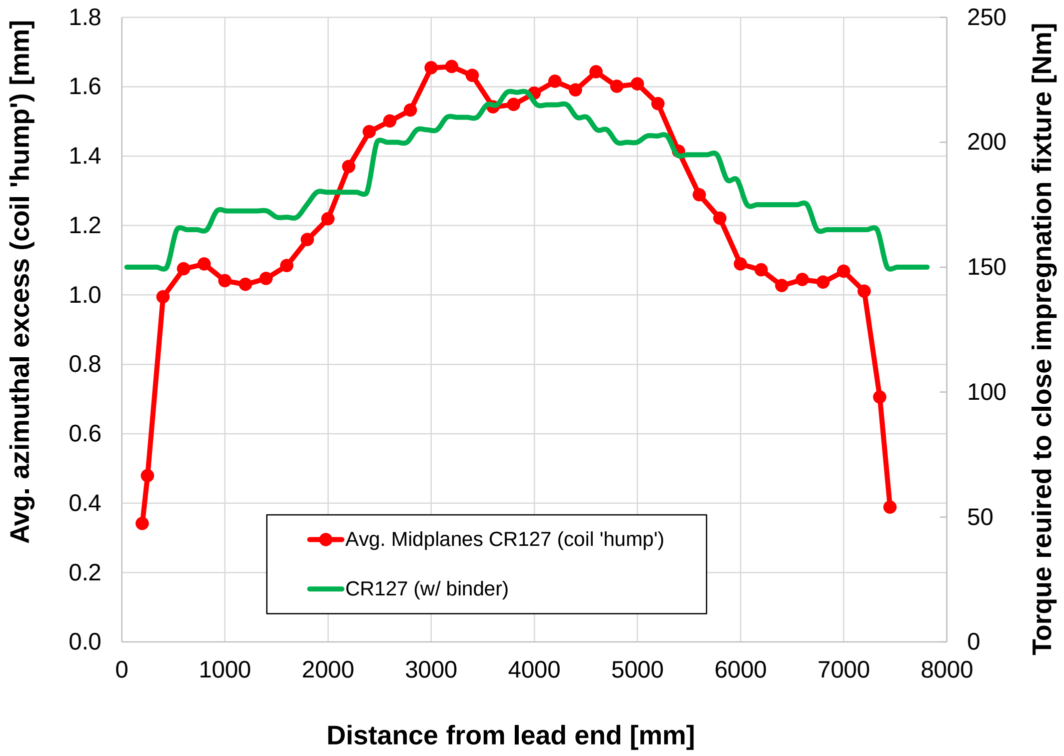
Thank you

Spare slides

Correlation between coil observables

- Coil ‘hump’ after reaction and coil ‘belly’ after impregnation seems to be correlated
- Coil ‘hump’ is confirmed by the torque monitoring during the impregnation fixture closure





New generation coils: results and measurables

- **Coil elongation upon reaction fixture opening**
  - Reacted coils gradually elongate on both ends during RHT fixture opening (from extremities to the middle)
  - Coil and Ti poles move outwards during the opening → importance of pole gap
  - New generation coils exhibit 40% less elongation → less friction effects (very limited statics on MQXFB coils with binder on both layers)

Coil #	LE side [mm]	RE side [mm]	Total elongation [mm]	Total/L_m [‰]	Manufacturing line
CR127	5.2	5.5	10.7	1.50	CERN w/ binder
CR128 – CR137	3.2 ± 0.8	3.5 ± 0.7	6.7 ± 1.5	0.93	CERN w/o OL binder
AUP146 – AUP147	3.3	0.5	3.8	0.88	FNAL
AUP237 – AUP238	1.9	1.9	3.8	0.88	BNL

New generation coils: results and measurables

- **Pole gap change**
  - Impacted by the removal of the ceramic binder from the OL of the coil
  - New generation coils exhibit lower pole reduction after reaction
  - MQXFB coils characterised by lower pole reduction after release of winding tension w.r.t. MQXFA

Pole gap change [mm/m]	After release of the winding tension		After reaction	
	Avg	σ	Avg	σ
MQXFA coils (92 coils)	1.48	0.21	1.10	0.24
MQXFB coils w/ binder (20 coils)	0.68	0.14	1.00	0.15
MQXFB coils w/o OL binder (10 coils)	0.63	0.09	0.74	0.16

New generation coil aspect