HFM

High Field Magnets

Feedback of HL-LHC Magnets to HFM

Susana Izquierdo Bermudez

Acknowledgements: Ezio Todesco, Attilio Milanese, Giorgio Ambrosio, Paolo Ferracin,
Frederic Savary, Gerard Willering, Franco Mangiarotti, Lucio Fiscarelli, Arnaud Devred, Luca Bottura.

Outline

- Introduction: the challenge of the HL-LHC Nb_3Sn magnets
- Coil fabrication
- Magnet assembly
- Field quality
- Protection and electrical integrity
- Training and performance
- Industrialization
- Conclusions

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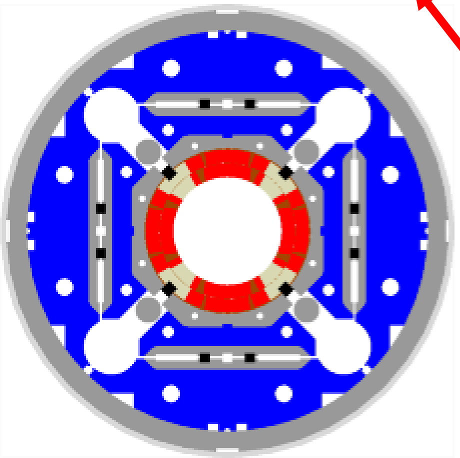
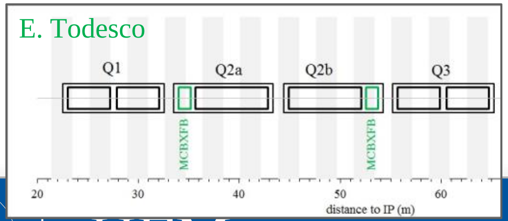
The HL-LHC Nb_3Sn magnets

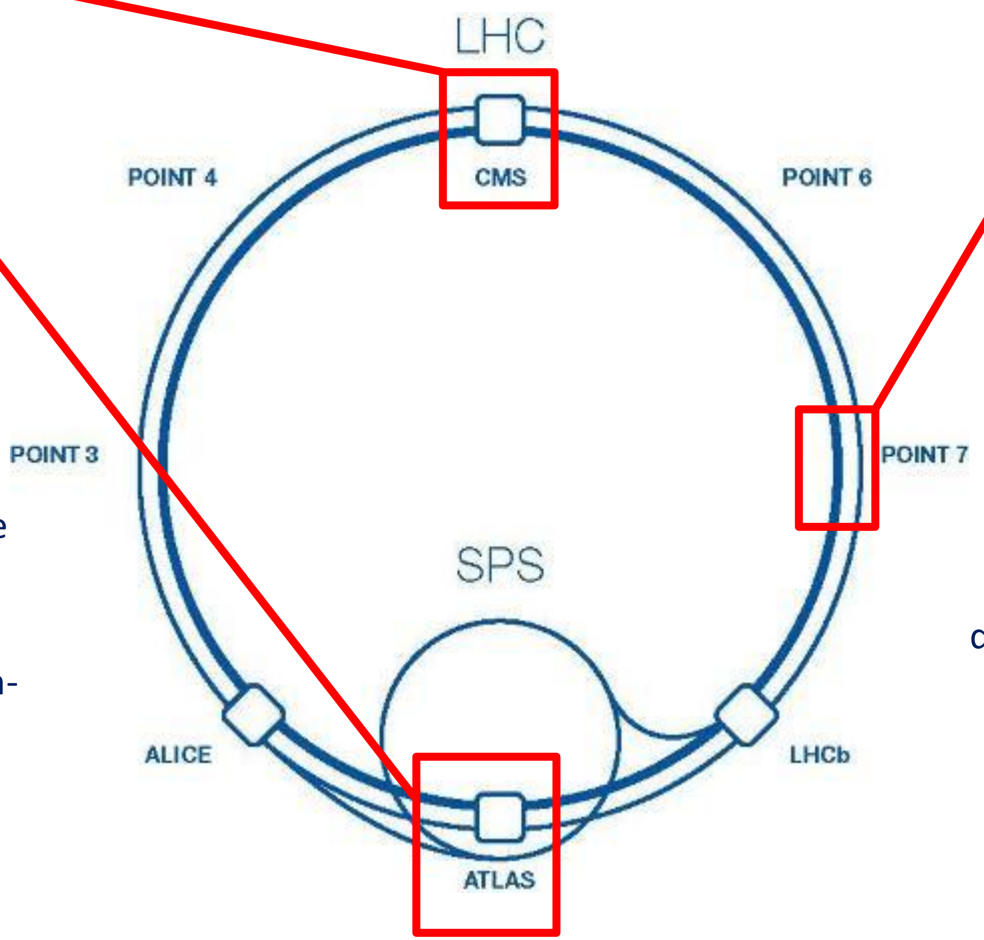
MQXF



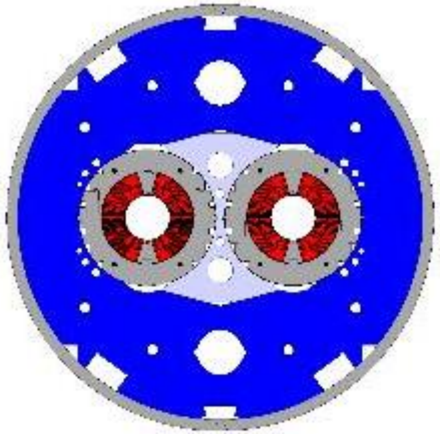
30 large aperture (150 m) and more powerful quadrupoles around ATLAS and CMS to decrease the beam size and increase the integrated luminosity by a factor 10

Construction of pre-series and series magnets on-going, joint effort between CERN (7.2 m length magnets) and US-AUP (4.2 m length magnets)



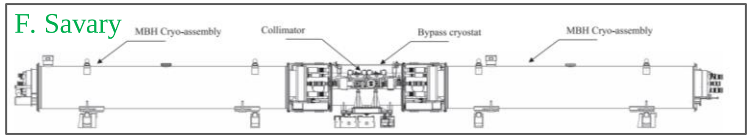


HL-LHC MBH 11 T

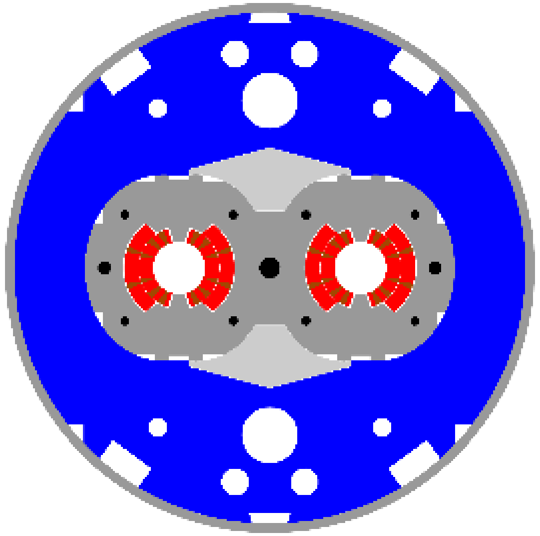


4 pairs of shorter (33 m) and more powerful dipole bending magnets to free up space for the new collimators (2x5.5 m length 11 T dipoles to replace 14.3-m-long LHC MB dipole)

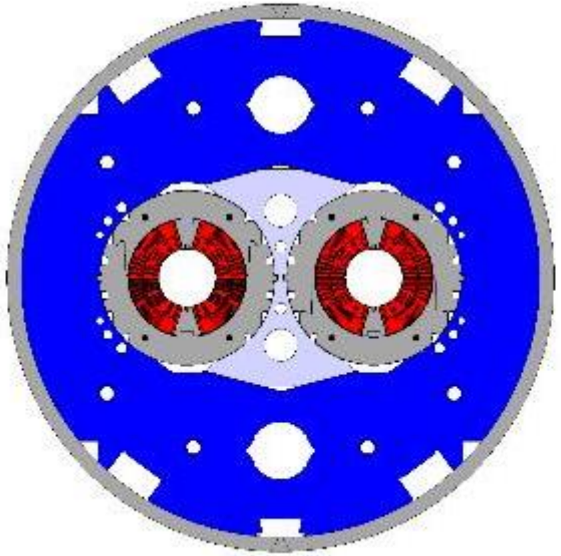
Initially planned for 2020, now de-scoped



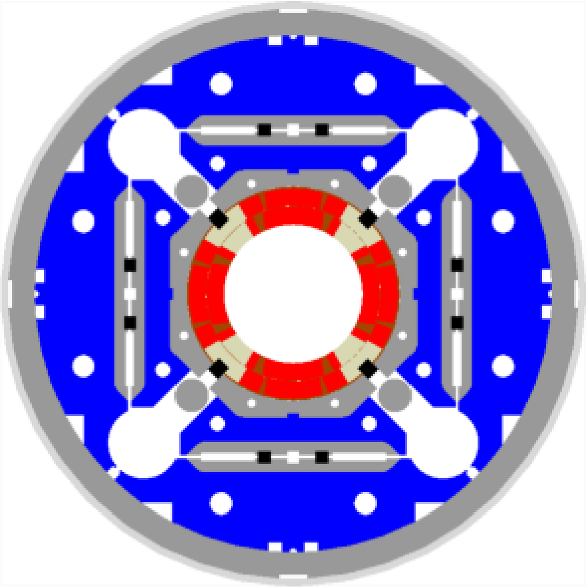
The 12 T challenge – current density



LHC MB
NbTi, $B_p = 8.6$ T
$w_{eq} = 27$ mm
$J_{strand} = 475/616$ A/mm^2



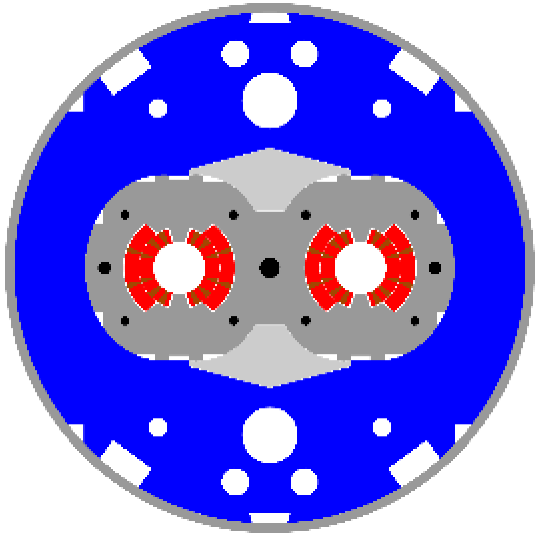
HL-LHC MBH 11 T
Nb_3Sn, $B_p = 11.7$ T
$w_{eq} = 28$ mm
$J_{strand} = 770$ A/mm^2



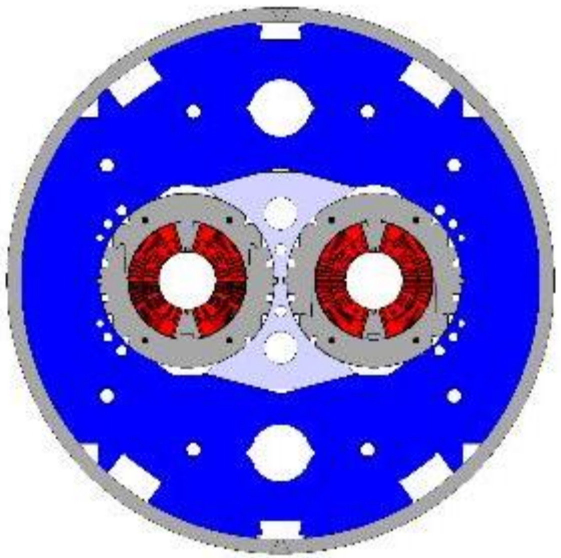
HL-LHC MQXF
Nb_3Sn, $B_p = 11.3$ T
$w_{eq} = 36$ mm
$J_{strand} = 715$ A/mm^2

The 12 T challenge – e.m. forces

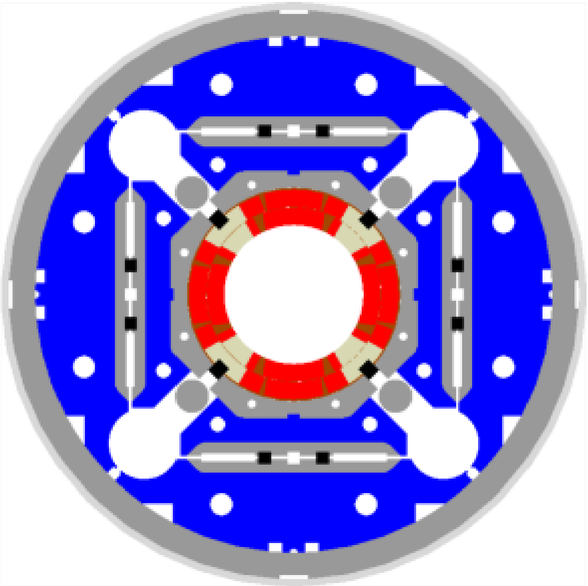
≈ 2 times more force/stress than in the LHC-MB dipoles, in a brittle conductor



LHC MB
NbTi, B_p = 8.6 T
F_x = 3.4 MN/m
$\sigma_{\theta,em}$ = 50-60 MPa
F_z = 265 kN



HL-LHC MBH 11 T
Nb_3Sn, B_p = 11.7 T
F_x = 7.2 MN/m
$\sigma_{\theta,em}$ = 100-110 MPa
F_z = 450 kN

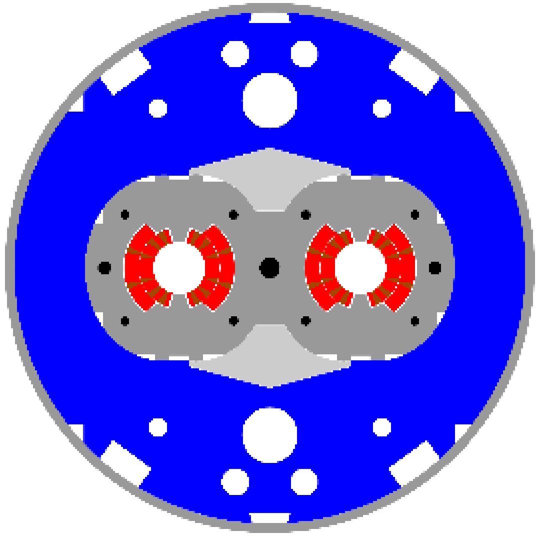


HL-LHC MQXF
Nb_3Sn, B_p = 11.3 T
F_x = 6.8 MN/m
$\sigma_{\theta,em}$ = 100-110 MPa
F_z = 1200 kN

F_x per half magnet; F_z per aperture

The 12 T challenge – protection

T_{hot} ≈ 100 K higher than in the LHC-MB dipoles, half the time margin



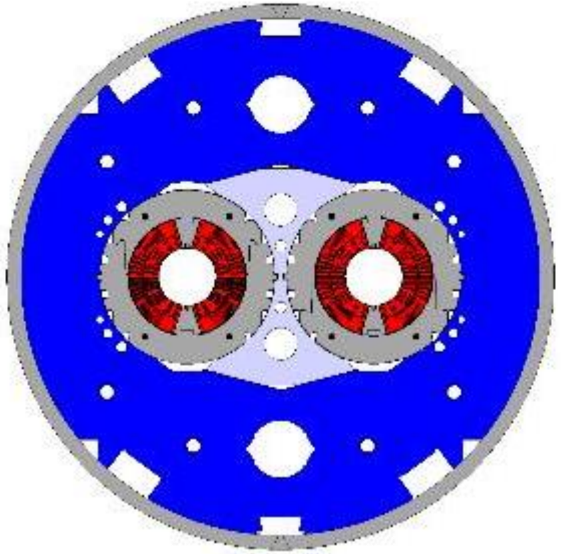
LHC MB

NbTi, B_p = 8.6 T

$J_{overall}(I_{nom})$ = 356/442 A/mm²

$J_{cu}(I_{nom})$ = 763/932 A/mm²

e_m (I_{nom}) = 71 J/cm²



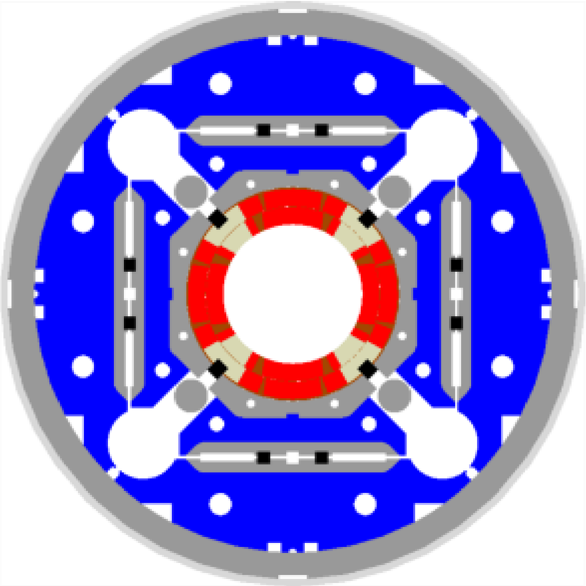
HL-LHC MBH 11 T

Nb_3Sn, B_p = 11.7 T

$J_{overall}(I_{nom})$ = 522 A/mm²

$J_{cu}(I_{nom})$= 1440 A/mm²

e_m (I_{nom})= 124 J/cm²



HL-LHC MQXF

Nb_3Sn, B_p = 11.3 T

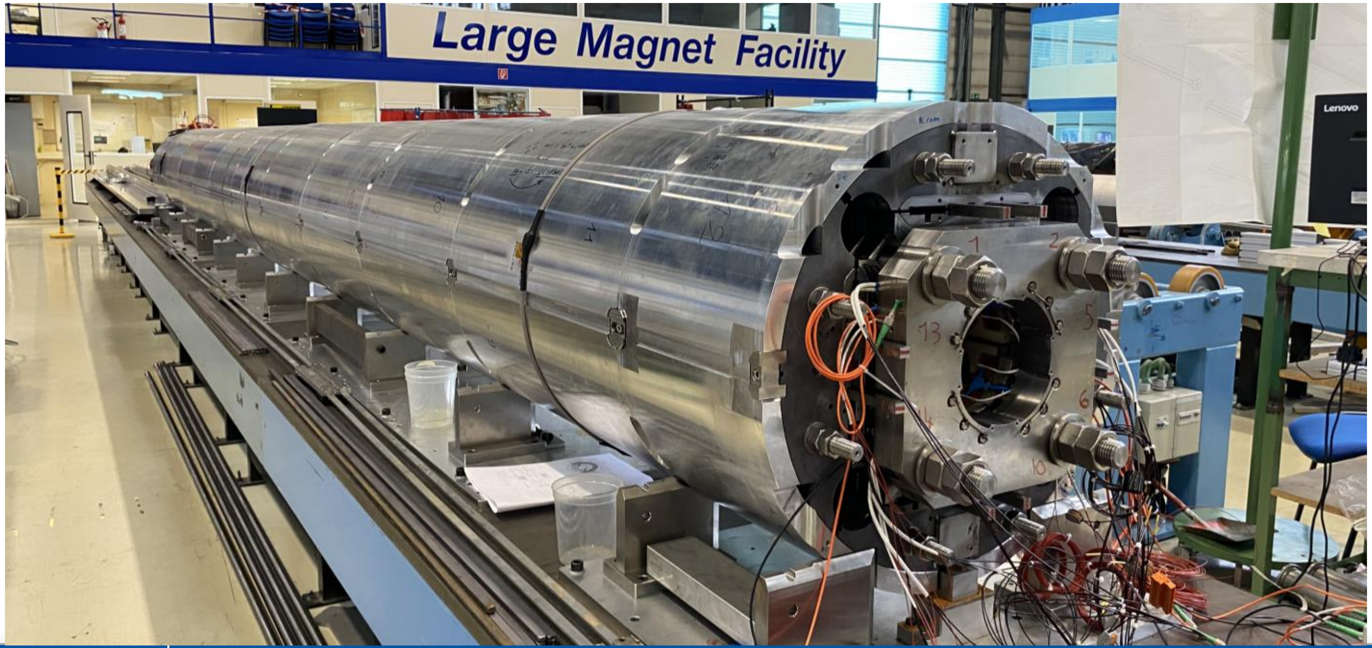
$J_{overall}(I_{nom})$= 462 A/mm²

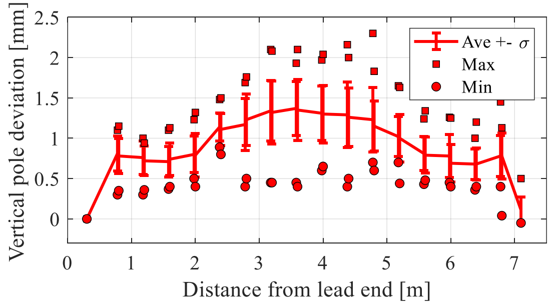
$J_{cu}(I_{nom})$ = 1311 A/mm²

e_m (I_{nom})= 120 J/cm²

The 12 T challenge – length

- Management of thermal contractions and dilatations (from 1.9 K during magnet operation to 650 º C during coil reaction) of the different components is still one of the main challenges
    - They scale with the magnet length, and need to be properly engineered with particular attention to transitions





The 12 T challenge

HL-LHC Nb_3Sn magnets present significant challenges, and decades of experience have shaped their development for accelerator applications. My goal is to provide an overview of key lessons learned from the HL-LHC construction relevant for HFM.

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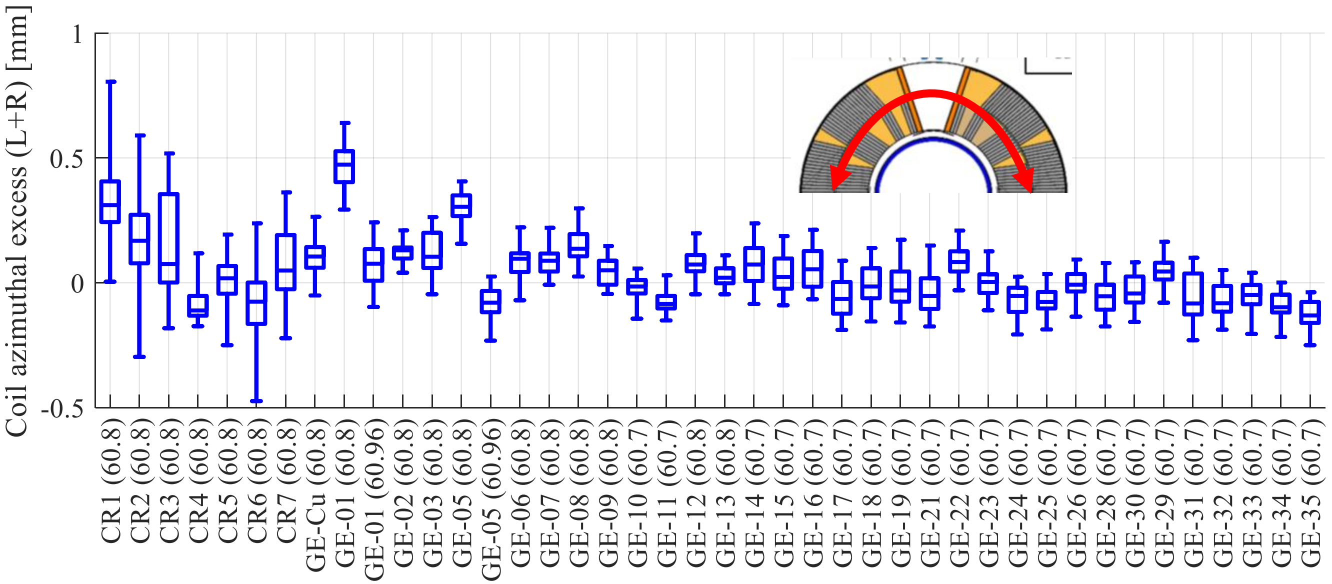
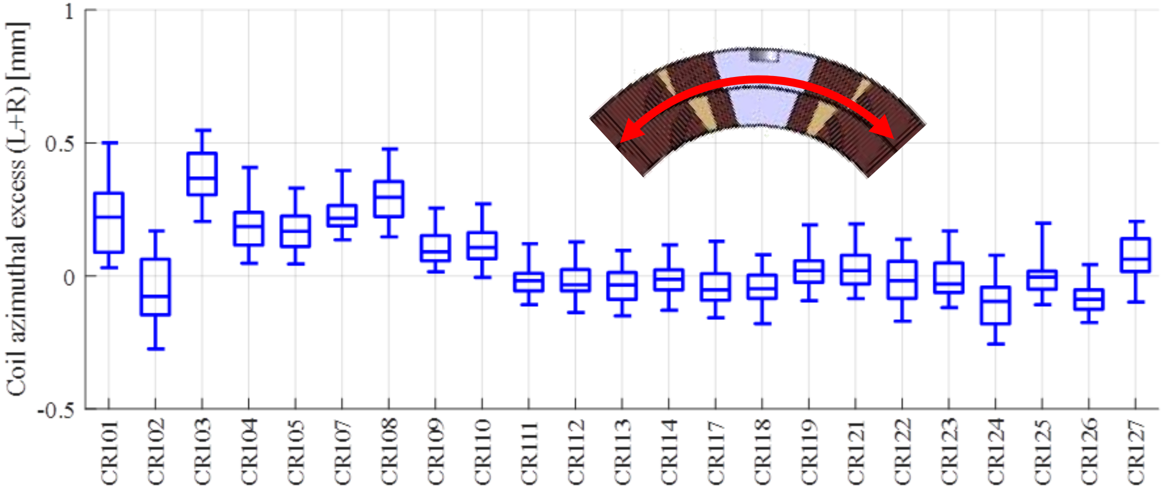
Coil geometry

- The target is to control the coil azimuthal size with a precision of ≈ 0.1 mm (for MQXF, ± 0.1 mm excess corresponds to ± 13 MPa coil stress)
  - For series production long coils, the average size and variation along the straight section length stabilized to ± 0.125 mm.
- The measurement repeatability with the tools we have today is 0.025-0.050 mm J. Ferradas Troitino et al, Vol 28, 2018

Coil azimuthal excess in 11 T prototype and series coil production



Coil azimuthal excess in MQXFB coil production



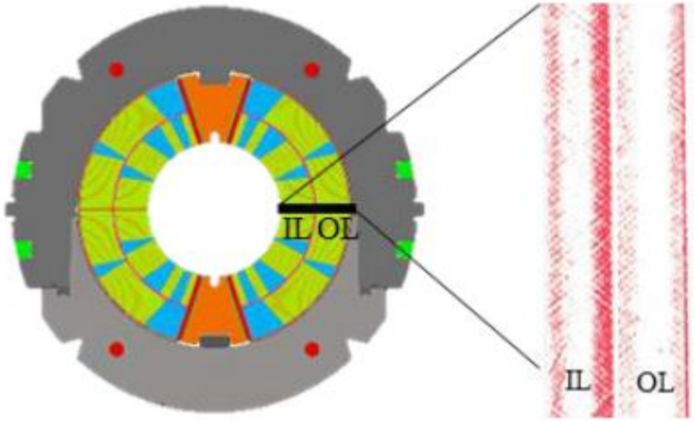
HFM High Field Magnets

Coil compaction and insulation

- Volumetric expansion of the conductor is ≈ 3%. The width/thickness expansion depends not only on the strand layout but also on the external constrains (insulation, friction to tooling…) E. Rochepault et al, vol 26, 2016
- Tooling must allow sufficient space to prevent over-compaction. The 11 T coils were initially very tight, which became a critical issue when manufacturing 5-meter-long coils. The problem was mitigated through an adjustment in insulation thickness S. Izquierdo Bermudez et al, SUST Vol 32 2019
- Challenges in finding durable insulators after the reaction cycle (see talk from Roland):
  - C-shaped mica increased stress at the cable edges in the 11 T and its brittleness reduced effectiveness.
  - Limited vendor availability for alumina coating of metallic parts: only one US-based vendor is qualified for MQXF spacers.

11 T Prototype coil

Stress enhancement due to mica insulation

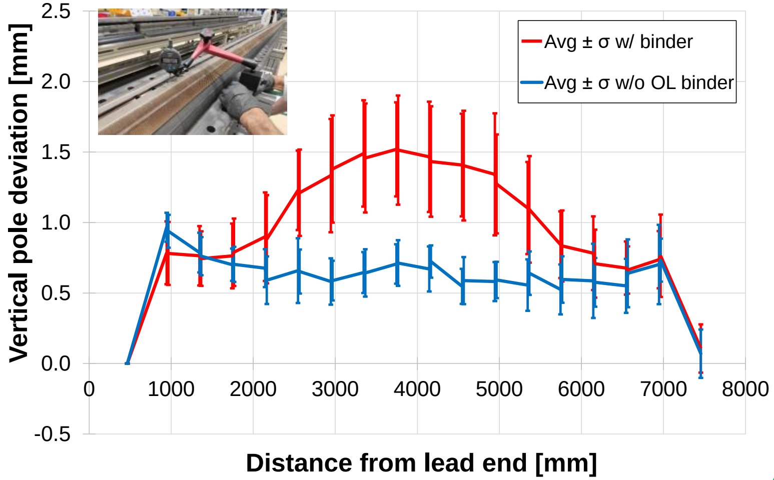


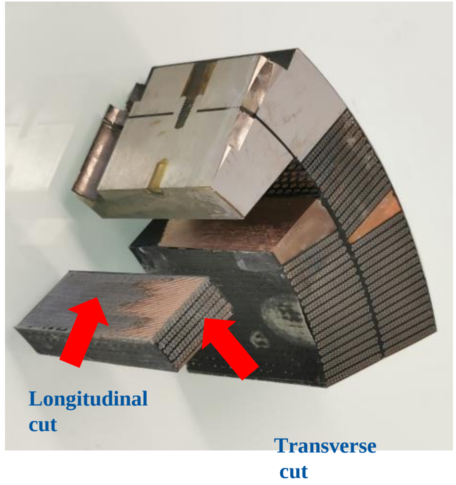
MQXFB Prototype coil

Singularities and transitions

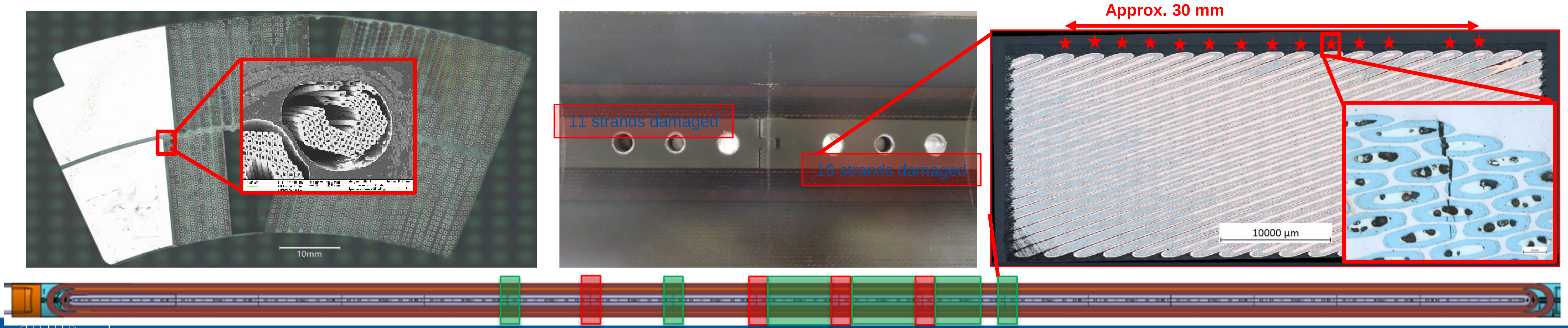
- MQXFB prototype magnets were limited, due to conductor damage in the pole-to-pole transition S. Izquierdo Bermudez et al, IEEE, vol 33, 2023
- Root cause was coil fabrication, mitigated by removing the ceramic binder in the outer layer to reduce longitudinal, radial and azimuthal friction between coil and the reaction fixture N. Lusa et al, IEEE Vol 34, 2024

Vertical pole deviation along the length (reacted coil)





A. Moros et al, IEEE Vol 33, 2023



20 slices 50 mm length,
damage only in the slices around transitions

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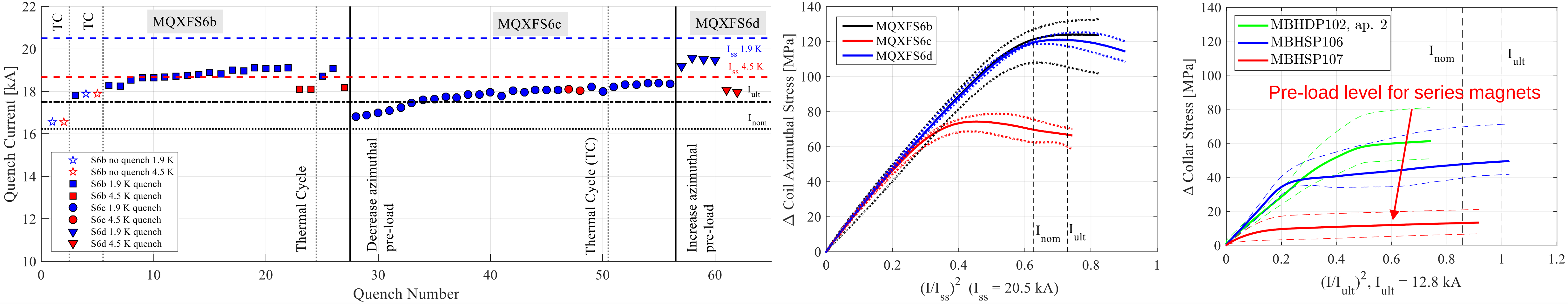
Azimuthal pre-load

- Wide pre-load window to reach ultimate current (-75 to -120 MPa) S. Izquierdo Bermudez et al, IEEE Vol 32 2022
  - Indication that larger preload is beneficial to reach > 90% of I_{ss}
- Impact of pre-stress at 1.9 K on maximum current studied with MQXFS7 (PIT and RRP) F. Mangiarotti et al, IEEE Vol 35 2025
  - Some degradation appears in the PIT conductor in the 170-190 MPa range
  - No degradation observed in RRP up to 190 MPa in the 85% of I_{ss} level
    - Crack onset at room temperature in cable stacks at lower level (110 MPa) K. Puthran et al., IEEE Vol 33, 2023, strongly dependent on the way the cable is constrained G. Vallone et al, IEEE Vol 34, 2024
  - Magnet above ultimate (and above 85% of I_{ss}) after 150 quenches, 600 power cycles, 14 thermal cycles, many re-loads up to 190 MPa
  - The extrapolation of these numbers to a specific magnet design requires a careful assessment J. Ferradas Troitino et al, 2023
- 11 T short models also reached performance requirements with very low pre-load S. Izquierdo Bermudez et al, SUST Vol 32 2019

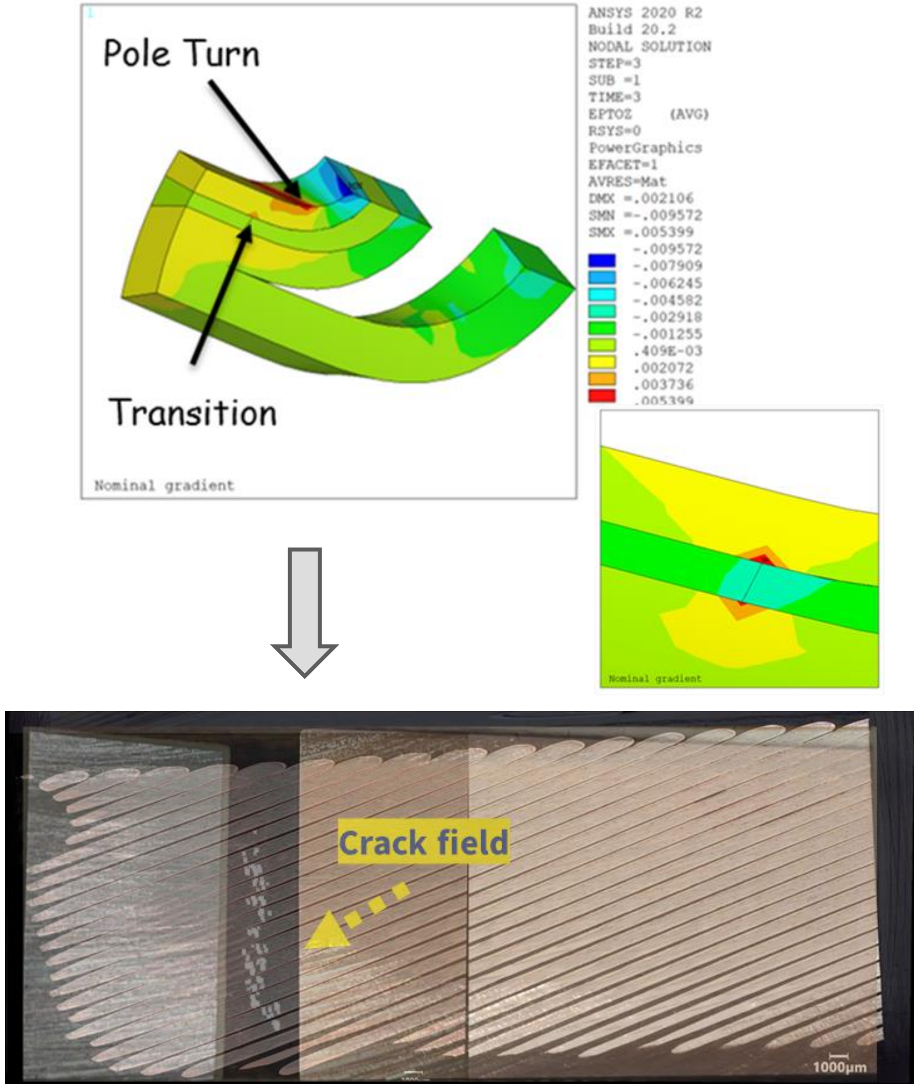


Axial pre-load

- In MQXF, by design, axial forces are counteracted by end support structure
  - Axial loading (end-plate) + azimuthal loading (with support structure)
- 4 MQXFA magnets with de-training after few training quenches G. Ambrosio et al, IEEE Appl. Sup., Vol 33, 2023. The current understanding is that the root cause is lack of end support caused by
  - Pole key interception of azimuthal loading (larger pole gap introduced)
  - Coil significantly smaller in the ends (graded shimmed introduced)

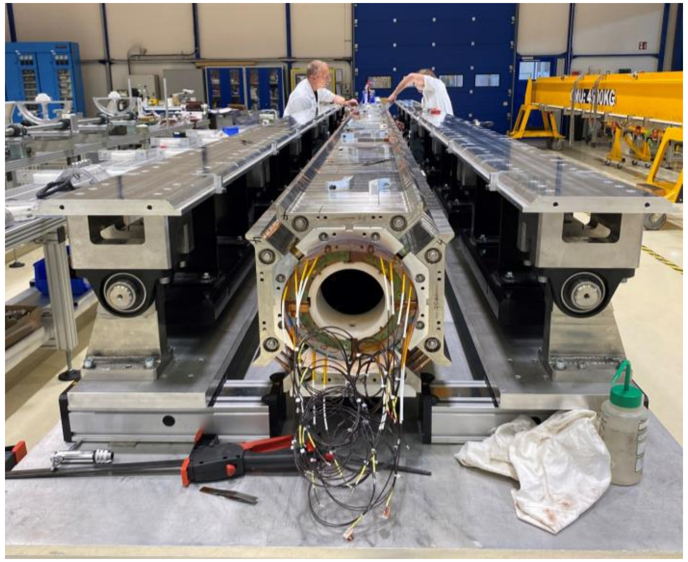
which results in high axial strain in the turn close to the transition G. Vallone et al, IEEE Appl. Sup., Vol 35, 2025

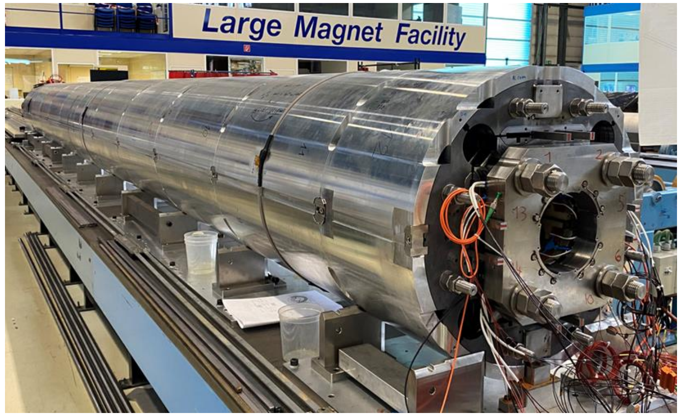
- Further studies planned within HFM technology development program using MQXFS8 (see talk from Ariel)
  - The handling of axial forces remains a challenge in view of building 15 m accelerator quality magnets for a big machine

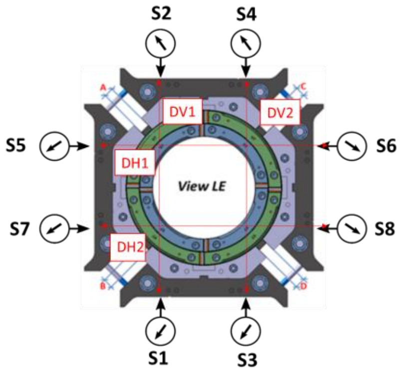


Production monitoring

- Systematic measurements taken in MQXFB magnets to monitor assembly:
  - Pole gap
  - Coil pack size
  - Yoke cavity size
  - Rods elongation
  - Magnet outer diameter and straightness
  - Strain in the rods/shells/coils
- Very good consistency of the measurements from the coil geometry to the coil pack and the assembled magnet (better than 0.050 mm)



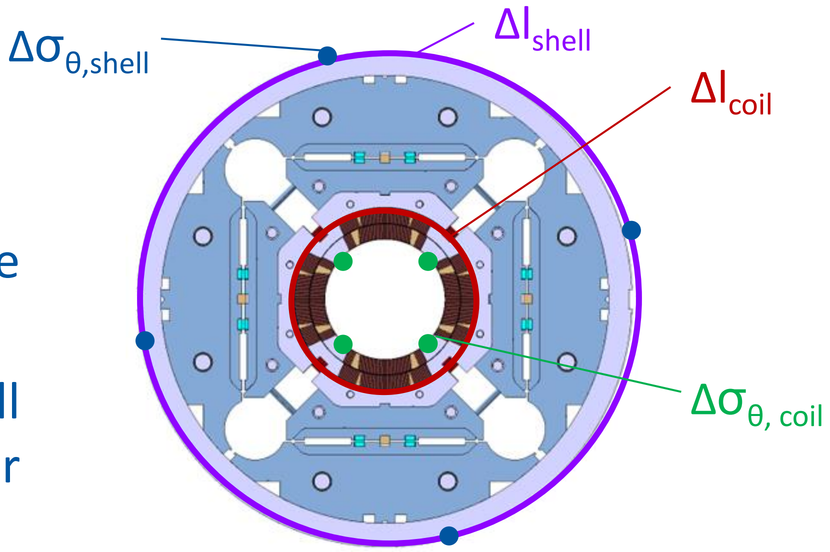





P. Quassolo et al., to be presented in MT29

Production monitoring

- High reproducibility in series magnets: geometrical measurements are sufficient to determine the pre-stress level within ±10 MPa.
- Comprehensive strain monitoring: strain in both the coil and shell will be recorded for all series magnets to establish full statistical data for this first-of-its-kind accelerator magnet structure



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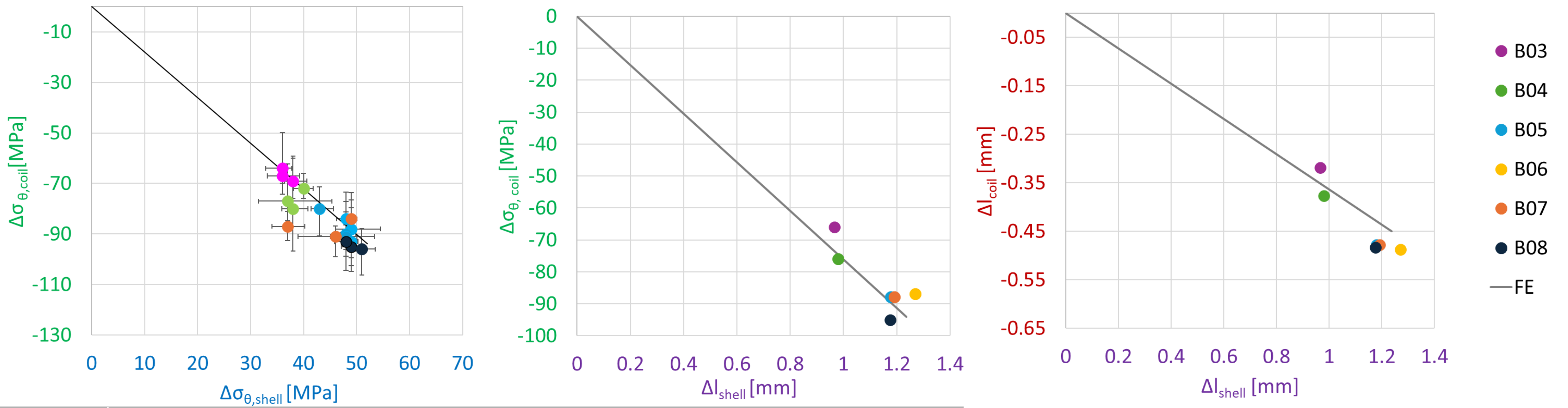

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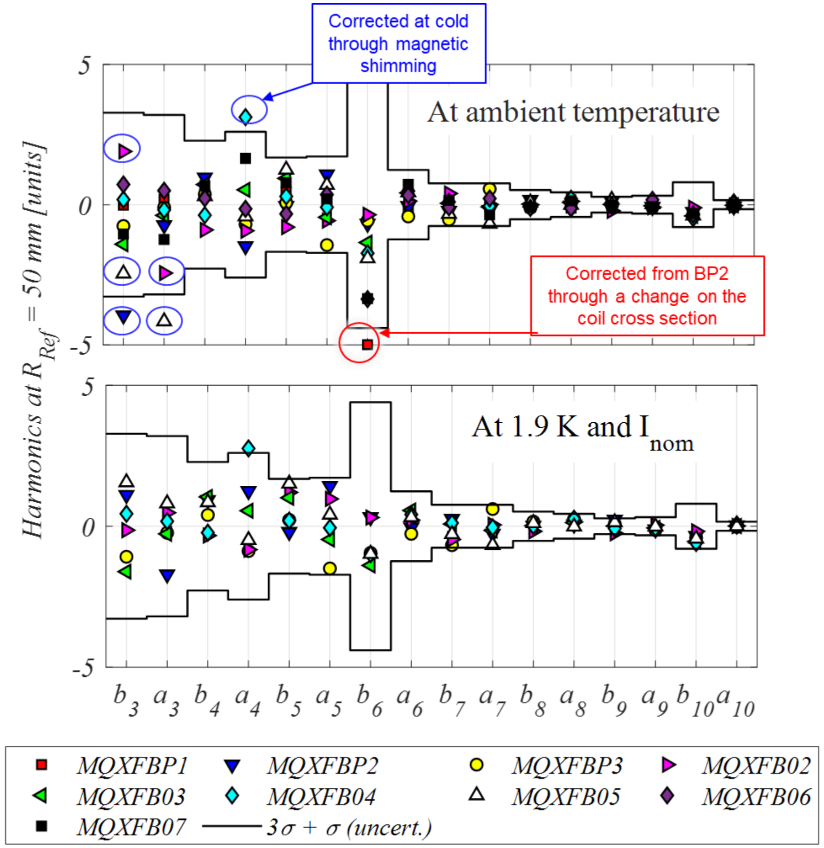
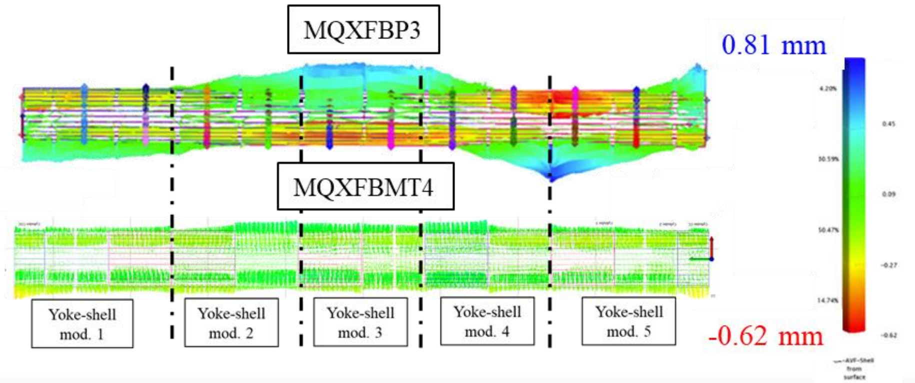
Geometric field errors

- Spread of the harmonics along the axis reached 0.030 – 0.050 mm accuracy, close to the 0.025 mm of the LHC-MB dipoles
- Reproducibility of the coil positioning over the production is 0.100-0.200 mm for the short model program, 0.040 – 0.060 mm for the final length magnets, only a factor two worse than the 0.025 mm of the LHC-MB dipoles
- MQXF is the first accelerator magnet based on an aluminum shrinking cylinder pre-loaded using bladder and keys.
    - The dominant source of field errors is the coil geometry and not its alignment on the magnet structure.
    - Good cold-warm correlation
    - The straightness of the field is defined by the straightness of the initial yoke-shell subassembly structure, which does not change significantly with the magnet loading, cold mass assembly, cool down and powering: improved from ±0.7 mm to ±0.2 mm

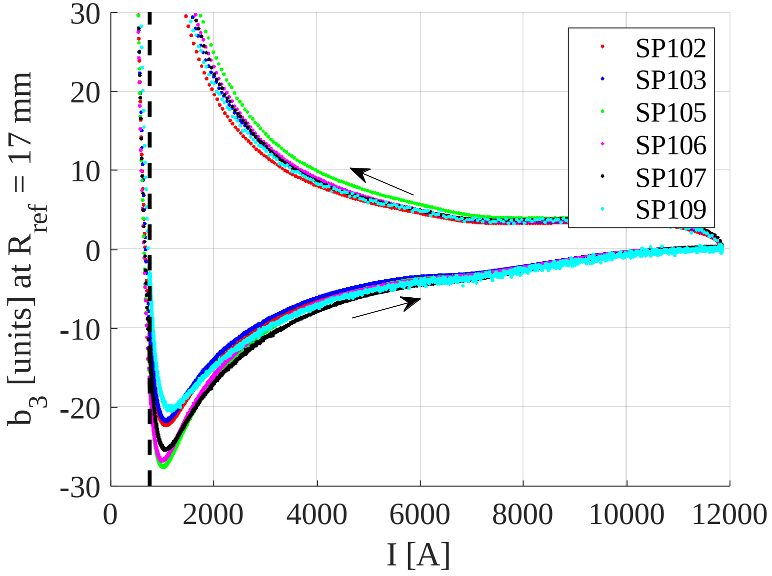


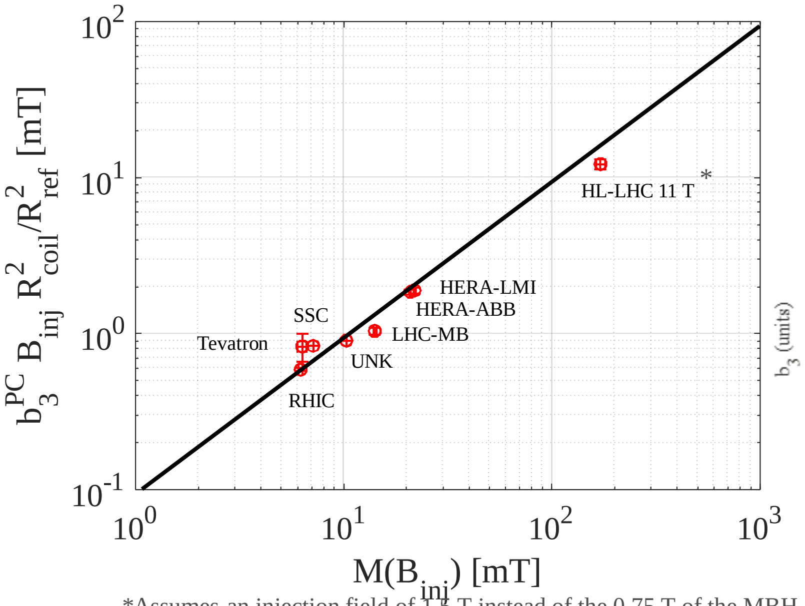
	d (mm), along axis	d (mm), over production
LHC-MB dipoles	0.025	0.025
MBH 11 T (short models, 5 apertures)	0.050	0.209
MBH 11 T (series, 11 apertures)	0.039	0.057
MQXFS (short models, 7 apertures)	0.030	0.079
MQXFB (prototypes and pre-series, 4 apertures)	0.040	0.040

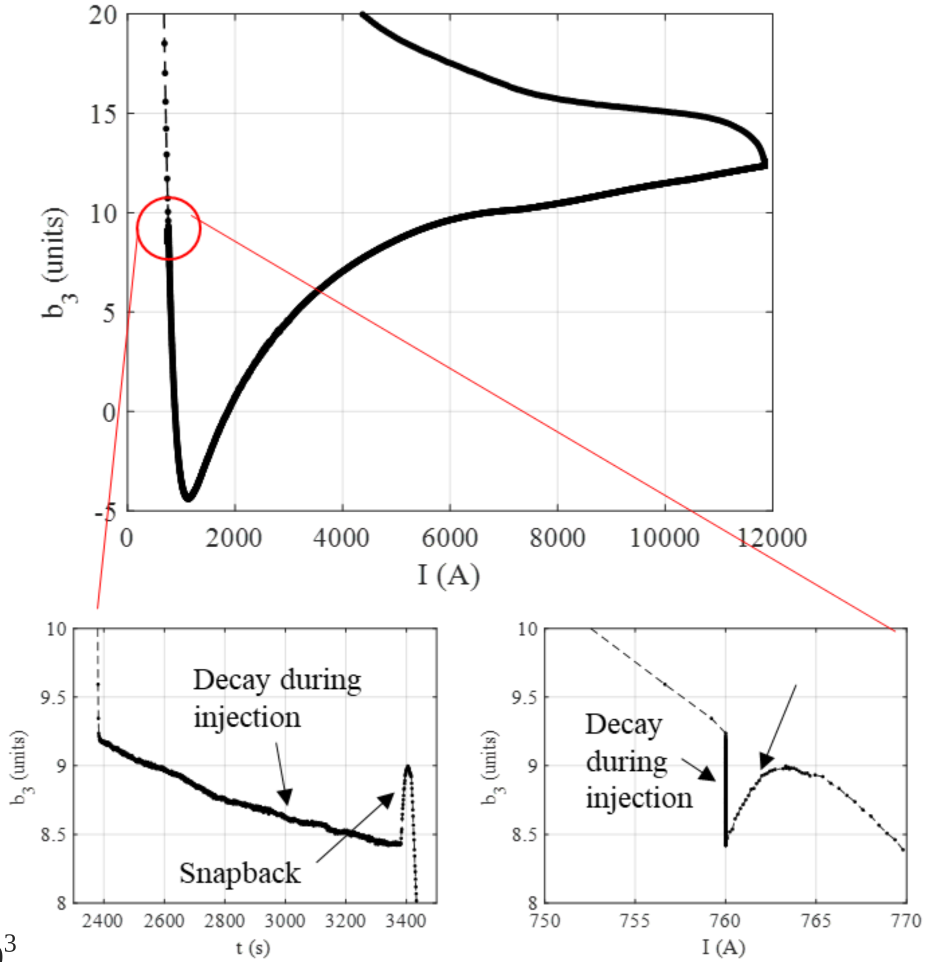


Persistent currents and dynamic effects

- D_{eff} is state of the art conductor is ∼ 50 µm, 10 times more than the LHC NbTi conductor, which translates in larger field errors at injection and heat load that must be absorbed by the cryogenic system (persistent currents).
  - The physics are well understood, and we know how to model them. However, flux jumps at 1.9 K introduce a degree of uncertainty in the contribution of the magnetization.
- For decay and snapback, there are similarities in the amplitudes and functional dependencies with the statistics established on LHC-MB dipoles, there is a striking difference: the sign of the decay is opposite and would suggest an average increase of the magnetization.







*Assumes an injection field of 1.5 T instead of the 0.75 T of the MBH-11T in HL-LHC to be above penetration field

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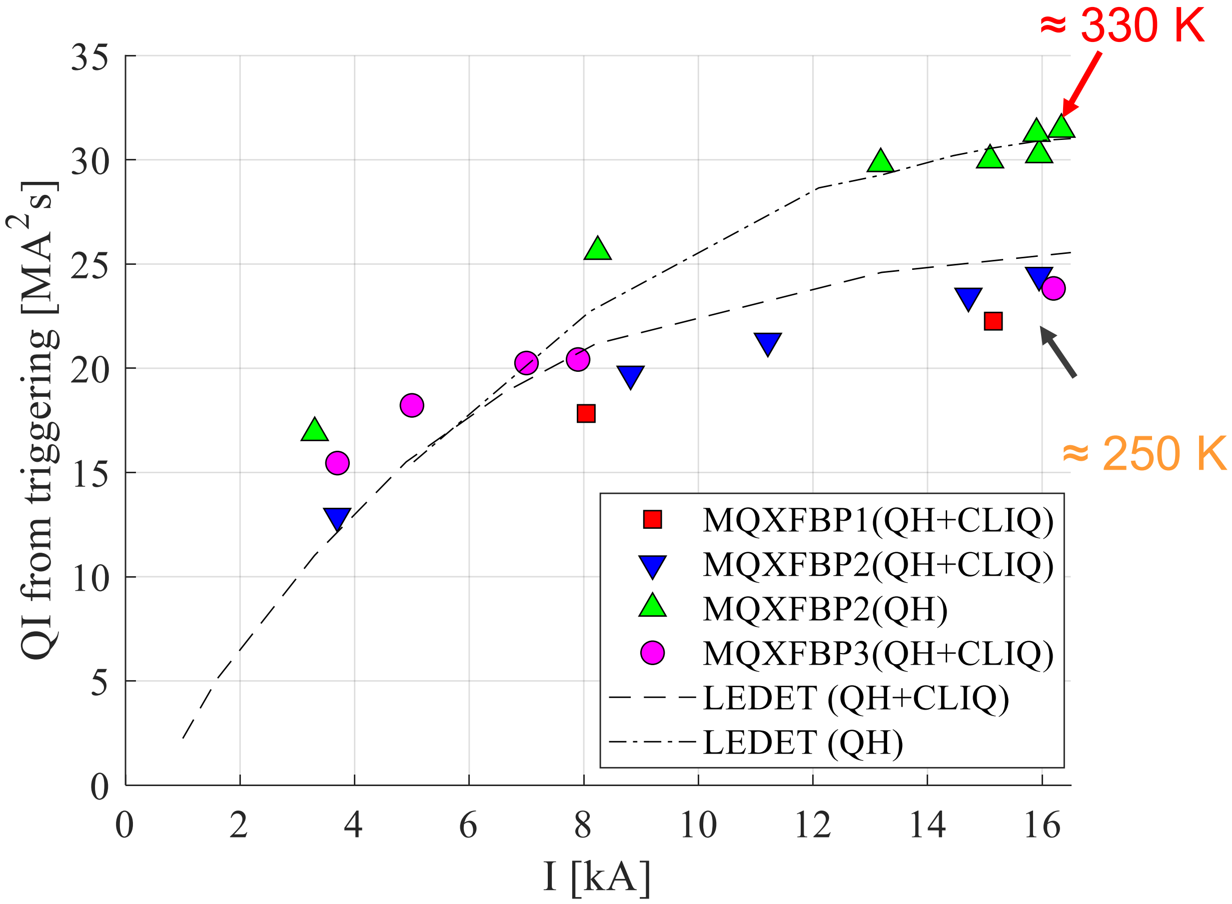
Protection - Redundancy

- Protection must be redundant, also in case of failure the temperature and voltage shall remain within acceptable limits.
  - Thanks to the use of CLIQ E. Ravaioli, PhD thesis (first time implementation in an accelerator!), T_{hot} decreases by ≈ 100 K.
  - New promising protection methods are under development for future machines (see talk from Mariusz)

E. Ravaioli et al, EDMS 1963398

	No failure		Worst case failure	
	I_{nom}	I_{ult}	I_{nom}	I_{ult}
Current [kA]	16.23	17.50	16.23	17.50
Hot-spot temperature [K]	231	253	375	404
Peak voltage to ground [V]	606	776	660	850
Peak turn to turn voltage [V]	57	69	76	89

- High quench integral tests in MQXF (J. Ferradas et al., EDMS 2354774) and 11 T (S. Izquierdo Bermudez et al, vol 29, 2019) show no performance degradation up to T_{hot} ≈ 400 K.

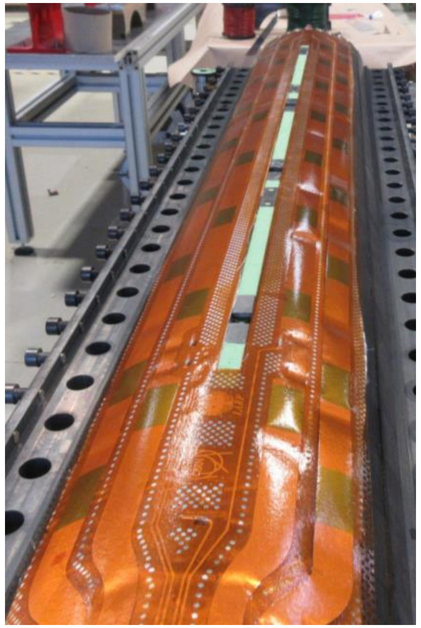


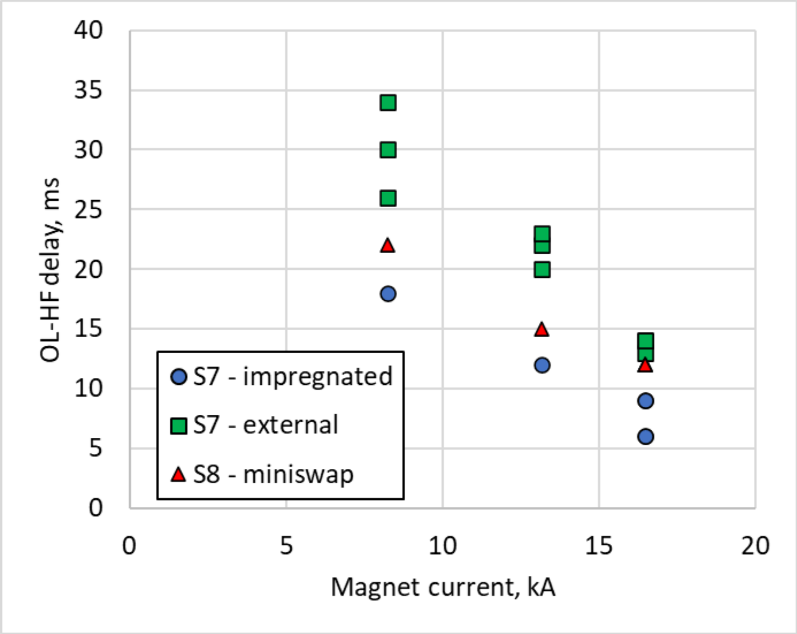
Simulations by E.Ravaioli with STEAM-LEDET + PSPICE coupled using STEAM-COSIM. Measurements F. Mangiarotti

Protection – outer layer heaters

- When the available time margin is only 35–40 ms, every millisecond counts. To ensure adequate protection, it may be necessary to accept certain fabrication risks, such as impregnated heaters.
- Three different quench heater layouts explored in MQXF:

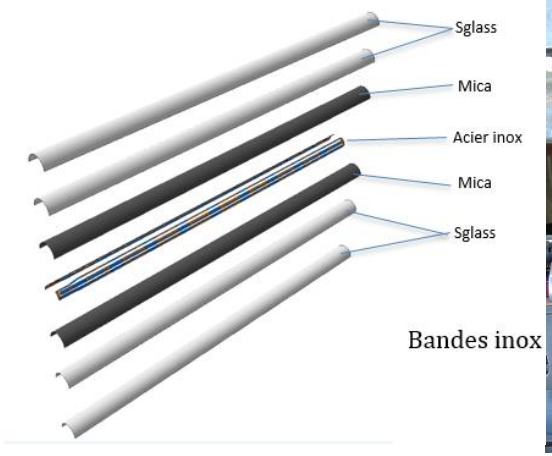
1. Impregnated (Baseline for MQXFA): Heaters are impregnated with the coil, with polyimide in direct contact with the insulated cable.
2. Mini-Swap (Baseline for MQXFB): Heaters are impregnated with the coil, but with a 0.05 mm E-glass sheet between the heater polyimide and the insulated cable (+30 K).
3. External: Heaters are glued to the coil after impregnation, with a 0.100 mm S2-glass sheet between the heater polyimide and the insulated cable (+50 K).

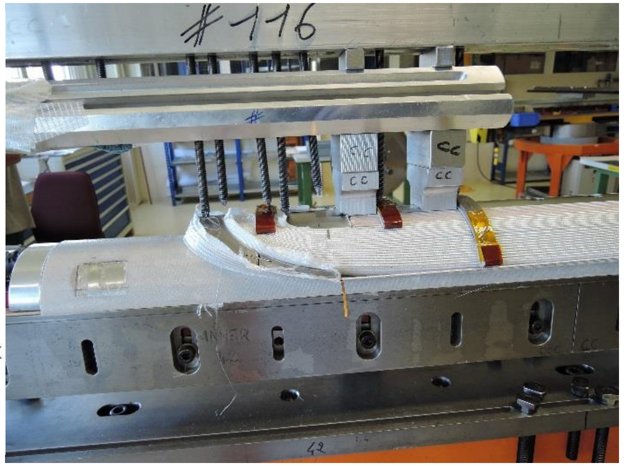




Protection – inter layer and inner layer heaters

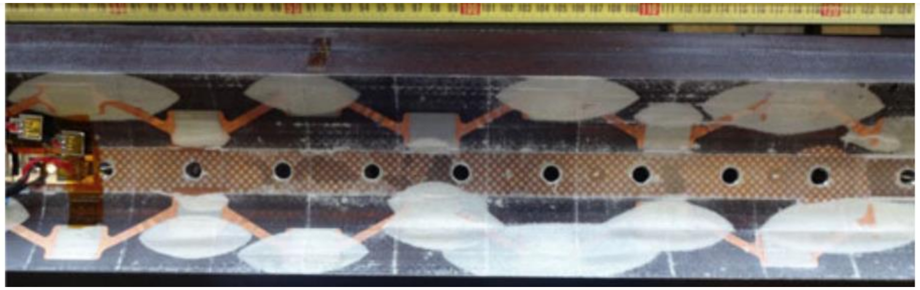
- Inter-layer quench heaters were implemented in an 11 T short model (MBHSP106)
  - Difficult to handle during coil reaction, required a good electrical insulation between heater and coil to avoid electrical integrity issues (i.e., less effective that outer layer quench heaters)
  - One circuit (out of 4) was lost during cool down, one more during powering. Failure at the terminals.

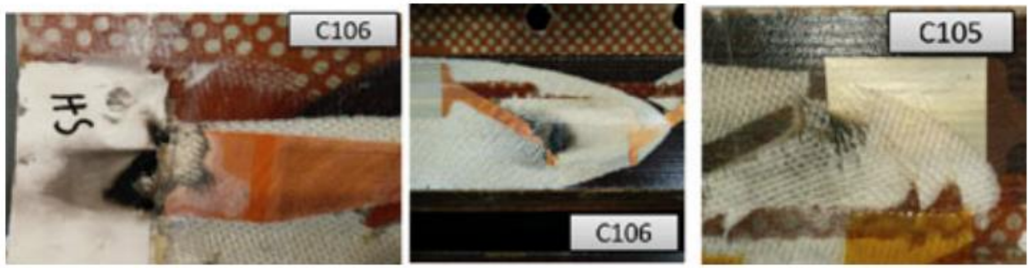




S. Izquierdo et al., EDMS 2032117

- Inner-layer heaters were tested in MQXFS but ultimately abandoned due to their high risk of failure.
  - About 30% of the inner layer heater strips failed during powering test due to glass-epoxy to heater delamination in the inner coil surface.





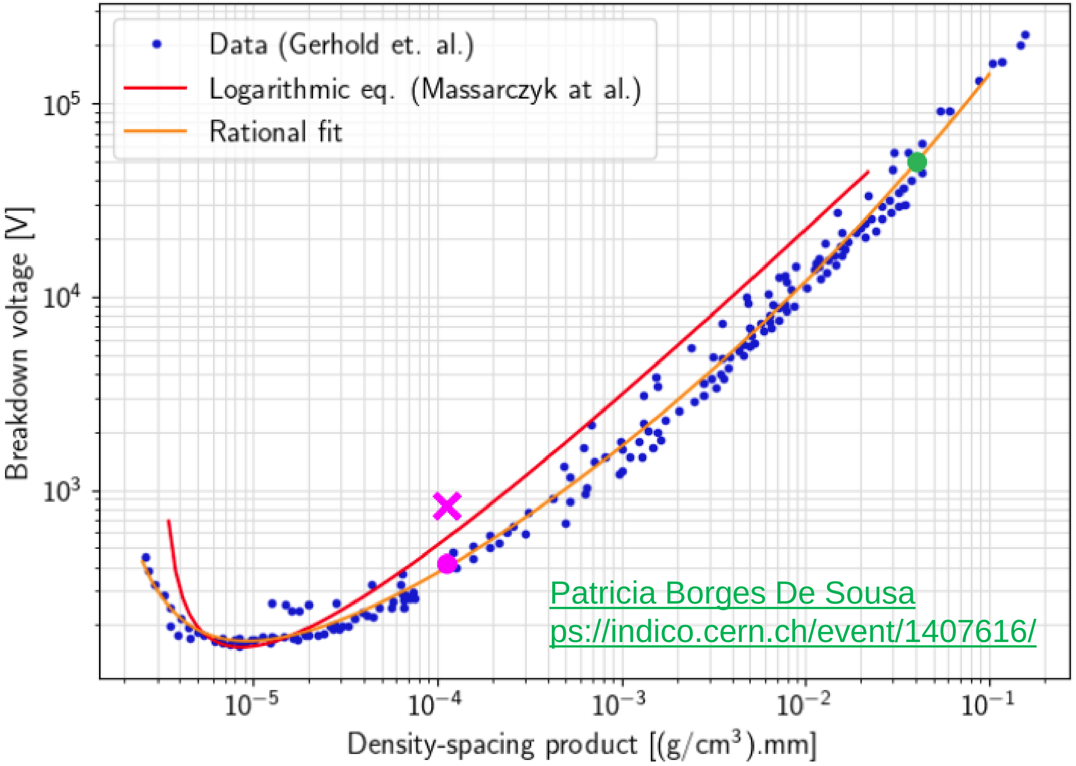
S. Izquierdo Bermudez et al, vol 28, 2018

Electrical integrity

- Usual rule: qualification voltage = $2*V_{max} + 500$ V (M. Bednarek et al, EDMS 1963398)
- In MQXFB, to assure the integrity of the quench heater polyimide, 850 V are applied quench heater to coil at 100 K and 1 bar.
  - For He at 1 bar, 100 K, and considering 0.3 mm spacing between QH and coil the breakdown voltage in those conditions is around 400 V ●
  - For He at 13 bar, 5 K (worst case expected 0.1 ms from quench start) and considering 0.3 mm spacing between QH and coil the breakdown voltage in these conditions is around 50 kV●
- When developing and qualifying technologies, requirements must be well understood from the start, with testing and safety margins aligned to operational needs.

Electrical short circuit quench heater to coil in a Nb_3Sn coil in MQXFAP1, result of a non-conforming testing procedure

V. Marinozzi et al., IEEE Vol 31 2021



Patricia Borges De Sousa
ps://indico.cern.ch/event/1407616/

Outline

- Introduction: the challenge of the HL-LHC Nb_3Sn magnets
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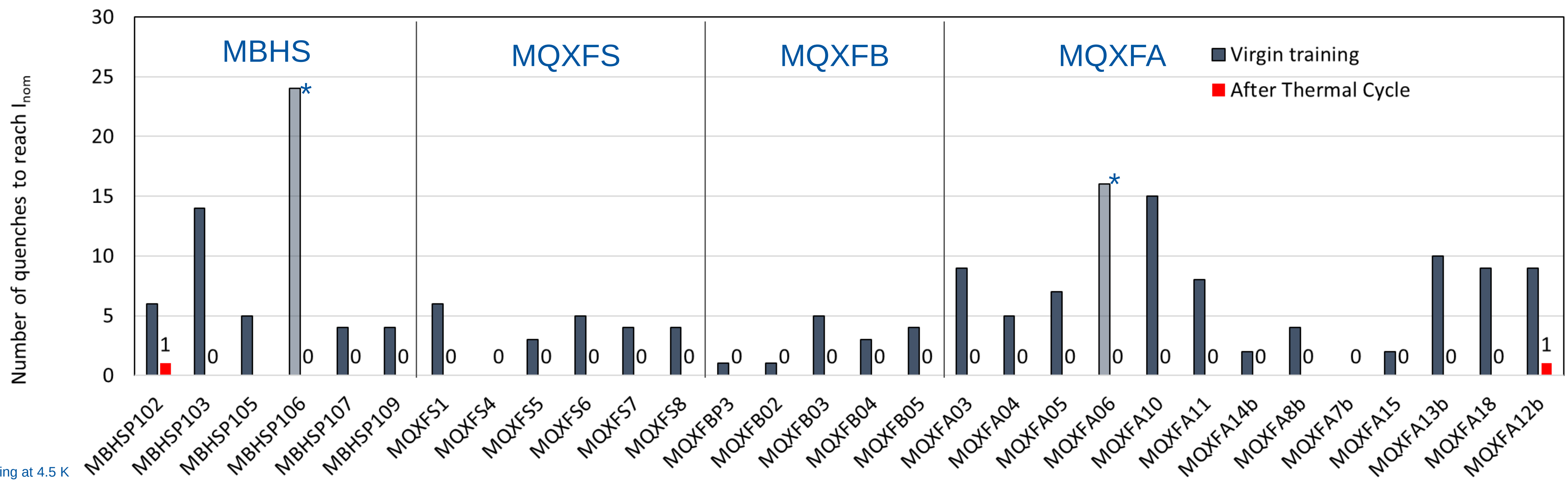
- Field quality
- Protection and electrical integrity
- **Training and performance**
- Industrialization
- Conclusions

Training

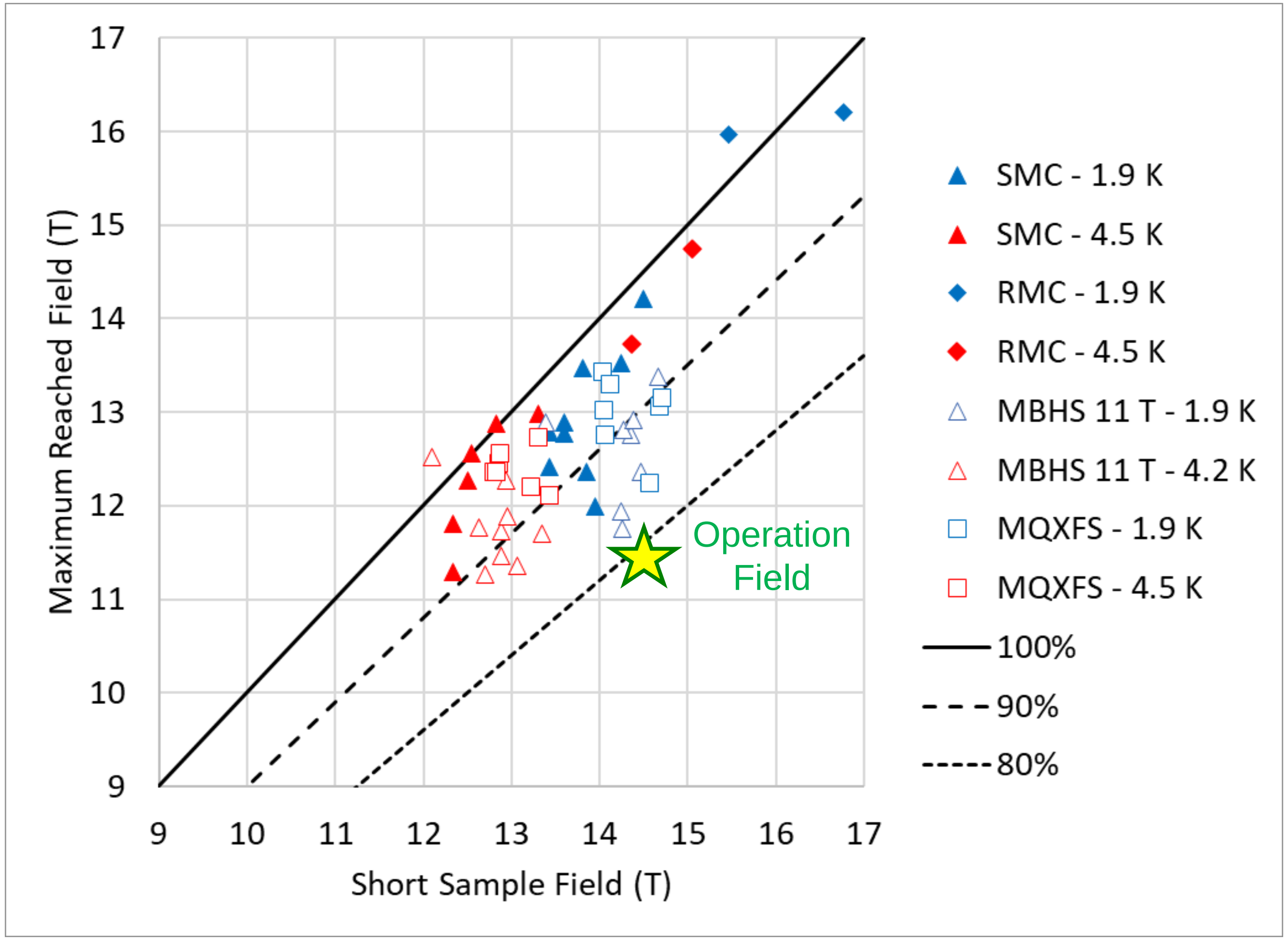
- In general, less than 10 quenches needed to reach nominal (less than 5 in MQXFB and MQXFS)
- In 30 magnets, two needed one re-training quench to reach nominal.
- The two magnets where the training was done at 4.5 K (MBHSP106 and MQXFA06) had longer training
- CLIQ impacts training: the two coils that see a positive current during CLIQ discharge do not train S. Stoynev, IEEE App. Sup. Vol 34 2024



*Training at 4.5 K

Performance

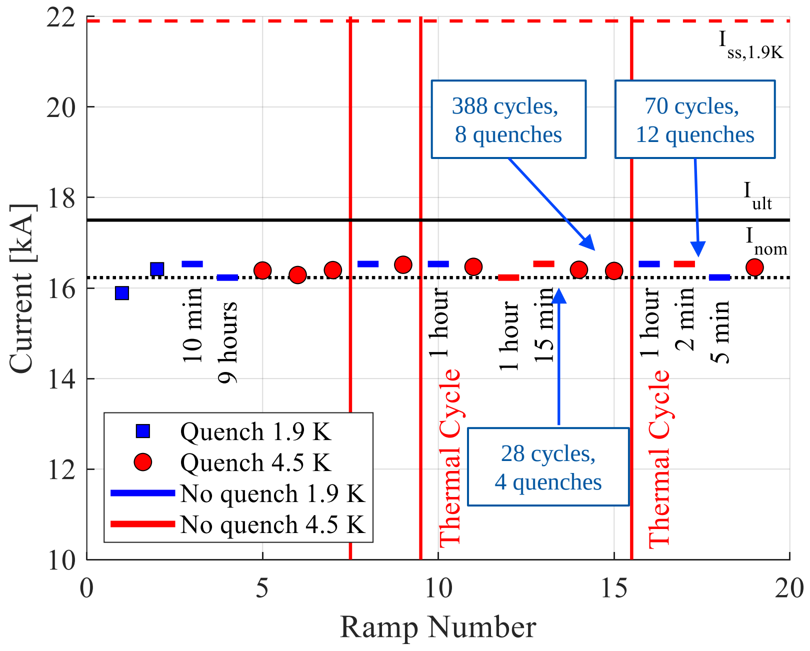
- HL-LHC magnets operate at ≈ 11.5 T and ≈ 80 % I/I_{ss}
  - Based on as built data, I/I_{ss} for MQXFB at I_{nom} is 72-74 % I/I_{ss}
- MQXF short models reached ≈ 12.5 T at 4.5 K (95 % I/I_{ss}) and ≈ 13.0 T at 1.9 K (90 % I/I_{ss})
- 11 T short models reached ≈ 11.7 T at 4.5 K (88 % I/I_{ss}) and ≈ 12.6 T at 1.9 K (90 % I/I_{ss})
- Racetracks (SMC and RMC) built to qualify conductor and validate technology reached 90 % - 100 % of I/I_{ss} both at 1.9 K and 4.5 K
- Long magnets were tested to I_{nom} + 300 A (for MQXFB, 75 %/84 % I/I_{ss} at 1.9 K and 4.5 K respectively)



Endurance

- Endurance tests in MQXFB show no performance degradation with current and thermal cycling S. Izquierdo Bermudez et al, IEEE 2025
- In 2024, MBHSP107 11 T short model was re-tested, showing stable operation at I_{nom} for 250 h at 4.5 K and 500 h at 1.9 K (see G. Willering EDMS 3202564)

Endurance test in MQXFB02



Endurance statistics MQXFB magnets

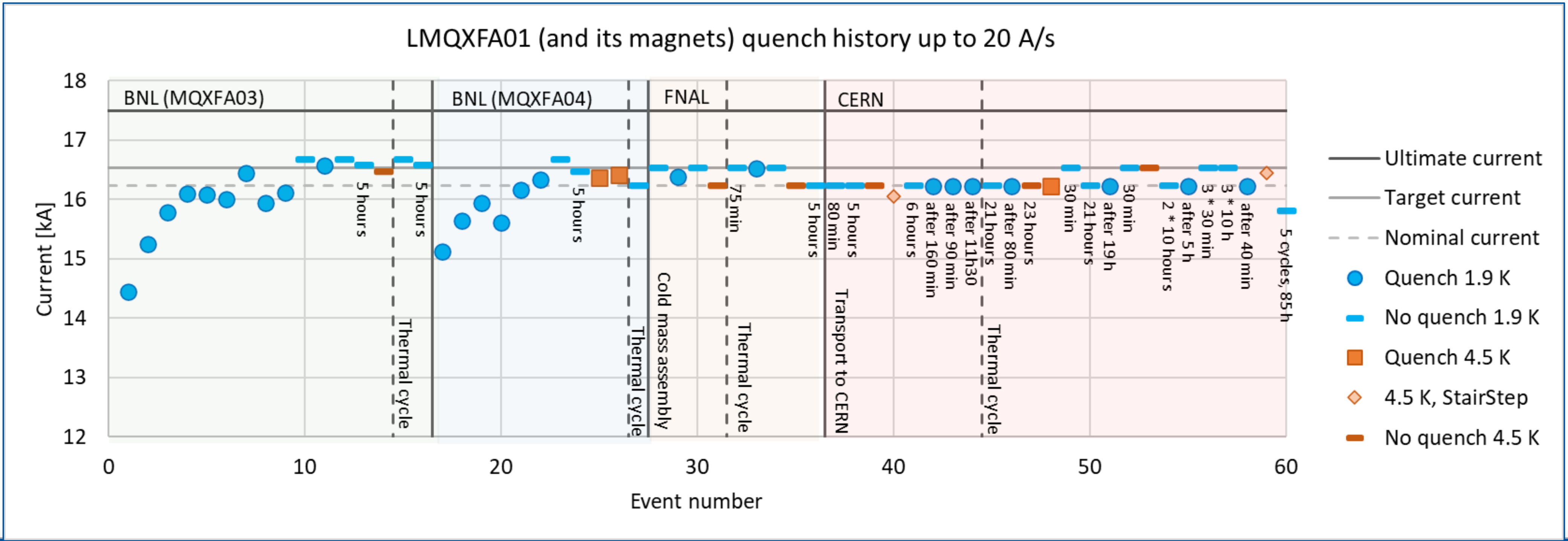
	Number of thermal cycles	Number of quenches at $I \geq 0.8I_{nom}$	Number of quenches at $I \geq I_{nom}$	Number of cycles to $\geq I_{nom}$	Time [h] at $I \geq I_{nom}$
BP1	2	21	0	0	0
BP2	5	56	7	17	14
BP3	4	26	10	70	44
B02	4	43	36	**508**	38
B03*	4	31	18	97	105
B04	2	12	7	44	28
B05	2	12	8	59	**147**
TOTAL	23	201	86	795	376

* Test ongoing

Test engineer: F. Mangiarotti

Holding current tests

- MQXFA magnets are tested first vertically (individual magnets) and then assembled in a cold mass (two magnets coupled together)
- The first LMQXFA Cryo-assembly, was tested at CERN, and even if it passed acceptance criteria, unexpected flattop quenches at nominal current (see NCR EDMS 3176918)
  - All quenches in the same coil and same longitudinal position
- Systematic long flattop cycles (3x20h) introduced now systematically in HL-LHC magnets



Quench performance of first MQXFA cold mass
(Test eng. G. Chlachidze, B. Yahia, G. Willering, F. Mangiarotti, WPE: G. Ambrosio, S. Feher, S. Izquierdo Bermudez, et al.)

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The overall picture

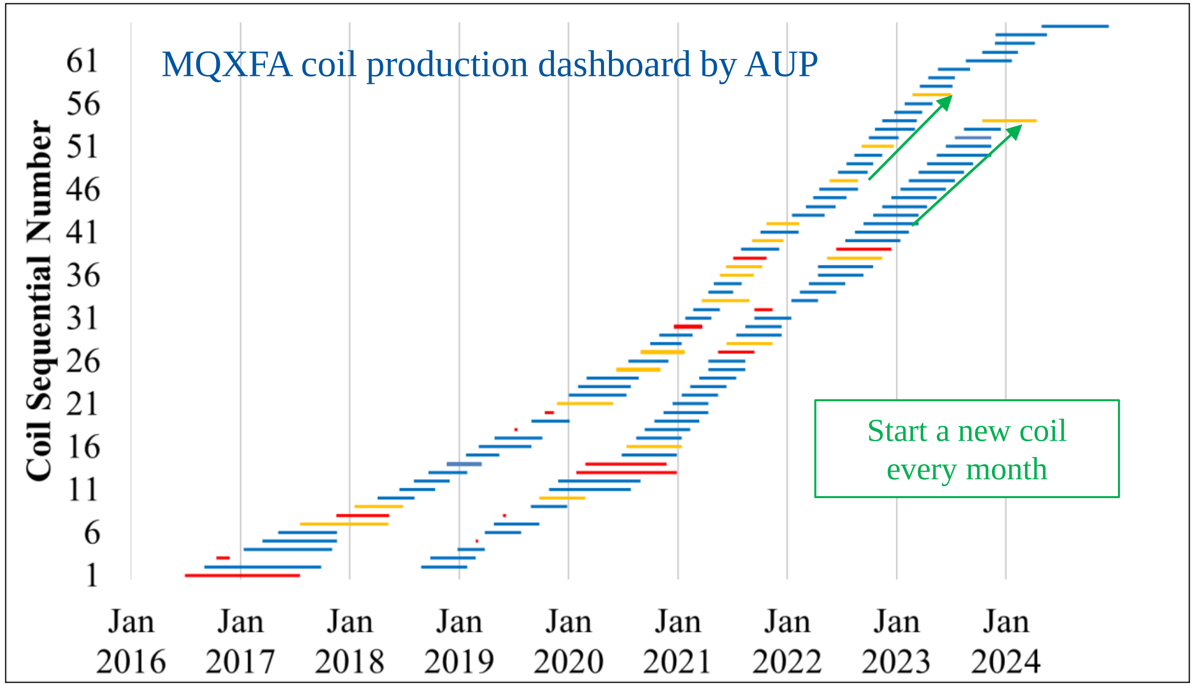
	LHC-MB Dipole L. Rossi 2014 DOI 10.5170/CERN-2014-005.517	MQXF
Technology	NbTi (14.5 m length, B_p = 8.6 T)	Nb_3Sn (MQXFA 4.2 m; MQXFB 7.2 m; B_p = 11.3 T)
Quantity	• 6 prototypes for each of the 3 generations • 3x30 pre-series magnets • Three contracts for the fabrication of 1146 (+30 spares)	• 2 MQXFA prototypes and 2 MQXFB prototypes • 20 MQXFA magnets + 10 MQXFB magnets (includes spares)

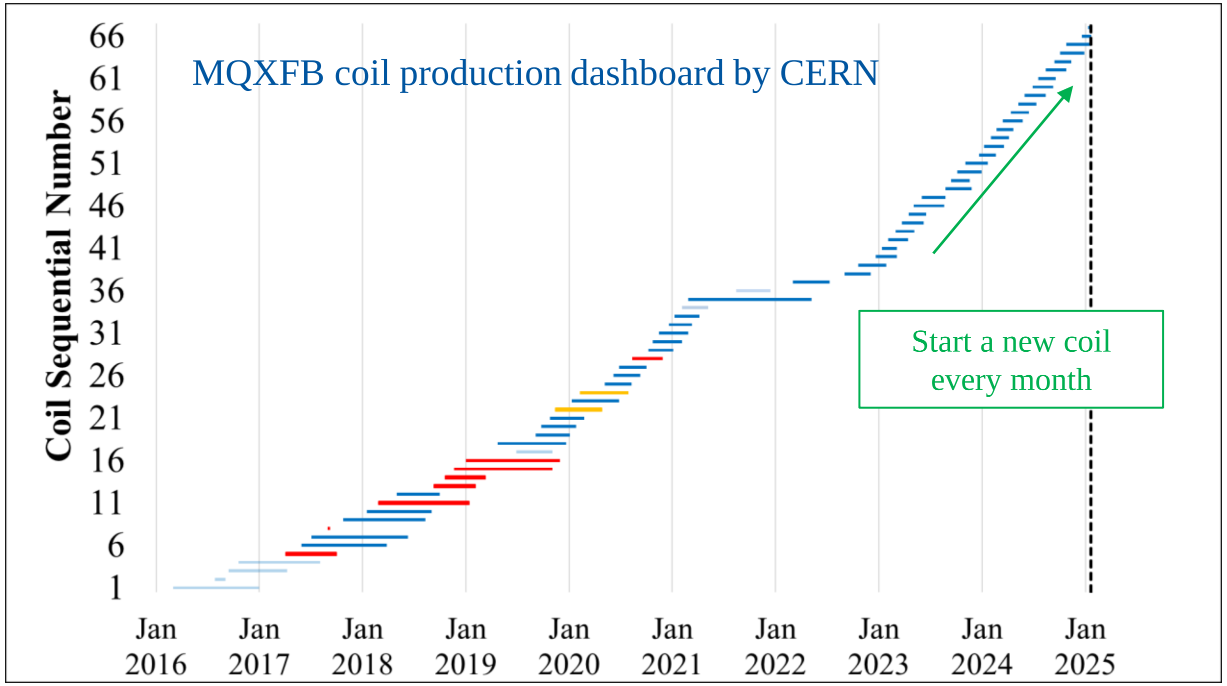
Production time	• ≈ 6 months/cold mass at full production speed, production stabilized after 30-40 units P. Fessia, et al., IEEE TAS vol 17 2007	• ≈ 6 months/magnet at full production speed for MQXFA (2 coil manufacturing lines)
		  • + 9 months for the cold mass and cryostating
		• ≈ 9 months/magnet at full production speed for MQXFB (1 coil manufacturing line).
		  • + 5 months for cold mass and cryostating

Production strategy	• Three firms, involved from the very beginning (short models and prototypes built in industry/CERN)
	• Procurements of all main components, tooling and set up of particular technologies by CERN (+ flexibility, uniformity and quality; - CERN responsible for everything)
		• Production in the laboratories
		  • MQXFA: cable (LBNL); coil (BNL+FNAL), magnet assembly (LBNL); vertical test (BNL); cold mass and horizontal test (FNAL)
		  • MQXFB: everything at CERN

The learning curve

- In Nb_3Sn, for an optimized production process, the clock is given by the production of the coils.
- Similar experience by AUP at CERN:
  - initial phase (≈ 20 coils) with low yield and longer manufacturing times
  - at full production speed, average time required to complete a coil 3 months (record for MQXFB is 7.5 weeks). Start a new coil every 3 weeks.



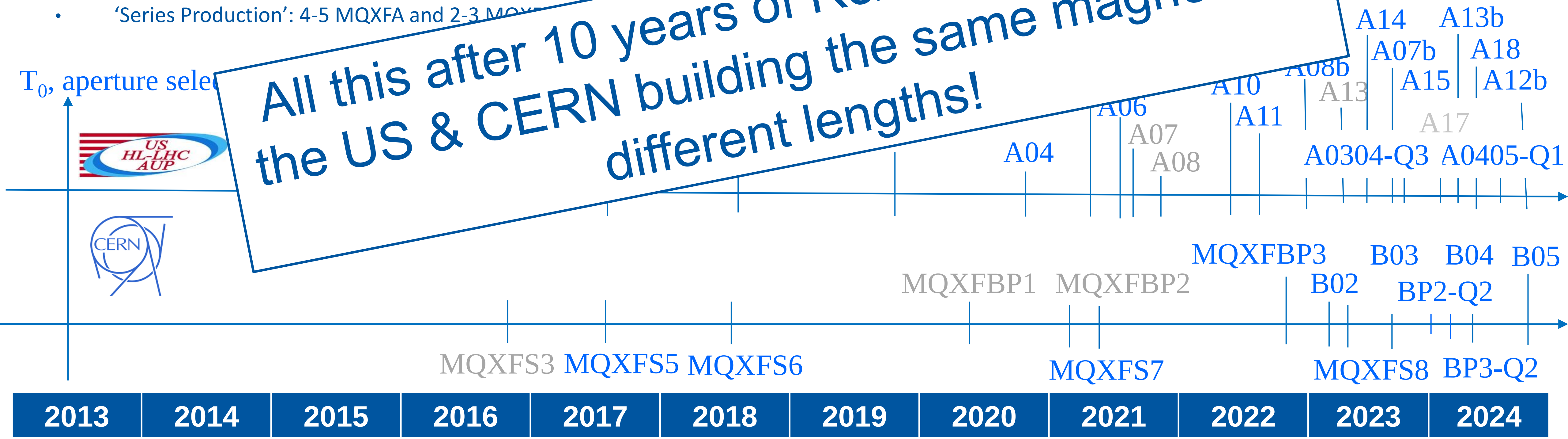


Legend: Rejected; Accepted; On hold; Practice coils

Key milestones timeline

- First validation of the coil fabrication (1.2 m length, MQXFSM1), testing in a mirror coil configuration, T_0 + 2 y
- First validation of the magnet design (1.2 m length, MQXFS1), T_0 + 2.5 y
- MQXFA coil fabrication process validated with the test of a 4 m length coil in mirror structure (MQXFAM1), T_0 + 3 y
- First 2 MQXFA prototypes did not reach requirements. First magnet fulfilling requirements was MQ…
- First two long prototype magnets did not reach performance requirements. MQXF… T_0 + 9 y
- First final cold masses LMQXFA01(A03/A04) and LMQXFB01 (BP…
- 'Series Production': 4-5 MQXFA and 2-3 MQXF…

All this after 10 years of R&D from LARP and the US & CERN building the same magnet but different lengths!



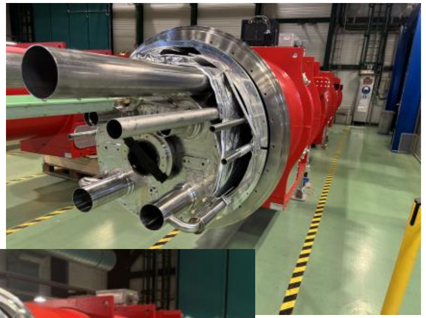
Grey means not reaching performance requirements

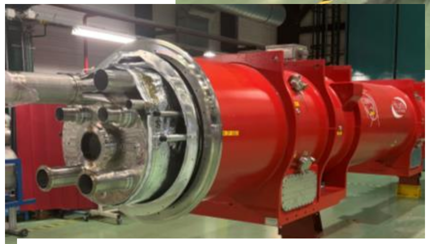
We are at full production speed!

MQXFBP2: being prepared for the HL-LHC string

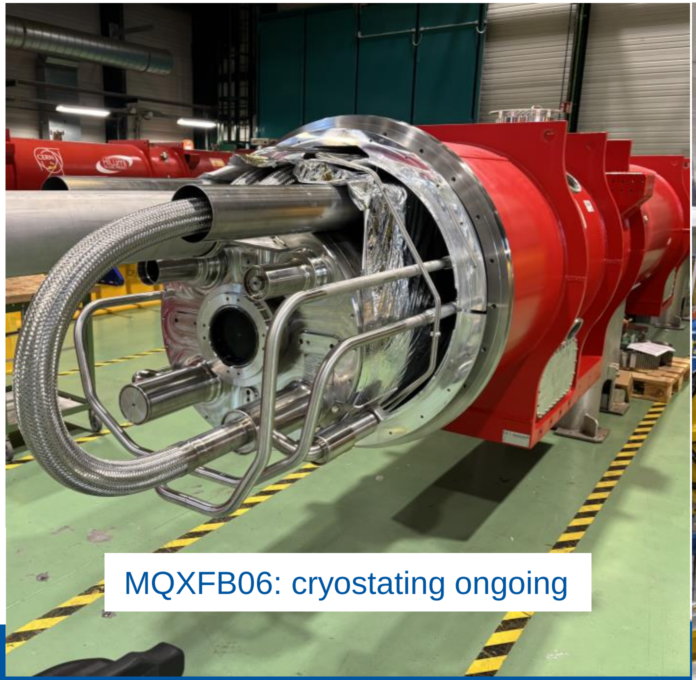
MQXFBP3: in the HL-LHC string

MQXFB03: test ongoing





MQXFB04: fully qualified for HL-LHC ✓
MQXFB05: fully qualified for HL-LHC ✓



MQXFB06: cryostating ongoing

MQXFB07: cold mass finishing

MQXFB08: magnet assembled

4 more magnets to build (B09-B12)

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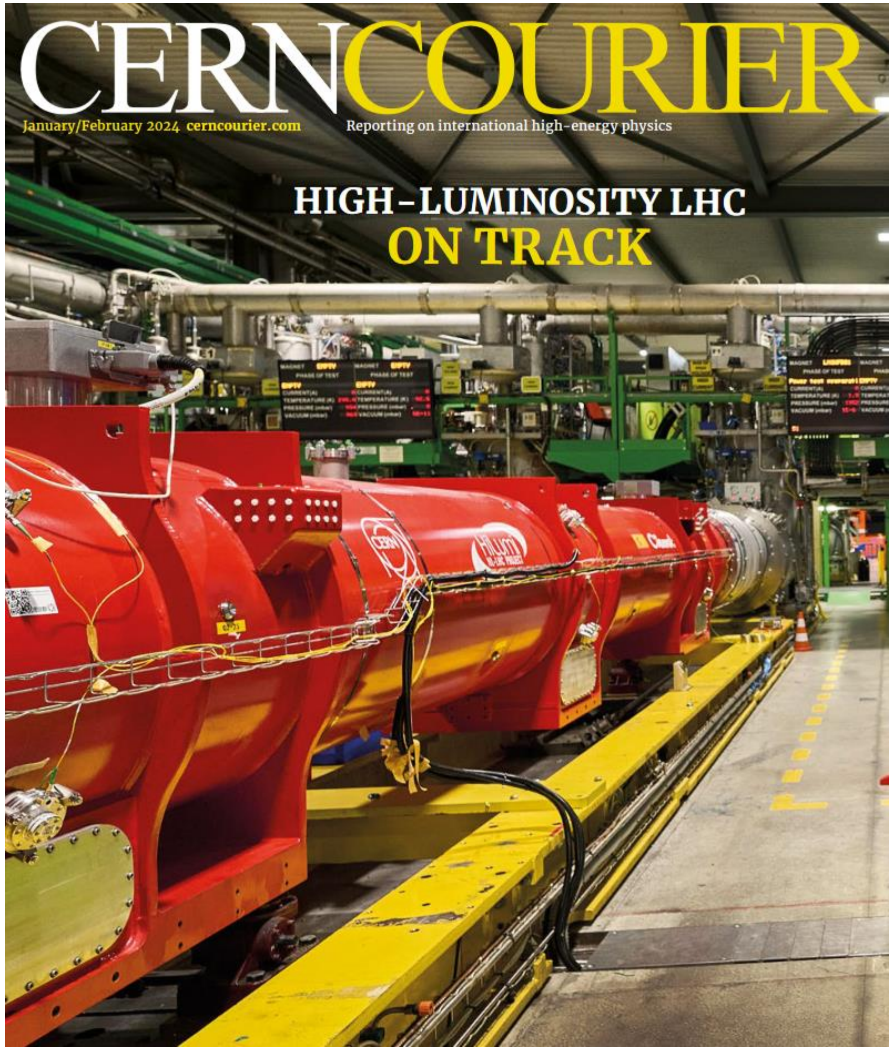
Conclusions

- Five consecutive MQXFB magnets reached HL-LHC requirements. Scaling in length has been nontrivial:
  - The first two prototypes, MQXFBP1 and MQXFBP2, did not meet requirements F. Mangiarotti et al, IEEE Vol 32 2022
  - The two next magnets, MQXFBP3 and MQXFB02 reached requirements but they still show signs of conductor degradation S. Izquierdo Bermudez et al, IEEE vol 33, 2023
  - MQXFB03, produced using new generation coils, does not show performance limitation (N. Lusa et al, IEEE Vol 34, 2024): first 7.2 m length magnet with no signs of conductor limitation!
  - MQXFB04 and MQXFB05, built with identical procedures, demonstrated the reproducibility of the performance S. Izquierdo Bermudez et al, IEEE 2025.
  - Three more magnets have been assembled (B06-B08), four more needed to complete production (B09-B12)

- Thirteen MQXFA magnets reached HL-LHC requirements.
  - The first two prototypes did not reach requirements (G. Ambrosio et al, IEEE Vol 31, 2021 and V. Marinozzi et al., IEEE Vol 31 2021)
  - 4 magnets did not reach requirements during vertical testing and required coil replacement G. Ambrosio et al, IEEE Appl. Sup., Vol 33, 2023
  - Eight more conform magnets needed to complete production.



Conclusions

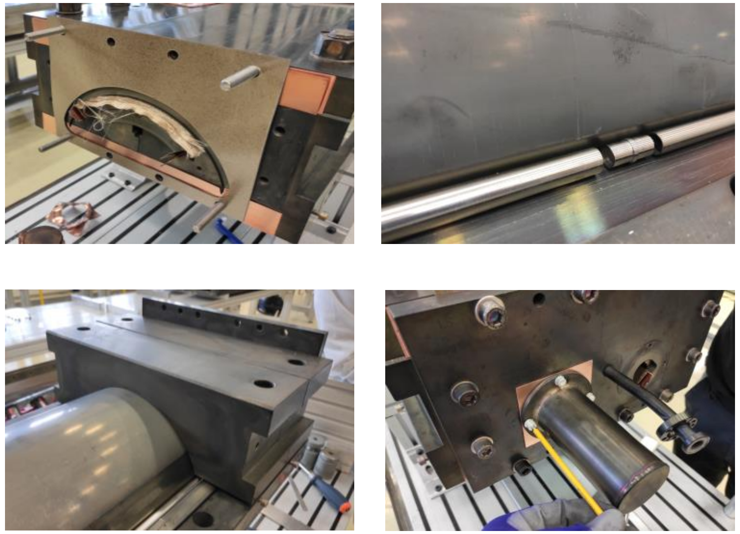
- Nb_3Sn is today the natural reference for future collider magnets, and the magnets produced for the HL-LHC upgrade is the first application of accelerator-quality Nb_3Sn magnet technology.
  - Field quality requirements in accelerator magnets are reachable with Nb_3Sn
  - Large margin in mechanics 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 proved
- In my opinion, the main (technical) areas to be improved in view of a production of thousands of units:
  - Engineering of transitions and singularities, to avoid the risk of conductor damage
  - Axial/Radial support of the coil ends
  - Electrical robustness
  - Optimization of the production flow in an industrial setting


Large Magnet Facility
Thank you!

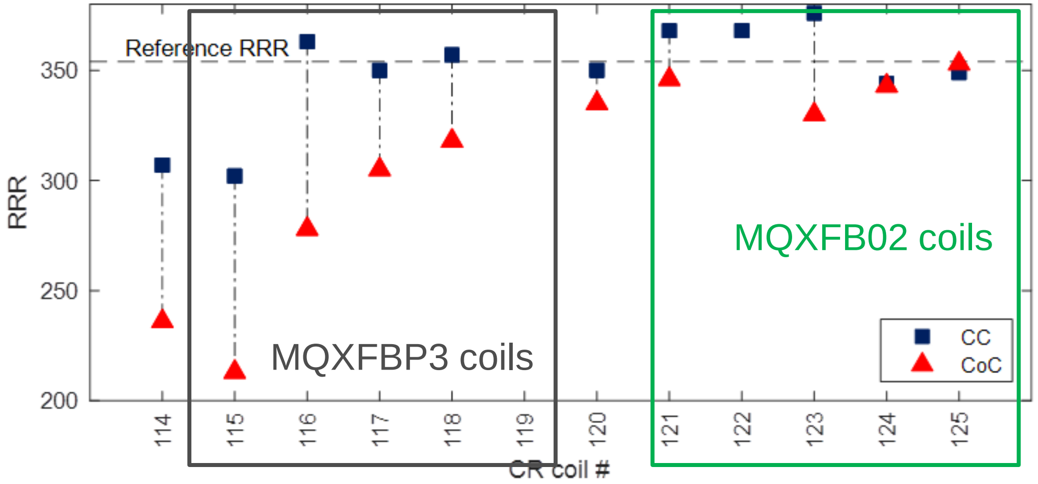
Additional slides

RRR degradation during reaction

- Significant difference in the RRR between the connection (outlet) and non-connection side (inlet). Improvements achieved through:
  - Stainless steel tubes on the base plate, acting as metallic joints (*from MQXFBP3 coils*).
  - Fitted copper shims to effectively seal the extremities (*from MQXFBP3 coils*).
  - Increased Argon flow in both the retort (750 l/h) and the mold (500 l/h) (*from MQXFB02 coils*).

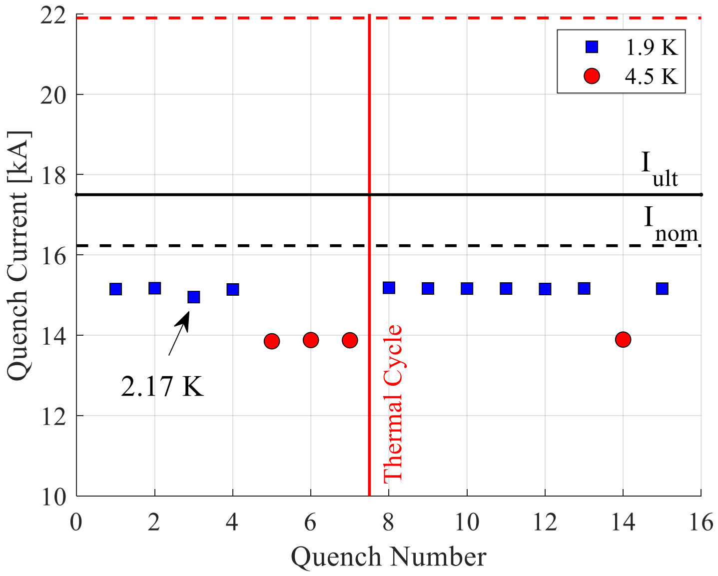


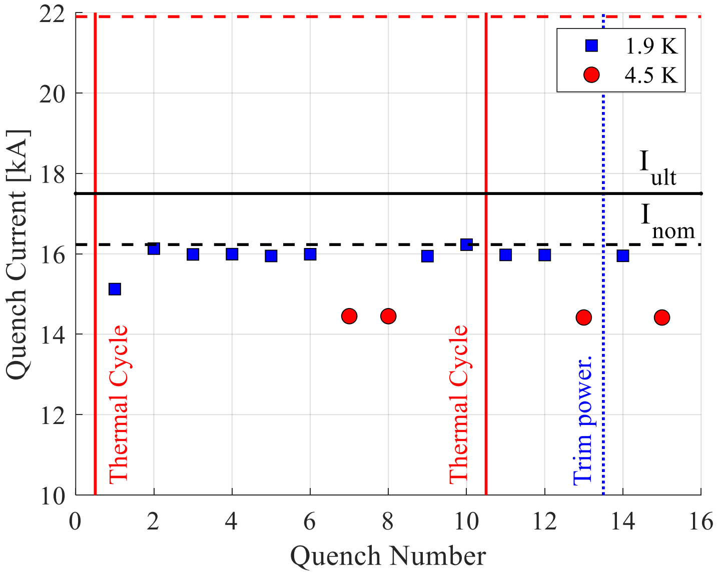
N. Lusa

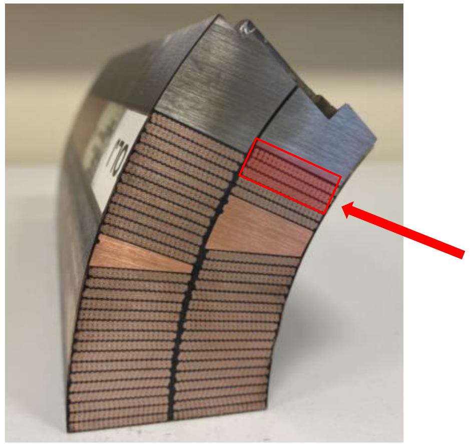


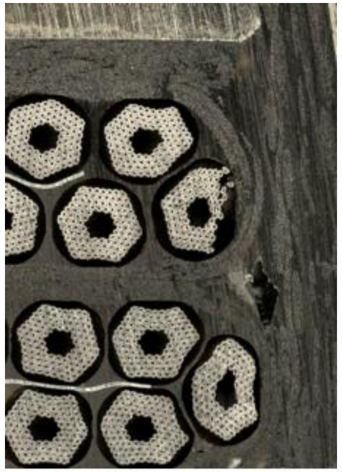
Performance limitation – MQXFB case

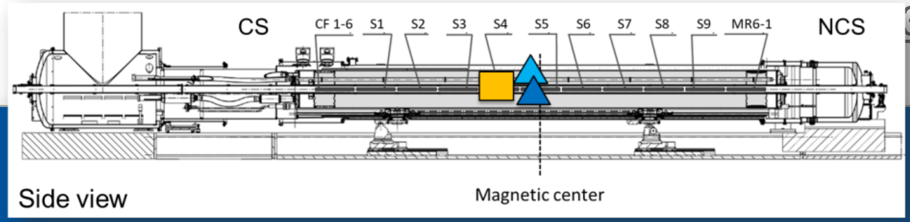
- MQXFBP1 and BP2 were limited below nominal current at 1.9 K (~15 and ~16 kA respectively) F. Mangiarotti et al., IEEE Appl. Sup., Vol 32, 2022
- 4.5 K behaviour compatible with magnet on the critical surface (70% of the short sample limit in MQXFBP1, 73 % in MQXFBP2).
- No retraining after thermal 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.
- Post-mortem metallurgical analysis indicated broken filaments in the quenching turns A. Moros et al, IEEE Vol 33, 2023
- Root cause was coil fabrication, mitigated by removing the ceramic binder in the outer layer to reduce longitudinal, radial and azimuthal friction between coil and the reaction N. Lusa et al, IEEE Vol 34, 2024.





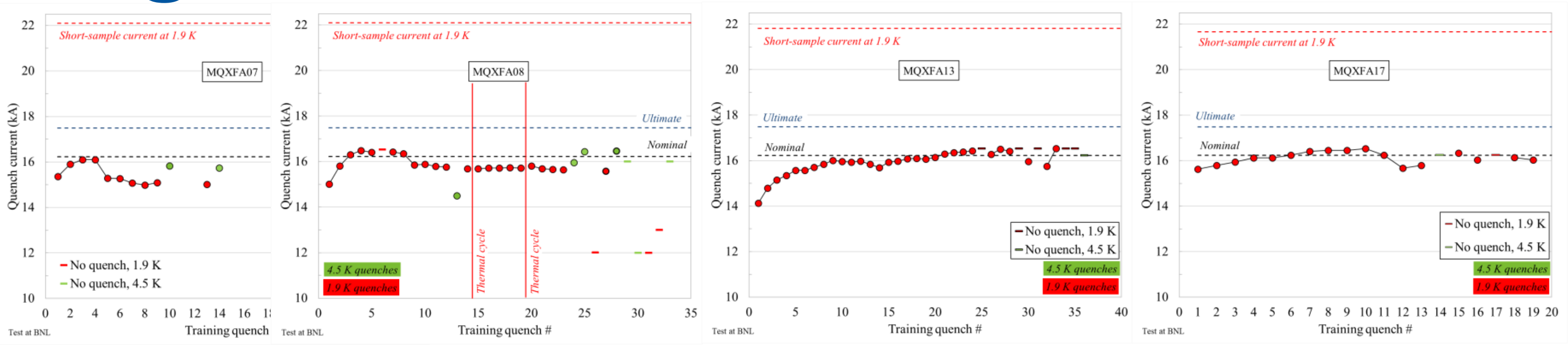




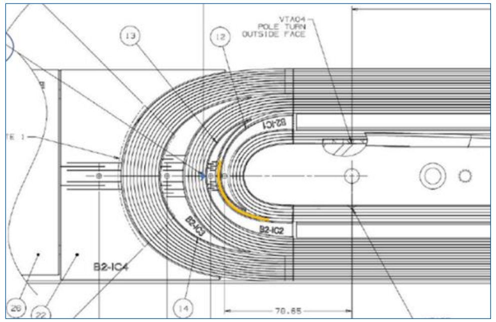


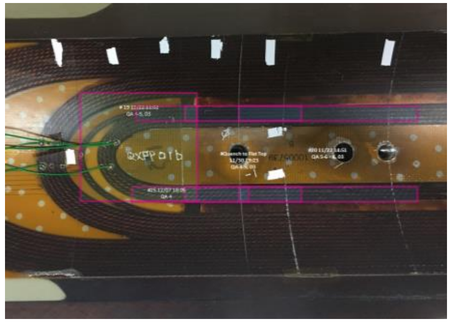
Performance degradation – MQXFA case

- 4 magnets with the MQXFA "disease"
    - De-training after few training quenches

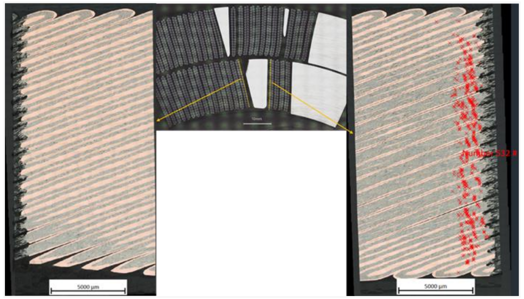


- Limited in the end region
    - Transition wedge to end-spacer

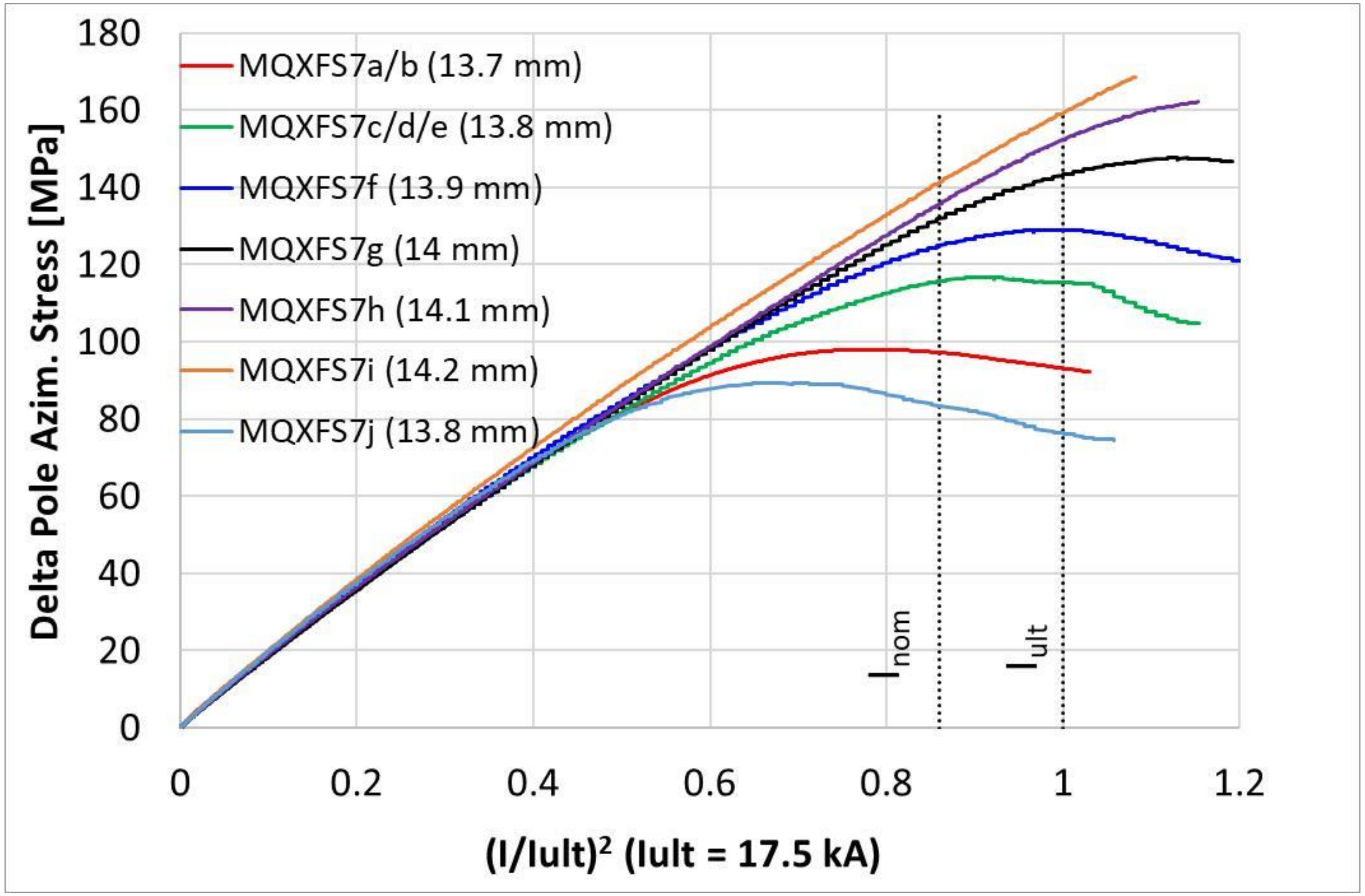




- Cracked filaments observed in limiting coils



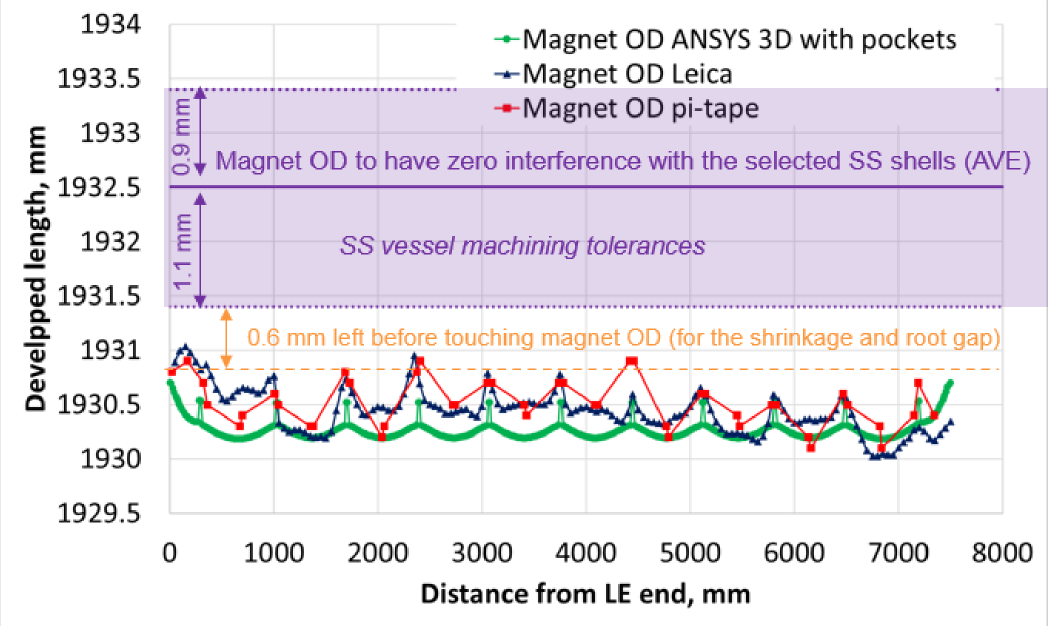
MQXFS7 from a mechanical point of view



Tolerances - Welding

- Stainless steel shells made by forming and machining: when pairing the two shells, ± 1 mm on developed length. In addition, extra tolerance needed for the welding shrinking and root gap. To limit the impact of the welding on the coil stress:
  - The iron yoke closes during the welding, so only part of the force reaches the coil (LHC dipole)
  - The stainless-steel vessel is welded with a ‘clearance’ to the magnet (MQXF quadrupole)

Forming of SS shells
12m press, 3’000 tons capacity



Performance summary – HL-LHC short models

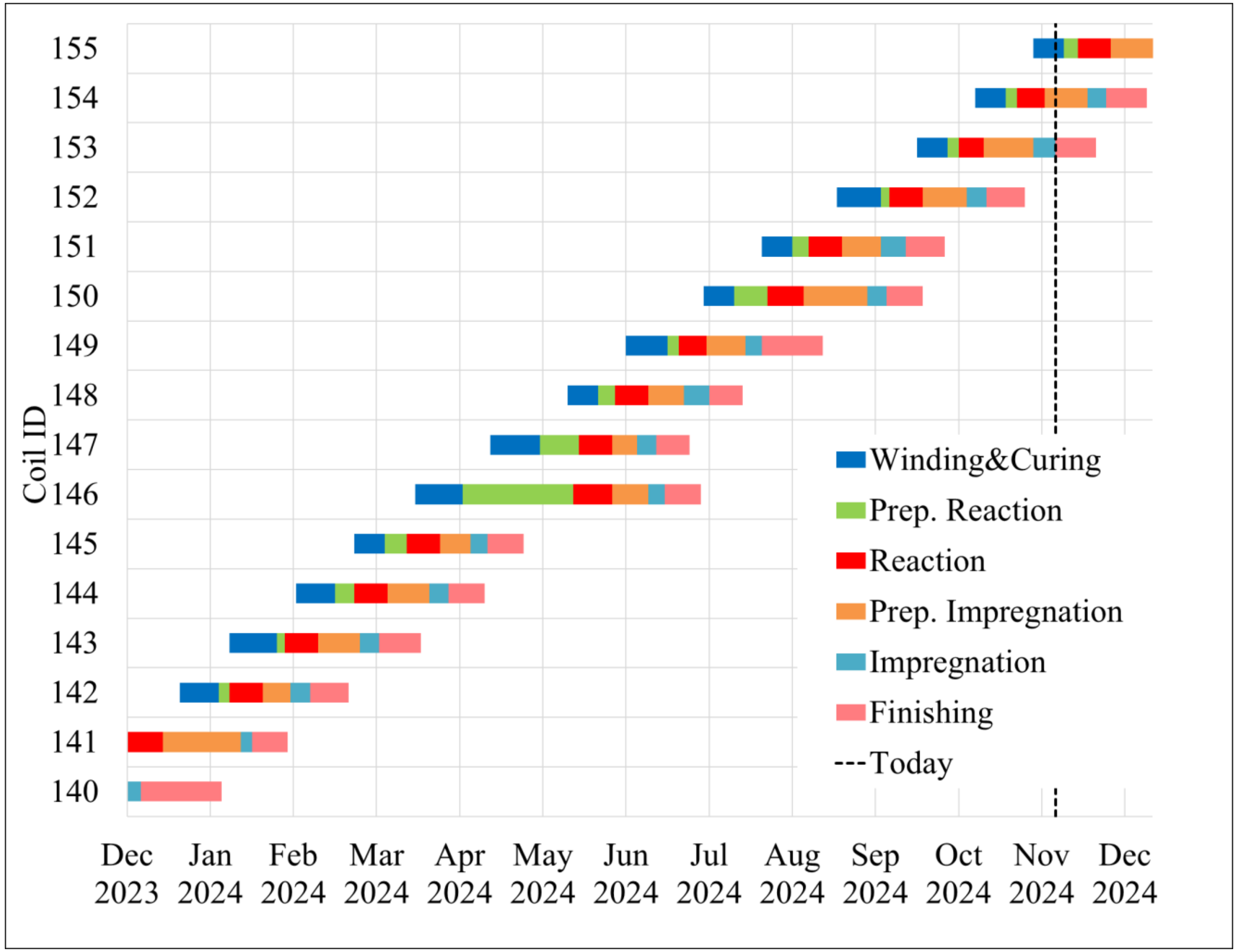
MBHS
(Single aperture 11 T short models, 8 magnets)

	B_{max} [T] (1.9 K)	B_{max} [T] (4.5 K)	I_{max}/I_{ss} % (1.9 K)	I_{max}/I_{ss} % (4.5 K)
average	12.6	11.7	87.5	89.8
max	13.4	12.3	93.9	94.5
min	11.8	11.3	81.5	86.1
std	0.5	0.3	3.9	2.8

MQXFS
(Single aperture 11 T short models, 8 magnets)

	B_{max} [T] (1.9 K)	B_{max} [T] (4.5 K)	I_{max}/I_{ss} % (1.9 K)	I_{max}/I_{ss} % (4.5 K)
average	13.0	12.4	90.3	94.8
max	13.4	12.7	95.4	97.5
min	12.3	12.1	83.2	89.6
std	0.4	0.2	3.8	2.7

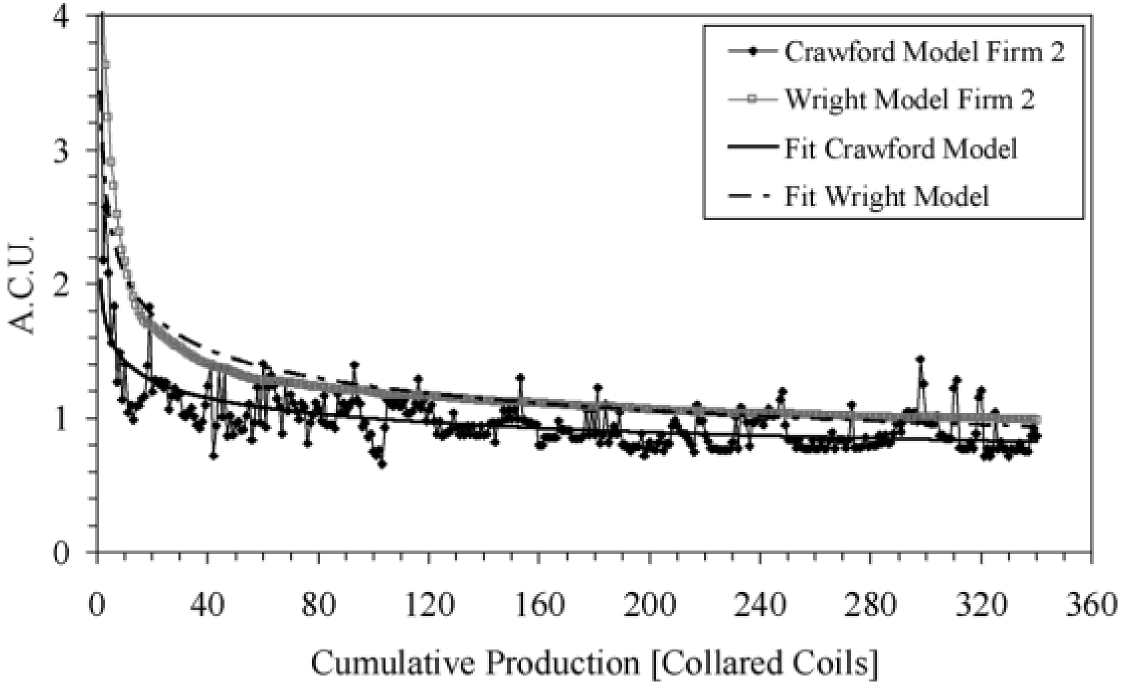
Coil production flow – MQXFB series

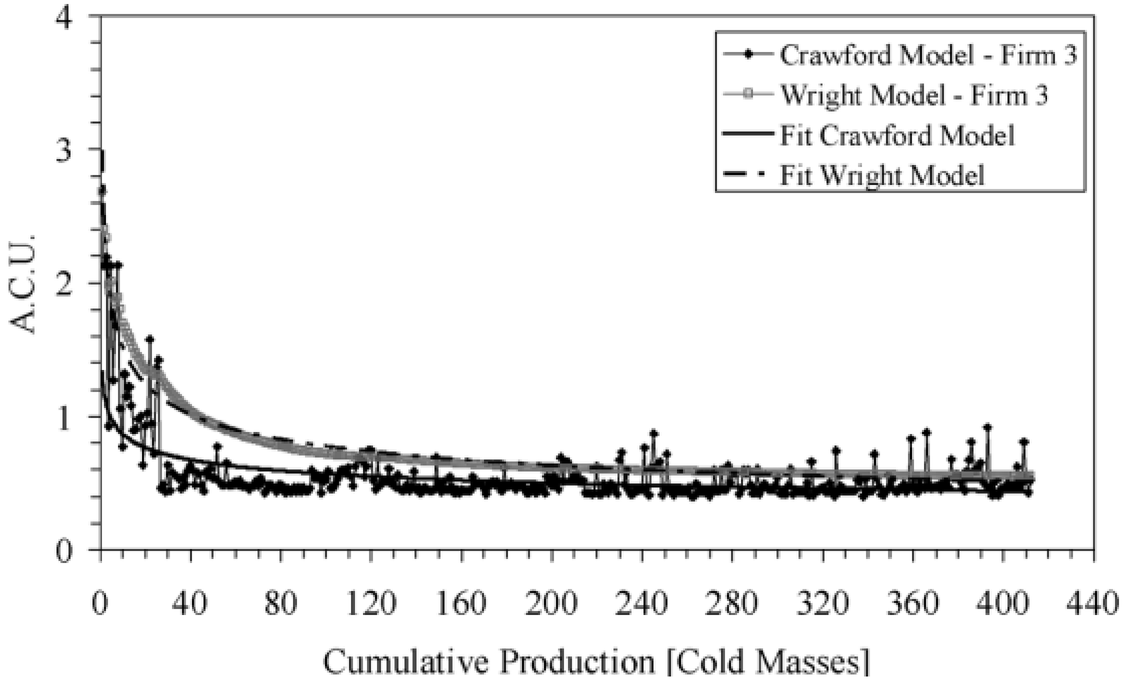


The learning curve

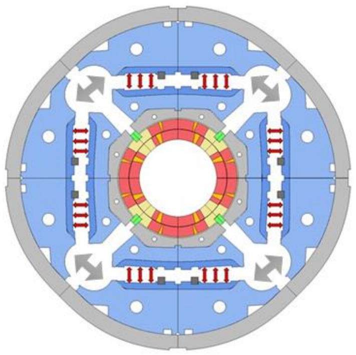
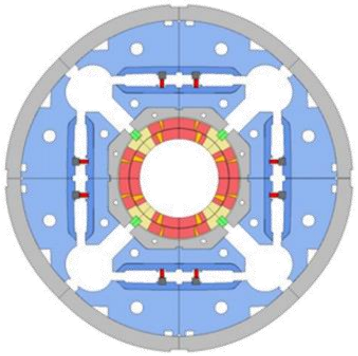
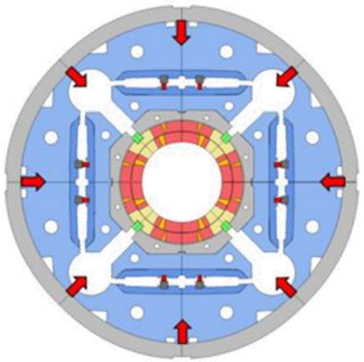
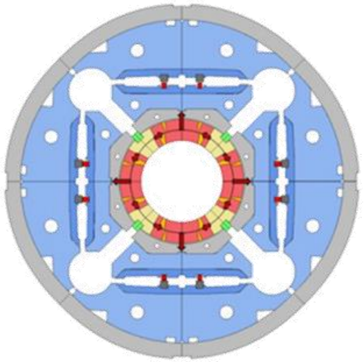
P. Fessia, et al., IEEE TAS 17 2007

- At full production speed, the time needed to produce an LHC-MB cold mass is ≈ 6 months
- Production stabilizes after the first 30-40 units
- The learning percentage is between 80-85 %



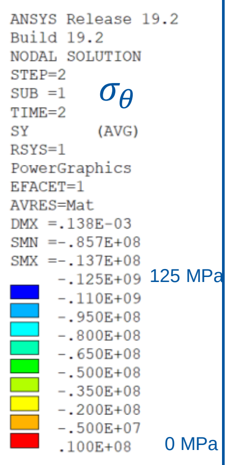


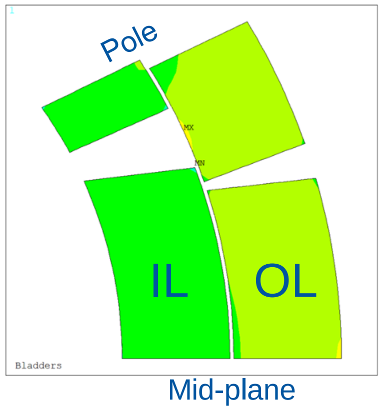
Magnet assembly

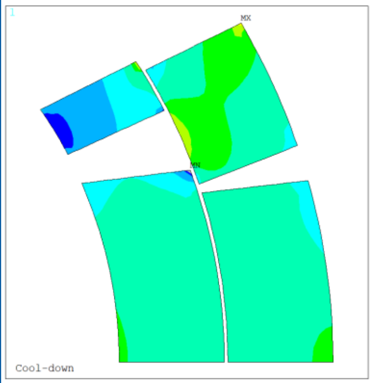
	Bladder pressurization*	Key insertion	Cool down	Powering
	Open enough clearance to insert the keys (key size + ≈ 0.2-0.3 mm clearance)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic forces
F_θ/F_{em} shell	--	40 %	87 %	93 %
F_θ/F_{em} pole	--	40 %	87 %	10 %
				

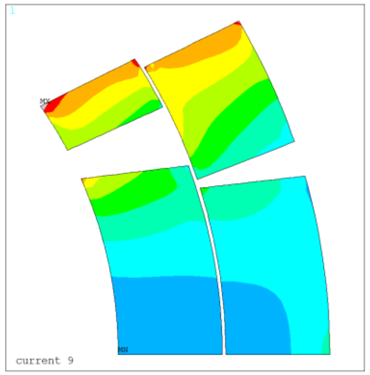
Coil stress for target pre-load

		Bladder pressurization	Key insertion	Cool down	Powering (16.23/17.5 kA)
		Open enough clearance to be insert the keys (key size + 0.2-0.3 mm)	Insert the keys to set the RT pre-load level	Increase of pre-load due to the diff. of thermal contraction between aluminum and iron	Coil un-loading due to electromagnetic forces
σ_θ coil, MPa	Ave Pole turn IL	-58	-52	-97	-6/-2
	Peak Pole turn IL	-72	-86	-113	-14/-8
	Peak Coil	-72	-86	-124	-109/-120









Stress map and stress values for the new procedure, loading with auxiliary bladders in the cooling holes.
Nominal assembly with 80 MPa pole compression at warm, 110 MPa at cold
Uncertainty due to material properties and assembly tolerances ± 15-20 MPa

From models to proto and series

✓*First validation of the coil fabrication (1.2 m length), testing in a mirror coil configuration (only 1 coil, easier mechanics)*

T_0, aperture selection

MQXFSM1

$T_0 + 2$

MQXFAM1

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

✓First validation of the magnet design (1.2 m length), 3 years after the selection of the aperture

T_0, aperture selection

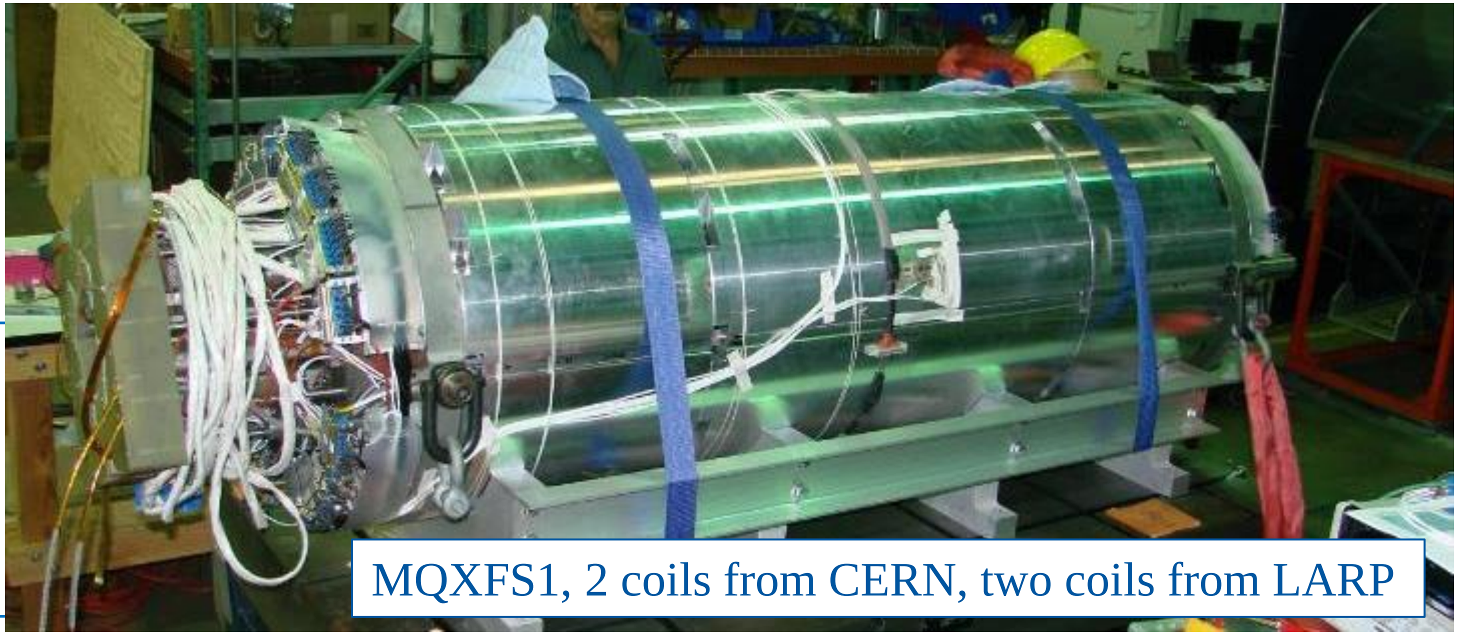
US HL-LHC AUP

CERN

MQXFSM1

MQXFS1

$T_0 + 3$



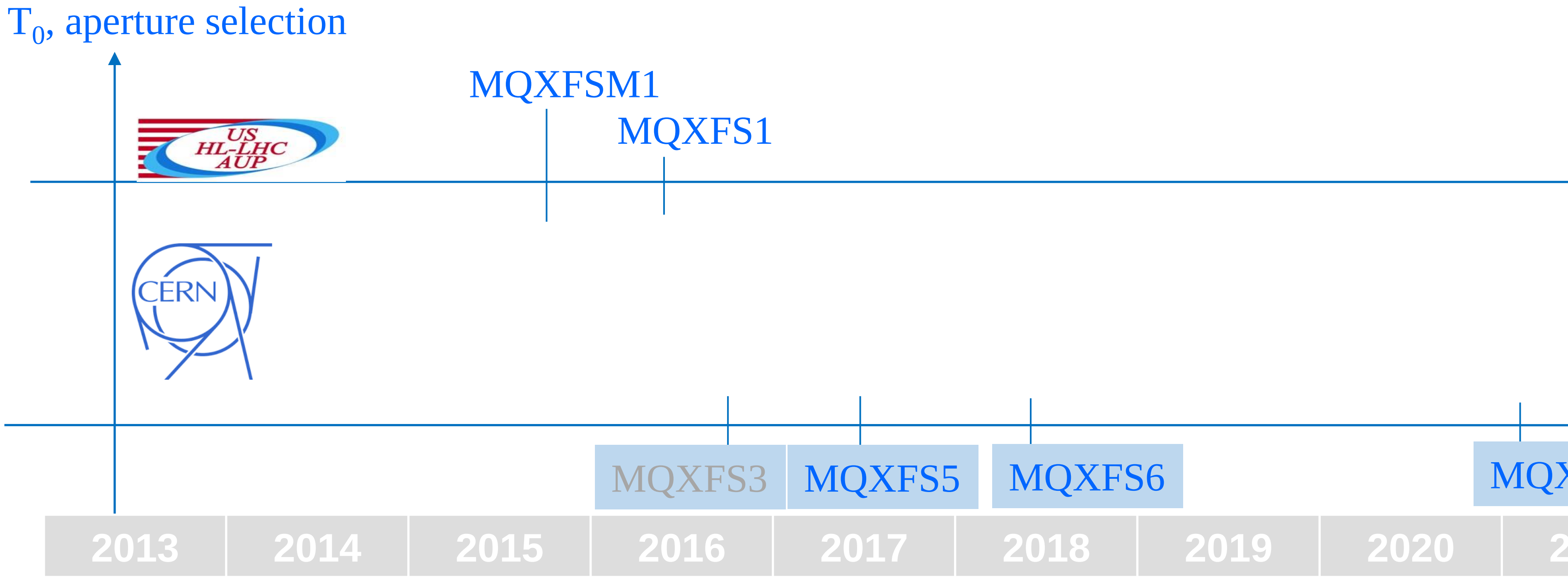
MQXFS1, 2 coils from CERN, two coils from LARP

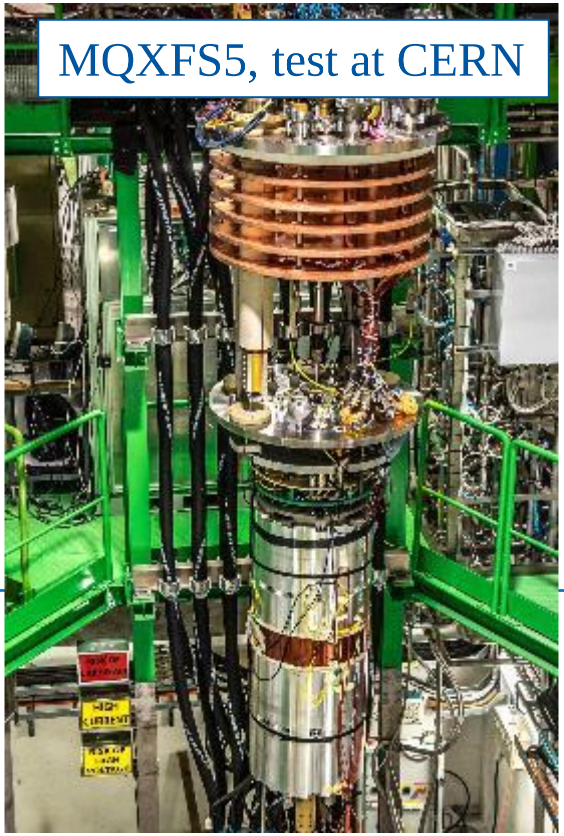
2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

✓MQXFS1 was followed by a series of short models at CERN, to validate design features and margins: today it is still a tool for guiding the construction process





Grey means not reaching performance requirements

From models to proto and series

✓MQXFA coil fabrication process validated with the test of a 4 m length coil in mirror structure

E. Holik et al, IEEE vol 27 2017

T_0, aperture selection

US HL-LHC AUP

MQXFSM1

MQXFS1

MQXFAM1

$T_0 + 4$

CERN

MQXFS3

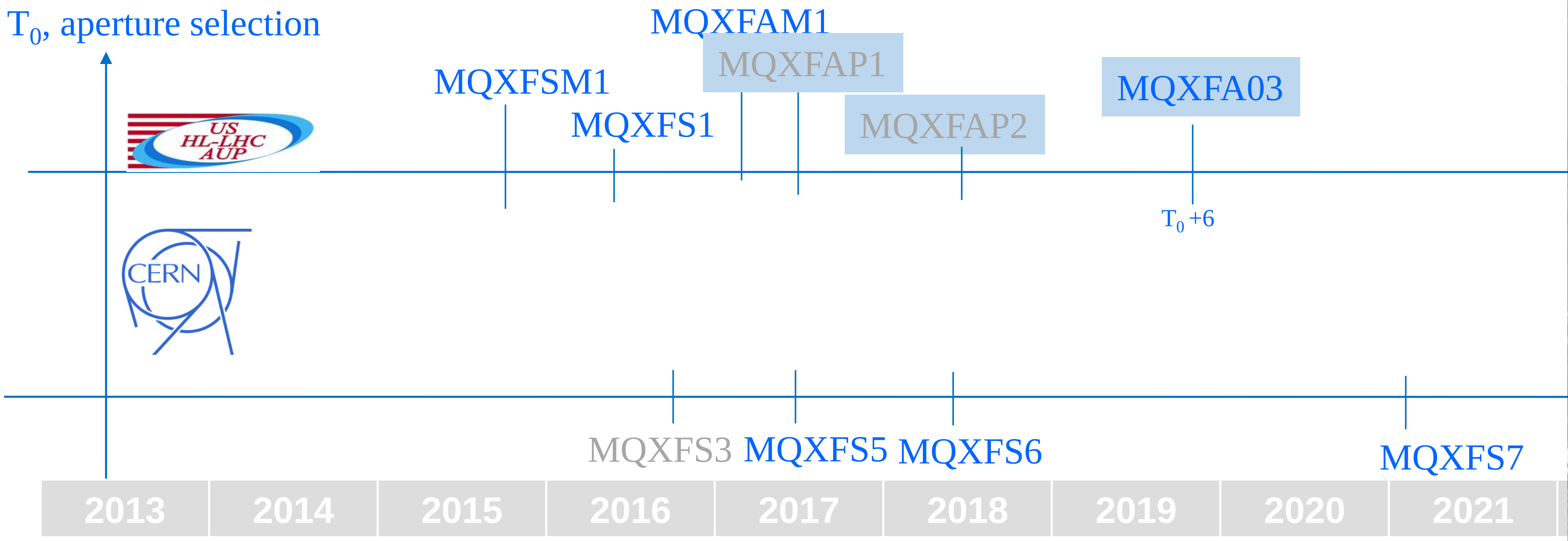
MQXFS5

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

First 2 MQXFA prototypes did not reach requirements. First magnet fulfilling requirements was MQXFA03 ✓



Grey means not reaching performance requirements

From models to proto and series

A series of magnets followed MQXFA03, not all reaching performance requirements (≈ 3 magnets/year)

T_0, aperture selection


Two MQXFA assembly lines at LBNL

MQXFA03

A04

A05

A06

A07

A08

A10

A11

A08b

A13

MQXFS7

MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

✓*First cold mass tested 10 years after the aperture selection*

From models to proto and series

T_0, apertu

XFAP1

MC

First two long prototype magnets did not reach performance requirements. MQXFBP3 first MQXFB magnet reaching requirements (T_0 +9)

MQXFBP3

MQXFBP1 MQXFBP2

5 MQXFS6

$T_0 + 7$ MQXFS7

$T_0 + 9$ MQXFS8

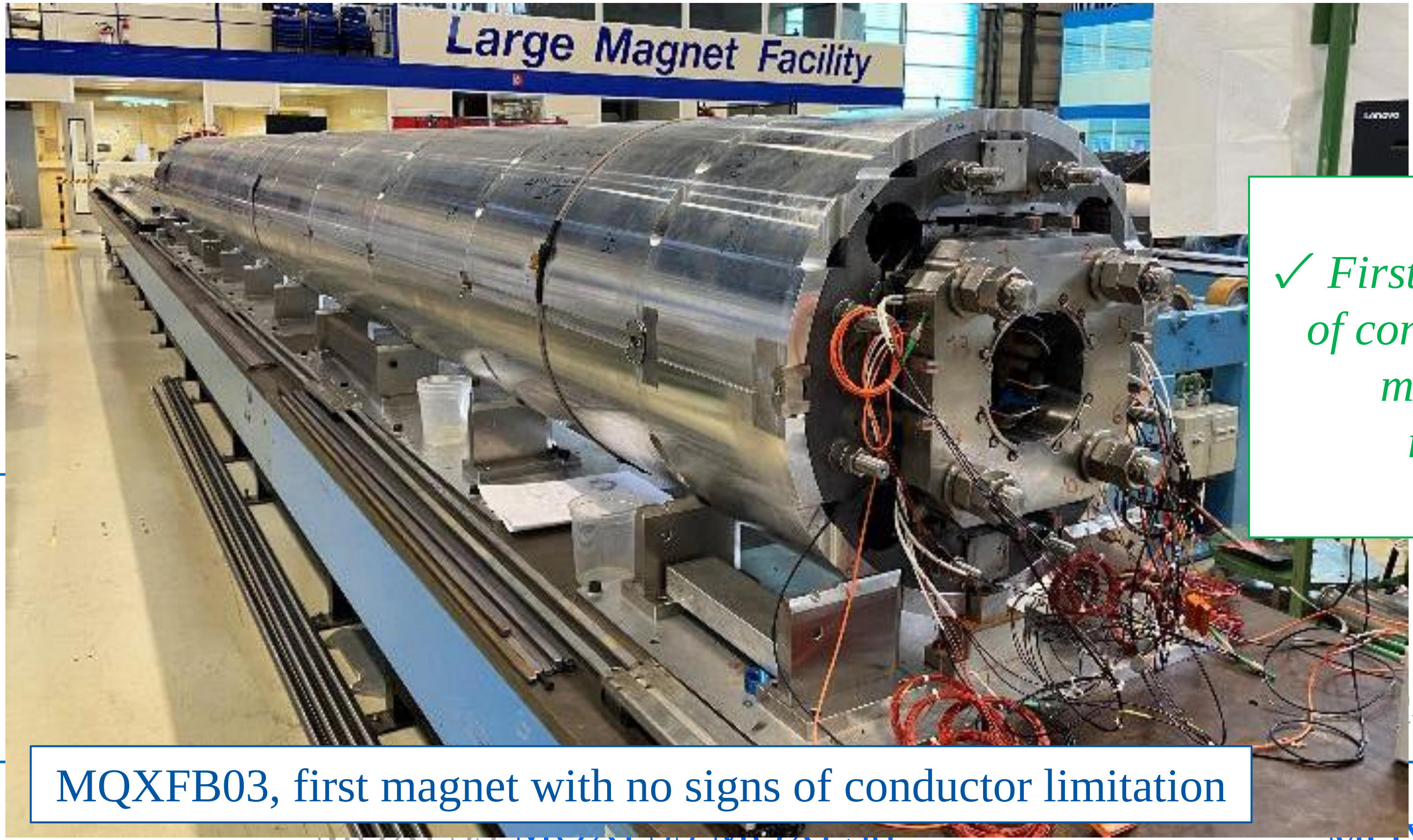
2 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

MQXFBP3 in temporary cold mas, first reaching HL-LHC requirements

Grey means not reaching performance requirements

From models to proto and series

T_0, aperture selection



MQXFB03, first magnet with no signs of conductor limitation

✓ *First MQXFB magnet with no signs of conductor limitation (T_0 +10). 3 magnets fulfilling HL-LHC requirements (out of 10)*

MQXFBP2

MQXFBP3

B02

B03

$T_0 + 10$

MQXFS7

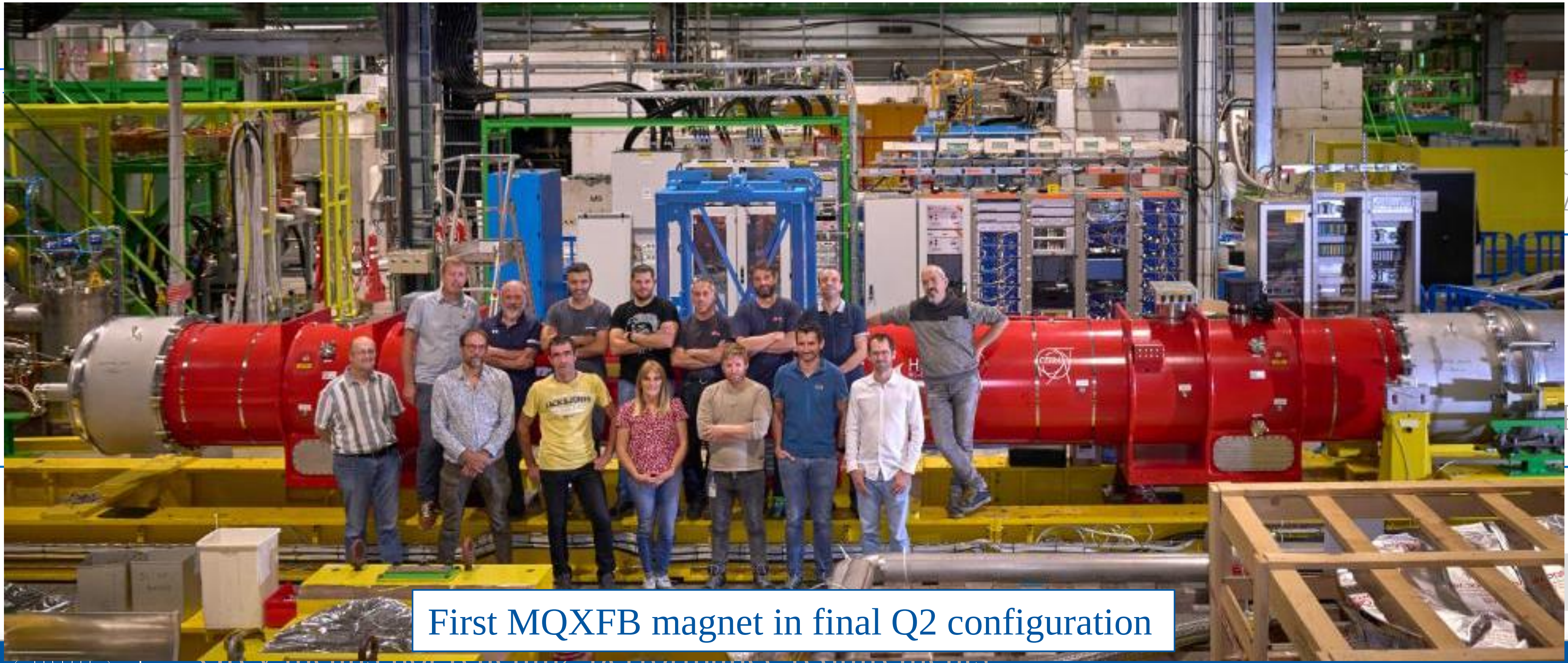
MQXFS8

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Grey means not reaching performance requirements

From models to proto and series

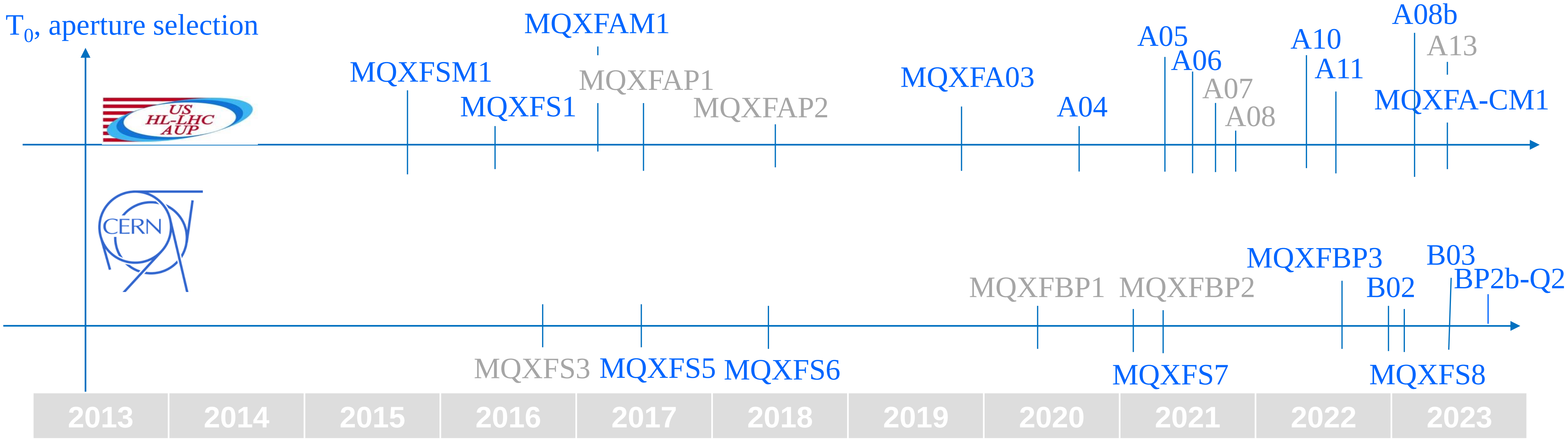
✓First Q2 final cold mass configuration is being tested now at CERN



First MQXFB magnet in final Q2 configuration

From models to proto and series

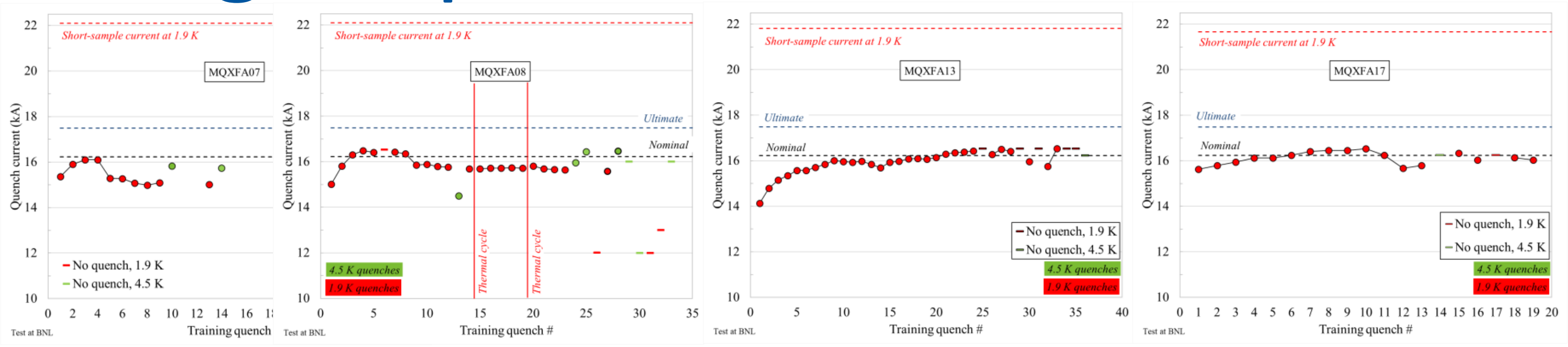
Personal note: for new technology such as Nb_3Sn, test as much as and as fast as you can afford, especially in the initial phase of models, prototype and pre-series



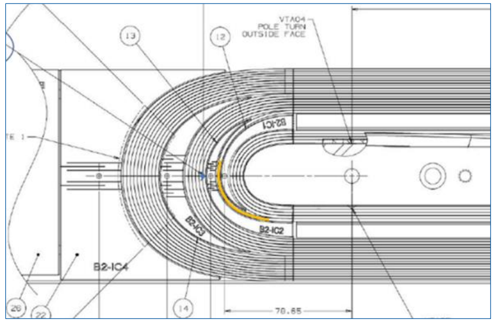
Grey means not reaching performance requirements

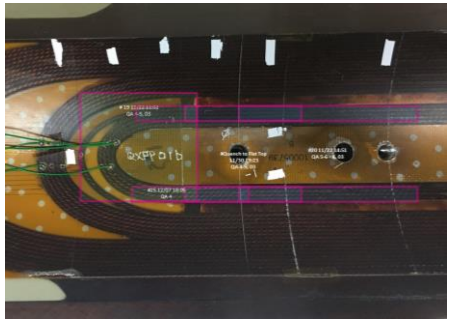
MQXFA series magnet performance

- 4 magnets with the MQXFA "disease"
  - De-training after few training quenches

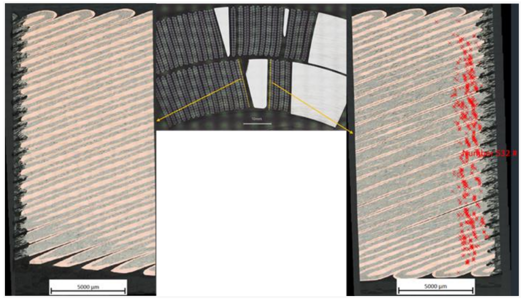


- Limited in the end region
  - Transition wedge to end-spacer





- Cracked filaments observed in limiting coils



MQXFA series magnet performance

- Our current understanding and action times
  - Effect of axial Lorentz forces in the coil end region
- By design, axial forces counteracted by end support structure
  - axial loading (end-plate) + azimuthal loading (friction with support structure)
- Lack of end support caused by
  - Pole key interception of azimuthal loading
    - Larger pole gap introduced
  - Coil significantly smaller in the end
    - So, increase overall pre-load and tapered shims
- High axial strain in turn close to the transition
- So far, out of spec magnets fixed with coil replacement and improved pre-load