Status of MQXFB Nb_3Sn quadrupoles for the HL-LHC

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Outline

- Introduction to MQXF, main findings from test results and destructive inspections
- Cold mass assembly
- Magnet assembly
- Coil fabrication
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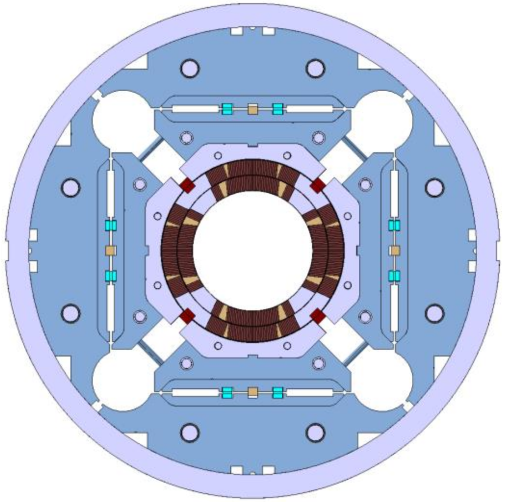
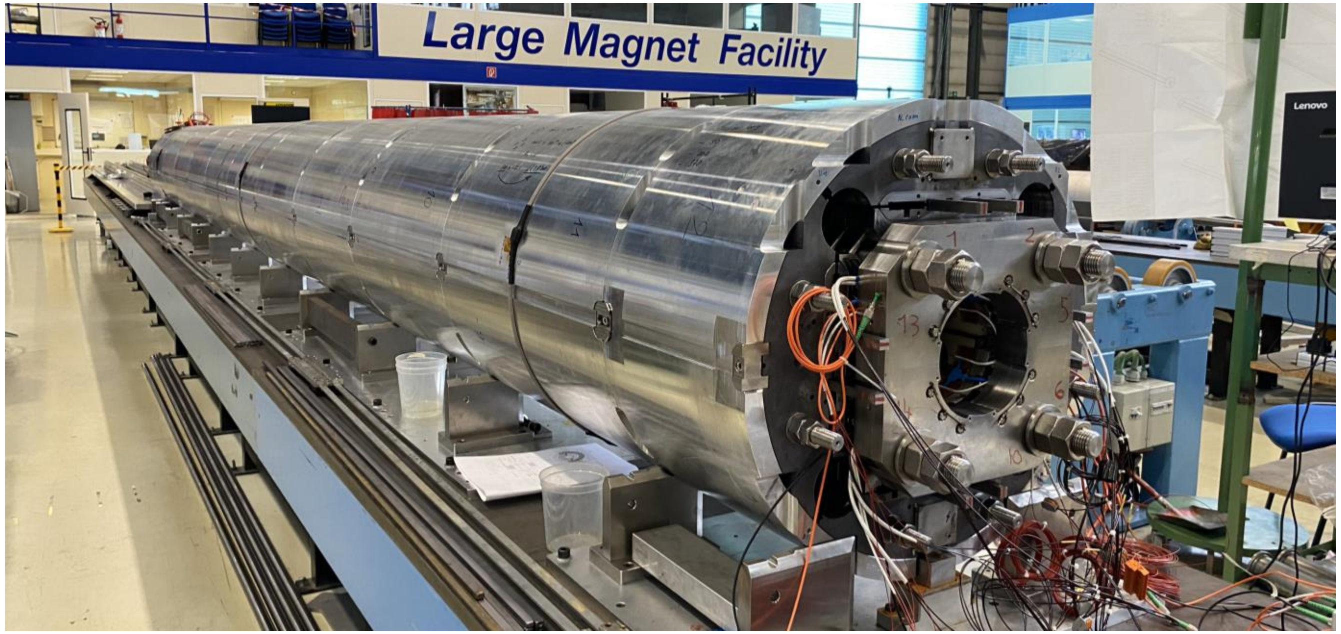
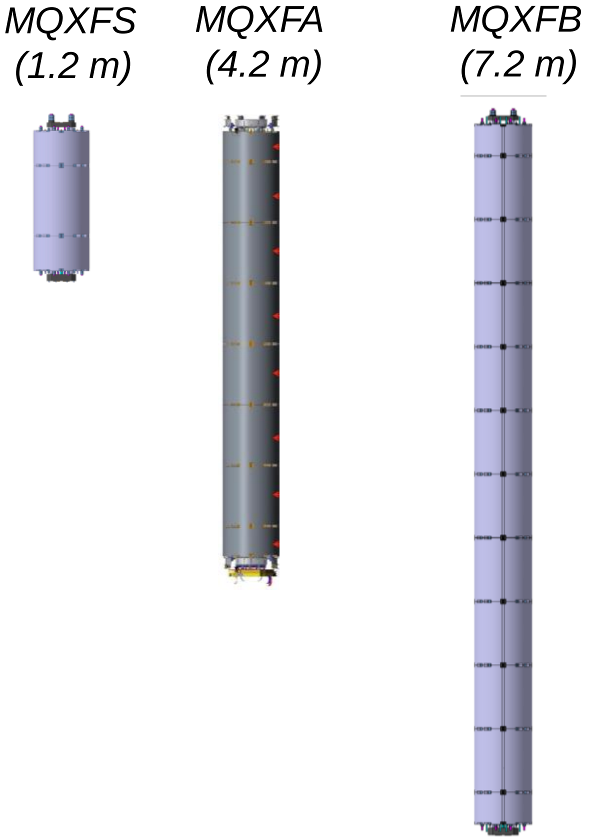
The MQXF magnet

- Nominal operation (7 TeV): 16.23 kA, 132.2 T/m; **11.3 T B_{peak}**
- Q1/Q3 (by US-AUP Project), 2 magnets **MQXFA** with 4.2 m L_m
- Q2a/Q2b (by CERN), 1 magnet **MQXFB** with 7.2 m L_m
- Joint short model development program **(MQXFS)** to validate the design
- Different lengths, same design, very similar manufacturing and assembly procedure



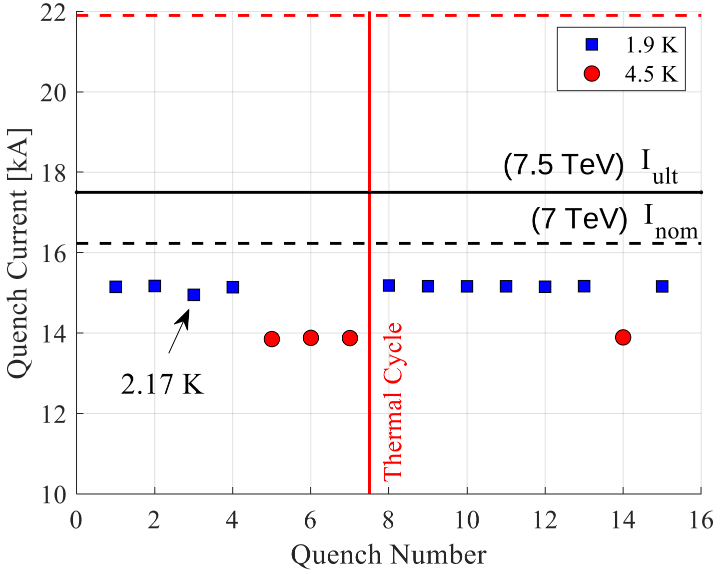




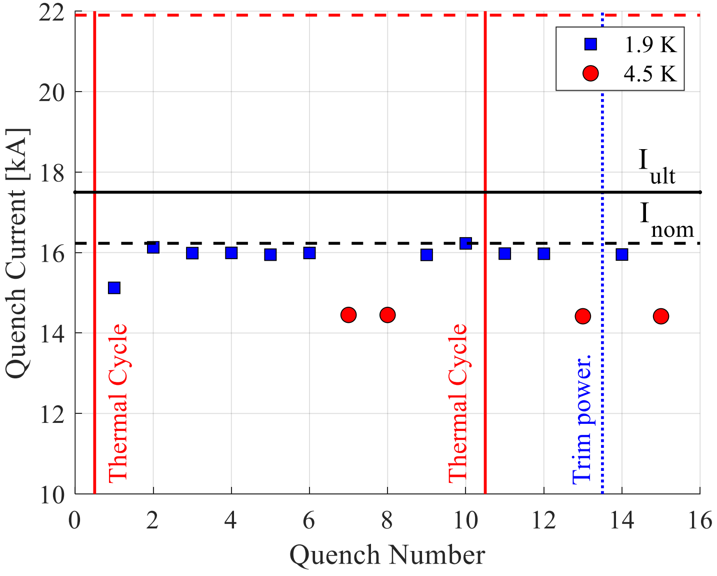
MQXFBP1&BP2 Prototypes Performance

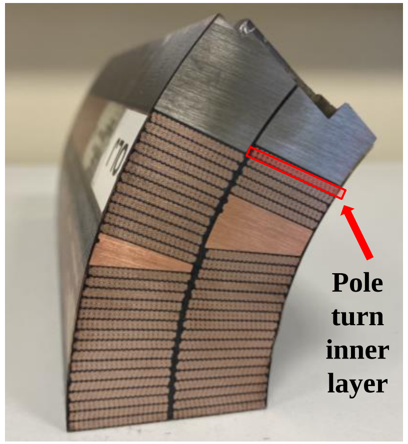
- **MQXFBP1** and **BP2** were **limited below nominal current** at 1.9 K (~15 and ~16 kA respectively).
- 4.5 K behaviour compatible with magnet on the critical surface (70% of the short sample limit in MQXFBP1, 73 % in MQXFBP2).
- Perfect training memory after thermal cycle and **magnet performance did not degrade with temperature cycles, quenches and current cycles.**
- In all the cases, the quench location was on the inner layer pole turns near the mechanical center of the magnet.

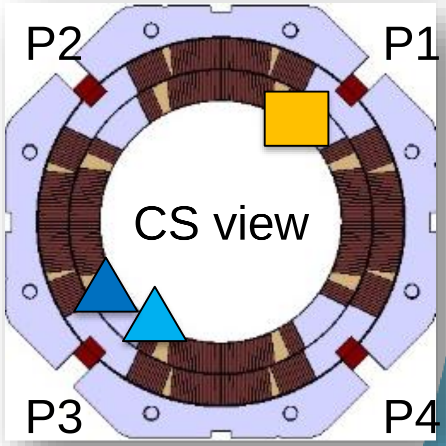
MQXFBP1

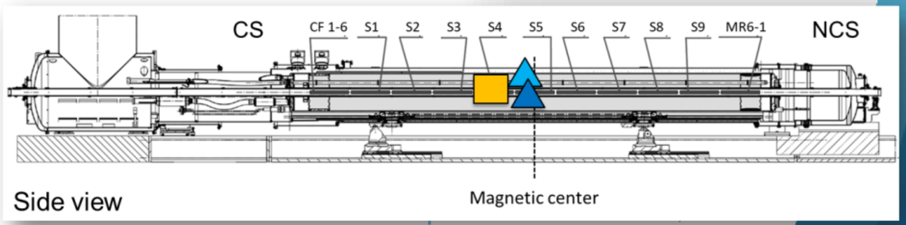


MQXFBP2



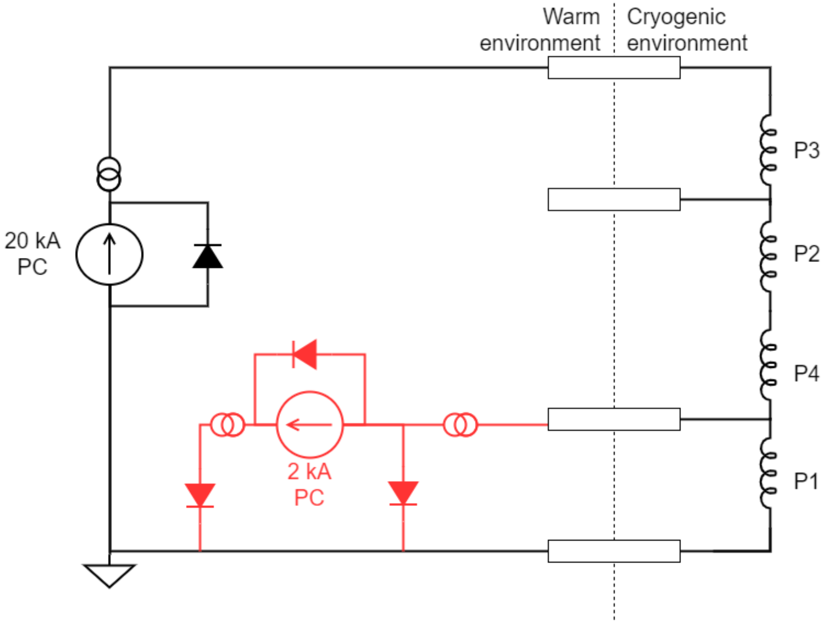


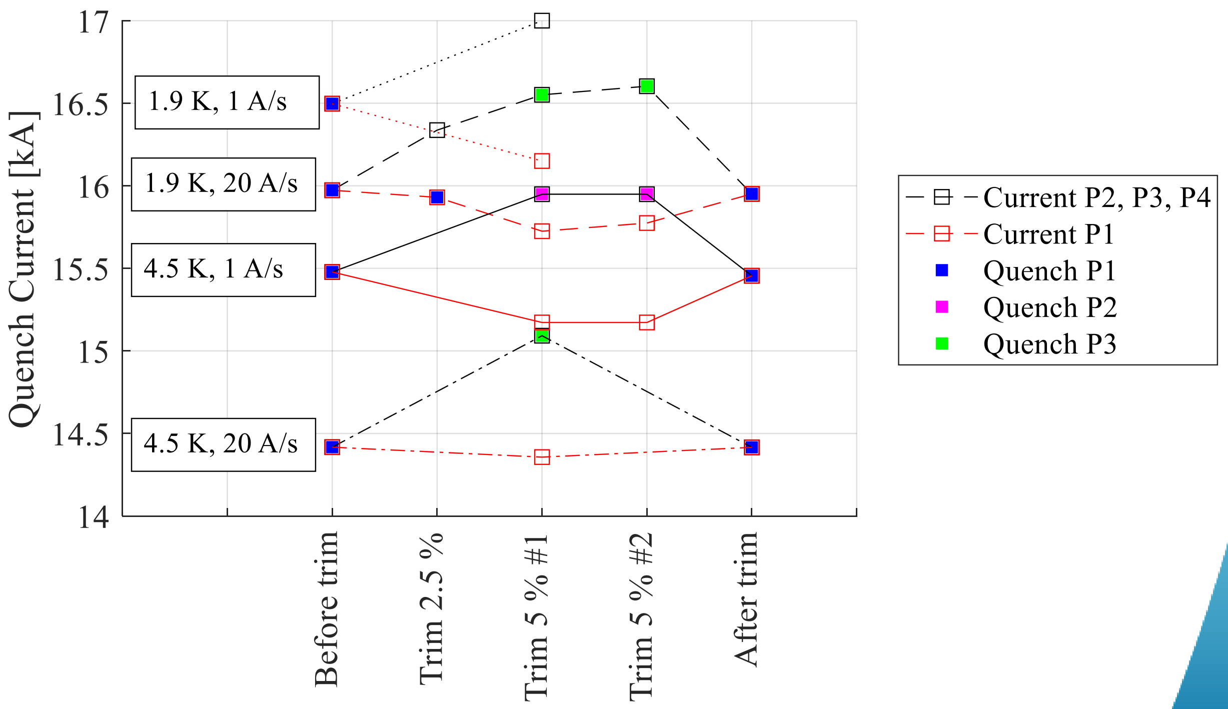




MQXFBP2: Trimmed powering

- **MQXFBP2** had a performance **limitation** at ~16 kA (~6.8 TeV equivalent, **98 %** of the nominal energy)
- **Power circuit modification** (in red) to evaluate the performance of non-limiting coils: coil P1 (limiting coil) was powered with less current than the other three
- **Other two coils** also limited with **similar** mechanism (straight part), at 16.5-17 kA – no quenches in the heads, and no degradation with thermal cycle

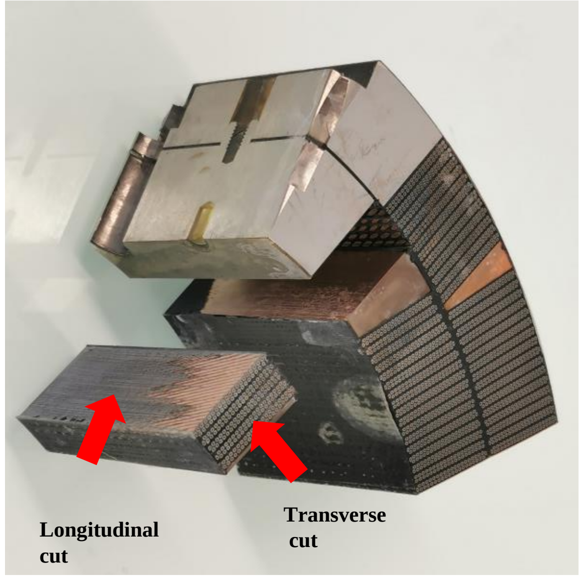


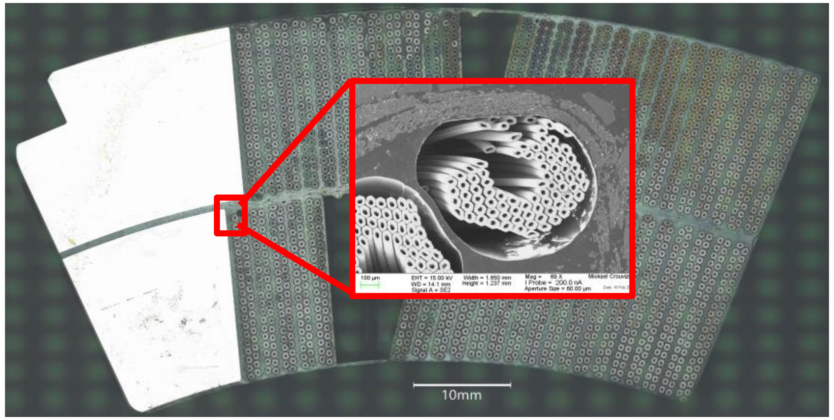


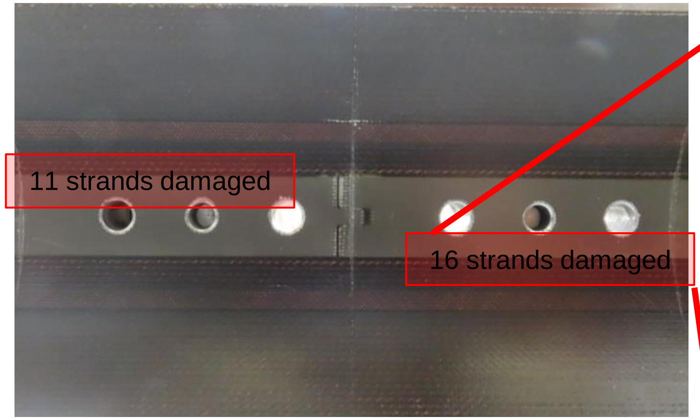
See S. Sgobba 1LOr2A-04

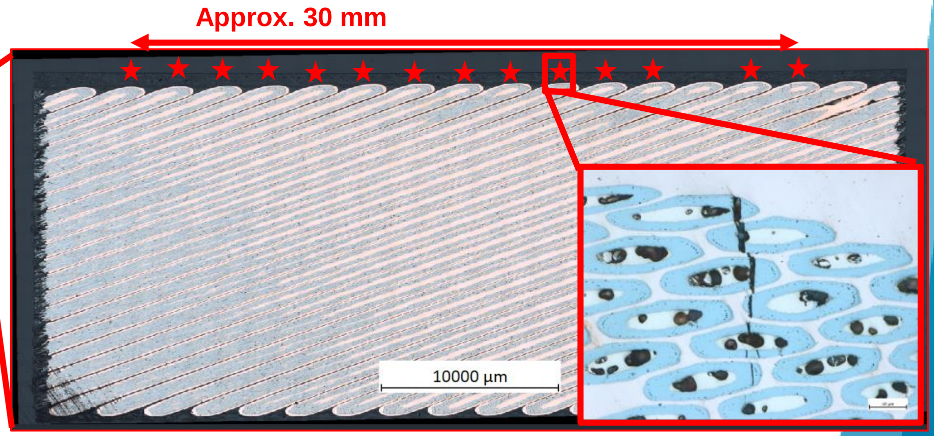
Destructive inspection of MQXFBP1 limiting segment

- The limiting segment in MQXFBP1 was analyzed using mainly two techniques:
  - Copper etching of transverse cuts, revealing **collapsed filaments in the upper edge of the inner layer pole turn**
  - Metallographic inspection after fine grinding and polishing , showing that the **extension of the damage** is ≈ **100 mm**.







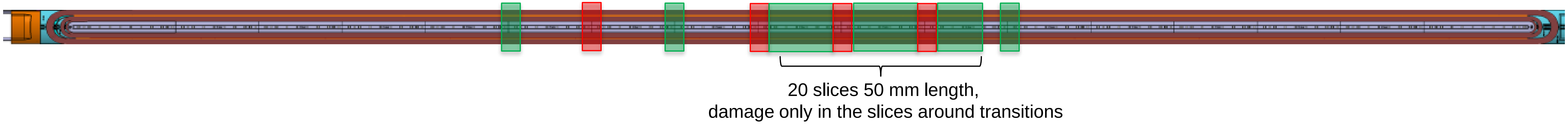


See S. Sgobba 1LOr2A-04

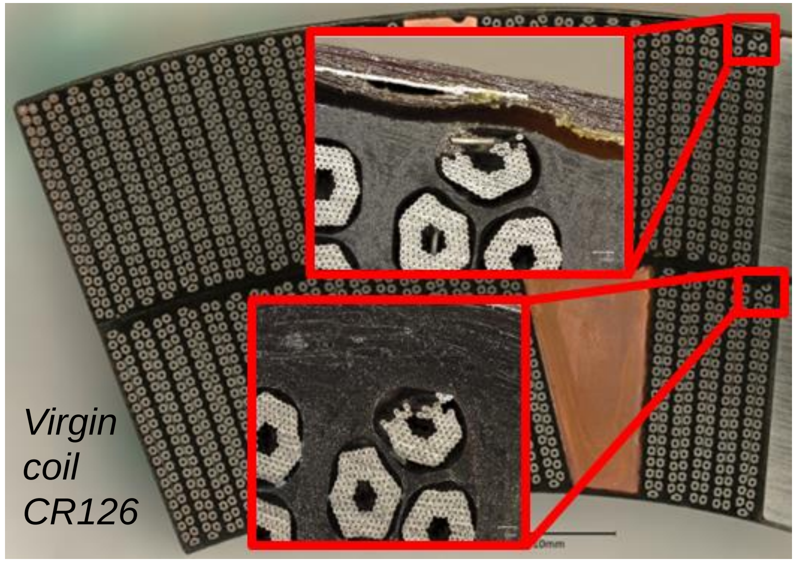
Coil post-mortem inspection

- Systematic inspection in coil 108 (limiting coil in BP1) through transverse cuts and copper etching in 1 m of coil with 50 mm granularity showed a **systematic problem in the pole-to-pole transitions**
  - Out of the 20 samples, only the samples around the two transitions showed damaged strands

Longitudinal distribution of the damage in CR108



- A **virgin coil**, never assembled in a magnet, shows **similar defects** but much smaller extension
  - Only 2 out of the 8 transitions examined had defects, and the extension of the defect in the longitudinal direction was 3 mm.



Overview on main findings and strategy definition

In Spring 2021, we stopped the production to identify and address possible root causes for the performance limitation:

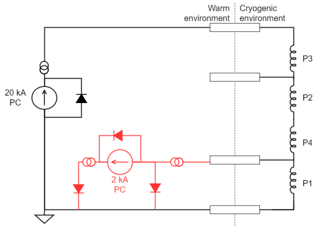
1. Cold mass assembly
2. Magnet assembly
3. Coil manufacturing

It may also be a combination of two of the three, or all of them

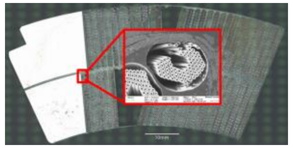
Limiting performance BP1

Very similar phenomenology in BP2 → systematic problem?

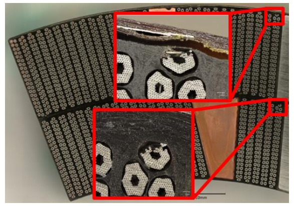
3 out of the 4 coils in BP2 show same type of limitation



Very localized defect in the limiting coil of BP1



Similar defect in a virgin coil (never assembled in a magnet)



2020				2021				2022			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
				STOP	Identify and assess potential root causes			Cold mass assembly: BP3			✓
									Magnet assembly: B02		
										Transition coils	

BP2 coils

BP3 coils

BP3 magnet

BP3 cold mass

B02 coils

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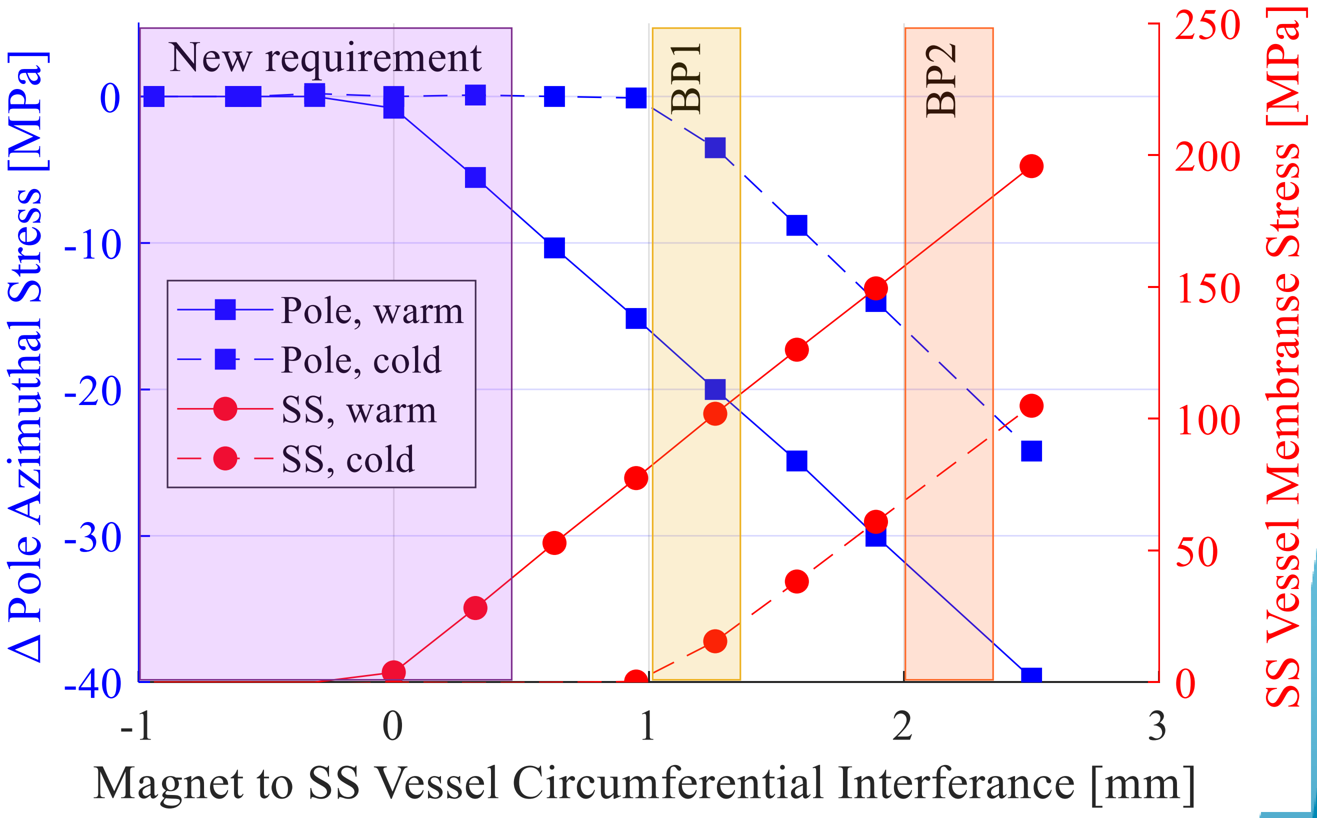
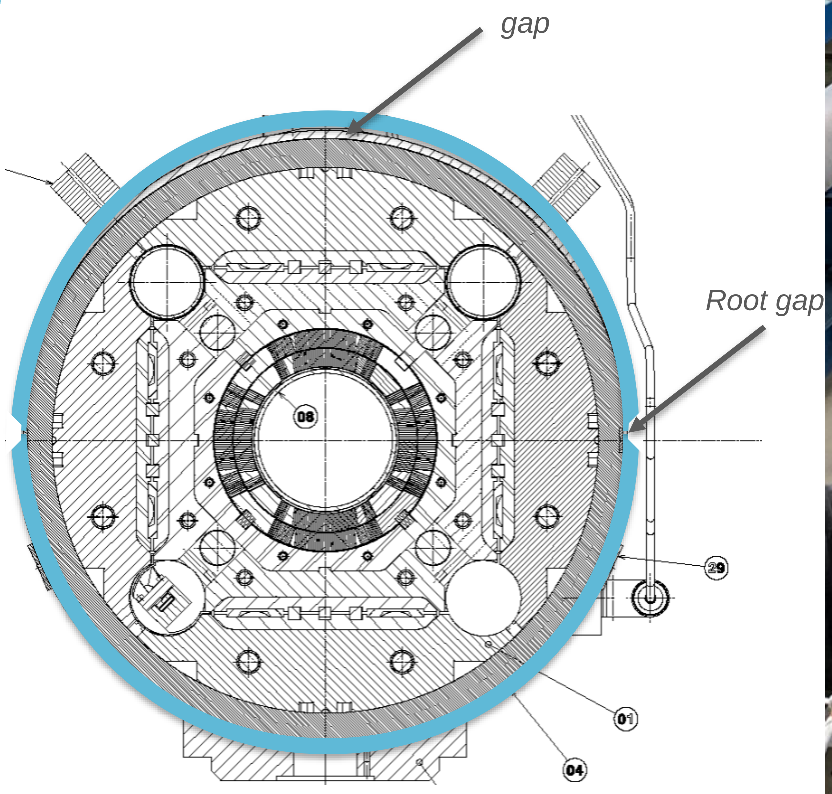
Cold mass assembly: mechanism and new requirements

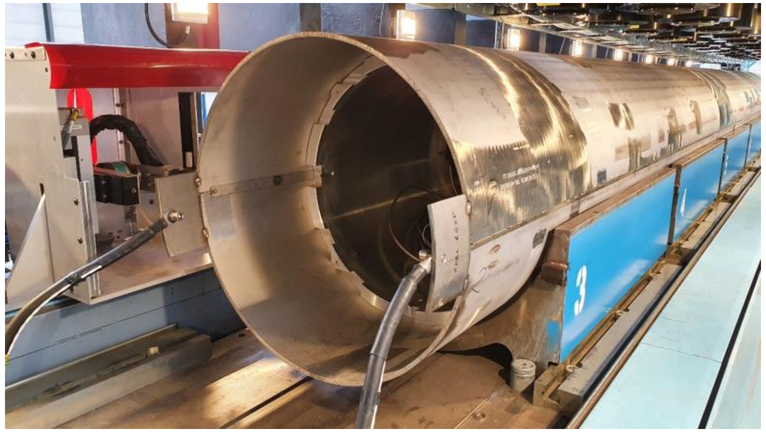
- MQXFBP1 and BP2 were the **first bladder and key magnets with a stainless-steel vessel** ever tested in horizontal position
- Original design: ≈ 75 MPa on the SS vessel at warm such that magnet and SS vessel are in contact after cool down
- **New requirement: no mechanical coupling** between SS vessel and magnet
  - AUP adopted the same specification for MQXFA



Cold mass assembly – implementation in MQXFBP3

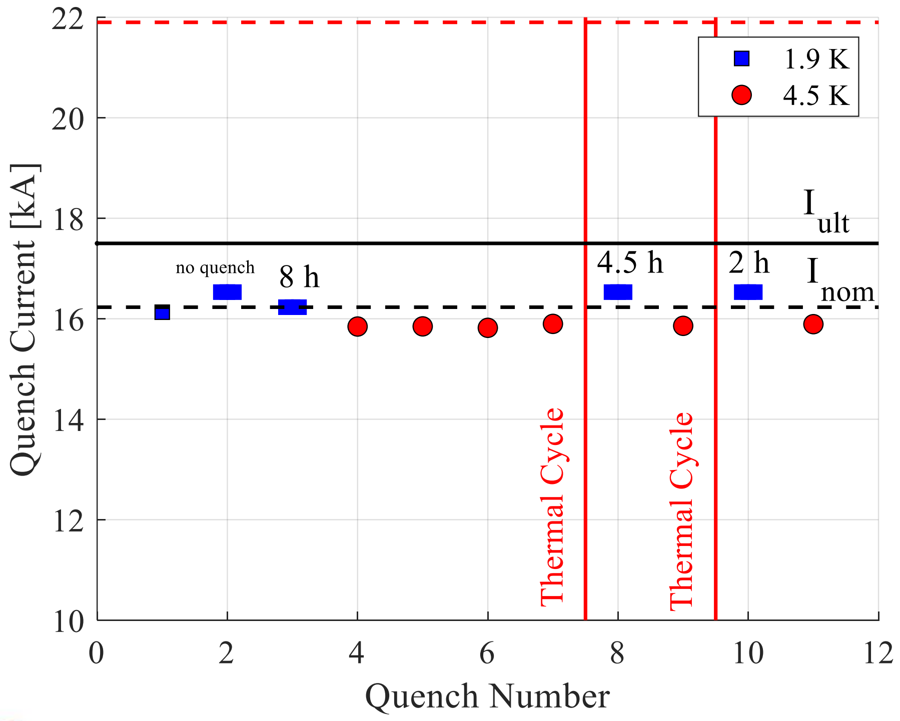
- Concept: **clearance SS vessel to magnet before welding**. To host the fixed point, the yoke had to be machined with the coils already assembled (in future magnets this operation will be done before assembly)
- All procedures were validated first on a short model tested at cold

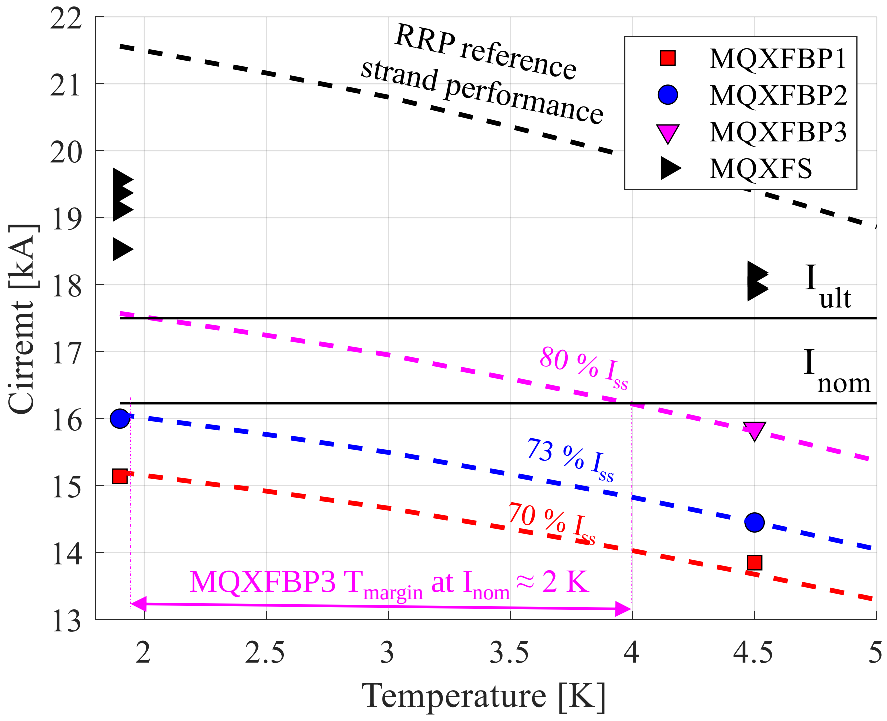




MQXFBP3 cold test results

- MQXFBP3 **reached the target current at 1.9 K** (I_{nom} + 300 A) after one quench. It operated during 4.5 hours at target current and 8 hours at I_{nom}.
- At 4.5 K, we see the same type of limitation observed in MQXFBP1 and MQXFBP2 but at much higher levels.
  - Quench level extrapolation for MQXFBP3 at 1.9 K: above ultimate current with a **temperature margin** at nominal current of **2 K** (0.35 K temperature margin needed for operation, see P. Borges de Sousa 2LOr2A-03).
- Perfect memory after thermal cycle. Magnet performance does not change with thermal and current cycling





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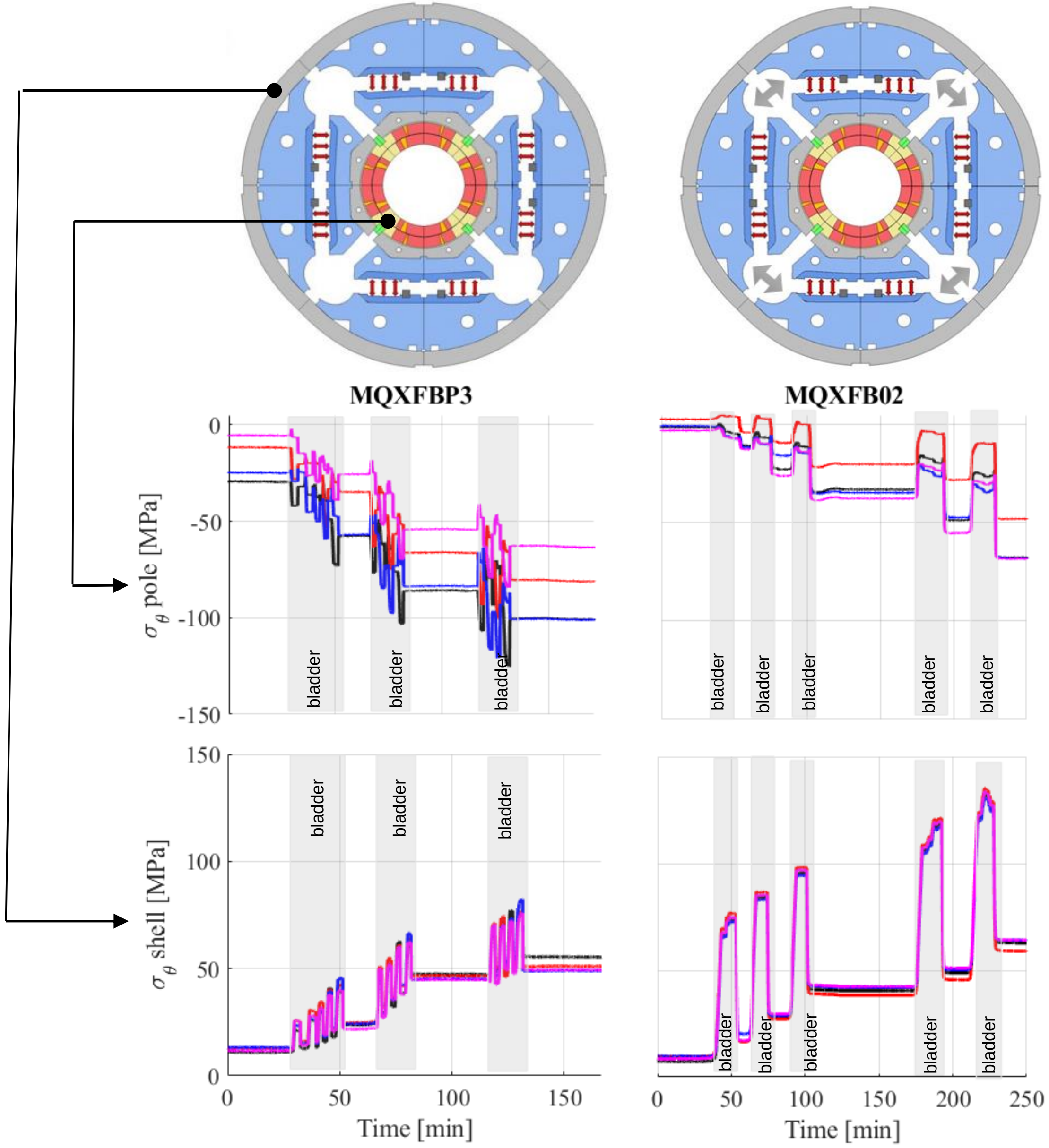
Magnet assembly: mechanism and new requirements

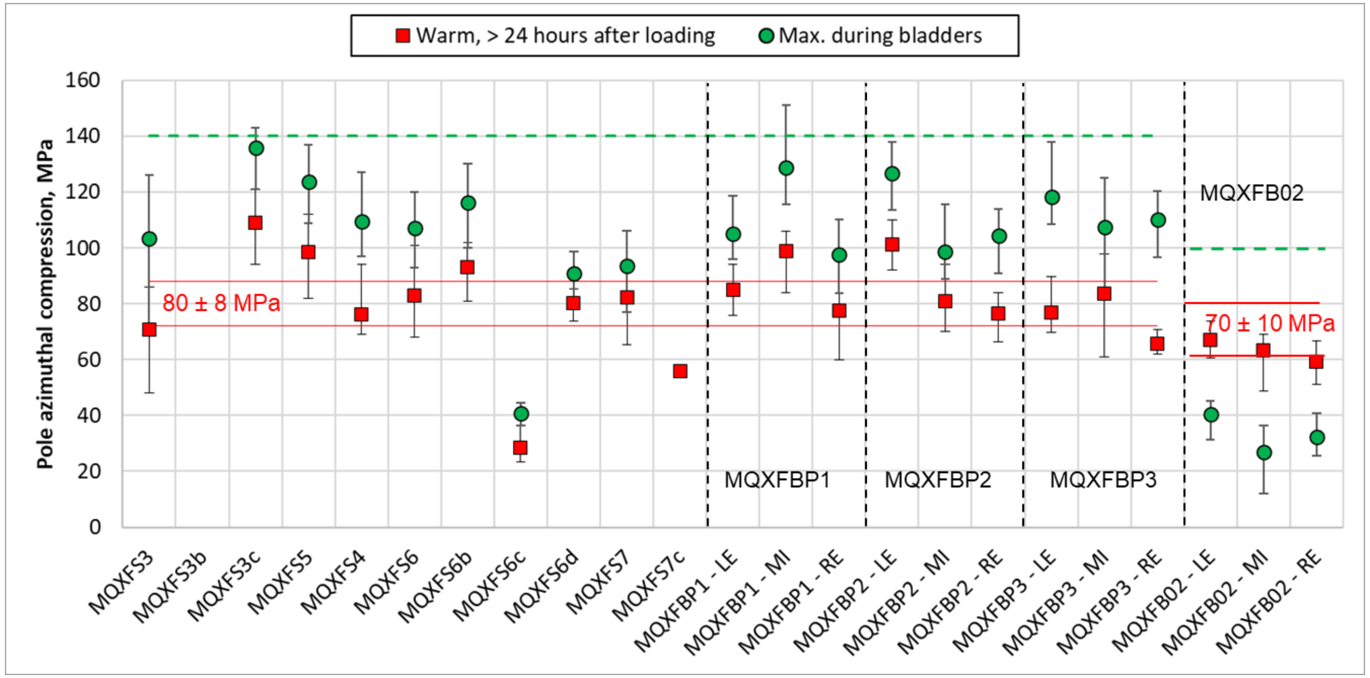
- An **optimized procedure of bladder and key loading** has been developed during the prototype phase and validated on a short model magnet
  - This procedure is based on stretching the outer structure via additional bladders in the cooling hole channels
  - It **eliminates the overshoot of coil azimuthal stress during loading** (−30 MPa, as high as 50 MPa), and minimizes peak stress
  - This is a major advancement for the bladder and key technology applied to long quadrupole magnets

See J. Ferradas Troitino 3LPo1D-10



Magnet assembly: implementation in MQXFB02

- The new procedure was applied to **MQXFB02**:
  - The **peak stress** in the coils is now **during the insertion of the keys** and not during bladder operations.
- Cold powering test expected in November 2022.
  - MQXFB02 has optimized welding and magnet assembly procedures, but the coils were fabricated before the stop of the production in spring 2021



See J. Ferradas Troitino 3LPo1D-10

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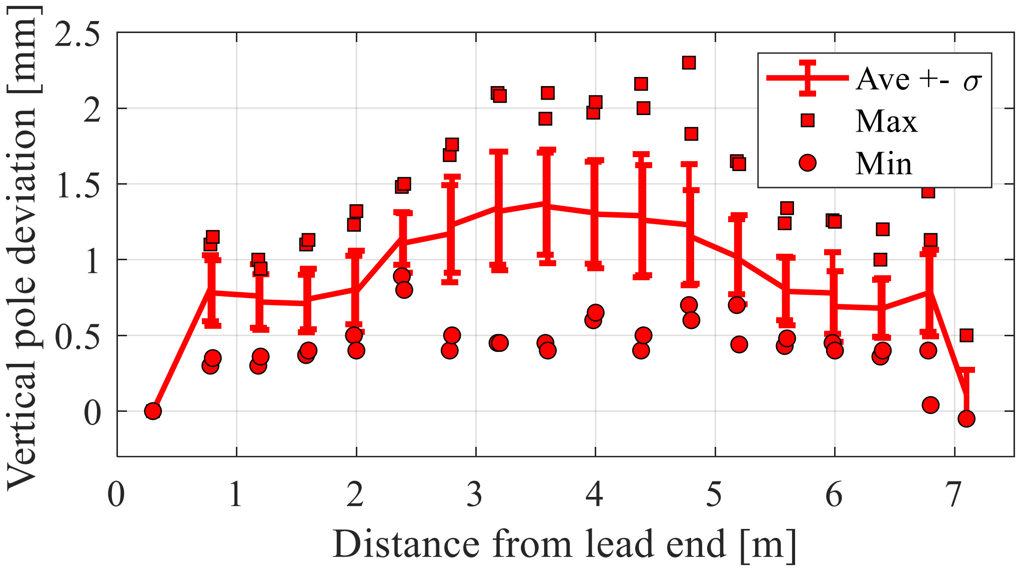
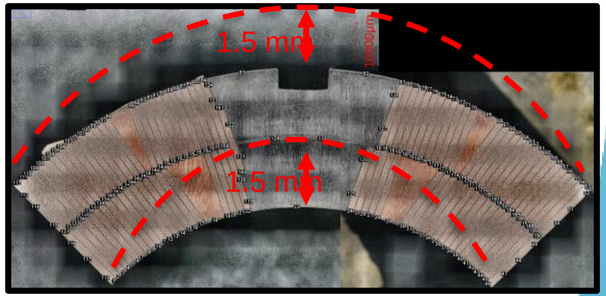
Coil fabrication: observables

- After reaction, a vertical deflection of the outer layer pole with respect to the base plate of 1-2 mm is typically observed after the opening of the reaction fixture.

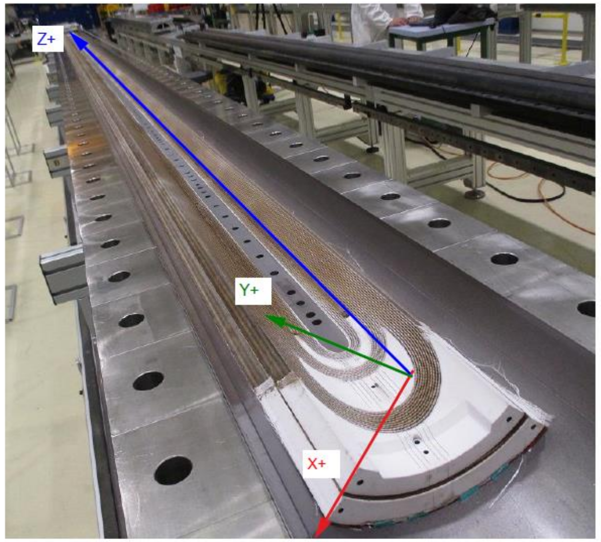


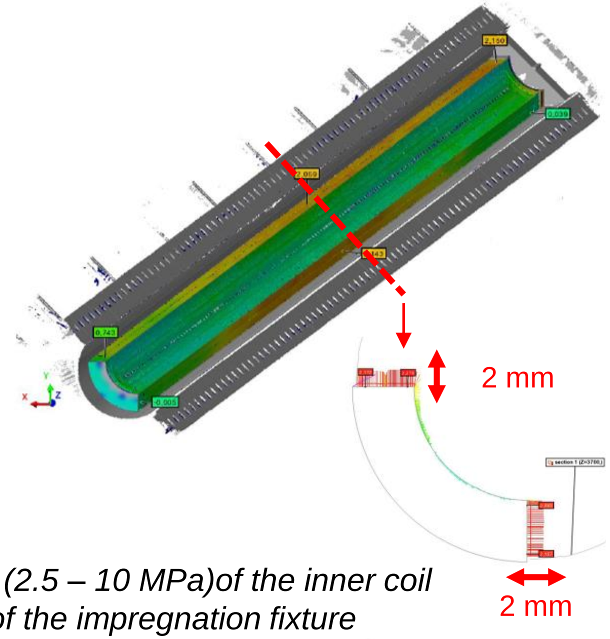


Coil fabrication: observables

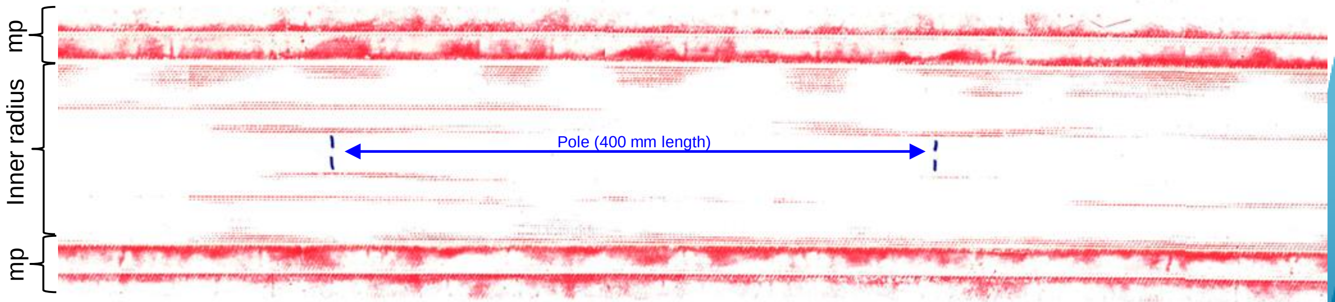
- When the coil is turned by 180 degrees to prepare the inner radius for impregnation, 2 mm excess per mid-plane towards the center of the coil
  - Indication of some excess of material towards the middle of the coil, consistent with the 1.5 mm vertical deflection of the pole when the coil is sitting in the mid-planes.
- Pressure sensitive film installed in the inner radius of the coil when preparing the coil for impregnation revealed a stress concentration region in the pole-to-pole transitions.

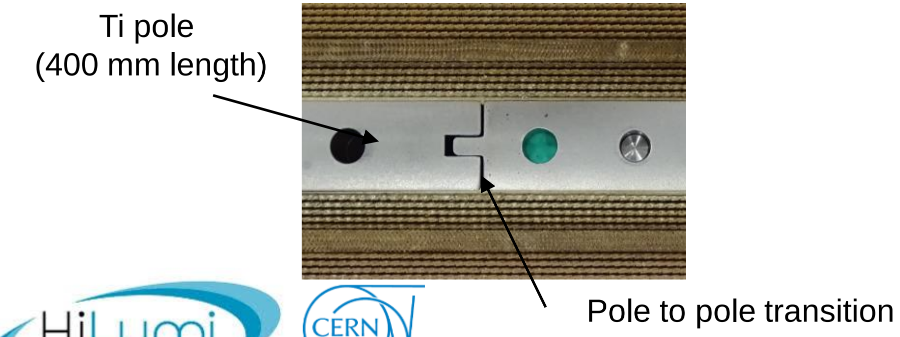
Metrological 3D scan of the inner coil radius and mid-planes after HT





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



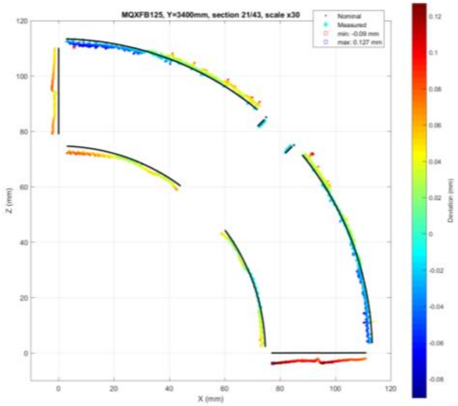


Coil fabrication: observables

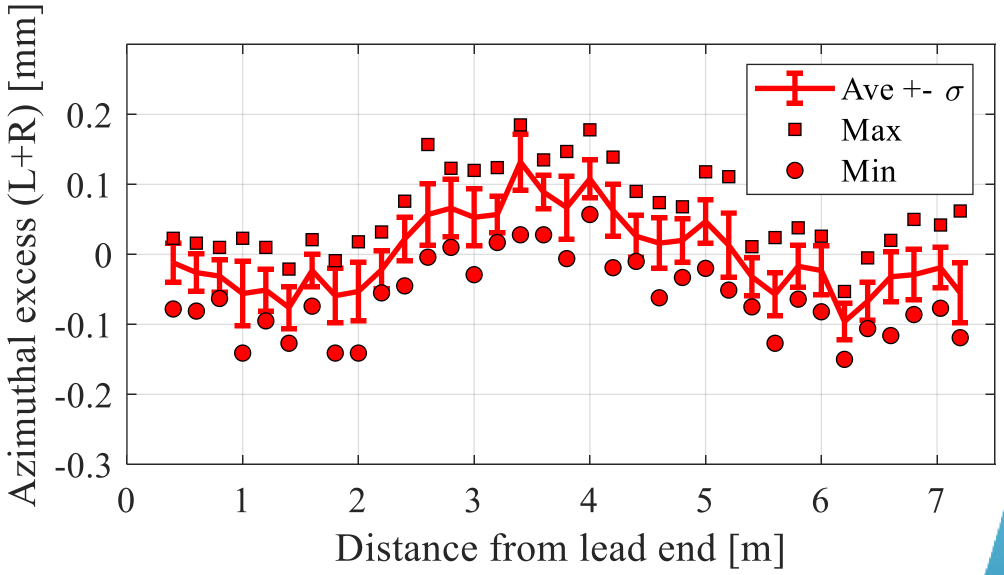
- **After impregnation**, the coil is azimuthally bigger in the middle (≈ 0.1 mm per mid-plane).
  - The coil is rigid enough to slightly deform the impregnation fixture, keeping the signature of a ‘fat’ coil in the middle (0.1 mm per mid-plane after impregnation vs 2 mm per mid-plane after reaction)

Coil closed in the impregnation fixture

Metrology measurements in the impregnated coil



Azimuthal coil arc excess (impregnated coils)

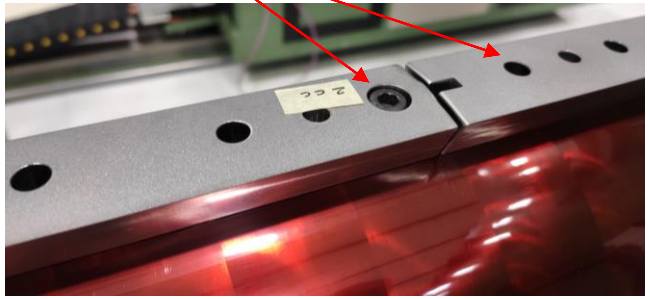


Coil fabrication: transition coils

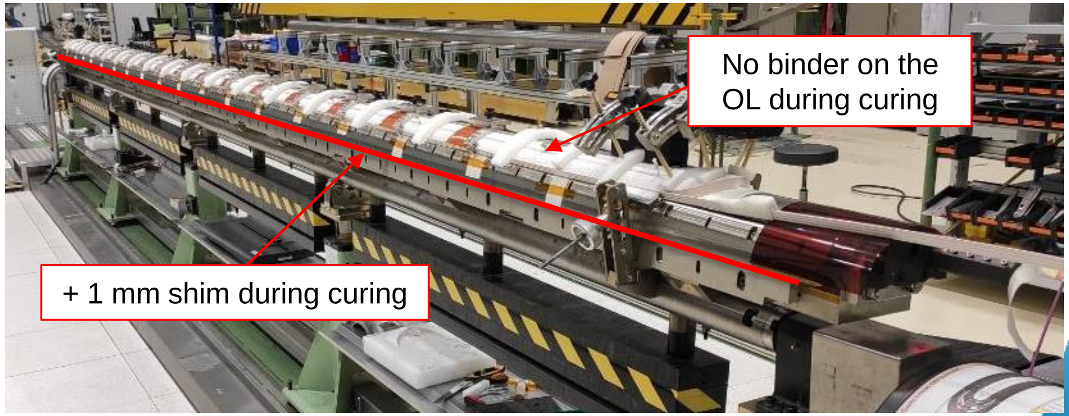
- Nb_3Sn expands during heat treatment. MQXF reaction fixtures accounts for 4.5 % azimuthal expansion, 1.5 % radial.
- Experiments on strands, cables and coils have shown that the volumetric expansion of the conductor is ≈ 3 %, but the azimuthal, radial and axial expansion depends on the way the cable is constrained.
- MQXFB coils are the longest Nb_3Sn accelerator coils ever built, and the friction coil to tooling might play a role on the constrain seen by the cable in during reaction: in the middle the coil might be locked by friction whereas closer to the ends can slide → focus on reducing the stored energy on the coil at the end of the reaction

- **1st transition coil**: provide more space to the coil during reaction in the **longitudinal** direction
  - Same macroscopic observables as previous coils

50 % increase of the distance between poles



- **2nd transition coil**: reduce **radial friction** coil to reaction fixture
  - Heat treatment ongoing



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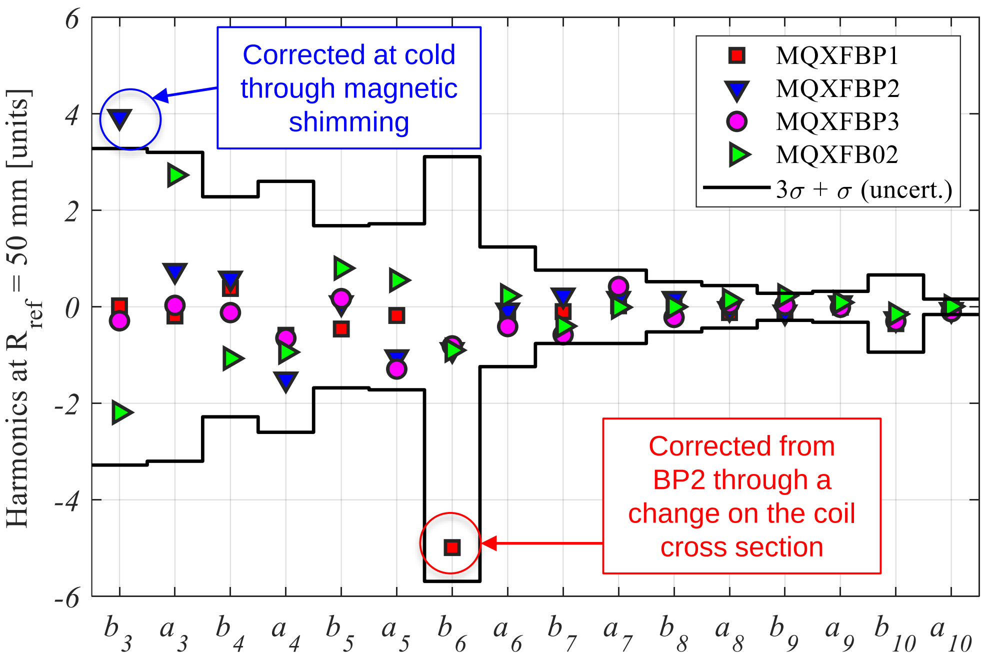
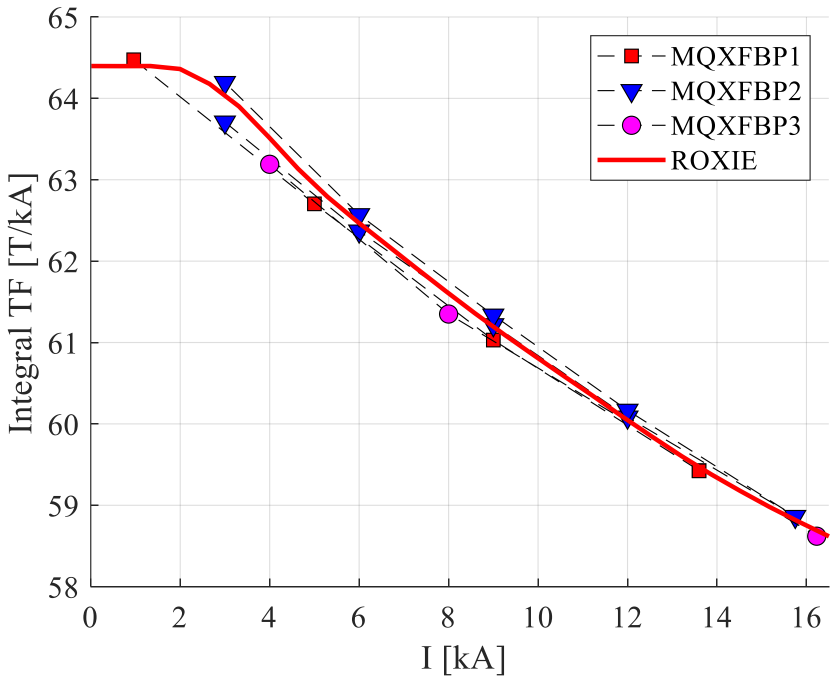
Validated design features: field quality

- Field errors well within the requirements :
  - Good cold/warm correlation and ability to correct field errors through magnetic shimming demonstrated in MQXFBP2
  - A systematic b_6 in a very early phase of the production was intercepted and corrected through a minor modification of the coil cross section
- Main field:
  - Stability of the main field at nominal current measured during an 8 h plateau in MQXFBP3, showing no change on the field within the measurement noise (1 unit)
  - Integrated gradient of the first three prototypes is within a range of 20 units, as required, already in this early phase

Field errors after loading

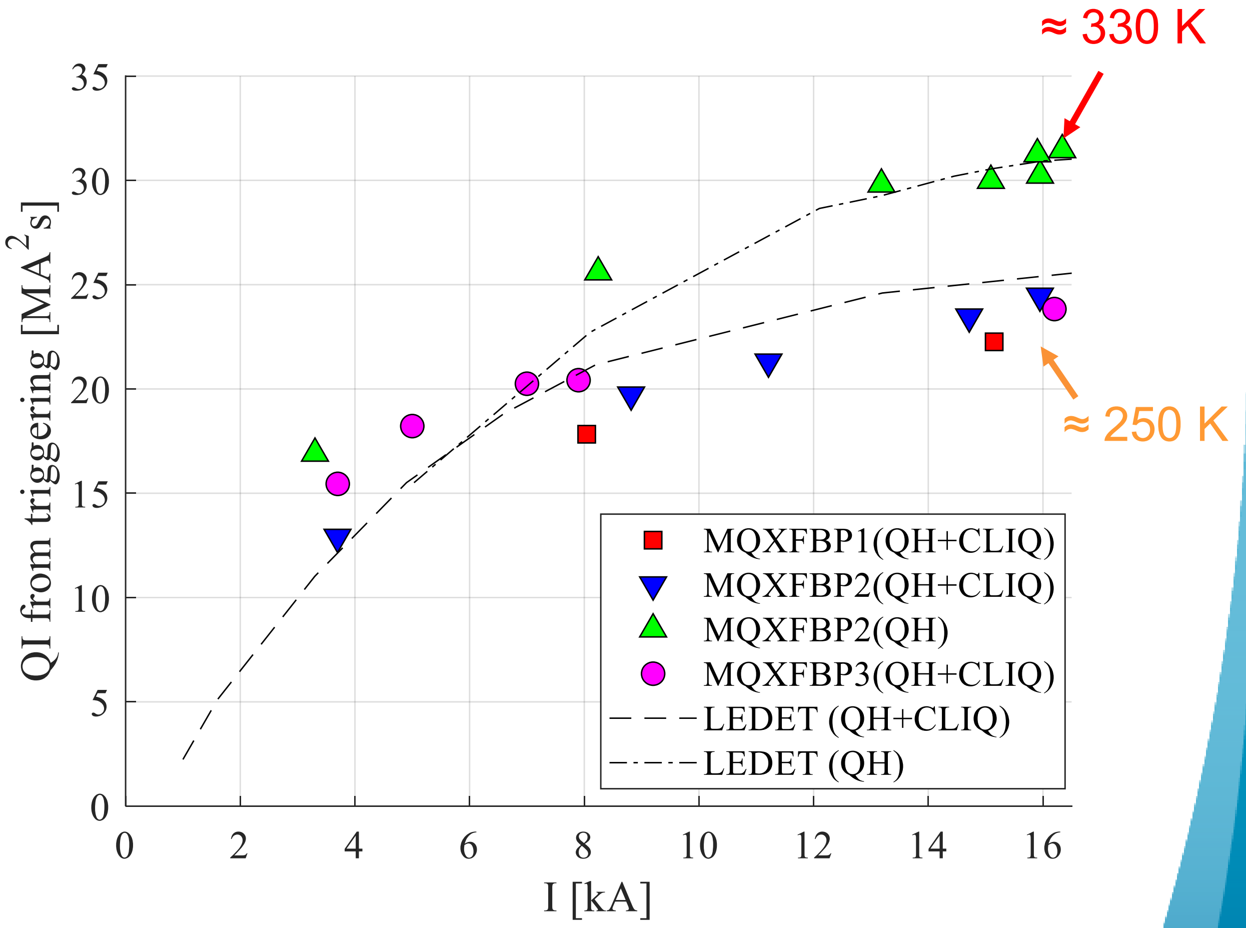


Measured integral gradient during powering



Validated design features: protection

- With MQXFB prototypes, we **validated the protection** relaying in CLIQ + QH for full size magnets. Measured quench integral in good agreement with computations.
  - For **nominal** protection configuration (CLIQ + QH), QI from triggering ≈ 25 MA^2s, with a **T_{hot} ≈ 250 K**
  - In MQXFBP2, during the trim current test, the magnet was protected **only with quench** heaters, reaching a hot spot temperature of **~330 K without impact on magnet performance** → validate design choice for allowable T_{hot}



Simulations by E.Ravaioli with STEAM-LEDET + PSPICE coupled using STEAM-COSIM

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Conclusions

- **MQXFBP1** and **BP2** were **limited** at 93 % and 98 % of the nominal current at 1.9 K, 20 A/s ramp. **MQXFBP3 reached I_{nom} + 300 A** at 1.9 K, with ≈ 2 K of temperature margin.
- Destructive inspection of the coils show a **systematic degradation of the conductor** in the transitions between poles.
- Possible root causes have been identified and are being addressed:
  - *Cold mass assembly*: new welding procedure implemented in **MQXFBP3**.
  - *Magnet assembly*: improved assembly procedure implemented in **MQXFB02**, **removing the coil stress overshoot** during loading operations. Test expected in November 2022.
  - *Coil fabrication:* the fabrication of **transition coils** is on going, with a focus on the operations between coil reaction and impregnation. Fast tracks for cold testing have been defined to assess the performance of the transition coils.
- **Key features** of the design have been **validated** through the MQXFB prototyping phase:
  - Integration of a bladder and key magnet in a **SS vessel**
  - **Field quality** well within the requirements needed for operation
  - **Protection** of a full-length magnet without a dump, both in normal operation (CLIQ + QH) and failure (protection only with QH)

Thank you