



# Scale up in length of Nb<sub>3</sub>Sn accelerator magnets: the case of MQXF

Susana Izquierdo Bermudez on behalf of the MQXF collaboration

Special thanks to Giorgio Ambrosio, Paolo Ferracin, Attilio Milanese, Ezio Todesco



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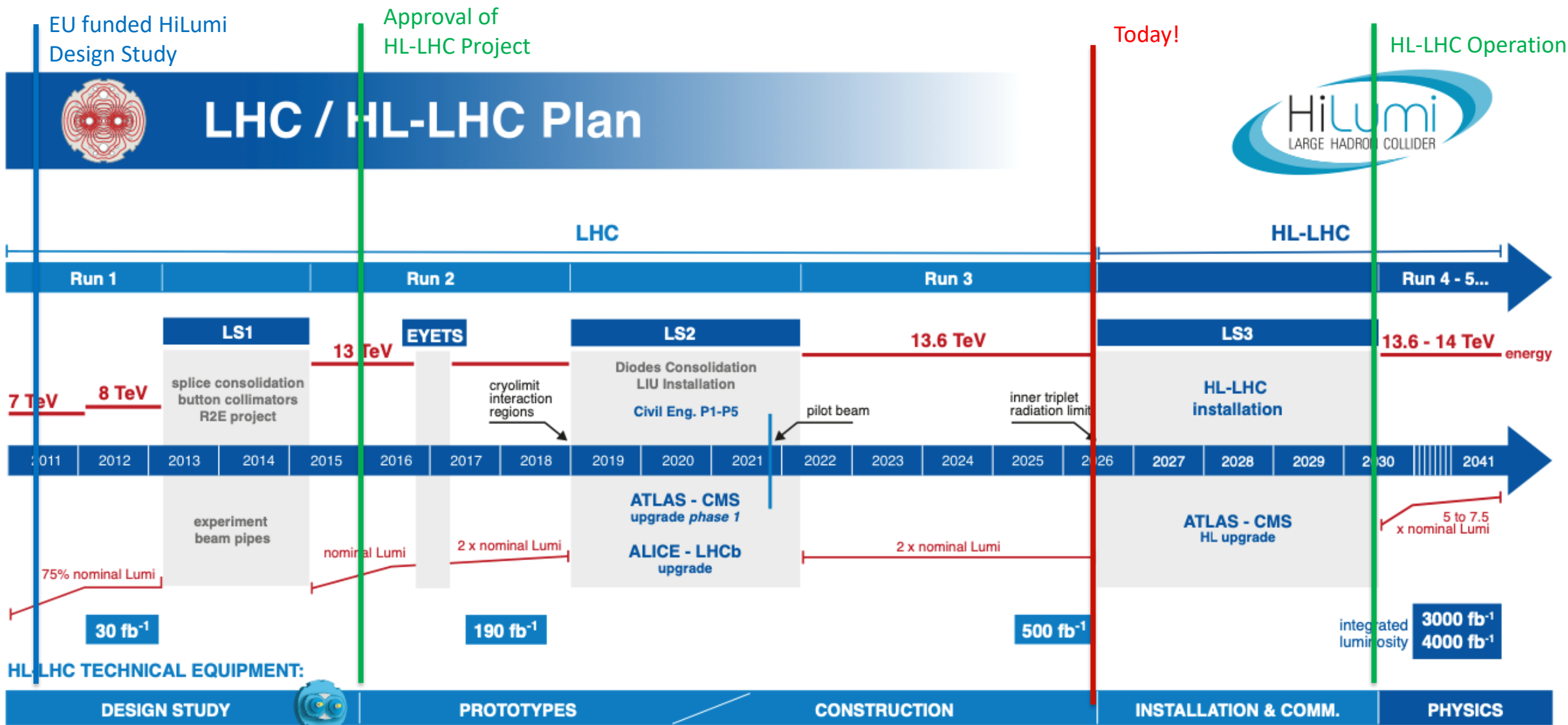
# Outline

- Introduction
- Production status
- Overview on cold powering test results
- Summary and conclusions

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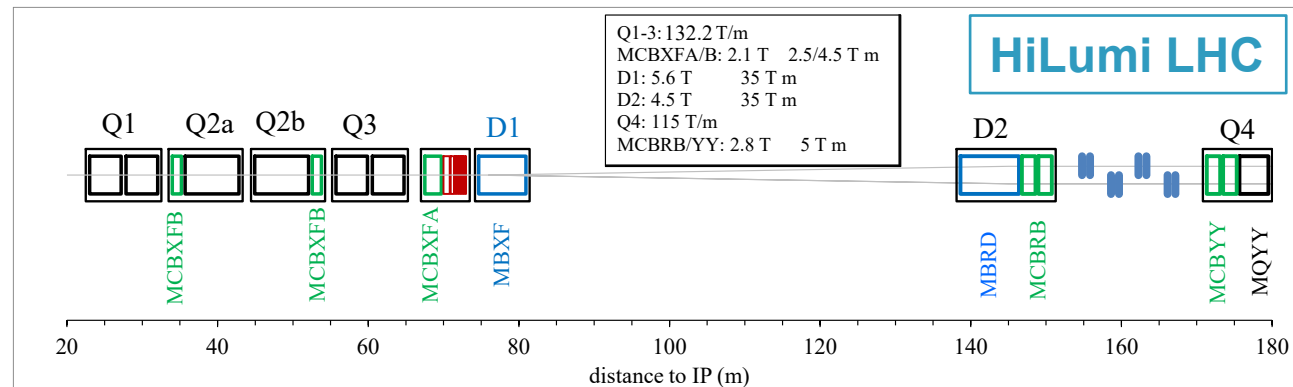
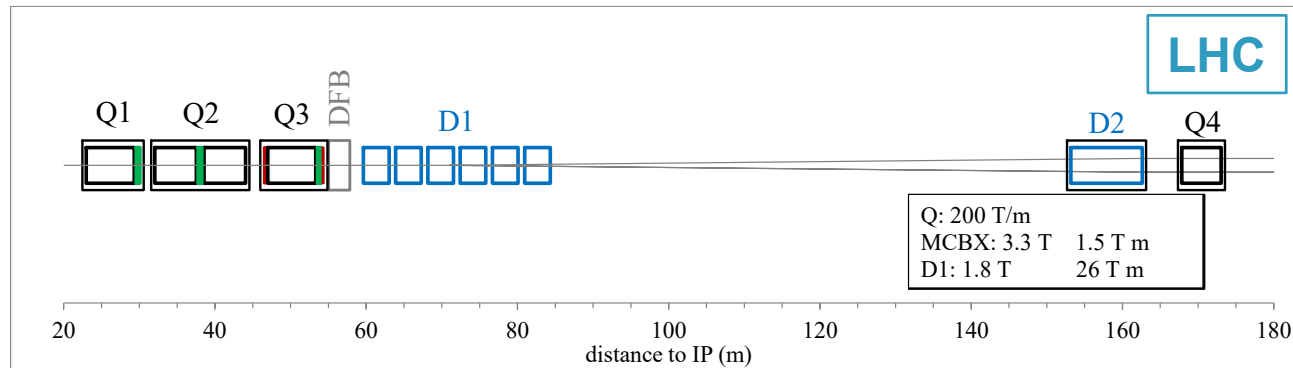
# Introduction: from LHC to HL-LHC



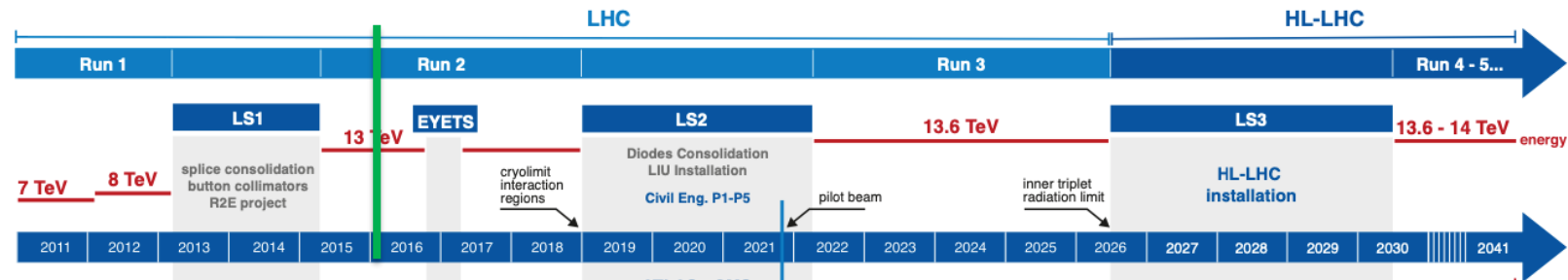
# Introduction: HL-LHC Interaction region

- New inner triplet quadrupole (**MQXF**)
  - Larger aperture to reduce the beam size: from 70 to 150 mm
  - From Nb-Ti at 8.6 T to Nb<sub>3</sub>Sn at 11.3 T

E. Todesco



# The journey of Nb<sub>3</sub>Sn technology for HL-LHC upgrade



## Approval of HL-LHC Project

### CERN joins the development efforts

- MQXF T<sub>0</sub> = 2013: aperture and cable selection



US DOE Conductor Development program, pushing the  $J_c(12\text{ T}, 4.2\text{ K}) > 3000\text{ A/mm}^2$



### LARP (LHC Accelerator R&D program) established the necessary technology. Goals:

- Investigate the Potential and Challenges of Nb<sub>3</sub>Sn Technology
- R&D Phases and main achievements from fundamental technology demonstration to accelerator quality magnets
- Bridge from proof-of-principle tests to accelerator readiness



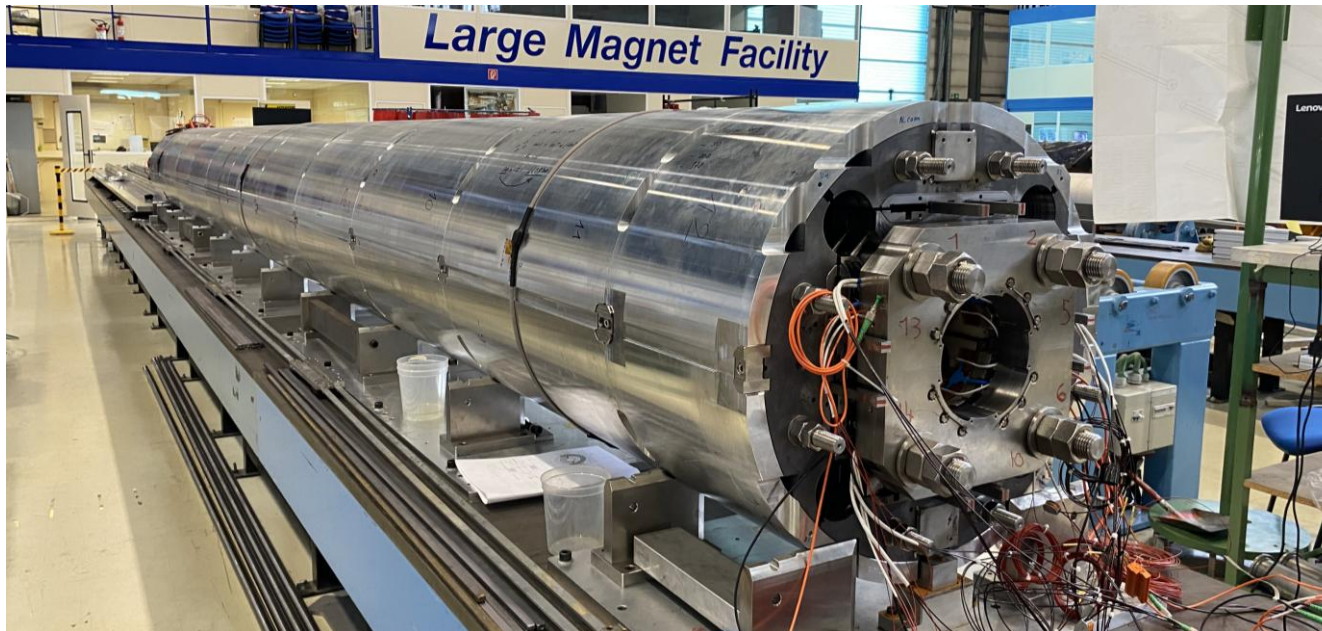
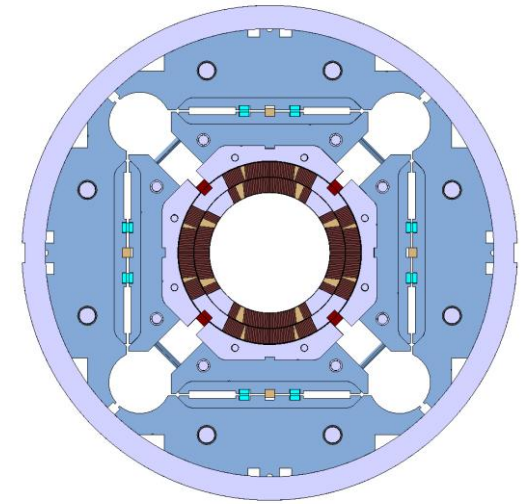
US DOE HL-LHC Accelerator Upgrade Project (AUP), coordinating efforts from US Labs (FNAL, BNL, LBNL with contributions from SLAC, JLAB, ODU & FSU) for the production and testing of the Q1/Q3 cryo-assemblies needed for the HL-LHC upgrade

European programs for development of Nb<sub>3</sub>Sn magnet technology ([NED](#) and [EUCARD](#))



# HL-LHC low- $\beta$ 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)

7 short models

MQXFA  
(4.2 m)

2 prototypes +  
16 installation + 5 spares

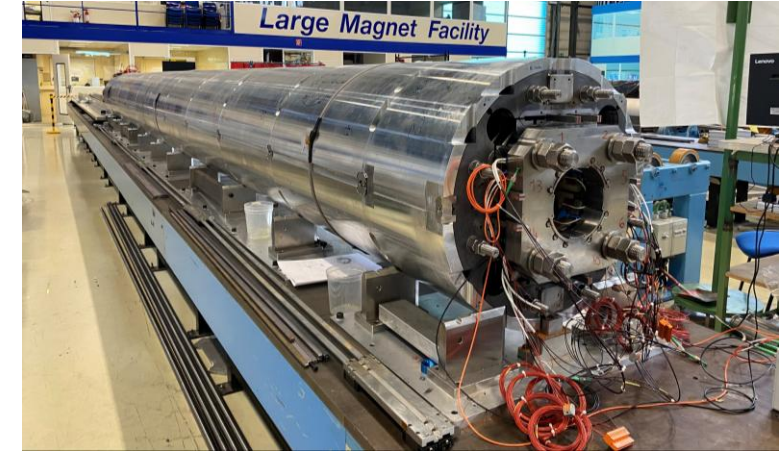
MQXFB  
(7.2 m)

3 prototypes +  
8 installation + 2 spares

# MQXF main milestones



First MQXFS magnet tested



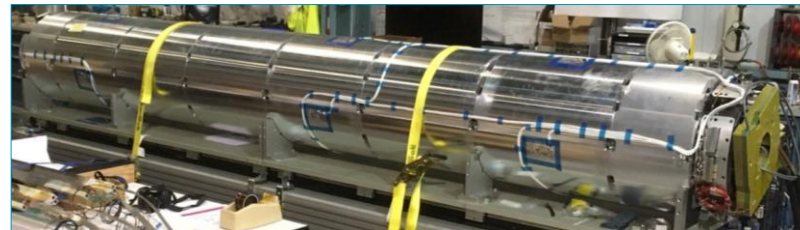
MQXFB03: First MQXFB magnet with no sign of conductor limitation ( $T_0 + 10$ )



$T_0$  = aperture and cable selection

MQXFAP1: First MQXFA prototype magnet tested (nonconform)

MQXFA3: First MQXFA conform magnet ( $T_0 + 6$ )



Today:

- 7 out of the 8 MQXFB magnets needed for installation are qualified
- All the MQXFA magnets for installation (16) are qualified

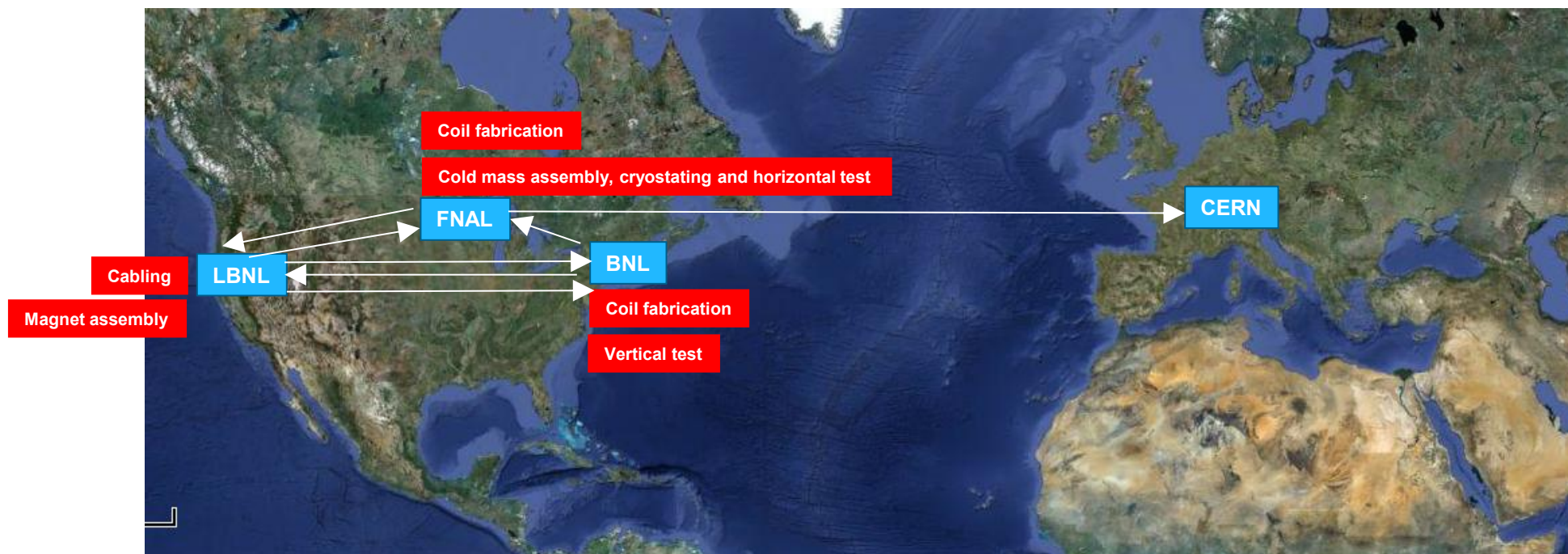
Focus of this talk: series production and main encountered challenges

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# Series production strategy

- A multi-lab effort.
  - MQXFB at CERN
  - MQXFA at BNL/LBNL/FNAL, under US-AUP project







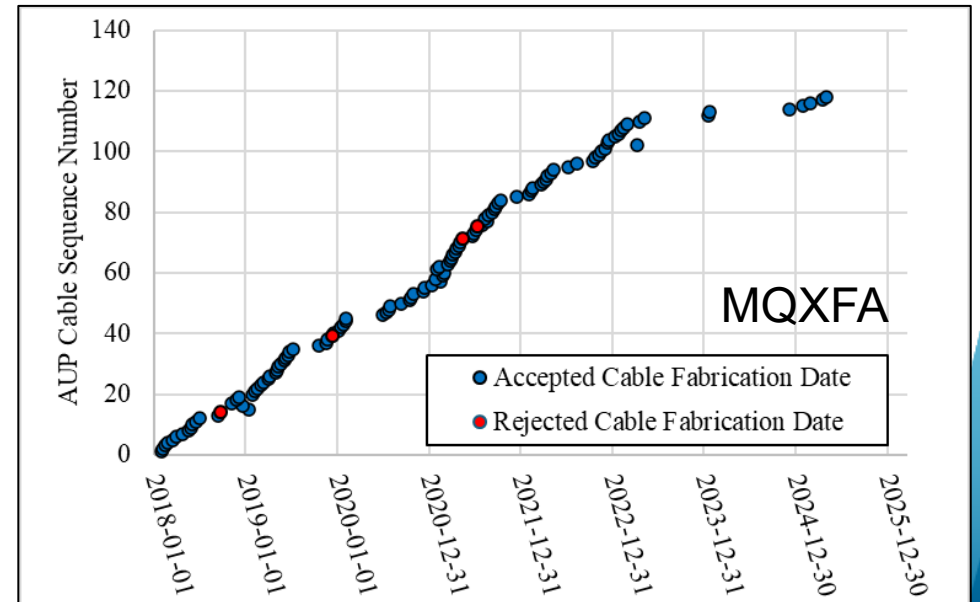
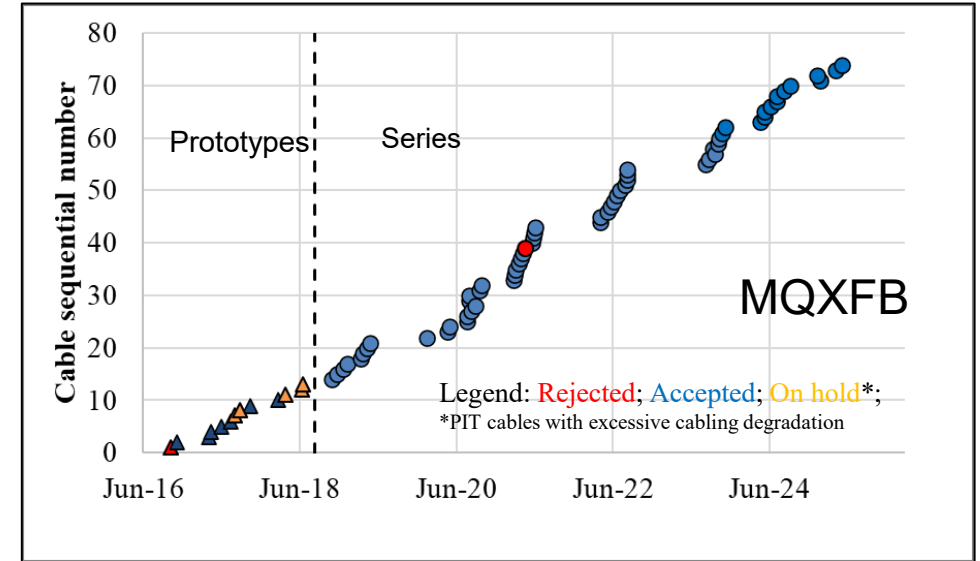
# Cable fabrication

- Cable fabrication completed, excellent yield!
  - 74 cables produced for MQXFB with only 2 rejected due to a critical NCR
  - 118 cables produced for MQXFA and only 4 rejected

MQXFB cabling team at CERN

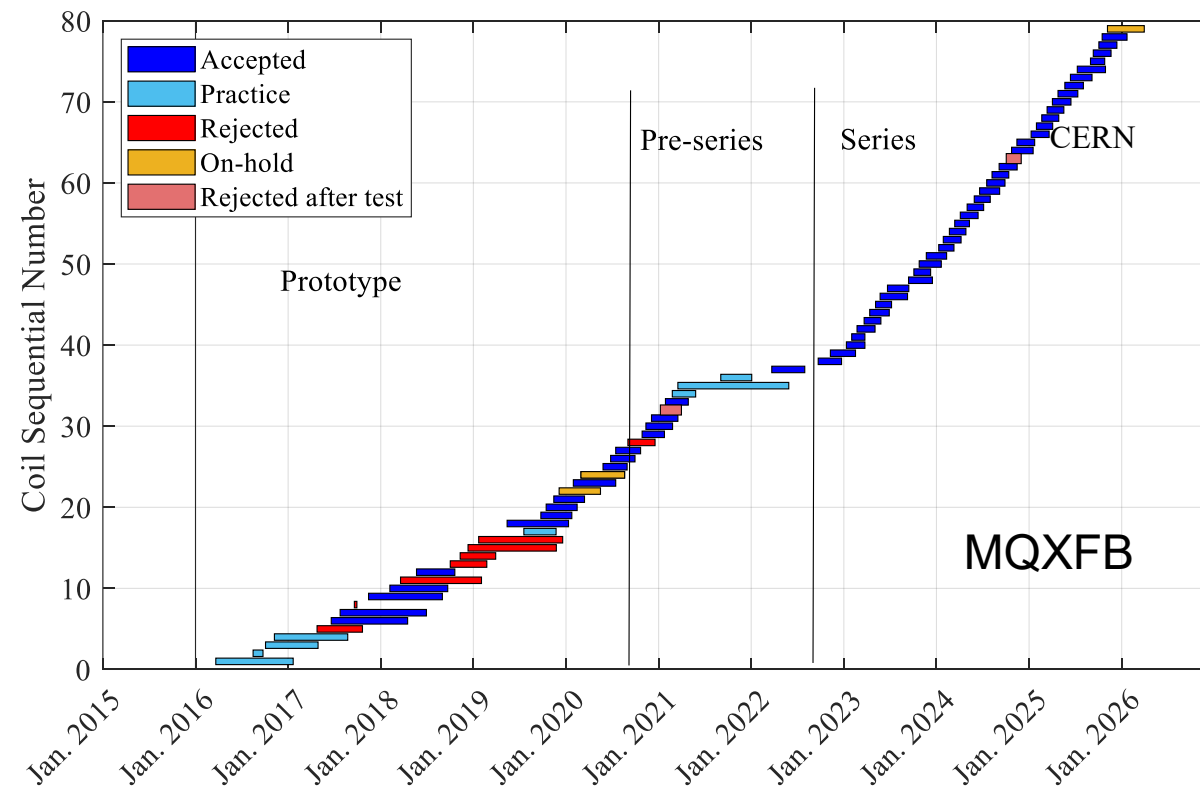
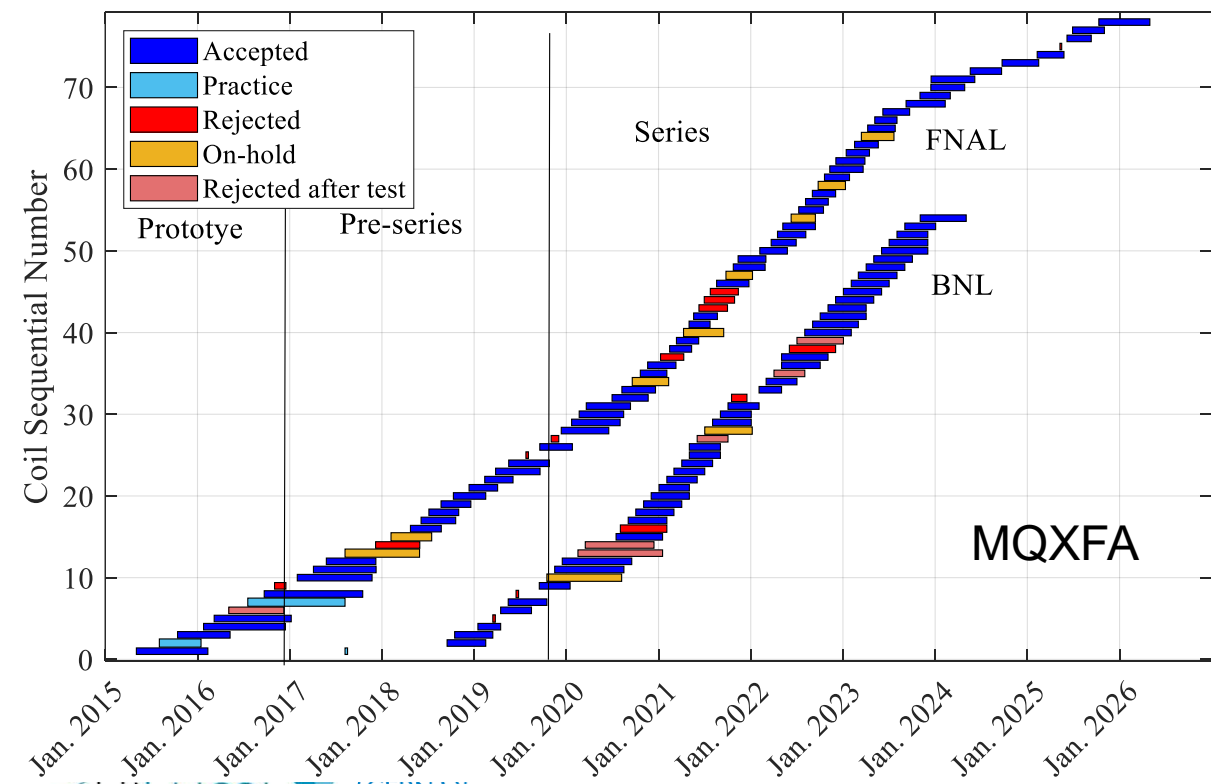


MQXFA cabling team at LBNL



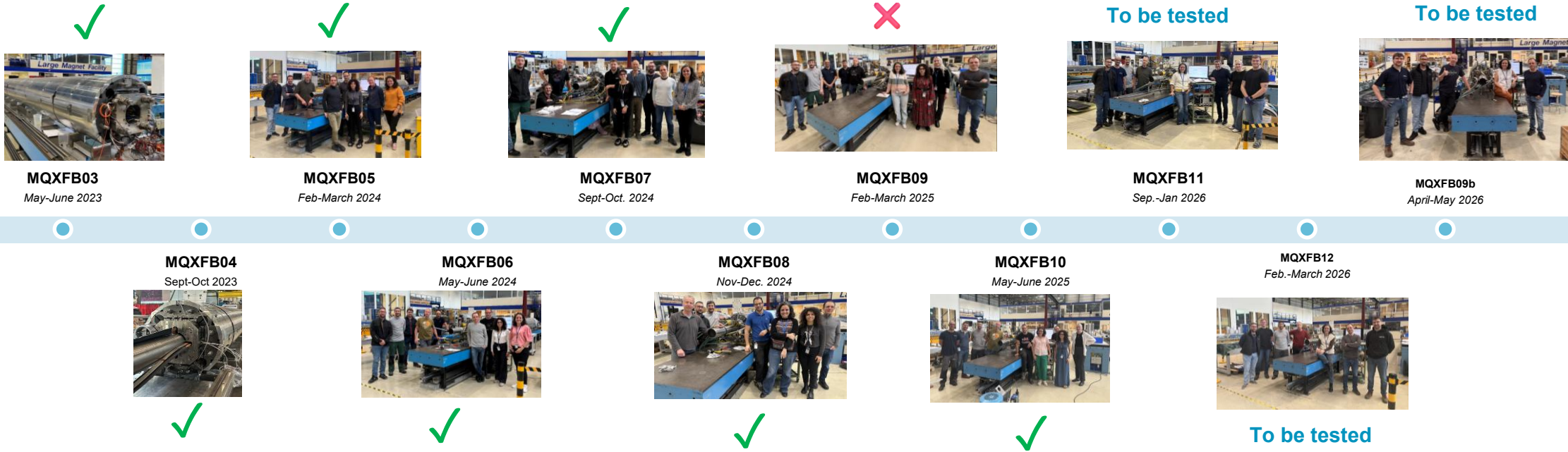
# Coil fabrication

- Including practice, prototype, and pre-series production, a total of  $\approx 120$  MQXFA coils and 80 MQXFB coils were manufactured
- The three manufacturing lines at peak production capacity had the capability to start a new coil every 3 weeks and complete a coil in approximately 3 months
- Excellent coil production yield achieved during MQXFB series production



# Magnet assembly

- For MQXFB, magnet assembly follows the 'coil clock', with one assembly line and one magnet assembled every  $\approx 3.5$  months
  - One series magnet failed during test, due to an electrical weakness (quench heater to coil short circuit)
- Very stable production, able to control assembly parameters to  $\approx 0.05$  mm level and derive coil stress based on geometrical measurements to  $\approx 10$  MPa

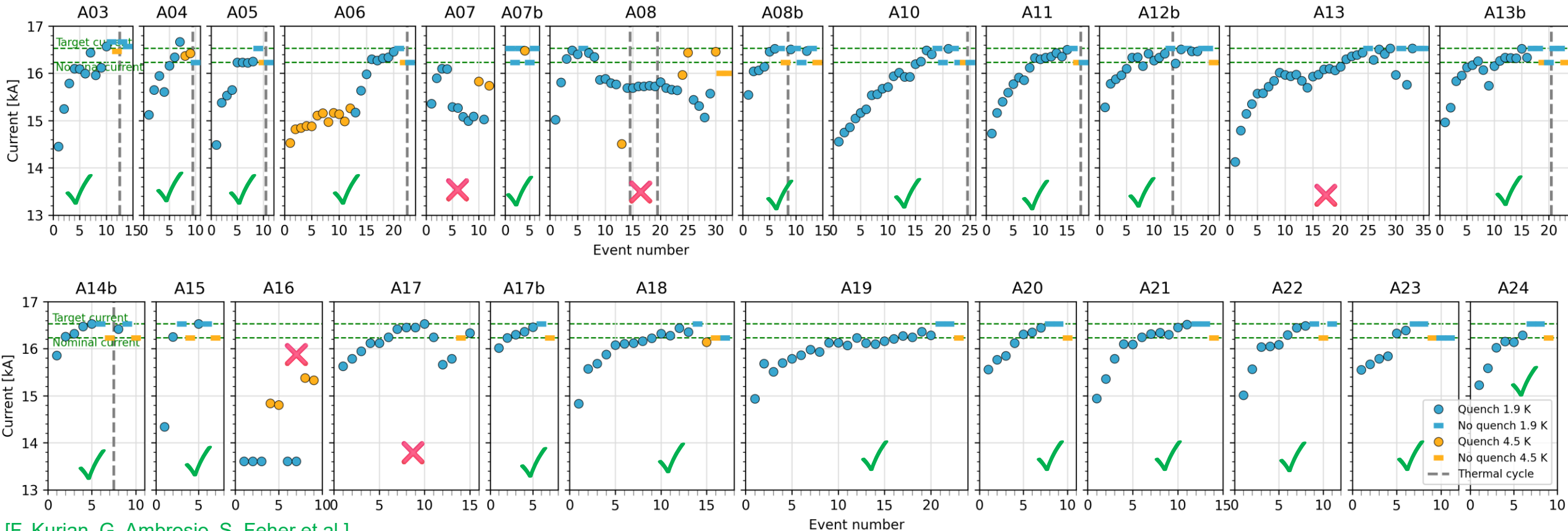


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# MQXFA – Magnet Performance

- All magnets for installation reached requirement, a major milestone 🎉
- 5 magnets did not meet requirements: the weak coil was replaced in 4 out of the 5 and the magnets were conform after coil replacement
  - The 5<sup>th</sup> magnet (MQXFA16b, spare) has been re-assembled replacing a coil, will be vertically tested at CERN

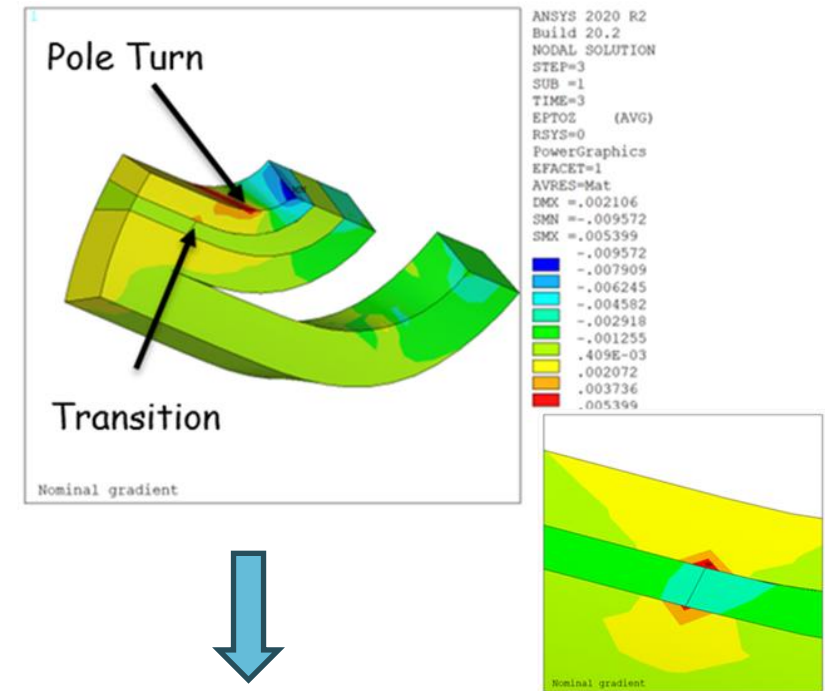


[F. Kurian, G. Ambrosio, S. Feher et al.]



# MQXFA – Axial Mechanics Challenge

- 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 which results in high axial strain in the turn close to the transition [G. Vallone et al, IEEE Appl. Sup., Vol 35, 2025](#)
- Out of spec magnets fixed with coil replacement and improved pre-load

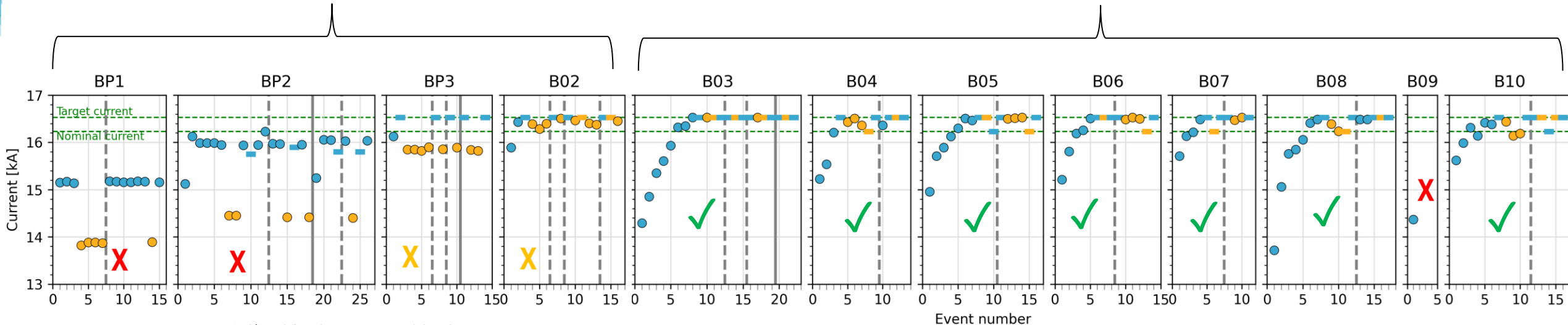


# MQXFB – Magnet Performance

- Systematic performance limitation in the prototype and pre-series magnets
  - Root cause identified and cured for series production
- All **series magnets reached requirements** with the exception of MQXFB09, due to an electrical integrity weakness (quench heater to coil short after the first quench)
  - Coil was replaced and the repaired magnet will be soon tested

## PROTOTYPE and PRE-SERIES

## SERIES



EDMS 3309905

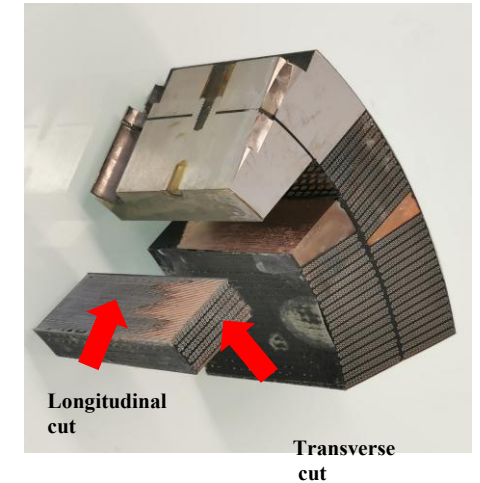
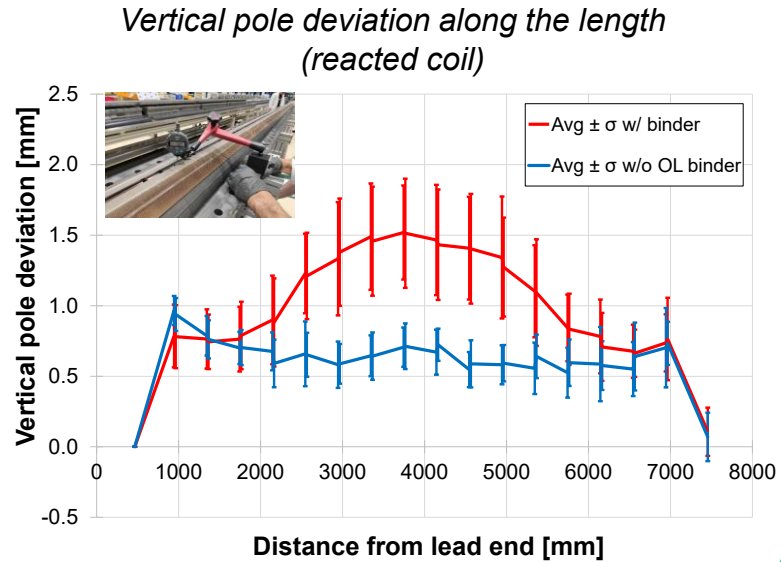
- Quench 1.9 K
- Quench 4.5 K
- No quench 1.9 K
- No quench 4.5 K
- Thermal cycle
- Cold mass change

F. Mangiarotti

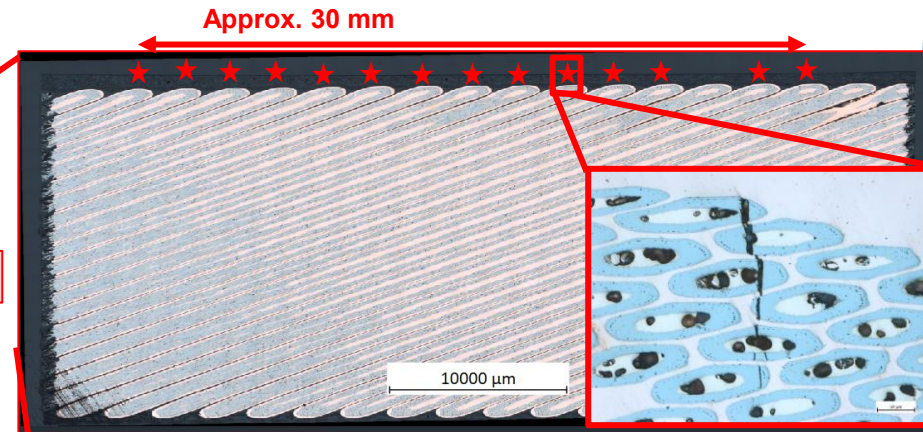
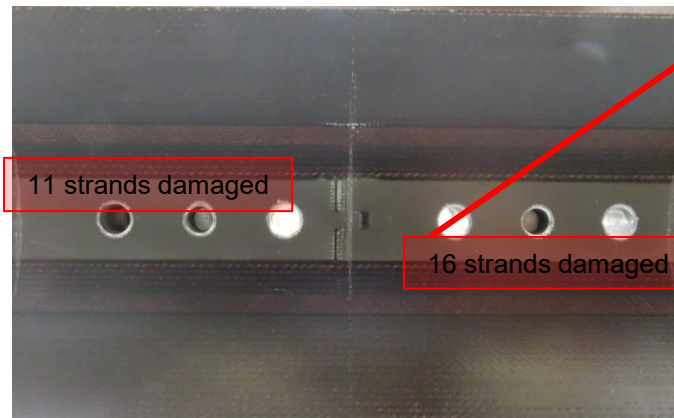
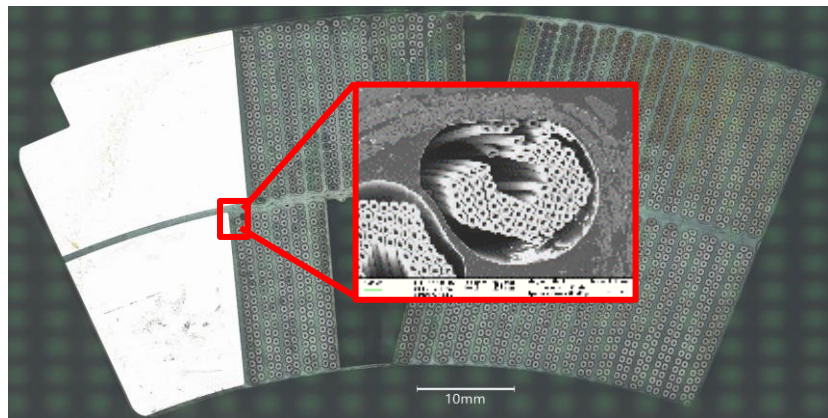


# MQXFB – Coil fabrication challenge

- 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](#)



[A. Moros et al, IEEE Vol 33, 2023](#)



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

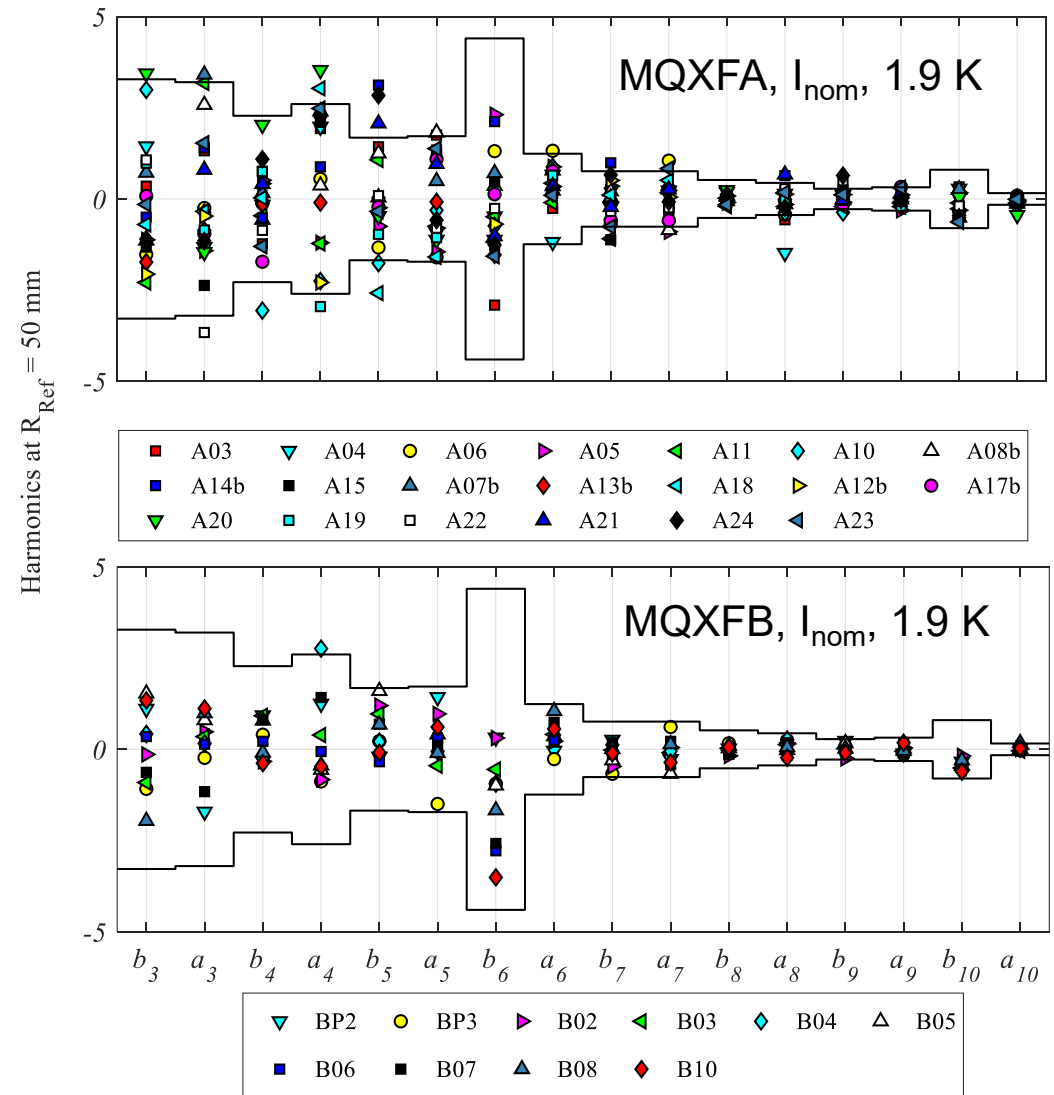
# Technology validation – prima for accelerators

- Good reproducibility on the transfer function, with good cold/warm correlation providing the capability to sort based on warm magnetic measurements
- Field errors within the requirements, and ability to correct field errors through magnetic shimming

Transfer function (T kA <sup>-1</sup> )		
	Room Temperature	1.9 K at I <sub>nom</sub>
MQXFB03	63.458	58.571
MQXFB04*	63.426	58.654
MQXFB05*	63.434	58.700
MQXFB06	63.396	58.523
MQXFB07	63.444	58.563
MQXFB08	63.470	58.594
MQXFB10	63.390	58.487
MQXFB11	63.405	--
MQXFB12	63.441	--
MQXFB09b	63.600	--
Average (B03-B12)	63.429	58.585
Range (B03-B12) (units)	13	36

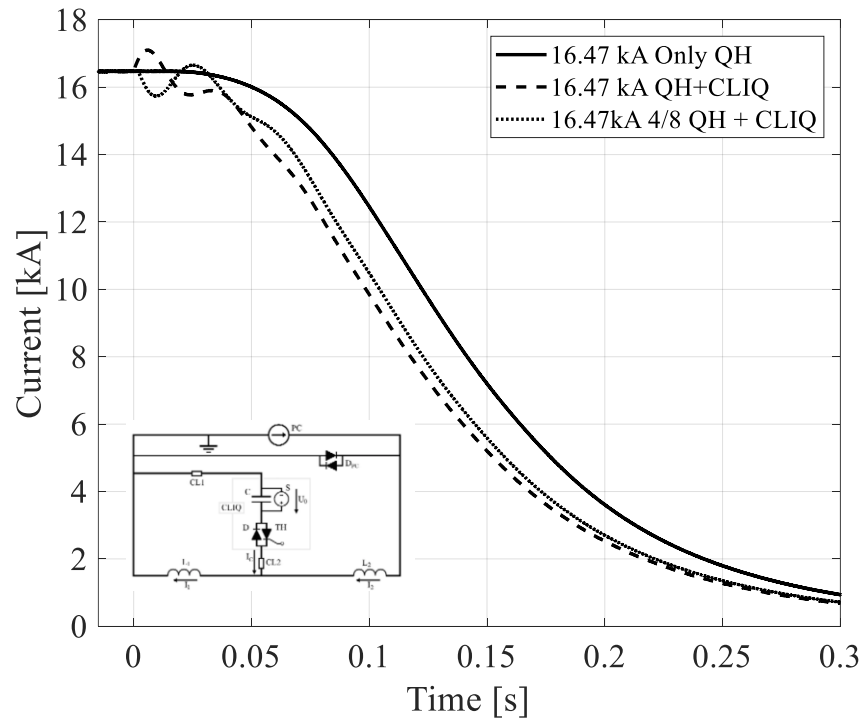
\*Magnets with magnetic shims

See M. Giovannozzi ([WEP5069](#)), M. Bonora ([MOP7083](#)) and A. Fornara ([WEP5068](#))



# Technology validation – prima for accelerators

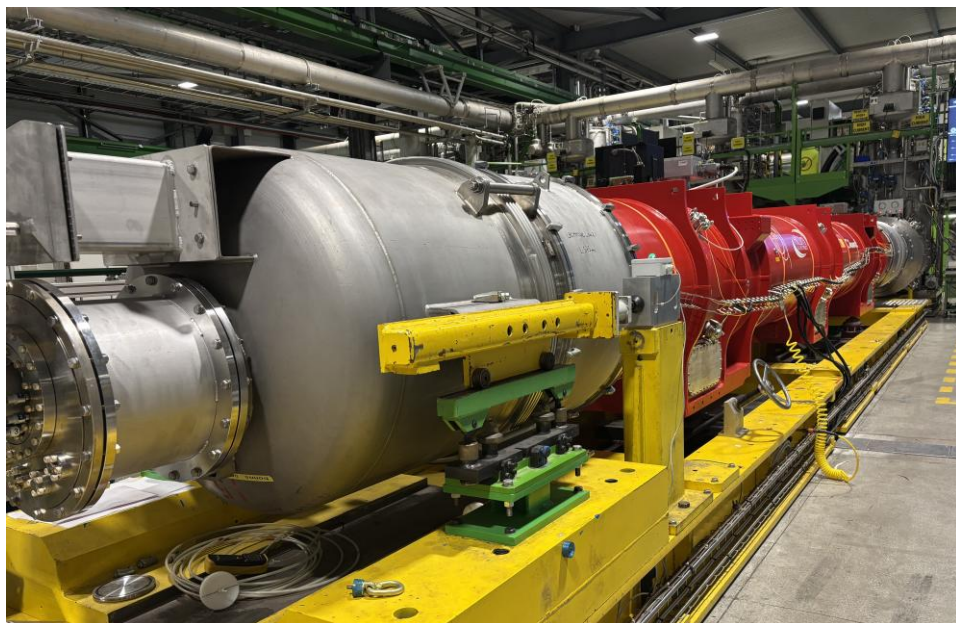
- First time implementation in an accelerator of CLIQ (Coupling Losses Induced Quench)
  - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor. The mechanism is the heating due to interfilament coupling losses induced by the variation of the field
  - In combination with QH, provides a redundant protection system. In the case of MQXF, it reduces the quench load by 20 % at high current, decreasing the hot spot temperature by ~ 100 K.



E. Ravaioli et al, [DOI 10.3990/1.9789036539081](https://doi.org/10.3990/1.9789036539081)

# Technology validation – prima for accelerators

- Stable operation and robustness demonstrated through extensive testing, with no performance degradation with current and thermal cycling



	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 $I \geq I_{nom}$
MQXFBP1	2	21	0	0	0
MQXFBP2	5	56	7	17	14
MQXFBP3	4	26	10	70	44
MQXFB02	4	43	36	508	38
MQXFB03	3	31	18	50	24
MQXFB04	2	12	7	44	28
MQXFB05	2	12	8	59	148
MQXFB06	2	10	6	54	140
MQXFB07	2	8	3	39	86
MQXFB08	2	15	8	54	137
MQXFB10	2	15	4	167	141
<b>TOTAL</b>	<b>30</b>	<b>249</b>	<b>107</b>	<b>1062</b>	<b>800</b>

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# Conclusions

- HL-LHC Nb<sub>3</sub>Sn magnet production is **approaching completion**
  - AUP: All magnets assembled; only one spare magnet remains to be vertically tested (at CERN)
  - CERN: All magnets assembled; three magnets remain to be qualified (1 for installation + 2 spares)
- Nb<sub>3</sub>Sn is today the natural reference for **future collider magnets**, and the magnets produced for the HL-LHC upgrade are the **first application** of accelerator-quality Nb<sub>3</sub>Sn magnet technology.
  - **Field quality** requirements in accelerator magnets are **reachable** with Nb<sub>3</sub>Sn
  - **Large margin in mechanics** proven for short models
  - **Large temperature margin** proven in short and long magnets (up to 2.6 K out of 5 K)
  - **Endurance** and **long-term stability** proved
- **Scaling** Nb<sub>3</sub>Sn technology **from short models to full-length** accelerator magnets was a major **challenge**, requiring the resolution of critical issues that only emerge when building longer magnets.
- **Thirty years of sustained R&D** have **matured Nb<sub>3</sub>Sn** into an industrially viable accelerator magnet technology providing a strong foundation for future collider projects and next-generation high-field magnet development