Scale up in length of Nb_3Sn 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

IPAC 2026, 19th May 2026, Deauville, Normandy

Acknowledgment

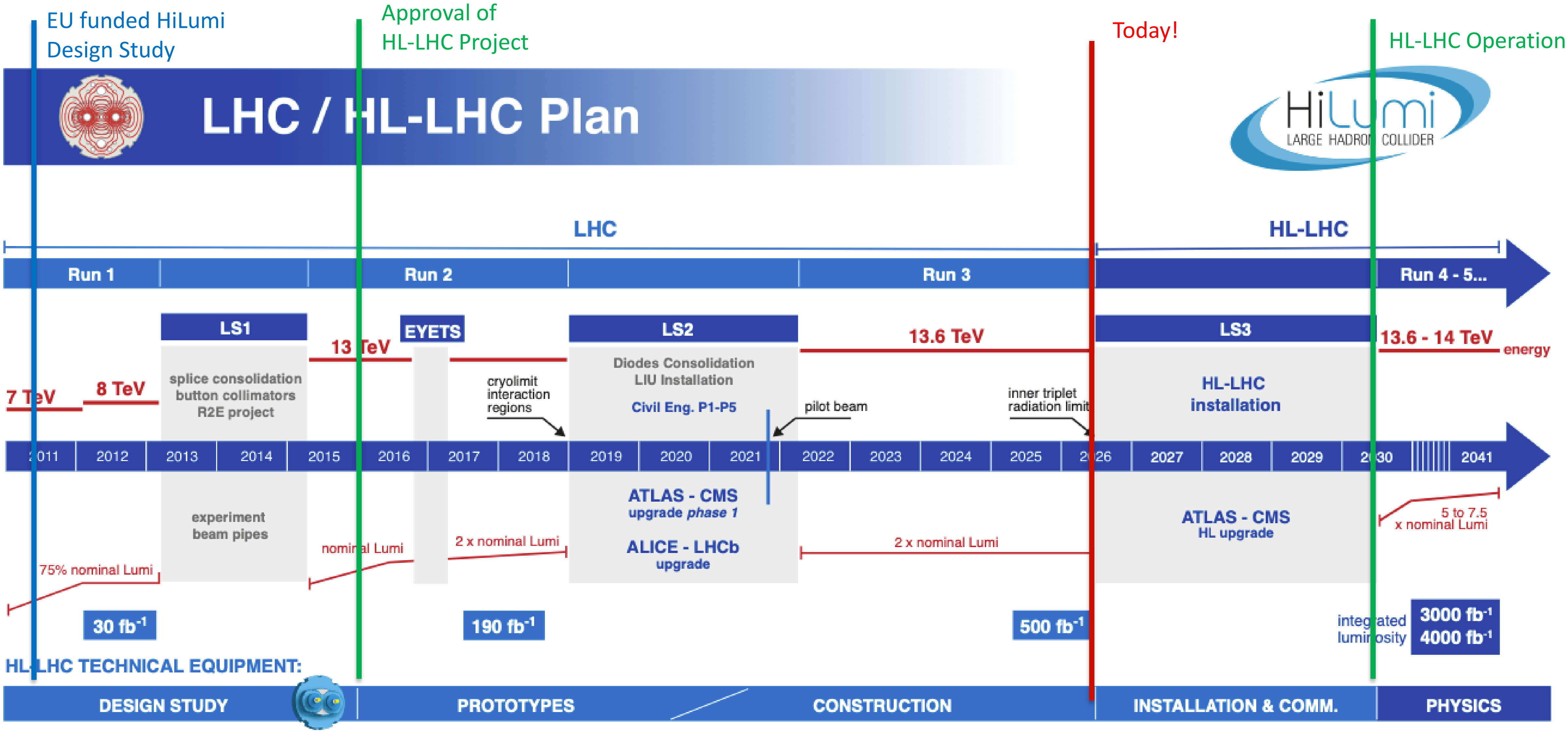
- US HL-LHC Accelerator Upgrade Project (AUP)
  - BNL: K. Amm, M. Anerella, A. Ben Yahia, H. Hocker, P. Joshi, J. Muratore, J. Schmalzle, H. Song, P. Wanderer
  - FNAL: G. Ambrosio, G. Apollinari, M. Baldini, J. Blowers, R. Bossert, R. Carcagno, G. Chlachidze, J. DiMarco, S. Feher, S. Krave, V. Lombardo, C. Narug, A. Nobrega, V. Marinozzi, C. Orozco, T. Page M. Parker, S. Stoynev, T. Strauss, M. Turenne, D. Turrioni, A. Vouris, M. Yu
  - LBNL: D. Cheng, P. Ferracin, L. Garcia Fajardo, E. Lee, M. Marchevsky, M. Naus, H. Pan, I. Pong, S. Prestemon, K. Ray, G. Sabbi, G. Vallone, X. Wang, E. Ravaioli
  - NHMFL: L. Cooley, J. Levitan, J. Lu, R. Walsh
- CERN
  - G. Arnau Izquierdo, A. Ballarino, M. Bajko, L. Baudin, C. Barth, N. Bourcey, B. Bordini, T. Boutboul, B. Bulat, M. Crouvizier, A. Devred, G. Dima, D. Duarte Ramos, J. Ferradas Troitino, S. Ferradas Troitino, L. Fiscarelli, J. Fleiter, J. Haack, S. Hopkins, K. Kandemir, M. Guinchard, J. Haack, O. Housiaux, S. Izquierdo Bermudez, N. Lusa, F. Mangiarotti, A. Milanese, A. Moros, P. Moyret, S. Mugnier, C. Petrone, J.C. Perez, H. Prin, R. Principe, K. Puthran, P. Quassolo, P. Rogacki, S. Russenschuck, T. Sahner, S. Sgobba, S. Straarup, E. Todesco, G. Willering.

HiLumi HL-LHC PROJECT
CERN

Outline

- Introduction
- Production status, with focus on the main challenges
- Overview on cold powering test results
- Summary and conclusions

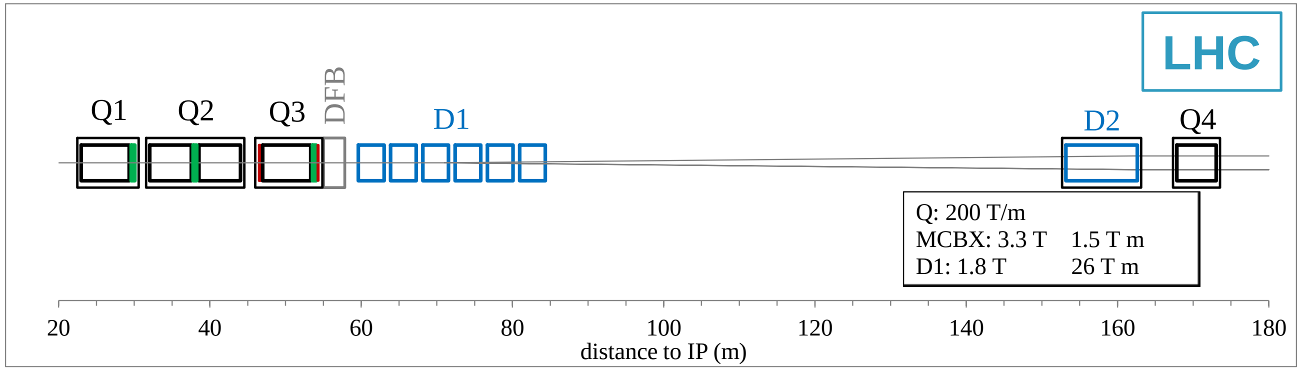
Introduction: from LHC to HL-LHC

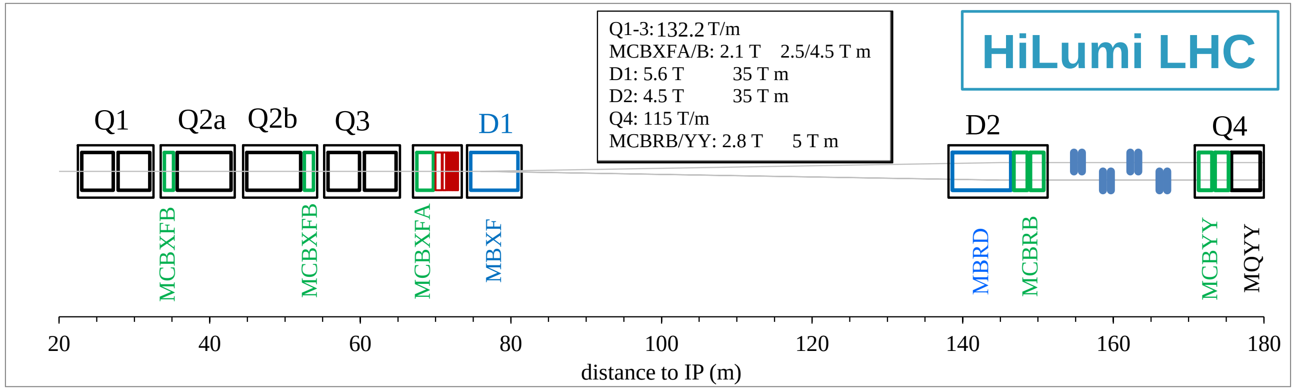


Introduction: HL-LHC Interaction region

- 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_3Sn at 11.3 T

E. Todesco





The journey of Nb_3Sn technology for HL-LHC upgrade

Approval of HL-LHC Project

CERN joins the development efforts

- MQXF T_0 = 2013: aperture and cable selection

1999 2000 2001 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

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

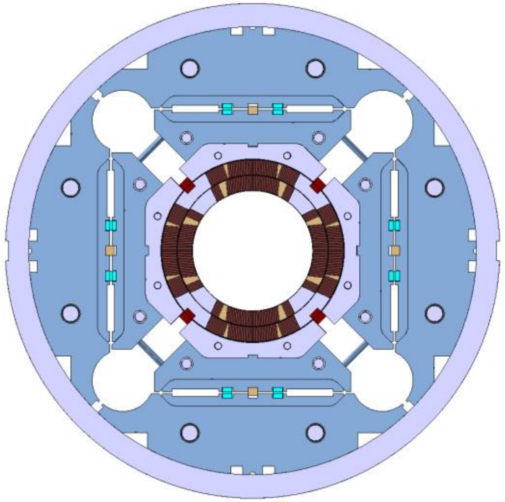
US DOE HL-LHC Accelerator Upgrade Project (AUP), coordinating efforts from US Labs (FNAL, BNL, LBNL with contributions from SLAC, JLAB, ODU & FSU) for the production and testing of the Q1/Q3 cryo-assemblies needed for the HL-LHC upgrade

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

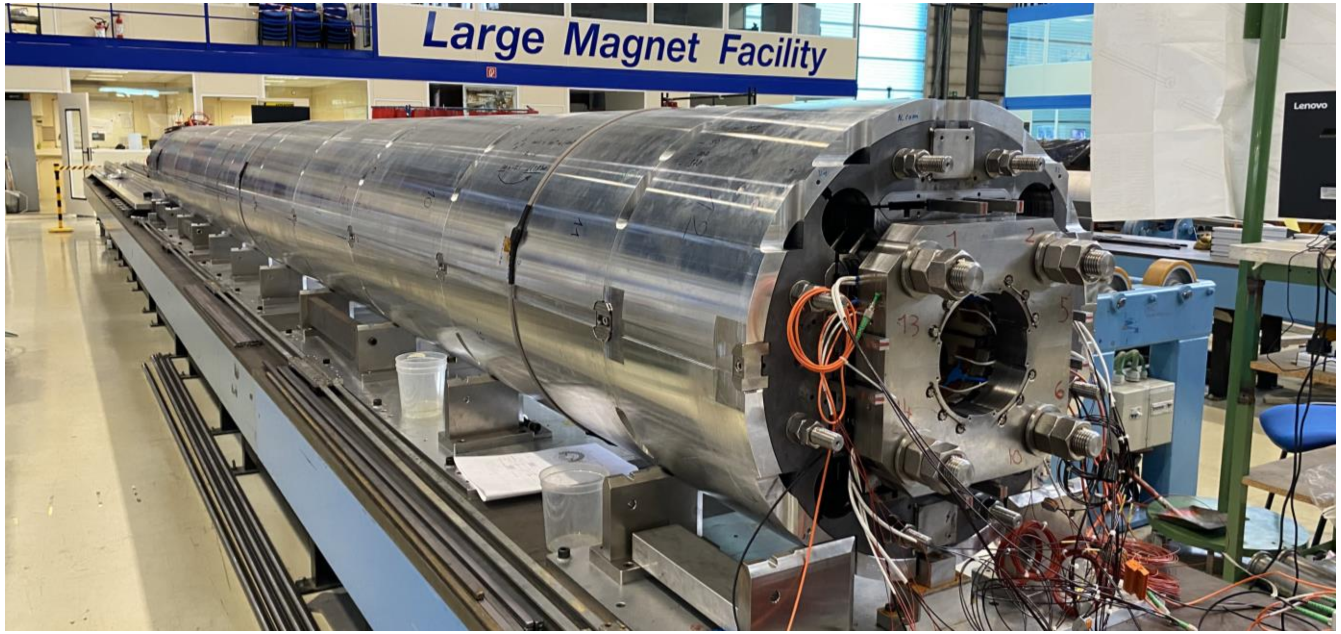
- Investigate the Potential and Challenges of Nb_3Sn Technology
- R&D Phases and main achievements from fundamental technology demonstration to accelerator quality magnets
- Bridge from proof-of-principle tests to accelerator readiness

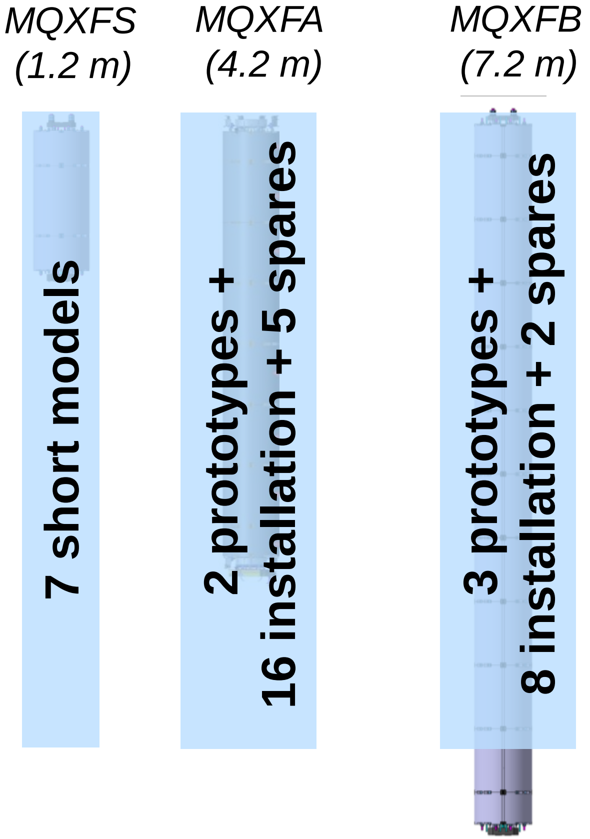
European programs for development of Nb3Sn magnet technology (NED and EUCARD)

HL-LHC low-β quadrupole MQXF

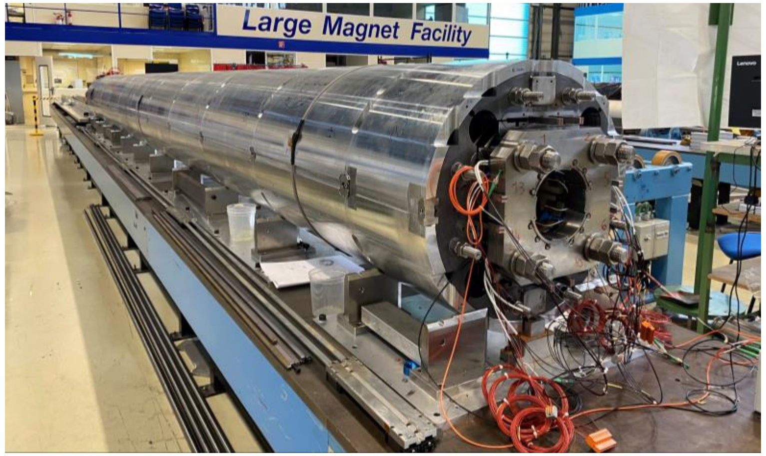


- Nominal operation (7 TeV): 16.23 kA, 132.2 T/m; 11.3 T B_{peak}
- Q1/Q3 (by US-AUP Project), 2 magnets MQXFA with 4.2 m L_m
- Q2a/Q2b (by CERN), 1 magnet MQXFB with 7.2 m L_m
- Joint short model development program (MQXFS) to validate the design
- Different lengths, same design, very similar manufacturing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





MQXF main milestones



First MQXFS magnet tested (2016)

MQXFBP1: First MQXFB prototype magnet tested (nonconform) (2020)

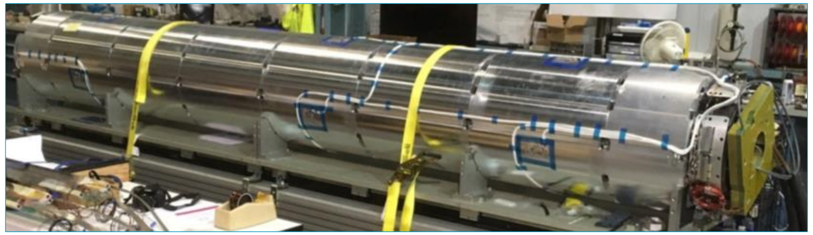
MQXFB03: First MQXFB magnet with no sign of conductor limitation (T_0 + 10) (2023)

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

T_0 = aperture and cable selection (2013)

MQXFA3: First MQXFA conform magnet (T_0 + 6) (2019)

MQXFAP1: First MQXFA prototype magnet tested (nonconform) (2017)



Today:

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

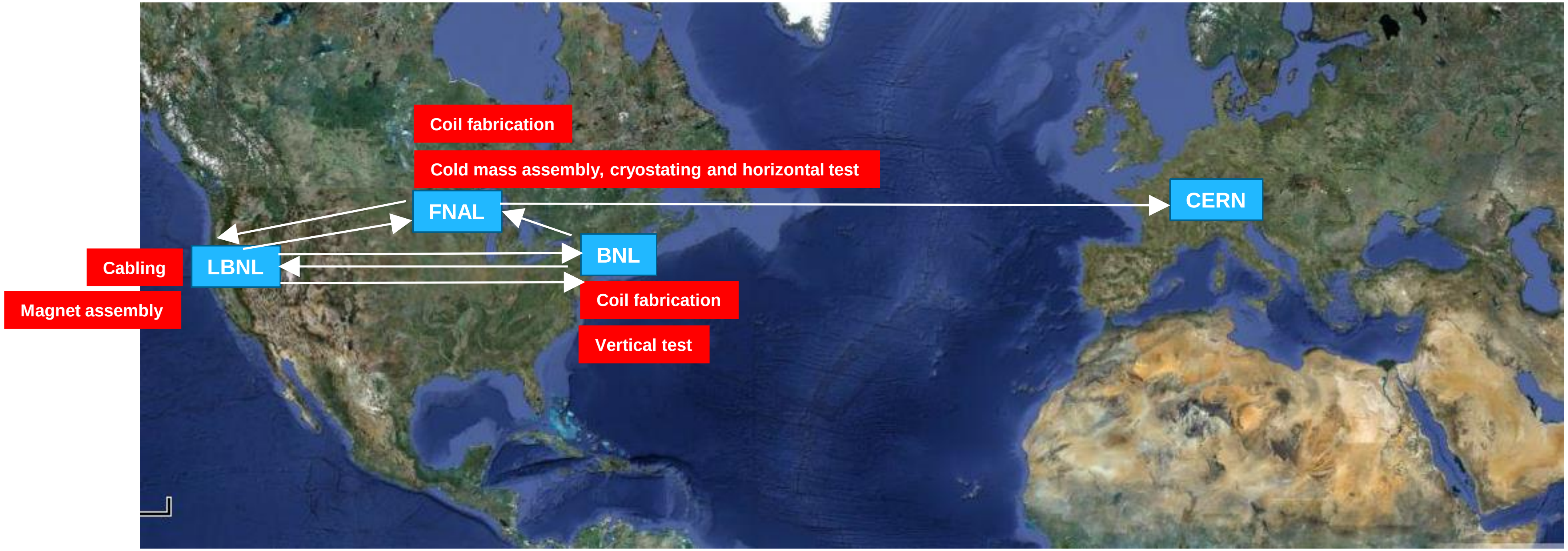
Focus of this talk: series production and main encountered challenges

Outline

- Introduction
- Production status, with focus on the main challenges
- Overview on cold powering test results
- Summary and conclusions

Series production strategy

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



MQXFB: Production status

- MQXFB coil and magnet fabrication is now completed
  - 1 more magnet for installation needs to be tested, plus the two spares

Coil										
Magnet										
Cold mass										
Cryost. Ph.1										
Test	MQXFB03	MQXFB04	MQXFB05	MQXFB06	MQXFB07	MQXFB08	MQXFB09b	MQXFB10	MQXFB11	MQXFB12
Cryost. Ph.2										

Completed
Ongoing
To-do

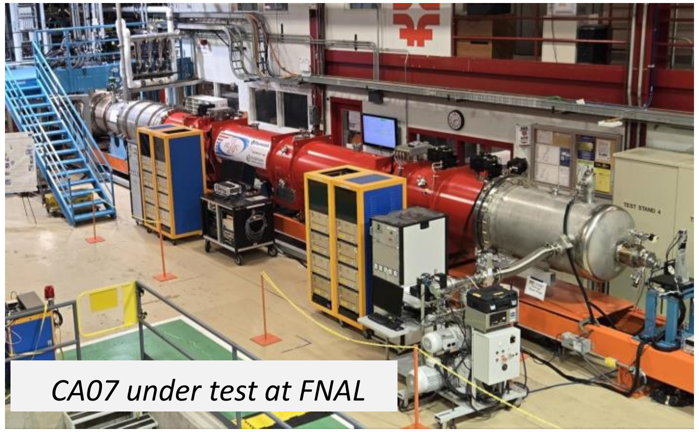
Grey indicates spares

MQXFA: Production status

- MQXFA coil and magnet fabrication is now completed
  - 1 more magnet (spare) needs to be qualified
- After magnet qualification during vertical tests, magnets need to be integrated in cold masses: 4 out of the 8 cryo-assemblies for installation are now qualified, and the construction of the remaining units is ongoing

LBNL team with MQXFA24

Cold mass and cryostating assembly area in FNAL



CA07 under test at FNAL

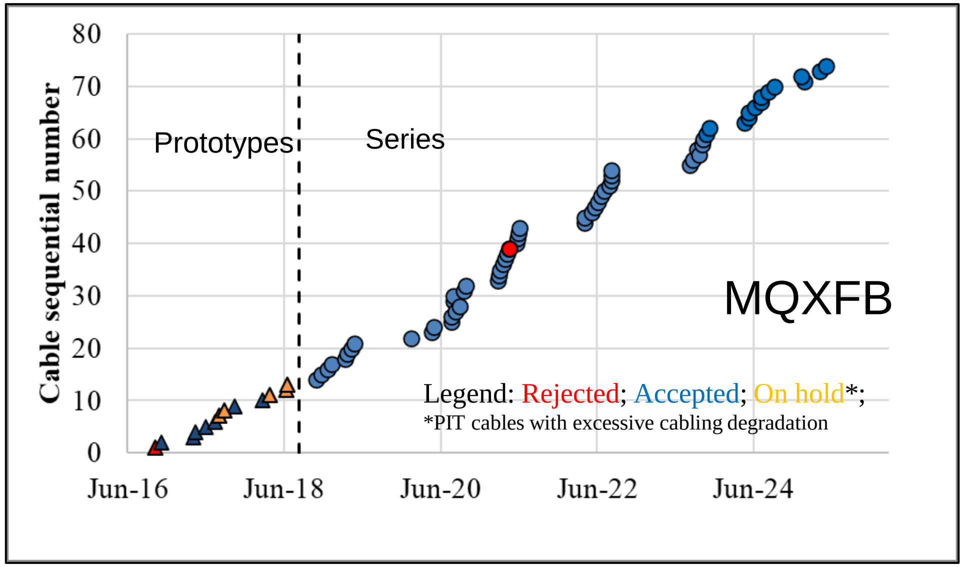
Coil FNAL																					
Coil BNL																					
Magnet assembly	3	4	5	6	10	11	14b	8b	7b	15	13b	18	12b	17b	19	20	21	22	23	24	16b
V test (BNL)																					
cold mass	LQXFA01		LQXFA02		LQXFA03		LQXFA04		LQXFA05		LQXFA06		LQXFA07		LQXFA08		LQXFA09		LQXFA10		
Cryost. Ph.1																					
H test																					
Cryost. Ph.2																					

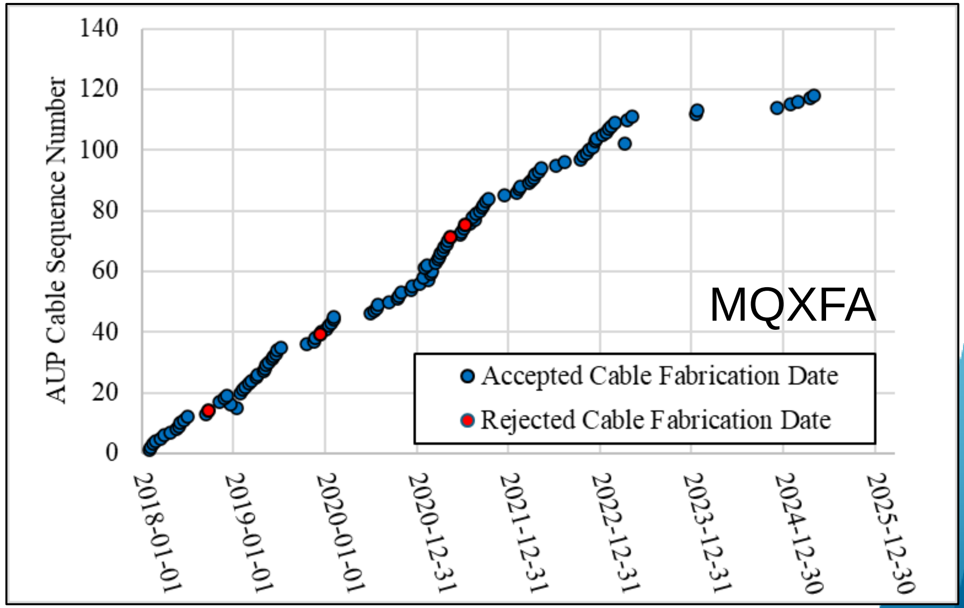
Cable fabrication

- 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

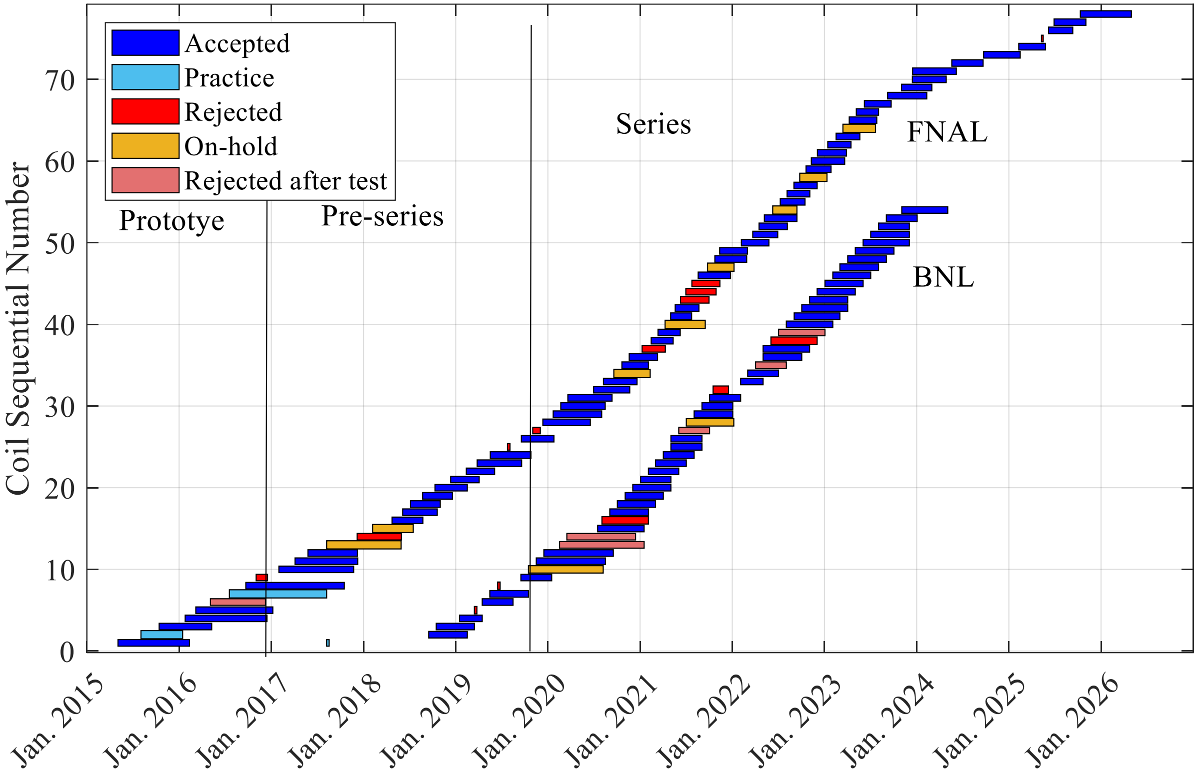
MQXFA cabling team at LBNL

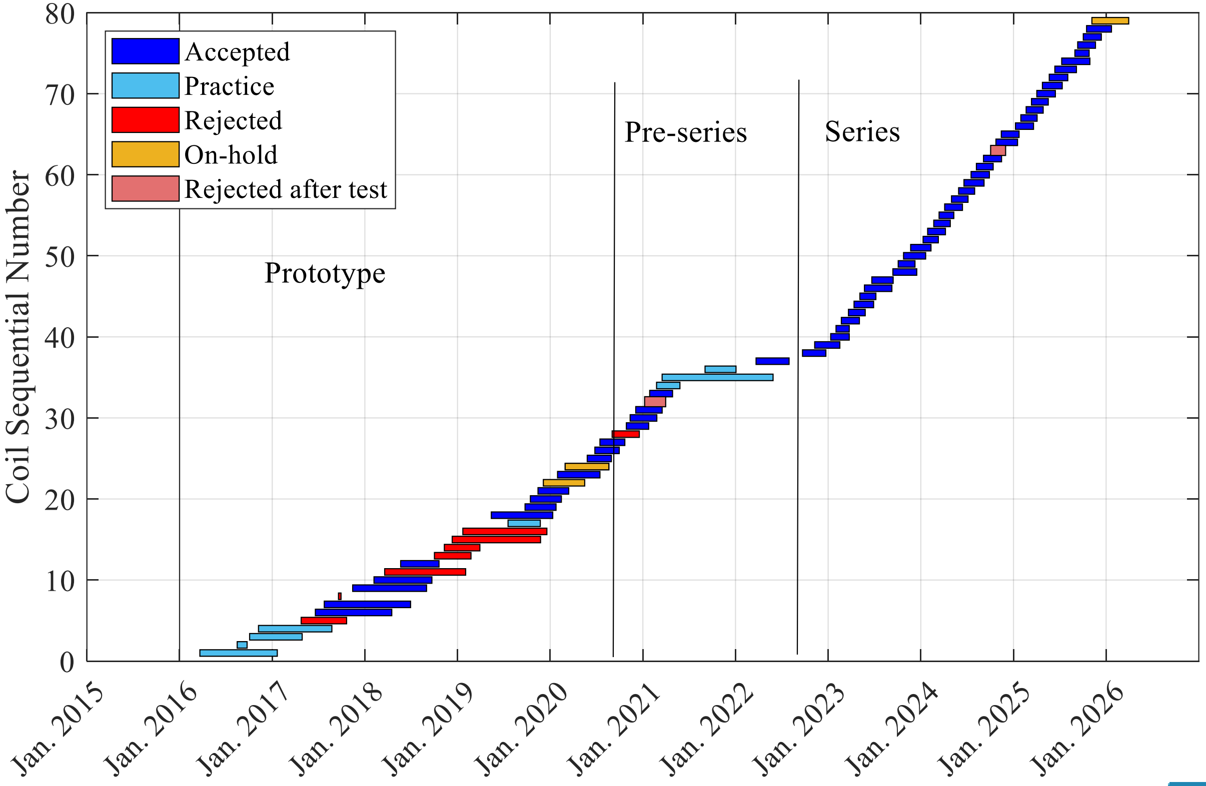




Coil fabrication

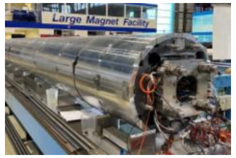
- Including practice, prototype, and pre-series production, a total of ≈ 120 MQXFA coils and 80 MQXFB coils were manufactured
- The three manufacturing lines at peak production capacity had the capability to start a new coil every 3 weeks and complete a coil in approximately 3 months
- Excellent coil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



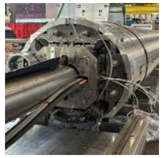


Magnet assembly

- For MQXFB, magnet assembly follows the ‘coil clock’, with one assembly line and one magnet assembled every ≈ 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 ≈ 0.05 mm level and derive coil stress based on geometrical measurements to ≈ 10 MPa

✓


MQXFB03
May-June 2023

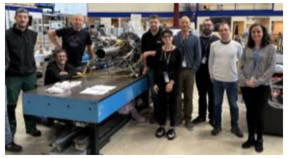
MQXFB04
Sept-Oct 2023

✓

✓

MQXFB05
Feb-March 2024

MQXFB06
May-June 2024

✓

✓

MQXFB07
Sept-Oct. 2024

MQXFB08
Nov-Dec. 2024

✓

✗

MQXFB09
Feb-March 2025

MQXFB10
May-June 2025

✓

To be tested

MQXFB11
Sep.-Jan 2026

MQXFB12
Feb.-March 2026

To be tested

To be tested

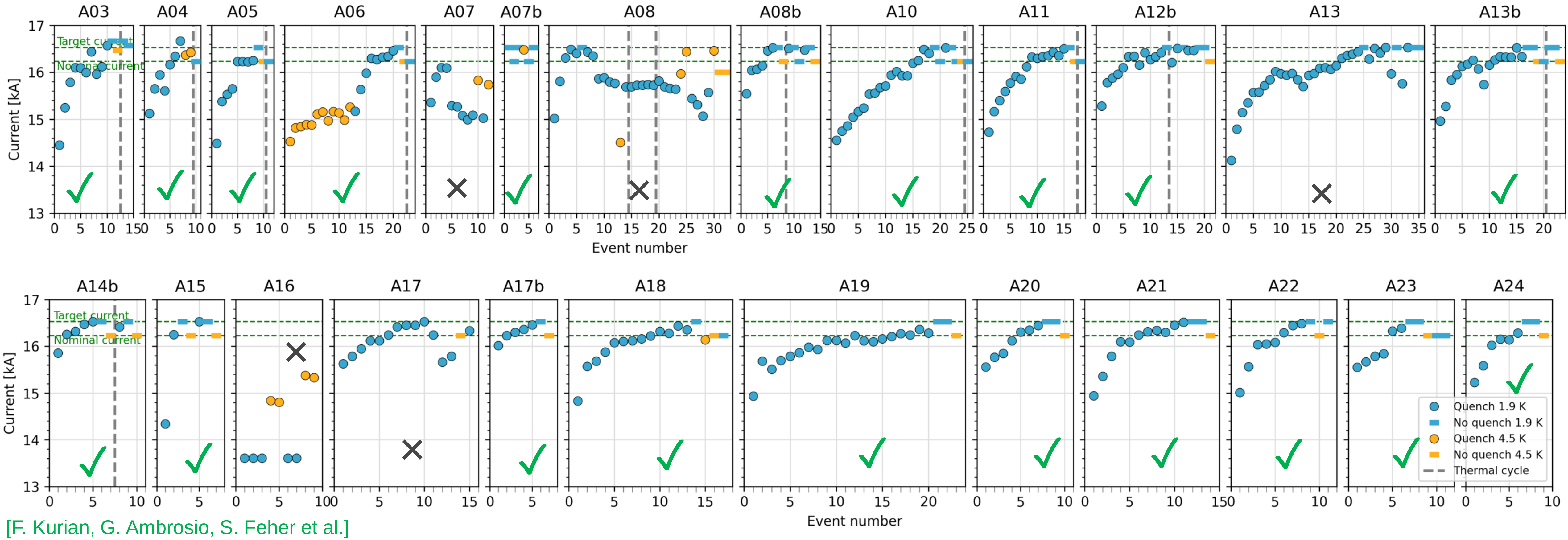
MQXFB09b
April-May 2026

Outline

- Introduction
- Production status, with focus on the main challenges
- **Overview on cold powering test results**
- Summary and conclusions

MQXFA – Magnet Performance

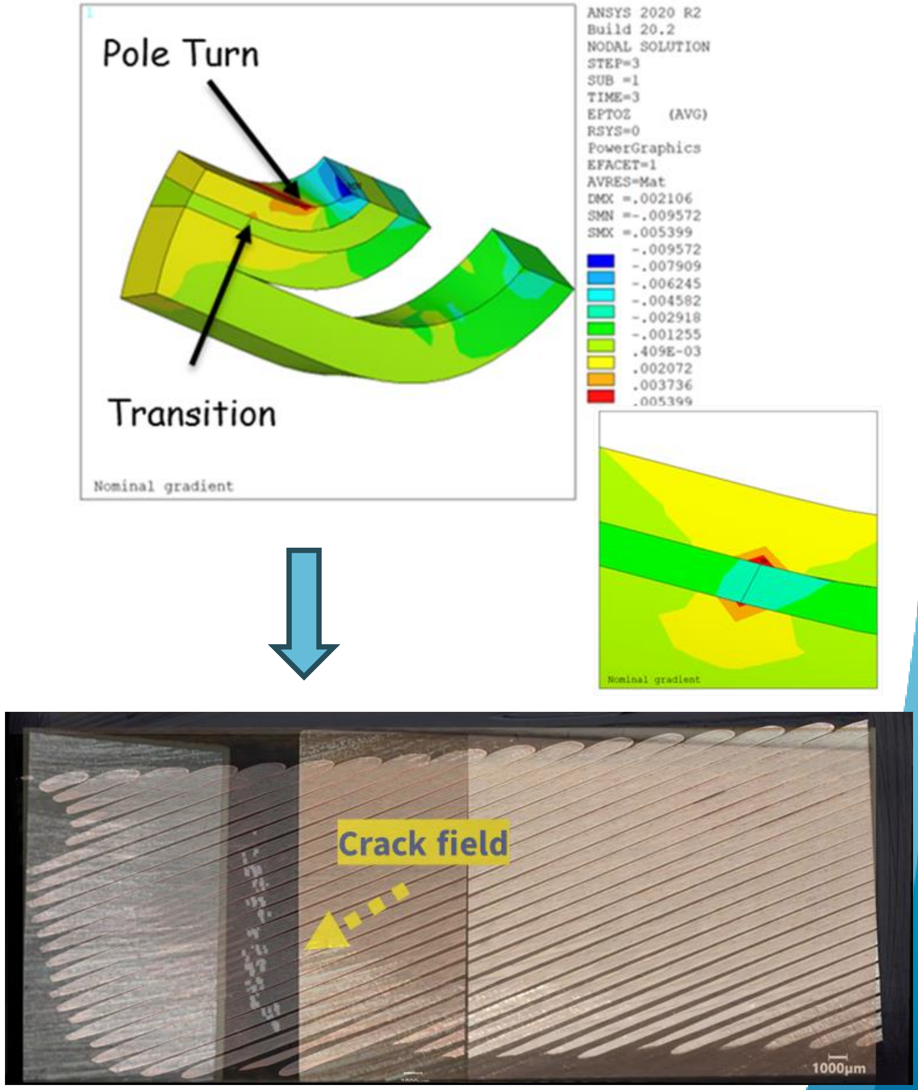
- All magnet for installation reached requirement, a major milestone 🎉
- 5 magnets did not meet requirements: the weak coil was replaced in 4 out of the 5 and the magnets were conform after coil replacement
  - The 5th magnet (MQXFA16b, spare) has been re-assembled replacing a coil, will be vertically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



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

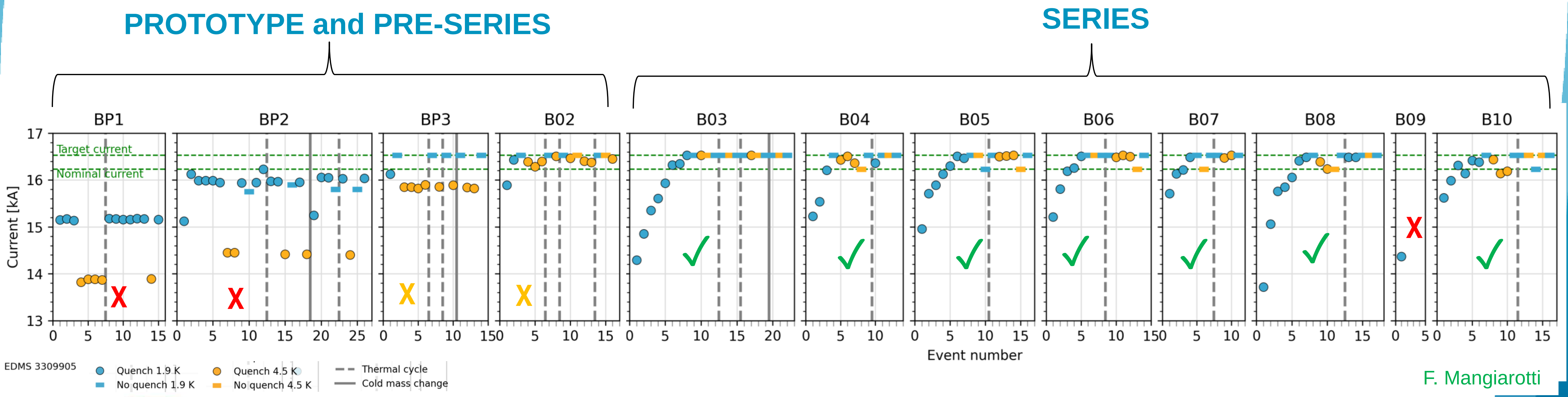
MQXFA – Axial Mechanics Challenge

- 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 caused by 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

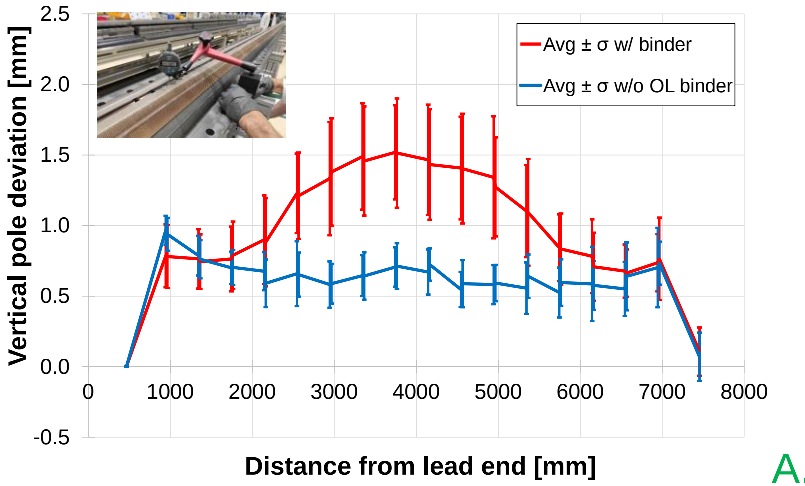


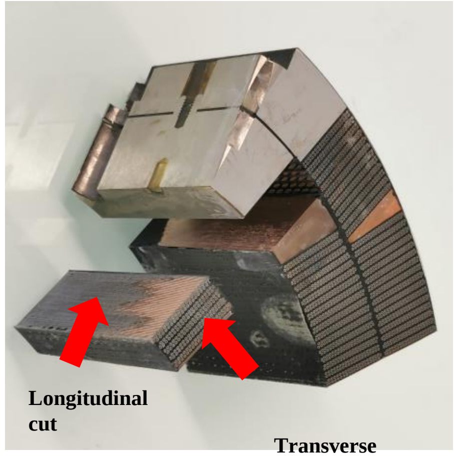
F. Mangiarotti

MQXFB – Coil fabrication challenge

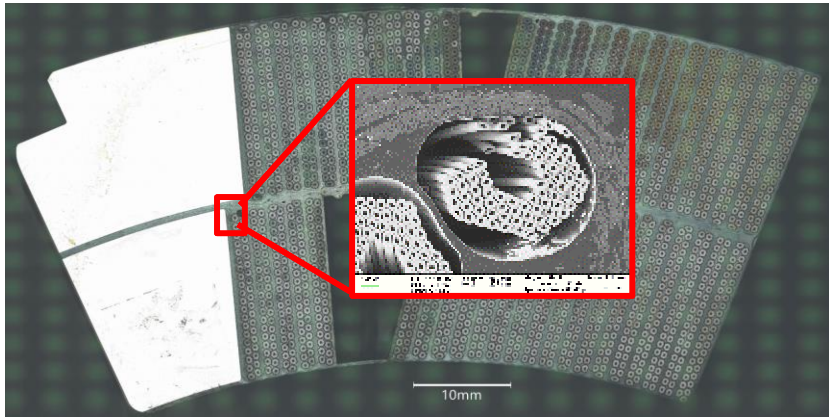
- MQXFB prototype magnets were limited, due to conductor damage in the pole-to-pole transition S. Izquierdo Bermudez et al, IEEE, vol 33, 2023
- Root cause was coil fabrication, mitigated by removing the ceramic binder in the outer layer to reduce longitudinal, radial and azimuthal friction between coil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

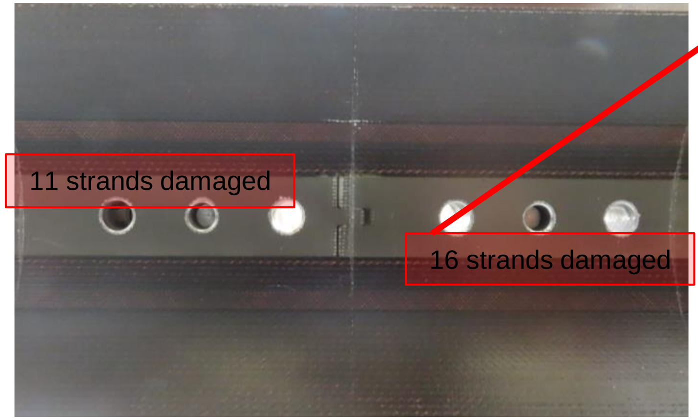
Vertical pole deviation along the length (reacted coil)

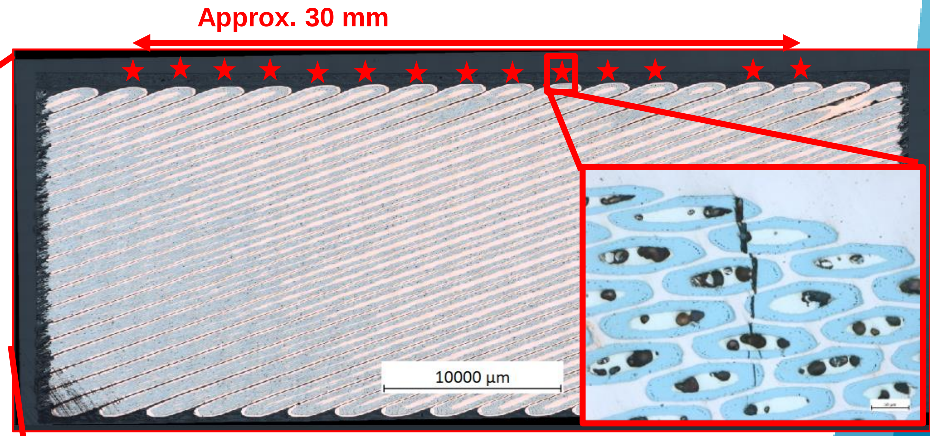


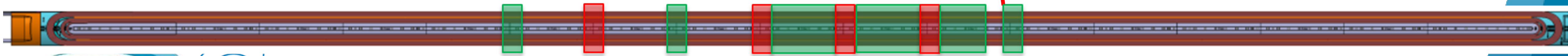


A. Moros et al, IEEE Vol 33, 2023









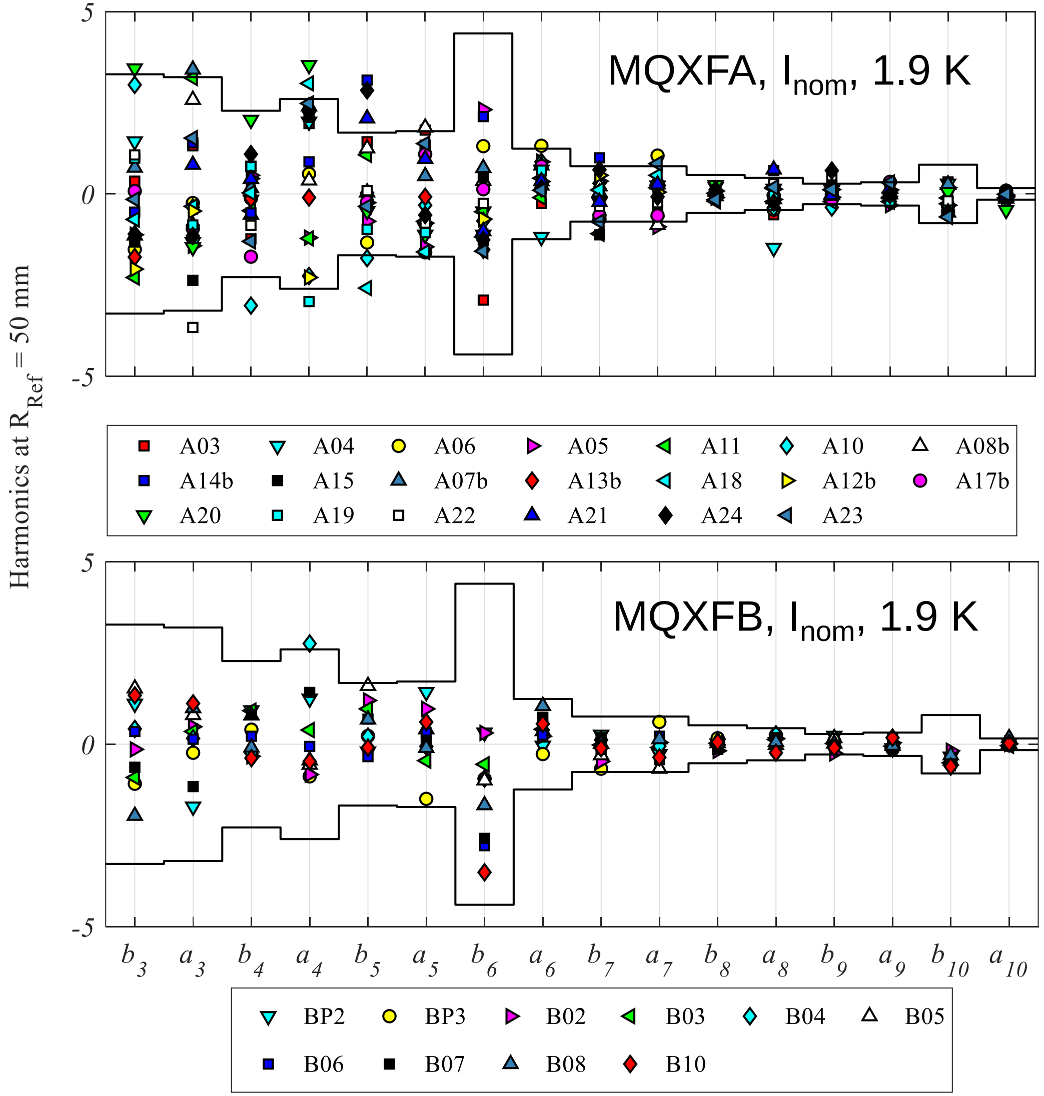
20 slices 50 mm length,
damage only in the slices around transitions

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^{-1})		
	Room Temperature	1.9 K at I_{nom}
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

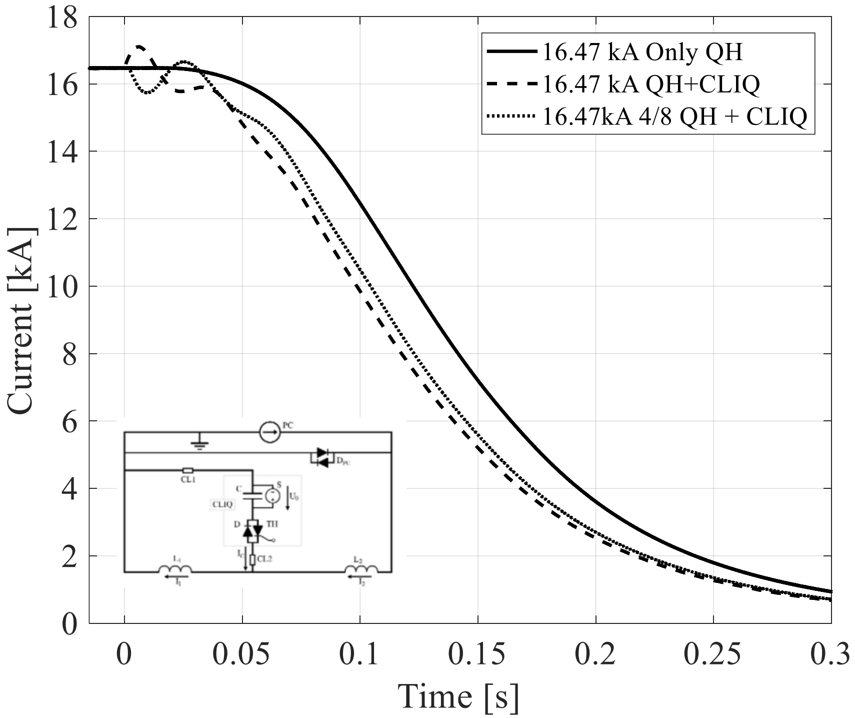
*Magnets with magnetic shims



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

Technology validation – prima for accelerators

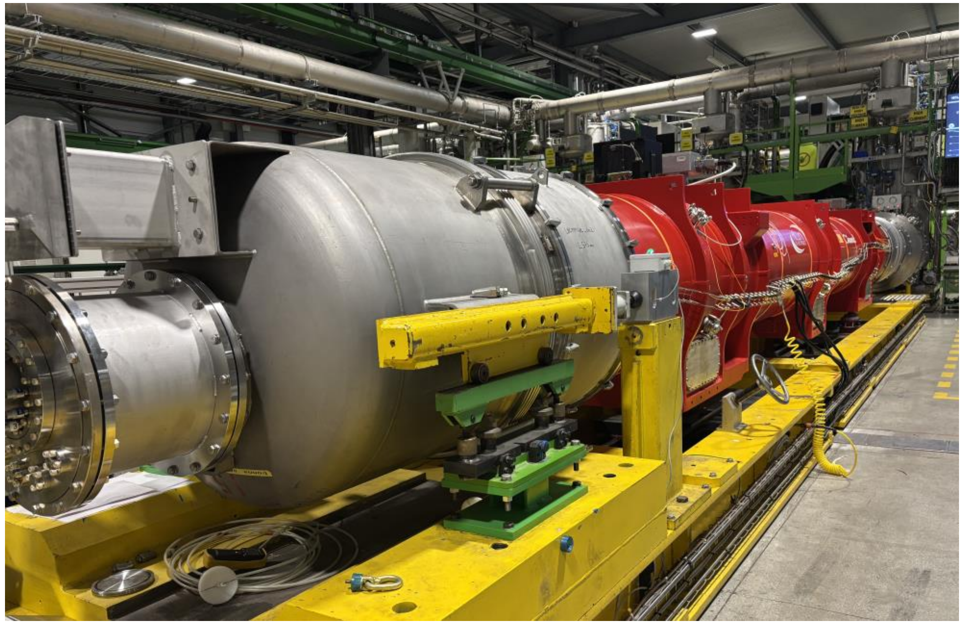
- First time implementation in an accelerator of CLIQ (Coupling Losses Induced Quench)
  - This system is based on injecting in the magnet coils two opposite impulses of current via a capacitor. The mechanism is the heating due to interfilament coupling losses induced by the variation of the field
  - 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

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 ≥ 0.8Inom	Number of quenches at I ≥ Inom	Number of cycles to ≥ Inom	Time [h] at I ≥ Inom
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
TOTAL	**30**	**249**	**107**	**1062**	**800**

Outline

- Introduction
- Production status, with focus on the main challenges
- Overview on cold powering test results
- **Summary and conclusions**

Conclusions

- HL-LHC Nb_3Sn 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_3Sn 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_3Sn magnet technology.
  - Field quality requirements in accelerator magnets are reachable with Nb_3Sn
  - 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_3Sn 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_3Sn into an industrially viable accelerator magnet technology providing a strong foundation for future collider projects and next-generation high-field magnet development