Status of MQXFB

Susana Izquierdo Bermudez
on behalf of the MQXF collaboration

14th HL-LHC collaboration meeting, Genoa (Italy), 7-10 October 2024

Acknowledgment

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Outline

- Introduction
- Timeline and test results
- Status of the production
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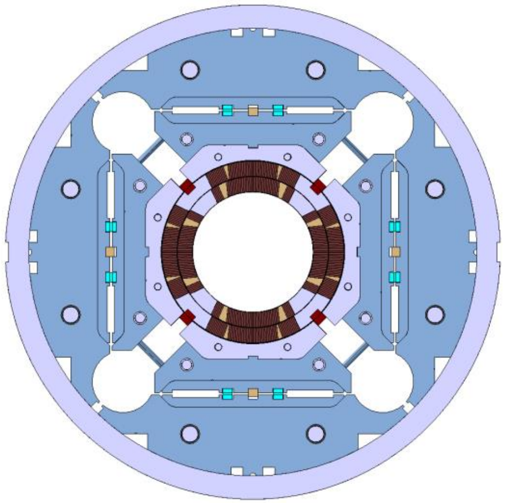
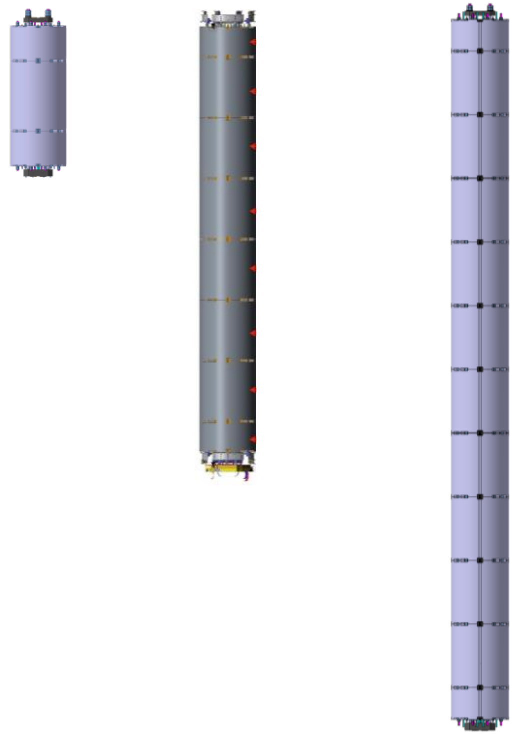
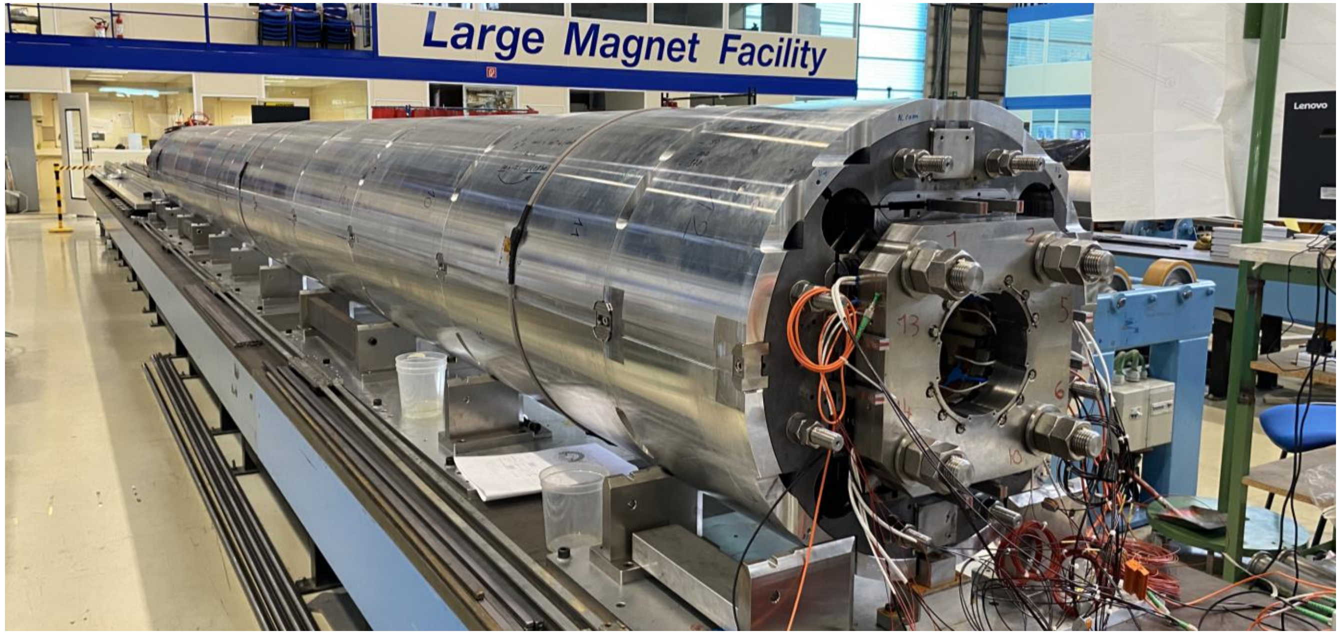
HL-LHC low-β quadrupole MQXF



- 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

MQXFS (1.2 m) *MQXFA (4.2 m)* *MQXFB (7.2 m)*





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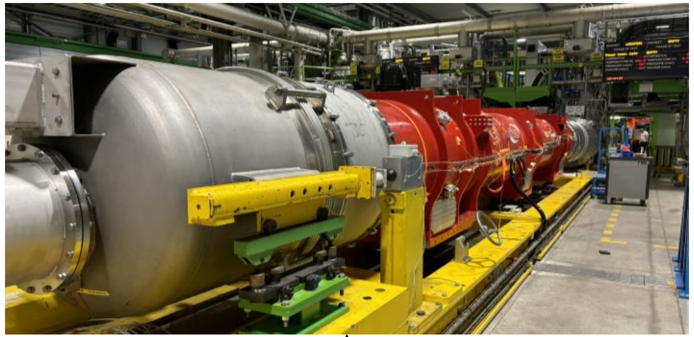
A summary of MQXFB program

- 132.2 T/m, 16.23 kA at 7 TeV, corresponding to 11.3 T peak field
  - Magnets are tested to 16.23 kA + 300 A, both at 1.9 K and 4.5 K

Current baseline:
3 prototypes + 10 series magnets (8 + 2 spares)

T_0: aperture and cable selection

MQXFB under test, in a temporary cryo-assembly configuration (w.o. corrector)



Q2 cryo-assembly under test, containing a MQXFB quadrupole and MCBXF corrector

T_0+7

MQXFBP1: ~6.5 TeV, ~10.5 T

MQXFBP2: ~6.9 TeV, ~11.2 T

MQXFBP3: conform

MQXFB02*: conform

MQXFB03: conform

MQXFB04: conform

MQXFB05: Test ongoing

MQXFB06: February

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026

7 more magnets to test (B07-B12)

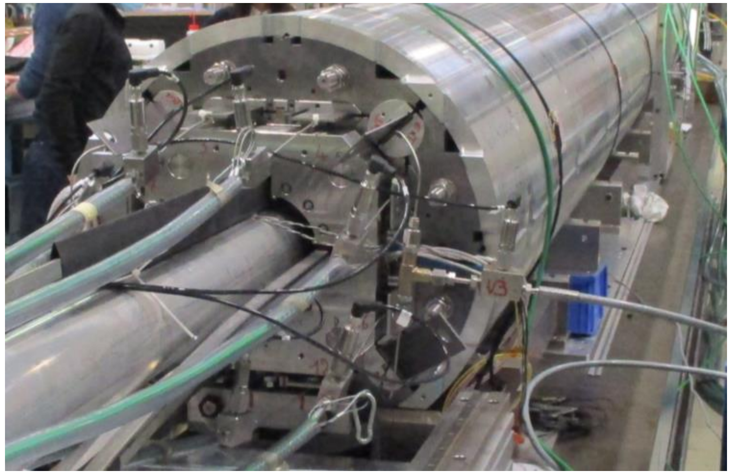
*MQXFB02 was disassembled due to a critical NCR during cold mass fabrication

Blue: conform
Black: non conform
Grey: coming soon

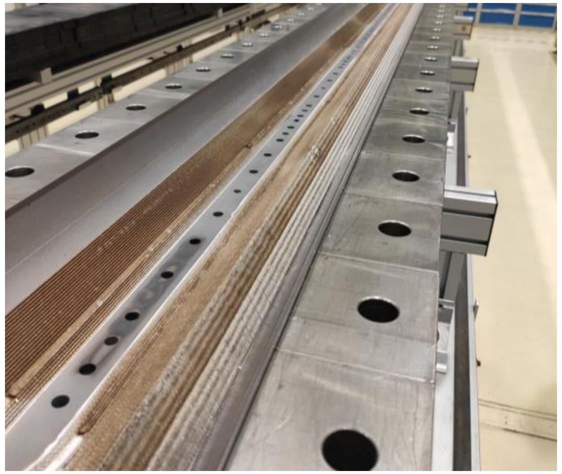
Addressing magnet performance limitations

- MQXFBP1 and BP2 were limited below nominal current at 1.9 K (~15 kA (6.5 TeV) and ~16 kA (6.9 TeV) respectively).
- Corrective strategy: focus on reducing strain in the conductor during coil fabrication and magnet/cold mass assembly
- Three steps
  1. Reducing the stress induced on the coil during ss shell welding
  2. Reducing the peak stress in the coil during bladder operation
  3. Providing more room the coil in the reaction fixture during heat treatment

H. Prin et al.,
10.1109/TASC.2024.3364134



J. Ferradas Troitino et al.,
2023 Supercond. Sci. Technol. 36 065002



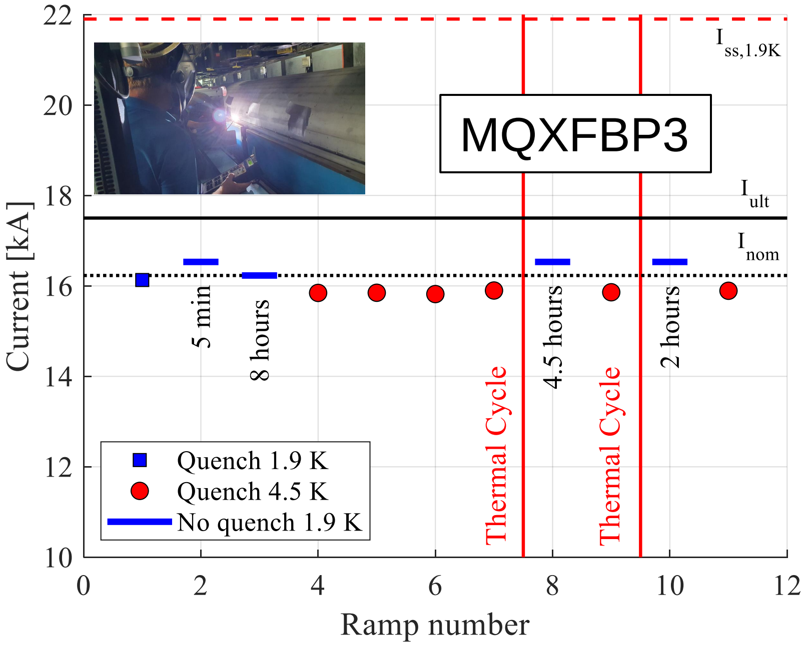
N. Lusa et al.,
10.1109/TASC.2024.3360928.

Addressing magnet performance limitations

- The corrective strategy was progressively implemented in the following 3 magnets

Addressing magnet performance limitations

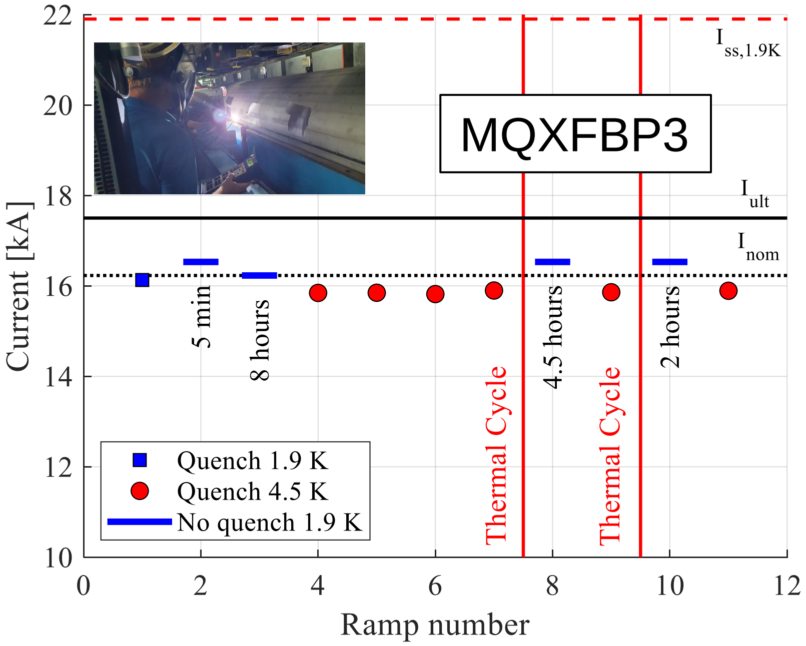
- The corrective strategy was progressively implemented in the following 3 magnets
- MQXFBP3 (new welding procedure) reached the target current at 1.9 K (I_{nom} + 300 A) at 1.9 K but not at 4.5 K.
  - phenomenology similar to the one observed on MQXFBP1&2

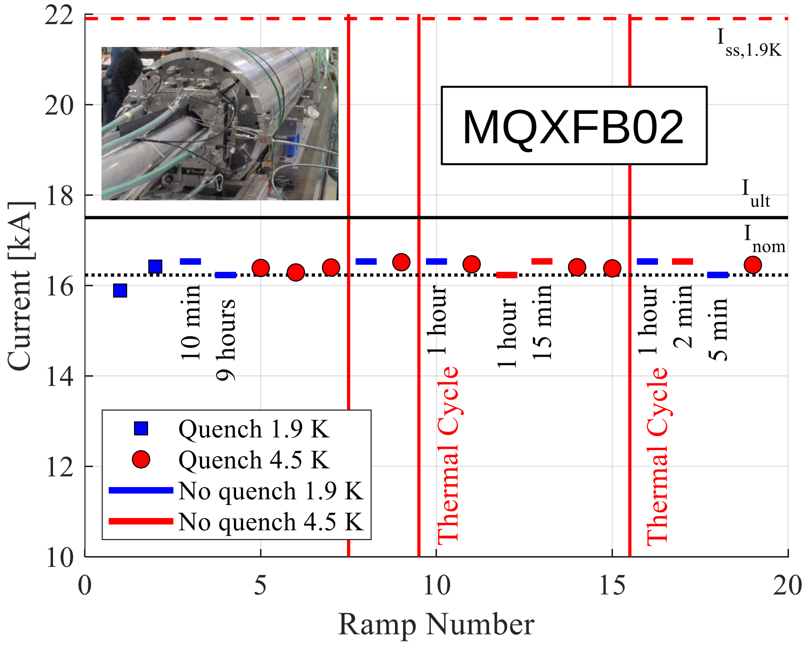


Only ramps at 20 A/s

Addressing magnet performance limitations

- The corrective strategy was progressively implemented in the following 3 magnets
- MQXFB02 (new welding and magnet assembly procedure) reached the target current (I_{nom} + 300 A) at 1.9 K and 4.5 K, but still show signs of conductor degradation
  - same phenomenology as previous magnets

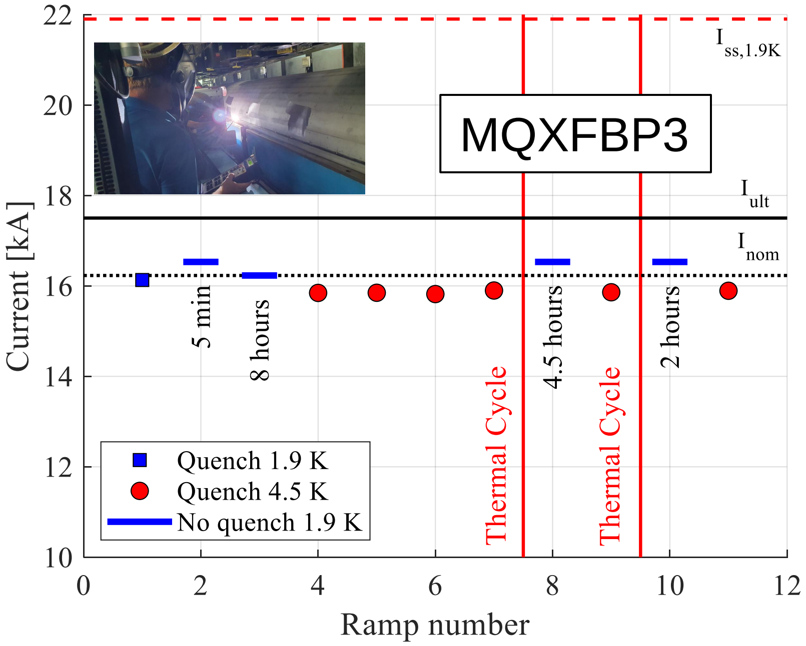


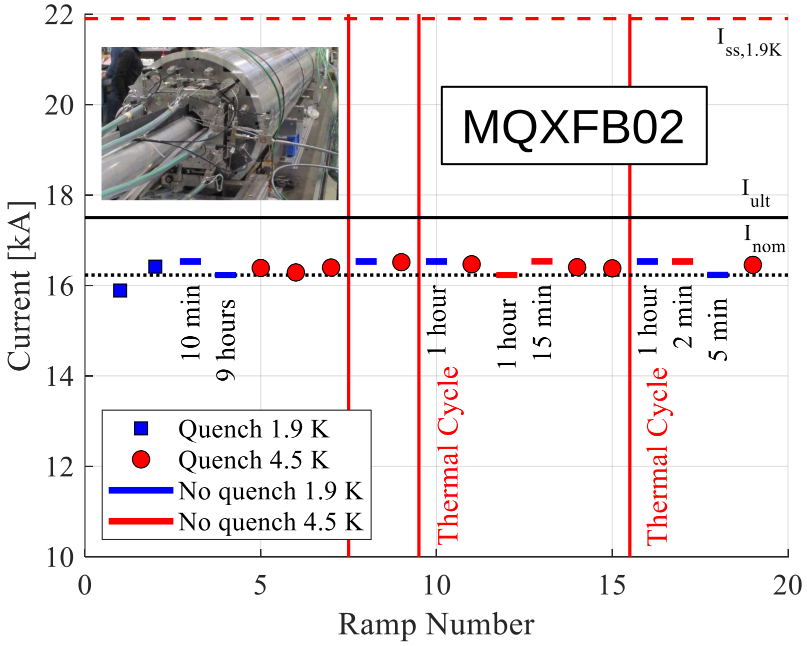


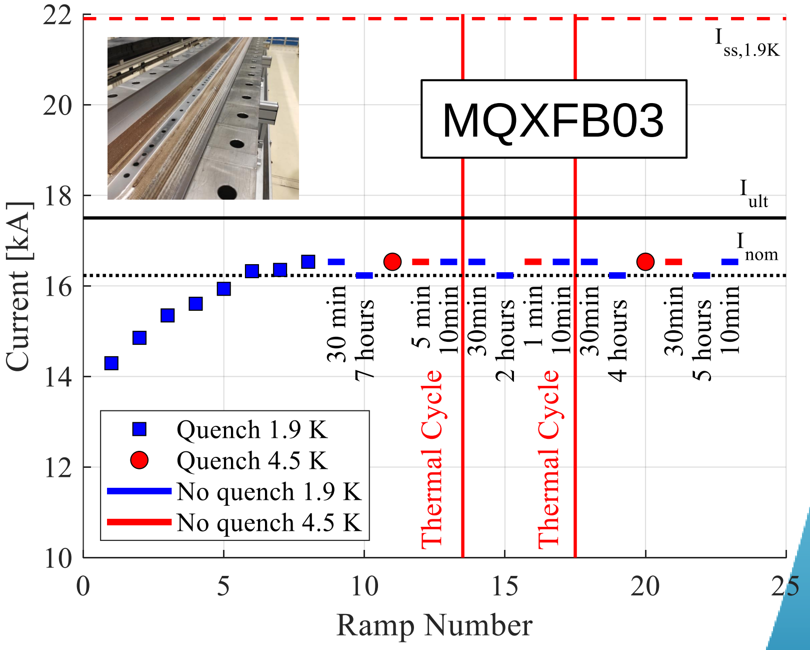
Only ramps at 20 A/s

Addressing magnet performance limitations

- The corrective strategy was progressively implemented in the following 3 magnets
- MQXFB03 (new welding, magnet assembly and coil fabrication procedure) reached the target current (I_{nom} + 300 A) at 1.9 K and 4.5 K without any sign of limitation





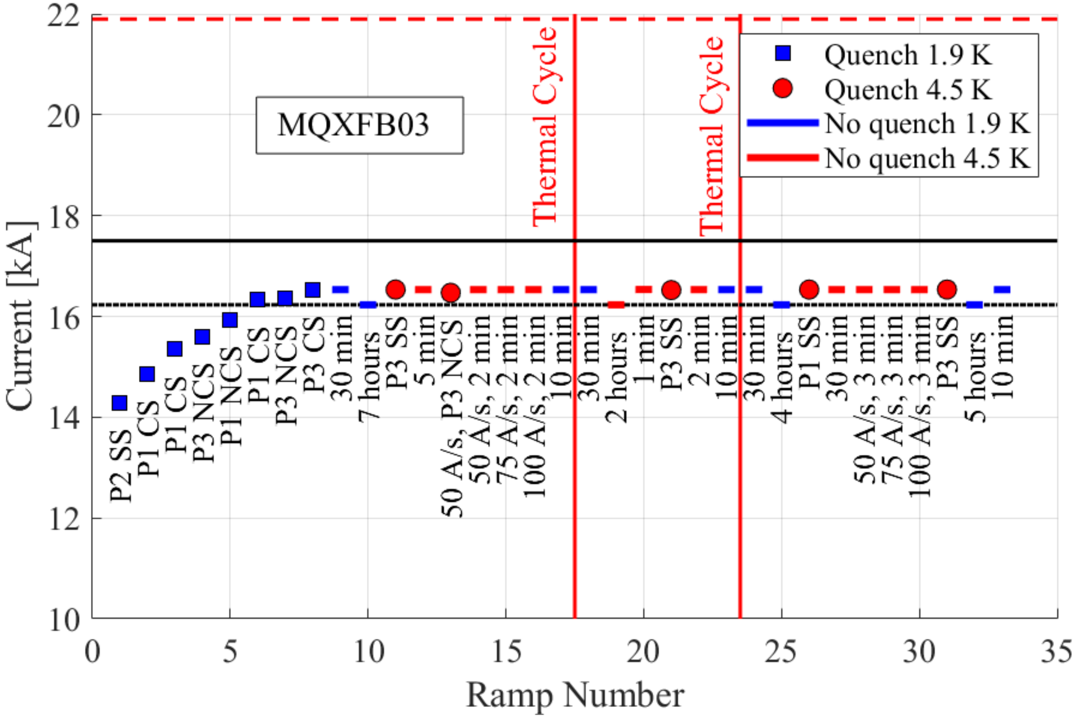


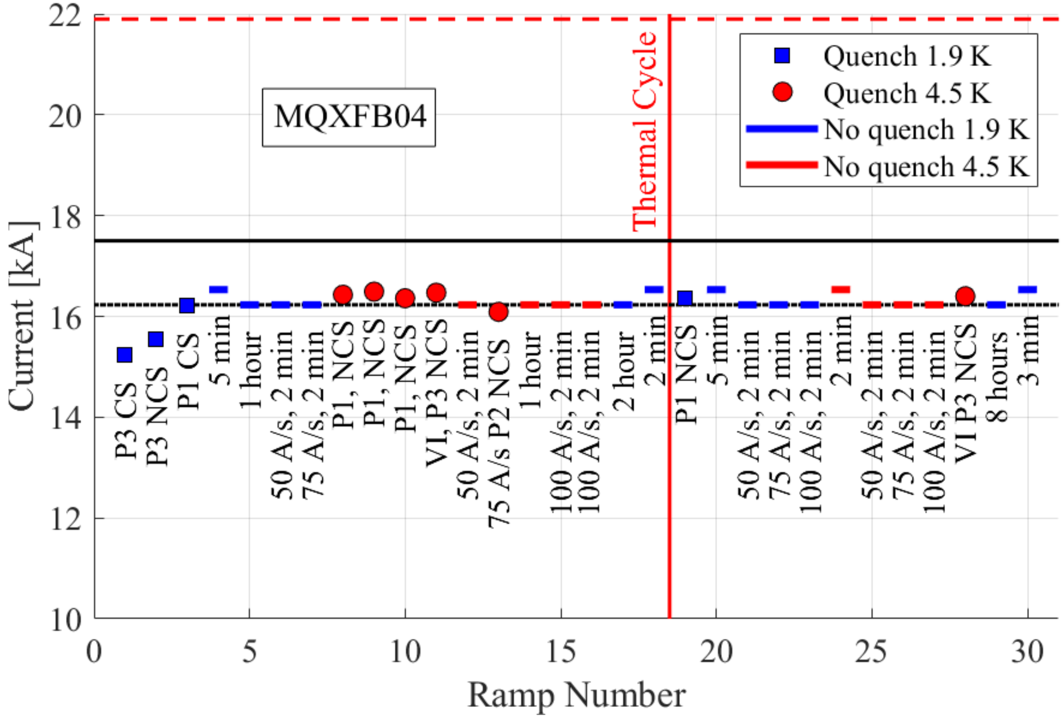
Only ramps at 20 A/s

More details F. Mangiarotti
Tuesday PM

Performance reproducibility

- A second magnet, MQXFB04, was built using identical procedures.
- MQXFB04 also reached the target current (I_{nom} + 300 A) at 1.9 K/4.5 K without any sign of conductor damage
  - B03&B04 reached nominal current at 4.5 K at 100 A/s (nominal 20 A/s), a good indication that we still have margin.

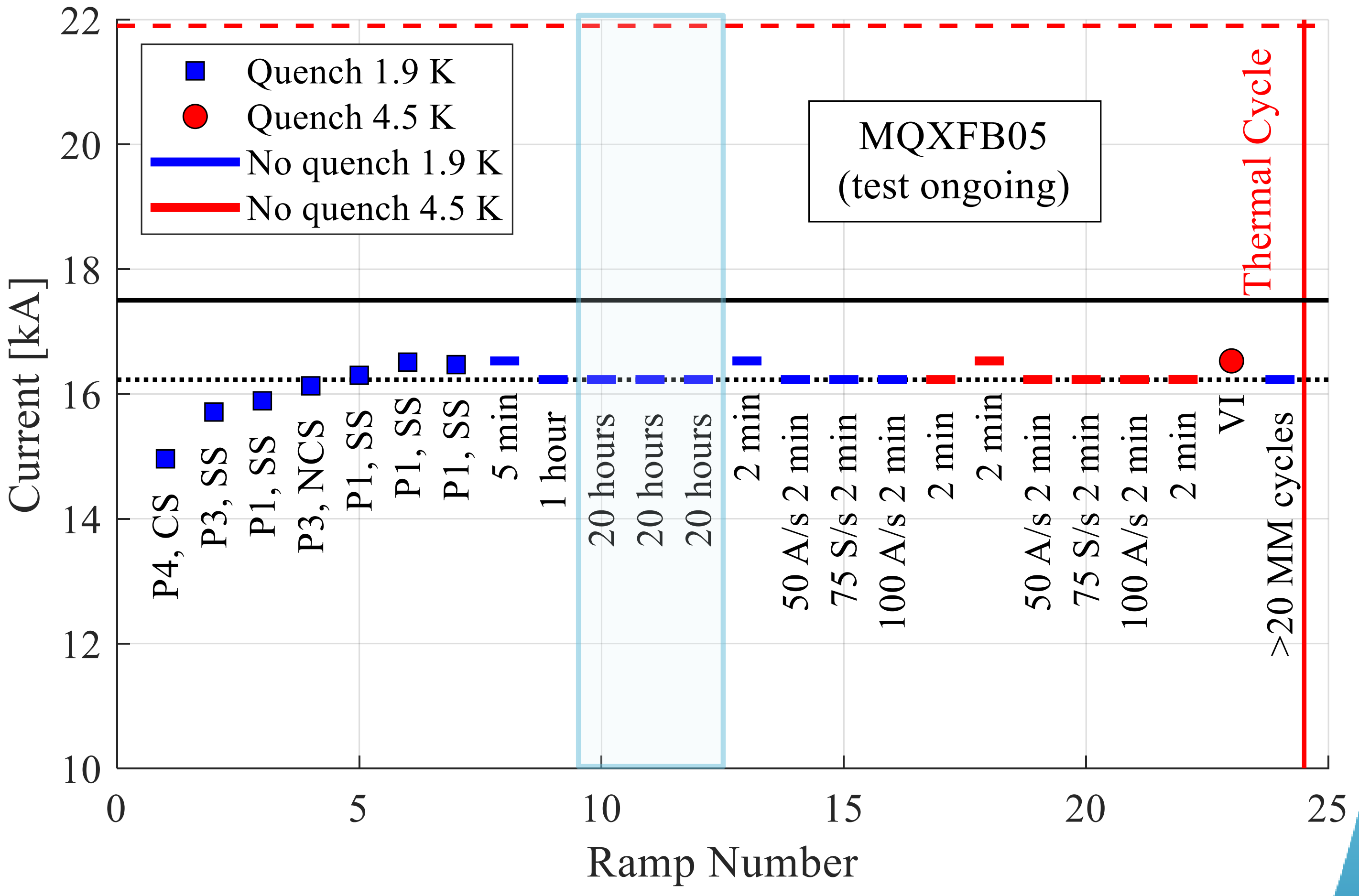




Performance reproducibility

More details F. Mangiarotti
Tuesday PM

- MQXFB05, third magnet built using identical procedures, is being tested.
- The magnet reached all performance requirements in the first thermal cycle
- 3 x 20 hours holding current test at nominal current has now being introduced systematically for Q2 cold powering test. MQXFB05 successfully passed the test.

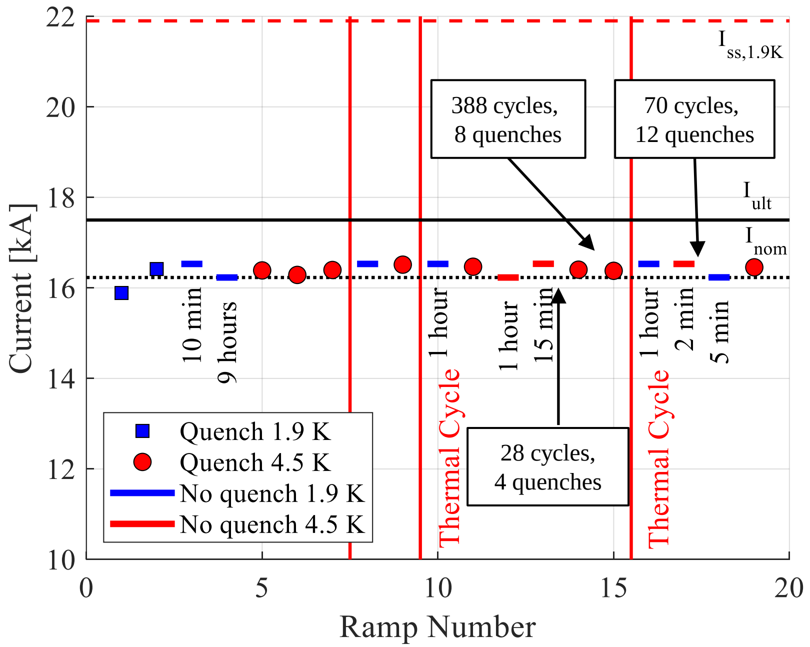


Endurance

More details F. Mangiarotti
Tuesday PM

- Endurance tests show no performance degradation with current and thermal cycling, and stable operation at nominal current (7 TeV).

Endurance test in MQXFB02



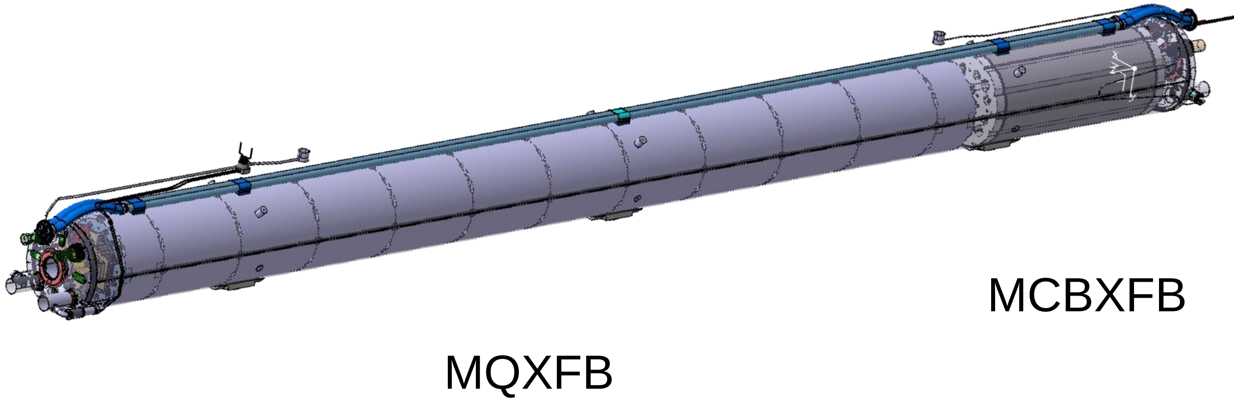
	Number of thermal cycles	Number of quenches at $I \geq 0.8I_{nom}$	Number of quenches at $I \geq I_{nom}$	Number of cycles to $\geq I_{nom}$	Time [h] at $I \geq I_{nom}$
BP1	2	21	0	0	0
BP2	5	56	7	17	14
BP3	4	26	10	70	44
B02	4	43	36	508	38
B03	3	31	18	50	24
B04	2	12	7	44	28
B05*	1	8	4	≈ 40	≈ 70
TOTAL	**21**	**197**	**82**	**729**	**218**

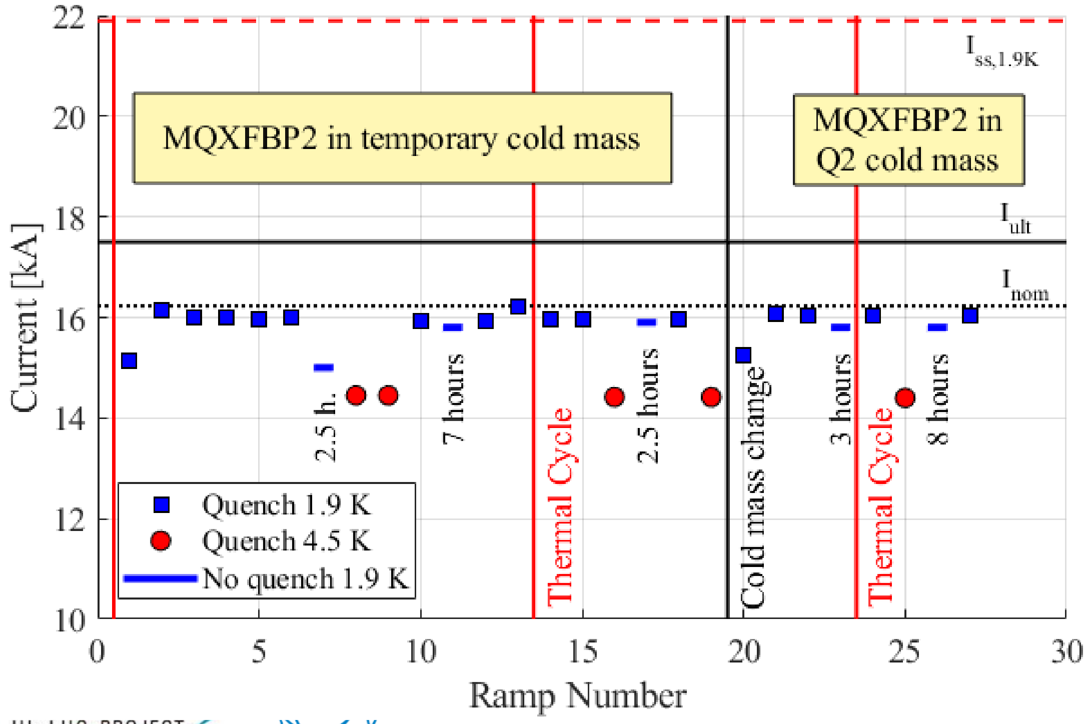
* Test ongoing

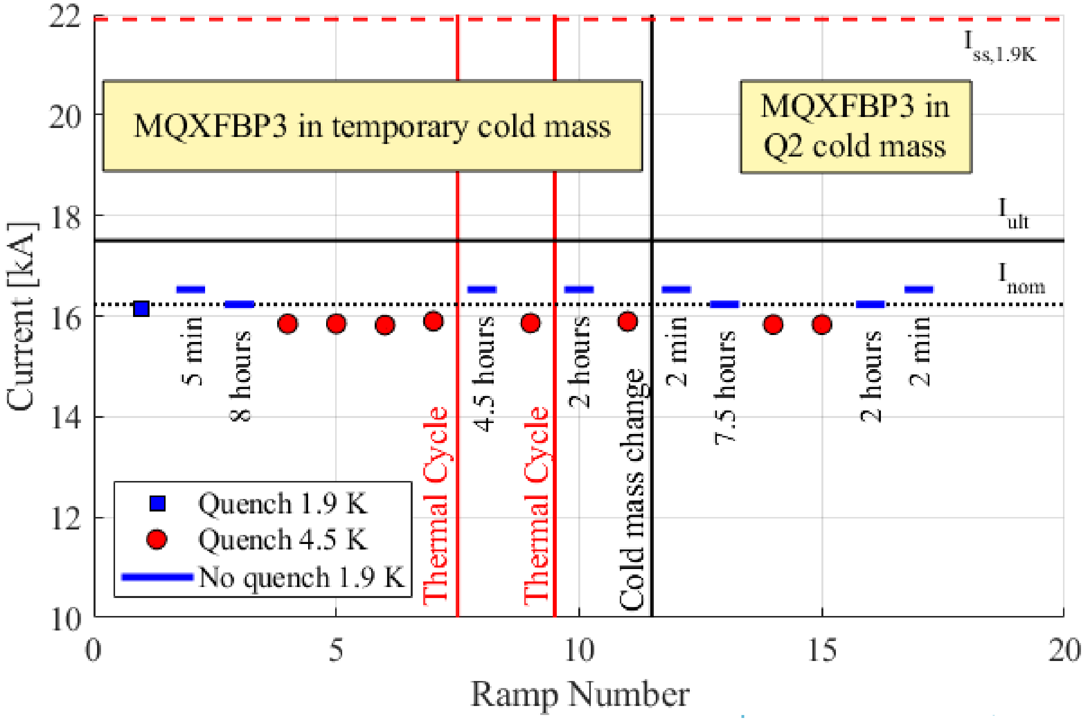
From temporary to Q2 cold mass

More details F. Mangiarotti
Tuesday PM

- The first MQXFB magnets were tested first in single cold mass configuration (faster turnaround time and test station availability).
- MQXFBP2 and MQXFBP3 have been now tested in Q2 cold mass configuration, assembled together with a MCBXF corrector
  - No change on performance





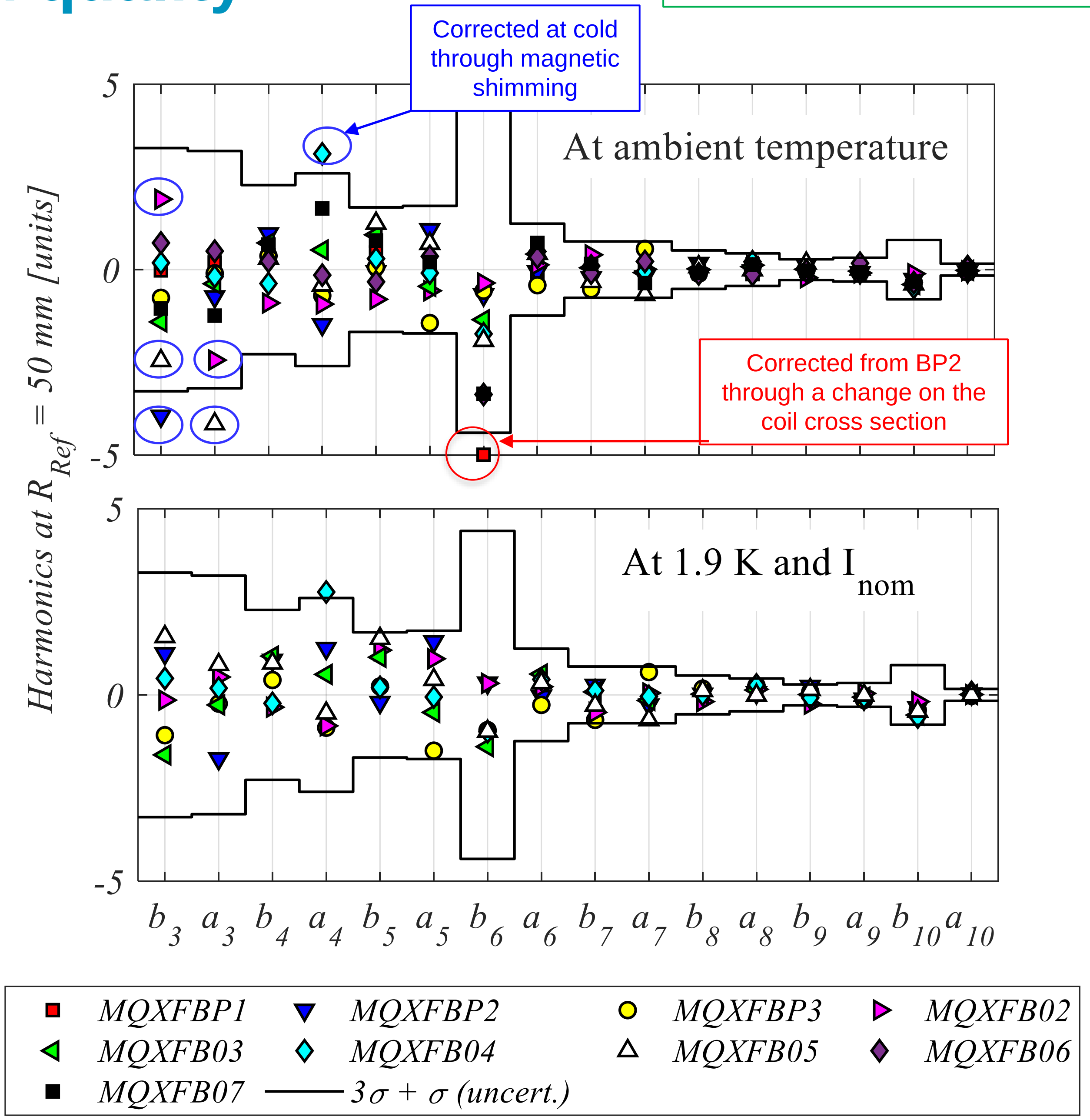


More details L. Fiscarelli
Wednesday AM

Field quality

- Field errors well within the requirements, with good cold/warm correlation and ability to correct field errors through magnetic shimming
- Integrated gradient is within a range of 20 units, as required, already in this early phase

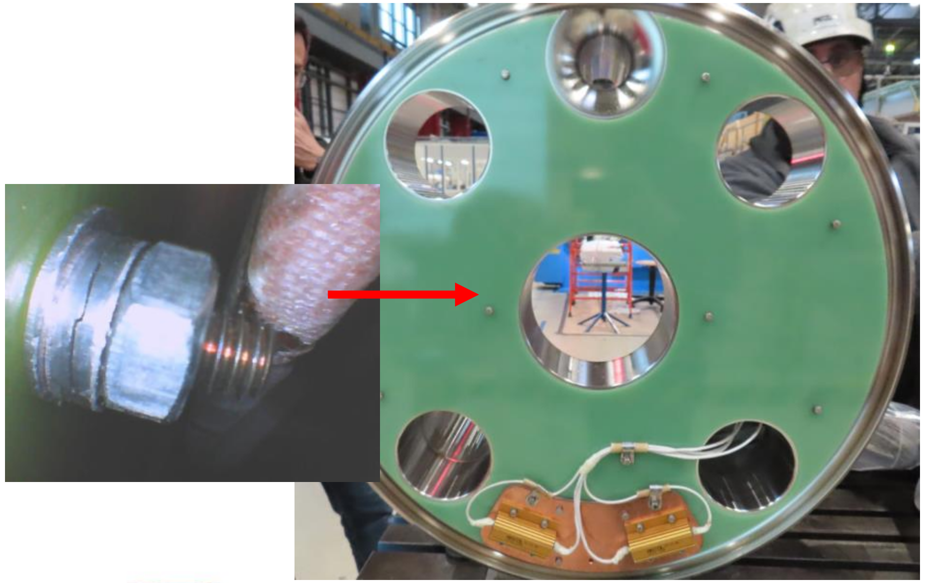
	Transfer function (T kA⁻¹)	
	Room Temperature	1.9 K at I_{nom}
MQXFBP1	63.394	58.562
MQXFBP2	63.359	58.708
MQXFBP3	63.328	58.616
MQXFB02	63.407	58.649
MQXFB03	63.458	58.571
MQXFB04	63.426	58.654
MQXFB05	63.434	–
MQXFB06	63.396	–
Average	63.400	58.627
Range (units)	20	25



Electrical integrity

- Electrical integrity remains a technical challenge, with three critical non-conformities which required cold mass repair/disassembly

MQXFBP2
Fault to ground in the main circuit, identified on the busbar, next to the end cover. The fault was repaired, and feedback implemented to next units.



MQXFB02
Quench heater to coil fault, due to non-conforming testing conditions. Cold mass disassembled.

MQXFBP3
One quench heater to coil fault during the 850 V at 100 K, 1 bar, the heater was disconnected, and the magnet will be use as is for the IT-string

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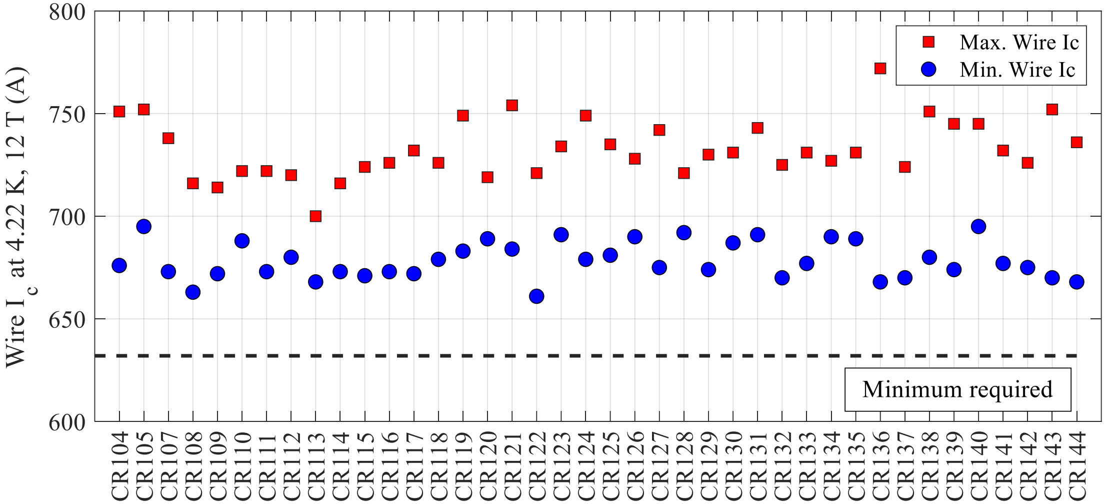
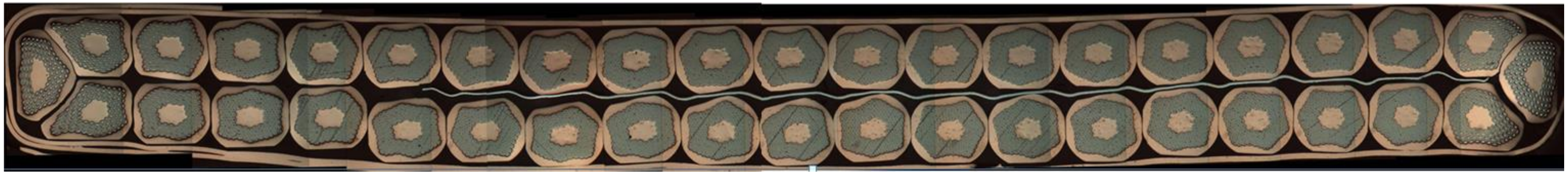
90 %

Conductor and cable

- MQXF coils are made with a Rutherford-type cable composed of 40 strands x 0.85 mm
  - Procurement of ≈ 3000 km of wire, with UL 840 m
    - 460 km for the prototypes
    - 2160 km for the series (90 % received and accepted)
    - 340 km additional order as strategic stock, to be delivered in 2025
  - 8 RRP prototype cables and 55 series cables have been produced so far, with only two rejected cables
    - The 5 remaining cables to produce the baseline number of coil will be completed early 2025.
  - Conductor performance well above the targets:
    - Critical current is in average 10 % higher than initially specified
    - The measured Residual Resistivity Ratio on samples reacted with the coil > 250 in average (spec. > 100)

Bruker-OST RRP 108/127



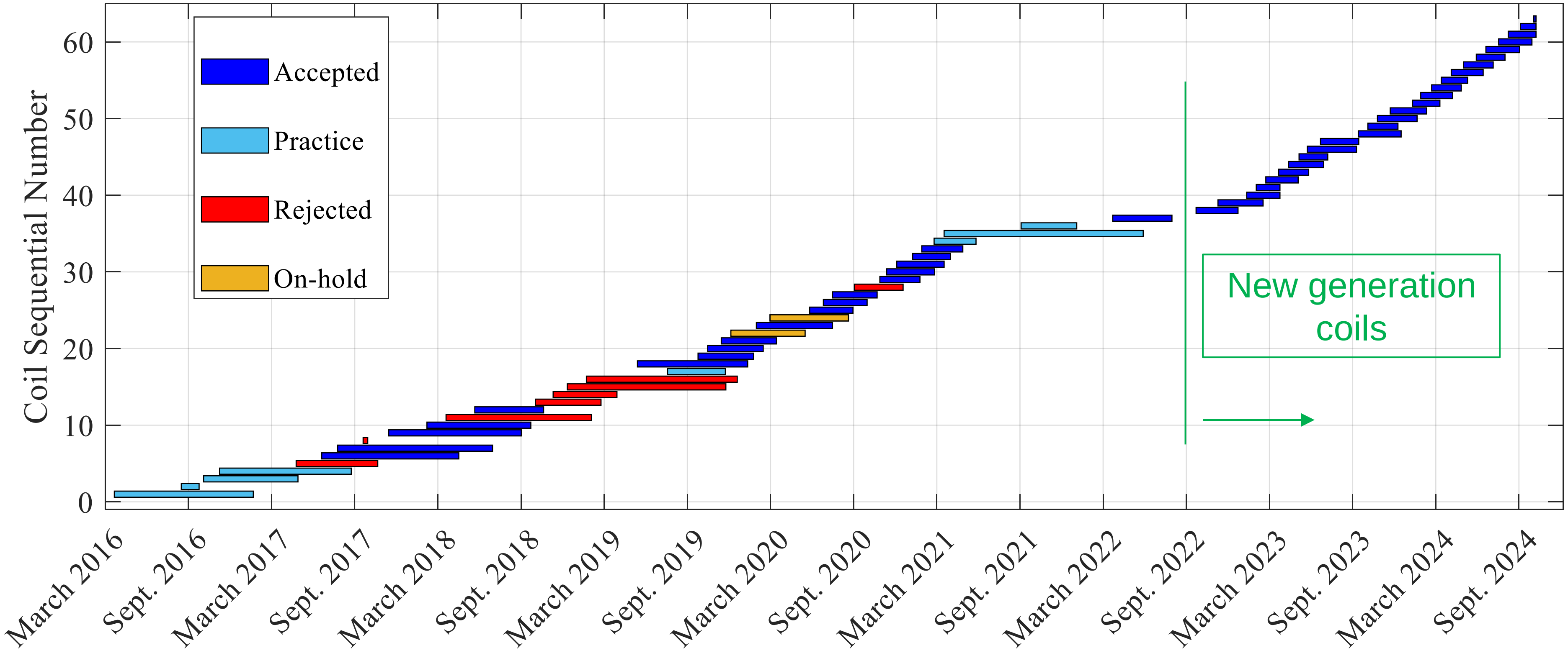


More details N. Lusa
Wednesday PM

70 %

Coil fabrication

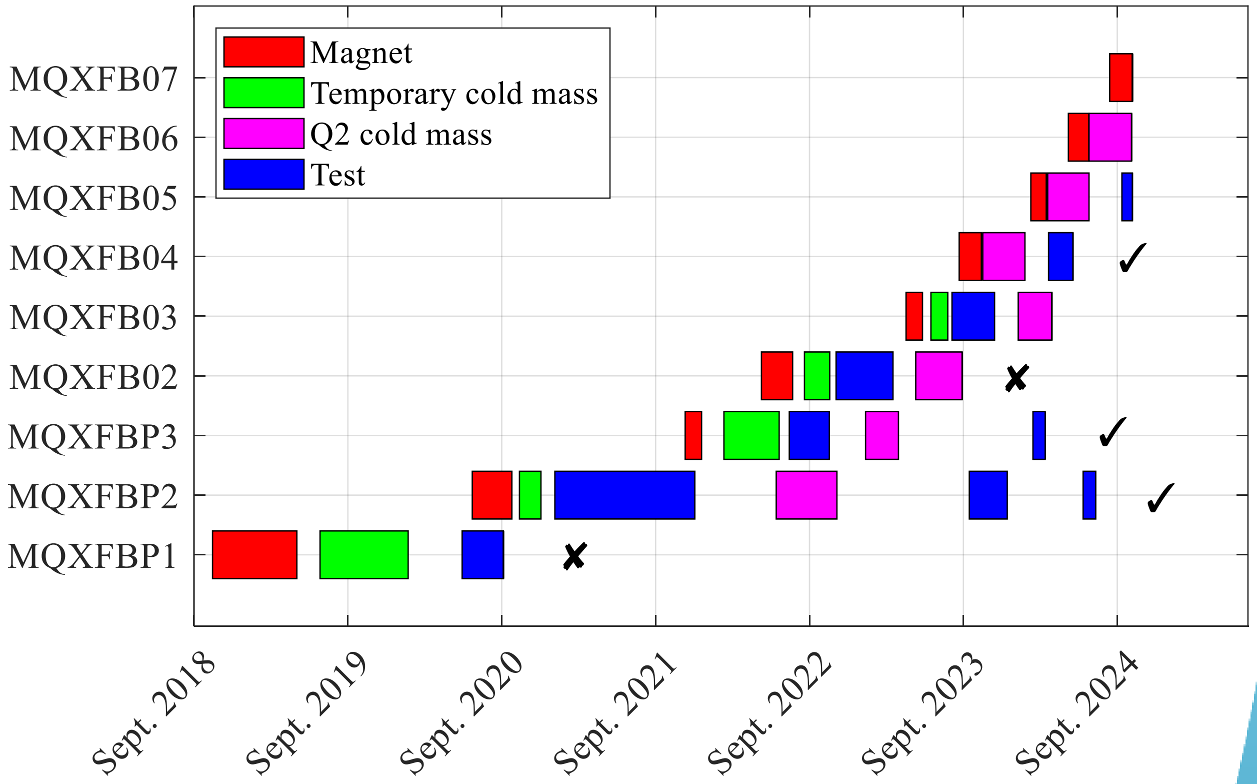
- In total, 63 coils have been already wound. Since the re-start of the coil production in September 2022, 22 coils have been completed and 4 coils are in fabrication.
- To complete the baseline number of coils, 16 more coils need to be wound. The plan is to complete coil fabrication first half of 2026.
- Exceptional coil yield, in the last 2 years there was not a critical nonconformity during coil fabrication which led to coil rejection.



Magnet and cold mass assembly

50 %

- From the last collaboration meeting:
  - 4.5 cryo-assemblies have been tested (B03 (2nd thermal cycle), B04, BP2 (Q2), BP3 (Q2), B05 (ongoing))
  - 3.5 cold masses have been built (B03 (Q2), B04,B05 and B06 (ongoing))
  - 4 magnets have been assembled (B04/B05/B06/B07)
  - 1 cold mass has been fully disassembled to recover components after a critical NCR (B02)



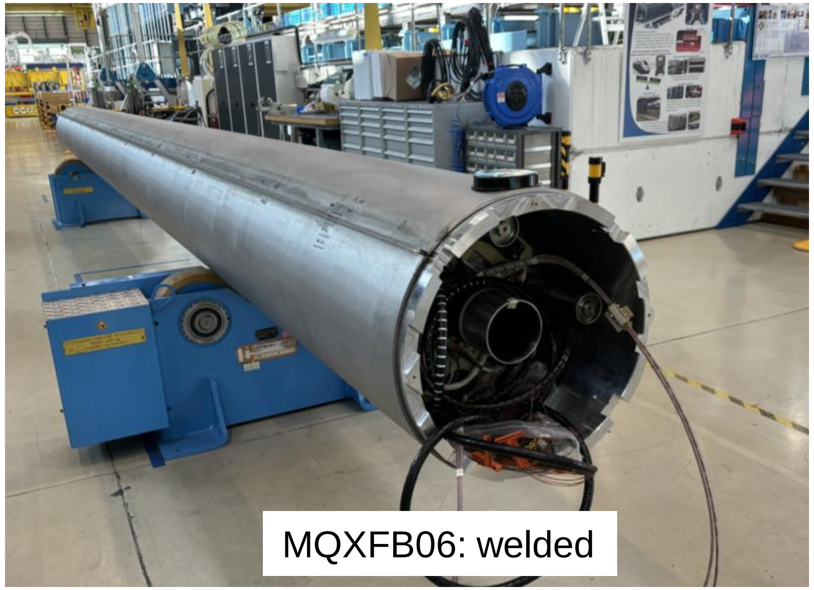
More details P. Quassolo Wednesday PM and H. Prin Wednesday PM


MQXFBP2: being prepared for the HL-LHC string


MQXFBP3: in the HL-LHC string


MQXFB03: ready to be tested in Q2 conf.
MQXFB04: to be prepared for HL-LHC


MQXFB05: test ongoing


MQXFB06: welded


MQXFB07: magnet loaded

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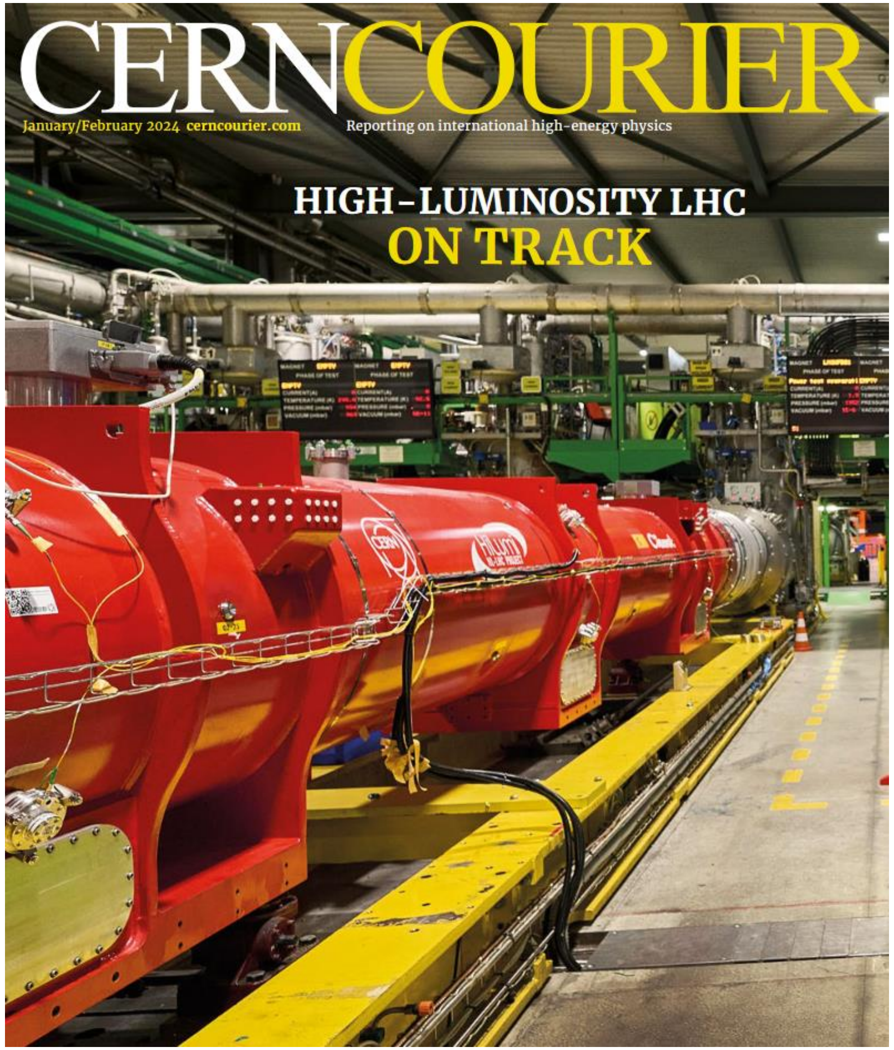
Conclusions

- Four MQXFB magnets reached HL-LHC requirements. Scaling in length has been nontrivial:
  - MQXFB03, produced using new generation coils, does not show performance limitation: first 7.2 m length magnet with no signs of conductor limitation!
  - MQXFB04, built with identical procedures, demonstrated the reproducibility of the performance.
  - The test of MQXFB05 is ongoing, confirming so far results from previous magnets.

- MQXFB is now in full series production phase, proving the Nb_3Sn technology for 7-m-long accelerator magnets operating at 11.3 T peak field:
  - Reached requirements in terms of protection and field quality
  - Large margin in mechanics proved for short models
  - Large temperature margin proved in short and long magnets (up to 2.6 K out of 5 K)
  - Endurance and long-term stability



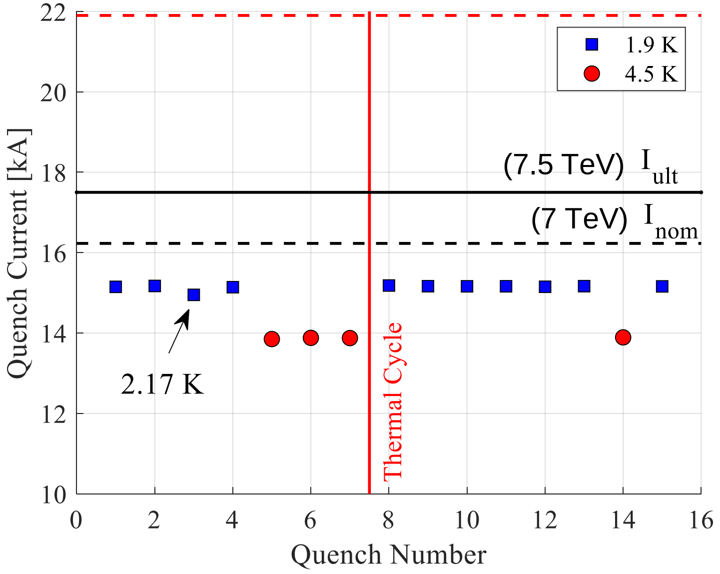
Thank you!

Additional slides

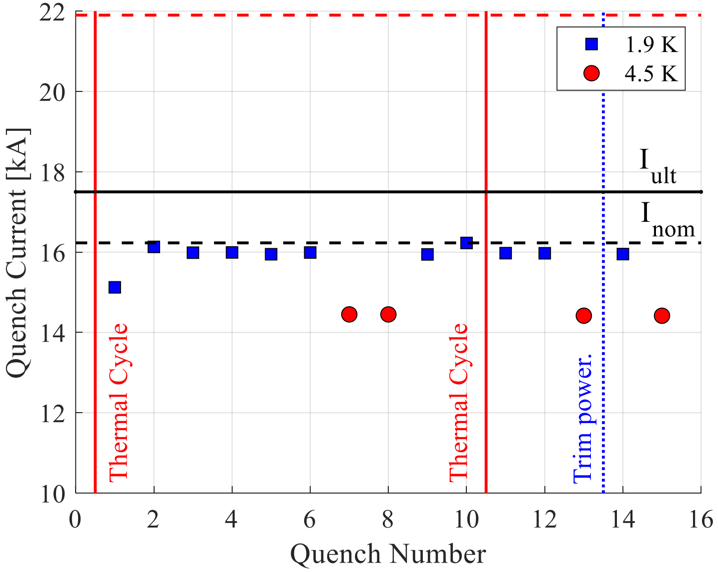
MQXFBP1&BP2 Prototypes Performance

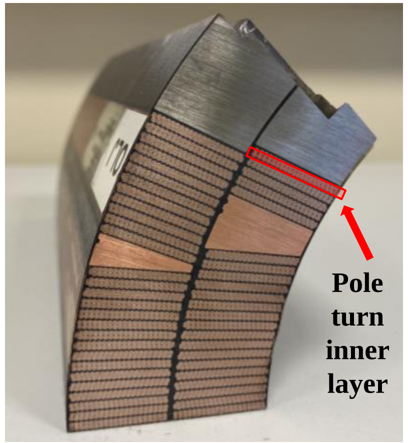
- MQXFBP1 and BP2 were limited below nominal current at 1.9 K (~15 and ~16 kA respectively).
- 4.5 K behaviour compatible with magnet on the critical surface (70% of the short sample limit in MQXFBP1, 73 % in MQXFBP2).
- No retraining after thermal cycle and magnet performance did not degrade with temperature 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.
- Power circuit modification (the so-called trimmed powering) to evaluate the performance of non-limiting coils → 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

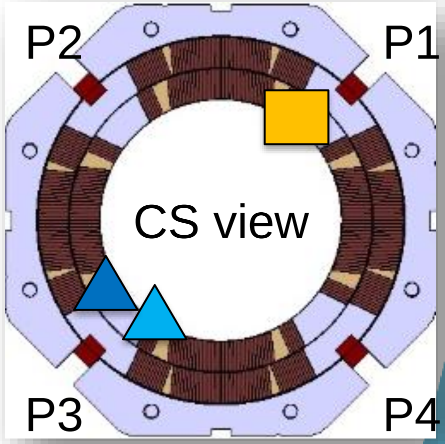
MQXFBP1

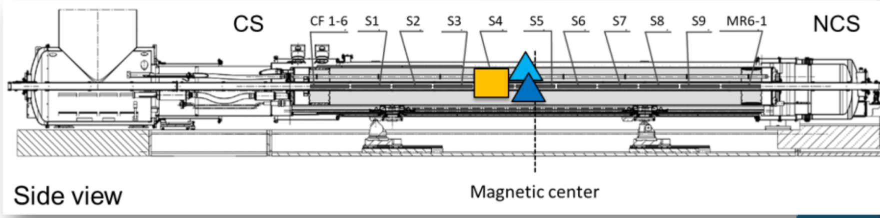


MQXFBP2





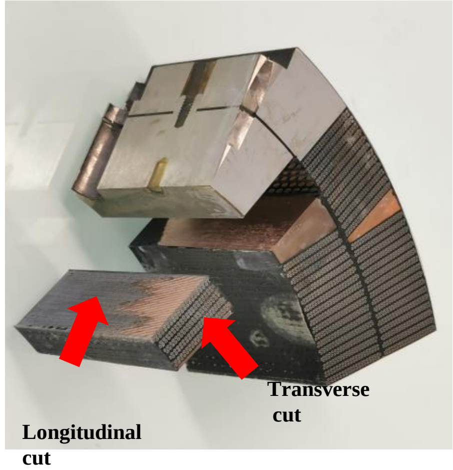


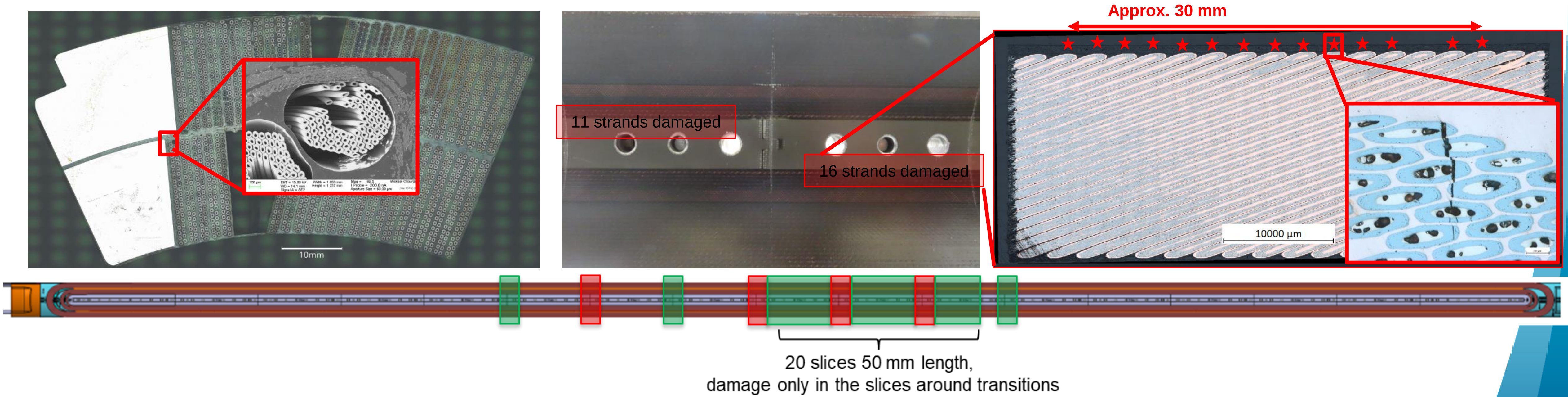


F. J. Mangiarotti et al., "Power Test of the First Two HL-LHC Insertion Quadrupole Magnets Built at CERN," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4003305, doi: 10.1109/TASC.2022.3157574.

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.
  - 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 problem in the pole-to-pole transitions .





A. Moros et al., "A metallurgical inspection method to assess the damage in performance-limiting Nb_3Sn accelerator magnet coils", 10.1109/TASC.2023.3237662
I. Aviles Santillana et al., "Advanced Examination of Nb3Sn Coils and Conductors for the LHC Luminosity Upgrade: A Methodology Based on Computed Tomography and Materialographic Analyses", 2024 Supercond. Sci. Technol. 37 085007

MQXFB: magnet performance