



Status of MQXFA magnets

*Giorgio Ambrosio - FNAL
with contributions from the
whole MQXFA team*



HIGH LUMINOSITY LHC

th

HL-LHC COLLABORATION MEETING

GENOA, ITALY, 7-10 October 2024

Jointly organised by **INFN** and **CERN**, the **14th HL-LHC Collaboration Meeting** will take place in person in **Genoa, Italy** from **7th to 10th October 2024**. This edition will provide the occasion to showcase the successful production and validation of the first series D2 magnets, produced by ASG in Genoa as an in-kind contribution

by INFN (Italy), as well as the completion of production of the MgB₂ wires for the superconducting link by ASG.

Based on the traditional programme with plenary and work package parallel sessions, this meeting will serve as a technical update forum for the 8th Cost and Schedule Review, scheduled for

11th to 14th November 2024. The main objectives will be to update all HiLumi collaborators on the advancement of the series production of components for the project, to showcase the status of the IT String test stand installation at CERN, and to update all collaborators on the latest schedule changes.



CERN – Organizing Committee

Oliver Brünning - Project Leader
Markus Zerlauth - Deputy Project Leader
Cécile Noels - Project Office & Communications
Florence Thompson - Project Office & Communications

INFN – Local Organizing Committee

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Barbara Caffi - MBRD Deputy Technical Coordinator
Mirko Corcos - IT Manager
Stefania Farion - MBRD Technical Coordinator
Filippo Levi - Deputy Conference Coordinator
Alessandra Pampaloni - Conference Coordinator
Marco Statera - HQ Connector Technical Coordinator

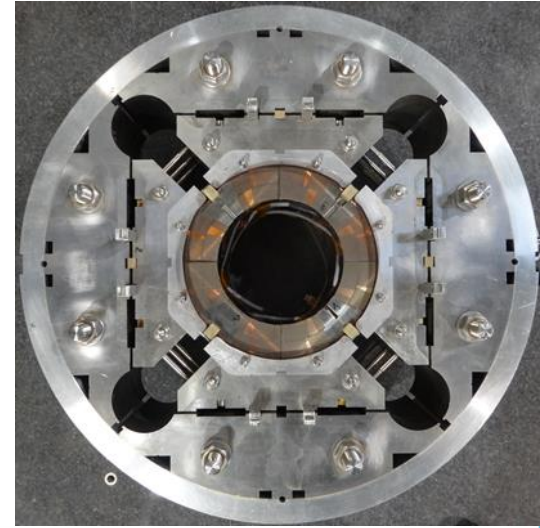
Acknowledgement

- **US HL-LHC Accelerator Upgrade Project (AUP)**
 - **BNL:** K. Amm, M. Anerella, A. Ben Yahia, M. Bornstein, H. Hocker, P. Joshi, F. Kurian, J. Muratore, J. Schmalzle, 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, J. Seyl, S. Stoynev, T. Strauss, M. Turenne, D. Turrioni, A. Vouris, M. Yu
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 - **NHMFL:** L. Cooley, J. Levitan, J. Lu, R. Walsh
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 - G. Arnau Izquierdo, A. Ballarino, M. Bajko, C. Barth, N. Bourcey, B. Bulat, M. Cruovizier, A. Devred, H. Felice, S. Ferradas Troitino, L. Fiscarelli, J. Fleiter, M. Guinchard, O. Housiaux, S. Izquierdo Bermudez, N. Lusa, F. Mangiarotti, A. Milanese, A. Moros, P. Moyret, C. Petrone, J.C. Perez, H. Prin, R. Principe, E. Ravaioli, T. Sahner, S. Sgobba, P. Tavares Coutinho Borges De Sousa, E. Todesco, J. Ferradas Troitino, R. Van Weelderren, G. Willering

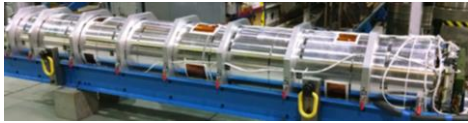
MQXFA (AUP 302.2) Deliverables

■ 21 Magnets

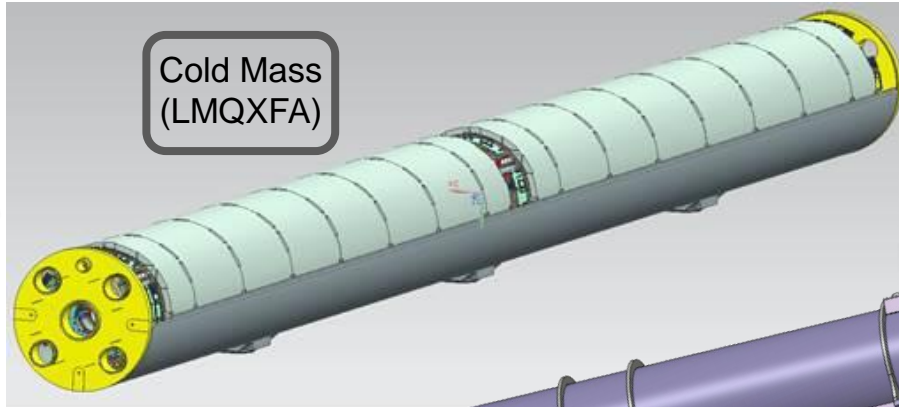
- 20 magnets for 10 Q1/Q3 cryo-assemblies
 - 2 magnets in each cryo-assembly
- 1 magnet to CERN for acceptance of CA01
- Assuming 6 re-assemblies
 - = post test re-work



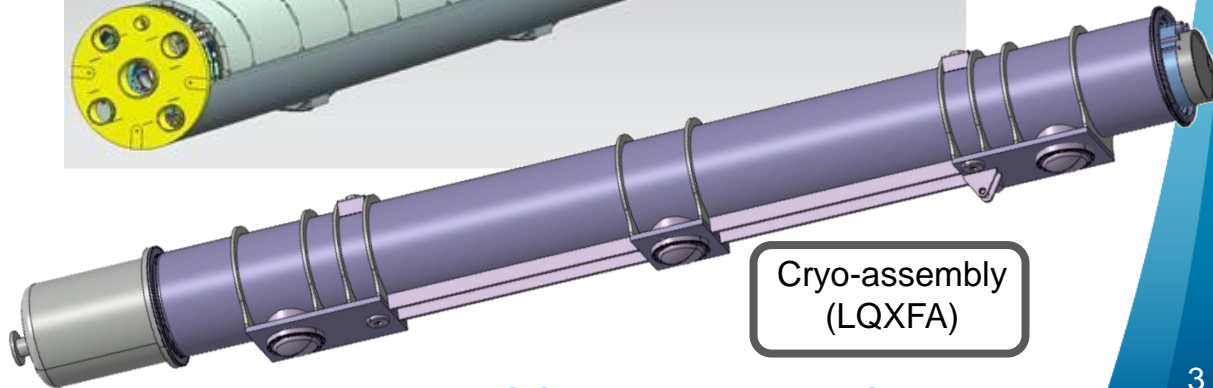
Magnet
(MQXFA)



Cold Mass
(LMQXFA)



Cryo-assembly
(LQXFA)



MQXFA Status Summary

Control Account	Component status wrt Baseline*	Comments
Strand procurement & QC (FNAL, FSU)	96% complete	Procuring spare cond.
Cable fabrication & insulation (LBNL)	100% complete	
Coil part procurement (FNAL)	~100% complete	Completing QC
Coil fabrication (FNAL)	98% complete	Last coil fabrication
Coil fabrication (BNL)	100% complete	
Magnet part procurement (LBNL)	100% complete	
Magnet assembly (LBNL)	58% complete	

*Will change if additional cables/coils are added to Baseline

➔ Main task is magnet assembly.

Supported by 4 reviews / meetings per magnet

More details in “MQXFA Fabrication Status and schedule” in **WP3 MQXF** session Wed PM

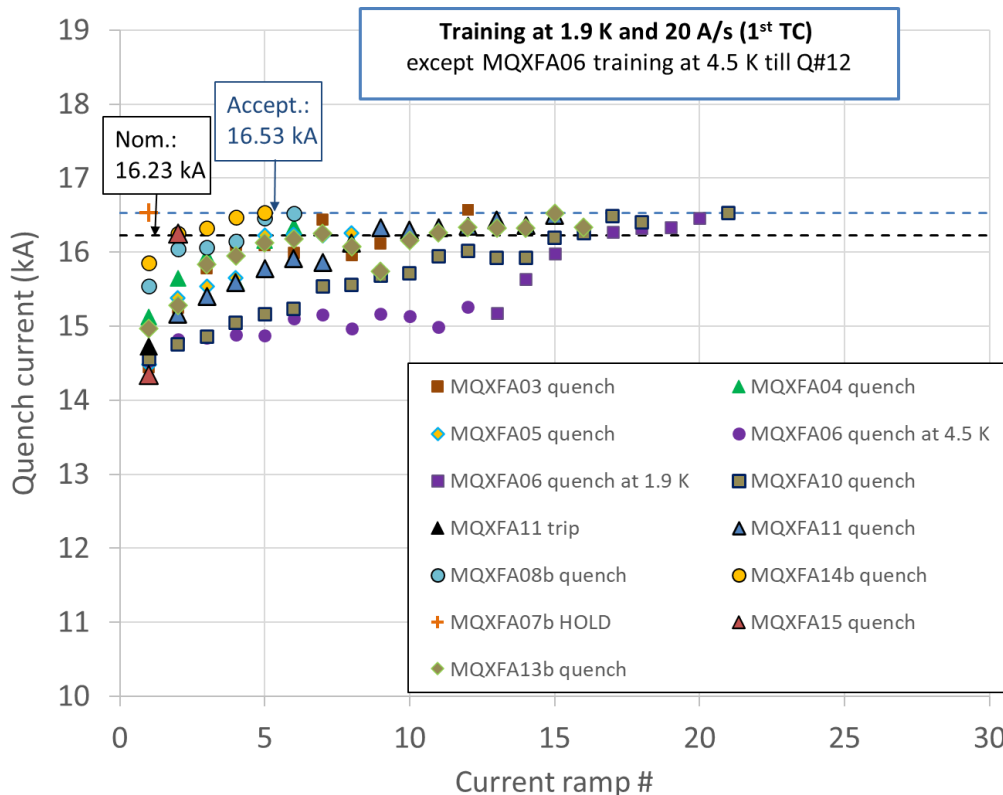


MQXFA at BNL after shipment from LBNL

Magnet Yield

Vertical test is done at BNL by 302.4.01, post-test analysis is done by 302.2.01

- 11 magnets met requirements during vertical test
 - 3 magnets (MQXFA07/08/13) needed a coil change to meet requirements
 - 1 magnet (MQXFA17) is waiting for a coil change
 - MQXFA05 passed an Endurance Test (7 thermal cycles, 52 quenches, ...)
 - MQXFA11 demonstrated resilience (after highway crash)

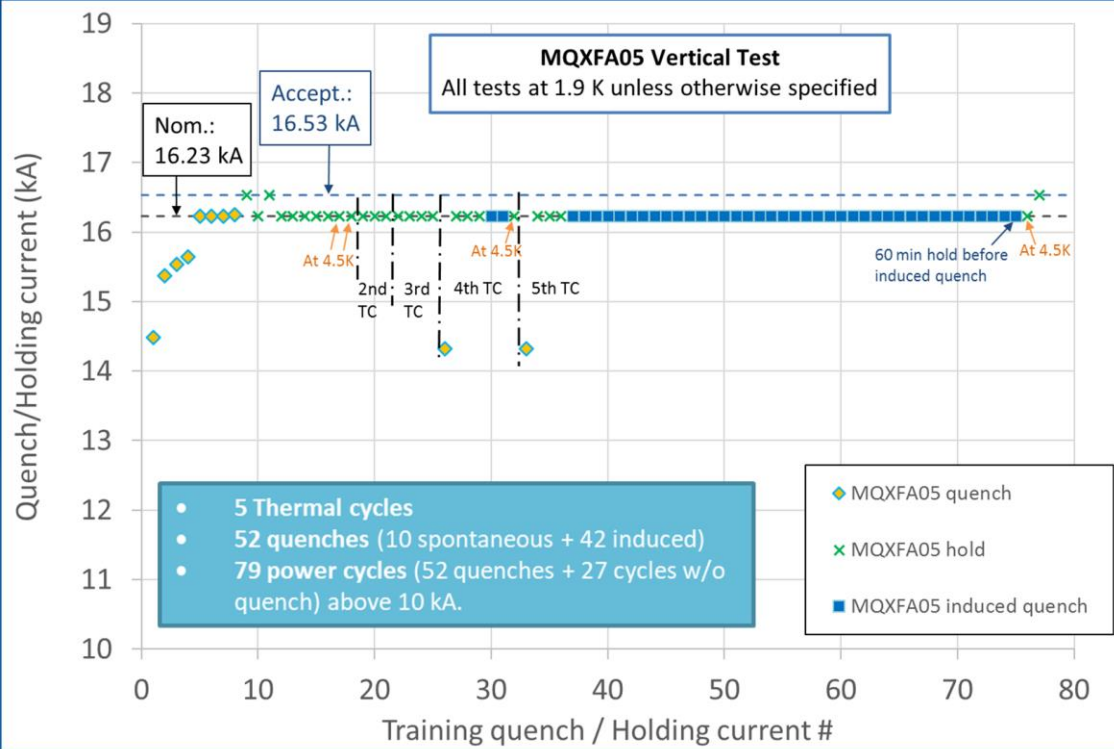


More details in "Production testing summary of the MQXFA magnets" in WP3 session Tue PM



MQXFA magnet being moved to vertical test station at BNL

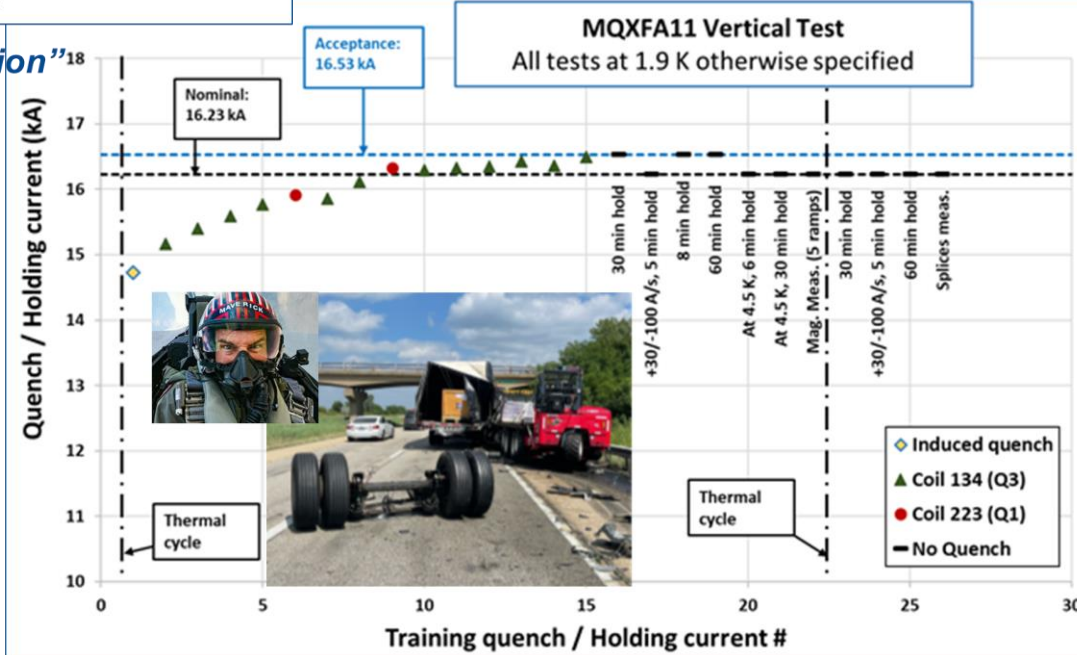
“Endurance” & “Resilience” Demonstrations



+ 2 additional thermal cycles in CA02

MQXFA05 “Endurance Demonstration”

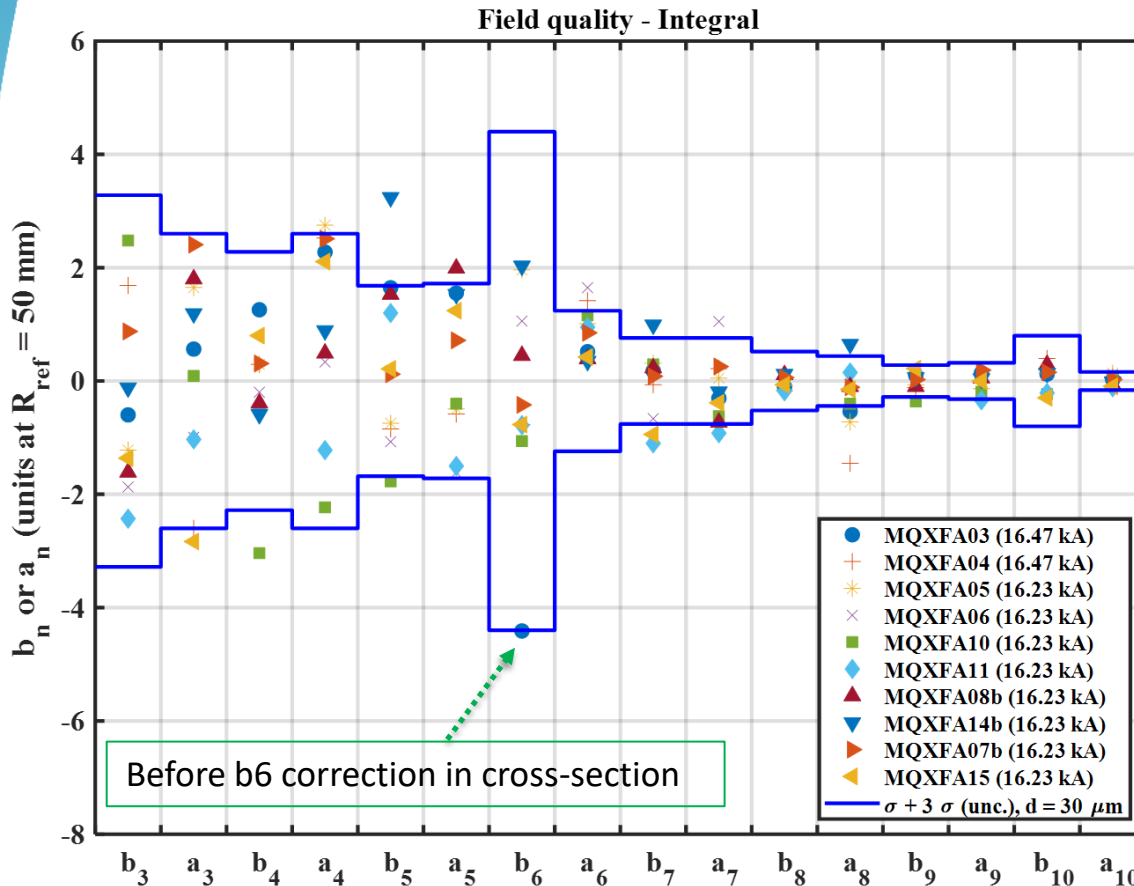
All magnets that met requirements demonstrated **very good memory** and **temperature margin**:
 I_{nom} @ 4.5 K



MQXFA11 “Resilience Demonstration”



MQXFAs Integral Harmonics at Nominal Curr.



b_6 correction introduced in one coil on MQXFA04 and all subsequent coils:
125 μm shift toward midplane

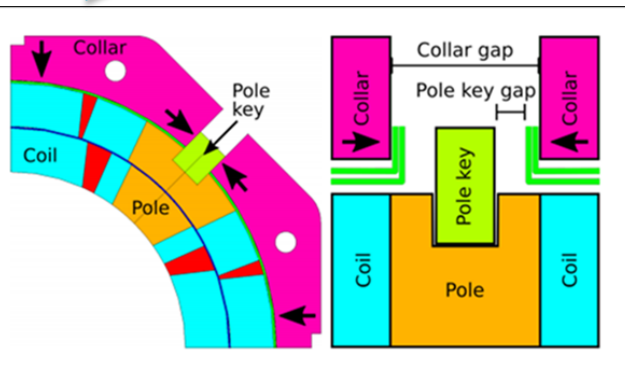
Magnetic shims used to correct low order harmonics

More details in “Production testing summary of the MQXFA magnets” in **WP3** session Tue PM

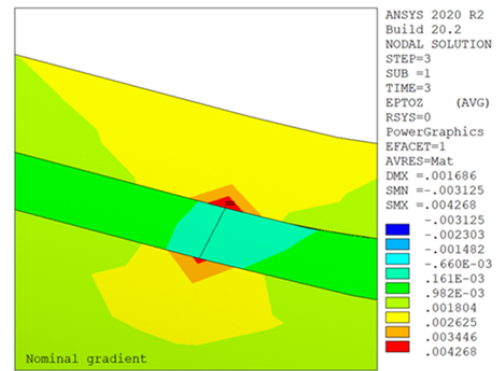
Lessons Learned from MQXFA07/08 test & analysis

- FE analysis of as-built magnets pointed to “critical area”
- Metallographic analysis by CERN team found the “Smoking gun” (broken Nb₃Sn filaments) in this area
- Excellent collaboration!
- Lessons learned:
 - Asymmetry during assembly may be looked-in by prestress
 - 2D asymmetry may cause poor preload in the ends
 - Seen in MQXFA07 and MQXFA08 (presented in Vancouver)
- Preventive action:
 - Larger gaps and revised assembly procedure

Presented at the
13th HL-LHC Collab. Mtg.

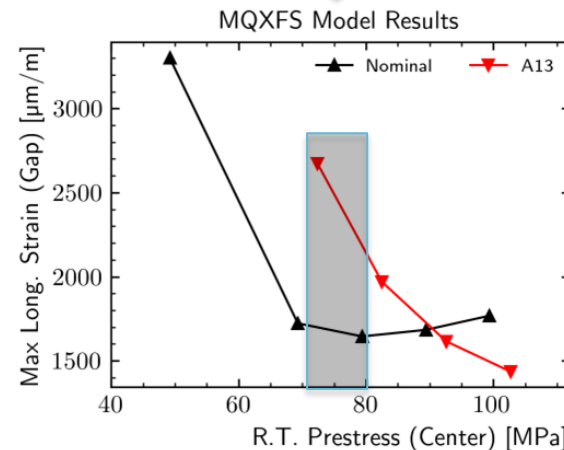
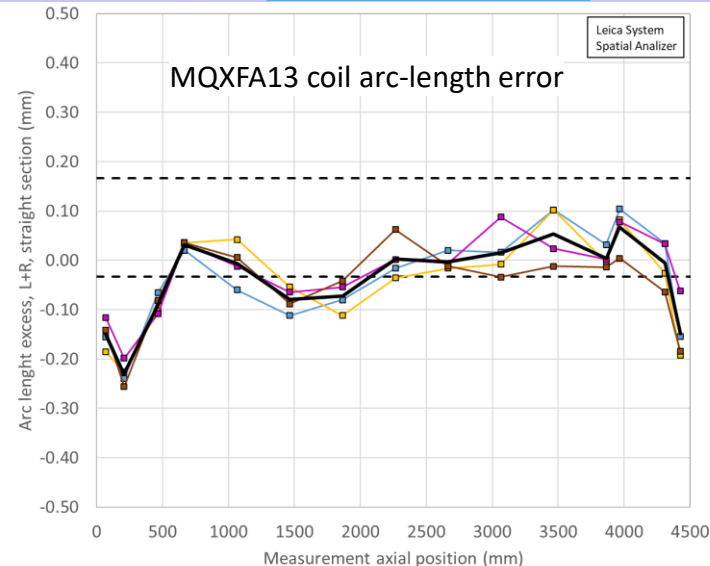
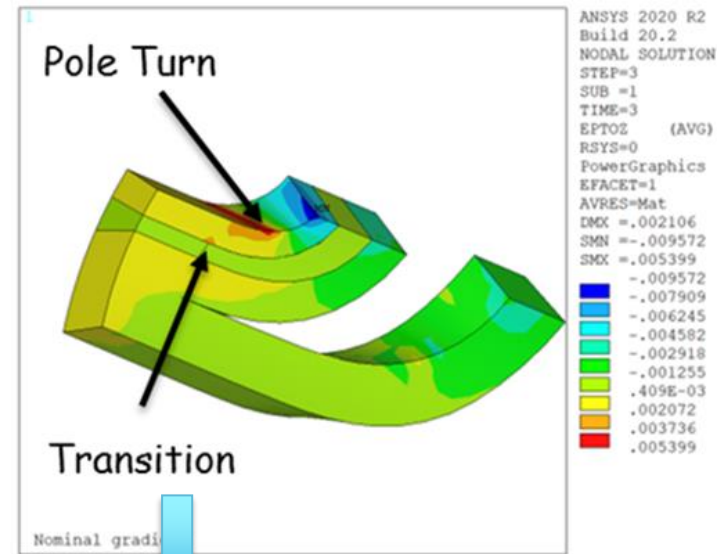
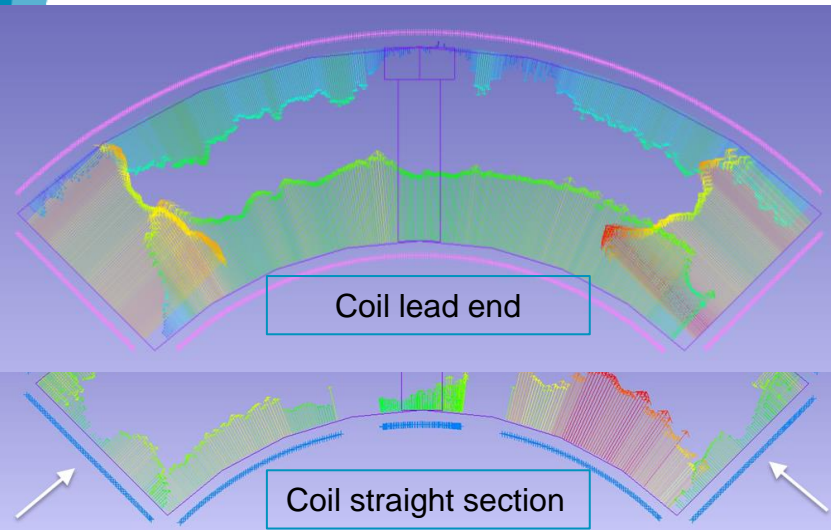


Closed pole key gap in a coil may lead to poor longitudinal preload in the ends of that coil at edge to end-spacer transition



Lessons Learned from MQXFA13/17 test & analysis

- If midplanes in coil ends are “too small” & there is low prestress → risk of excessive strain



Relative differences are more relevant than absolute numbers because of mesh size and de-bonding assumptions

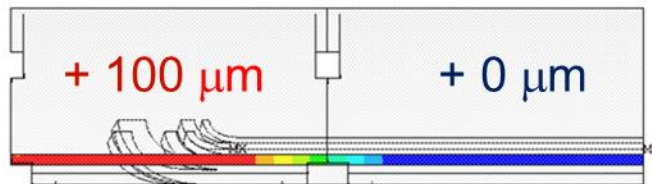
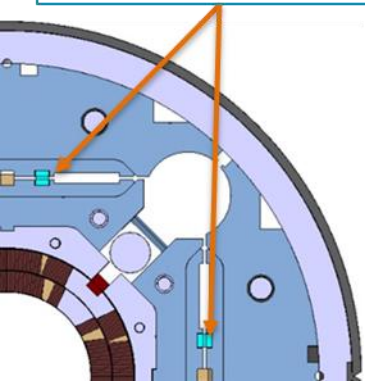


Courtesy of A. Bartkowska 9

Preventive Actions

- Main actions:
 - Added Tapered Load Shims in magnet Lead End
 - During last step of azimuthal preload
 - Added coil dimension measurements in the critical area and FE analysis based on measured coil size
 - Set target for minimum loading key size based on coil dimensions → higher pre-stress controlled by dimensions
 - Comparison with best magnets
 - Increased the maximum allowable stress during preload from 110 to 135 MPa
 - Based on feedback from CERN MQXFS program

Load keys & shims



Tapered load shims in Lead End

Coil Status & Parts

After 11 magnets met requirements:

Coils available (fabricated and passed QC)	38
Coils in production	1
Coils to be recovered from on-hold – future issues	1
Coils needed for 10 magnets	- 40
Expected coils balance	0

- Inventory:
 - Available: strands for 1 MQXFB cable
 - Incoming strands: for 3 MQXFA cables by end of October + for 2 cables by January 2026 (maybe earlier).
 - Available parts: 3 full sets (poles + ends + traces)
 - Incoming parts: 2 traces
- Two risks for additional coils in Risk Register

Plans and Schedule

- Plans for next magnets:
 - MQXFA18 (1st with TLS) is at BNL under test
 - MQXFA12b retrofitted with TLS (50 um) is at BNL
 - MQXFA16 retrofitted with TLS (50 um) almost complete
 - Re-assembly of MQXFA17b has started

Magnet Assembly	P6 Schedule	
P6 Label	Start	Finish
MQXFA-12b	2-Feb-24	9-Sep-24
MQXFA-16TLS	9-Sep-24	10-Oct-24
MQXFA-R4/17b	23-Aug-24	21-Nov-24
MQXFA-19	27-Jun-24	12-Dec-24
MQXFA-20	15-Oct-24	28-Jan-25
MQXFA-21	26-Nov-24	11-Mar-25
MQXFA-22	15-Jan-25	22-Apr-25
MQXFA-23	27-Feb-25	28-May-25
MQXFA-24	10-Apr-25	24-Jun-25
MQXFA-R5	27-May-25	1-Aug-25



- Working Schedule
 - August update:

- All magnets will be vertically tested at BNL
 - Only one thermal cycle during vertical test

MQXFA Summary

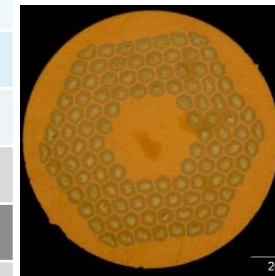
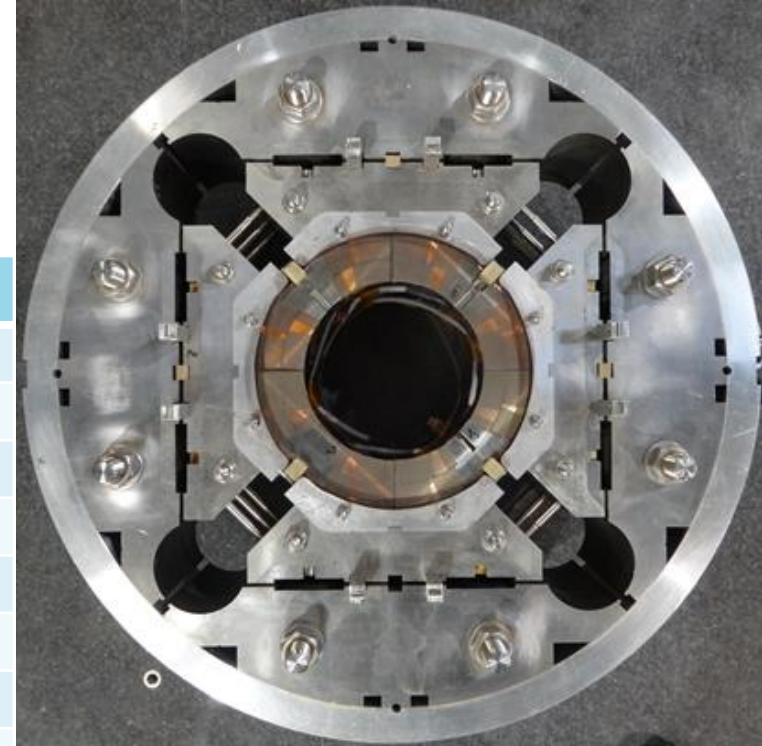
- 11 magnets met requirements, 10 more to go
 - 3 magnets that did not meet requirements were repaired by changing one coil and met requirement.
 - 1 magnet is to be repaired
 - All magnets will be vertically tested
- Major procurements are complete
- Last coil is in fabrication at Fermilab
- Strands and parts in inventory for up ~5 coils (6 max)
- Magnet assembly is at peak production rate
- Lessons learned have been implemented in revised design features and assembly specs.
- We plan completing the assembly of all magnets around next HL-LHC Collaboration Meeting

Back up Slides

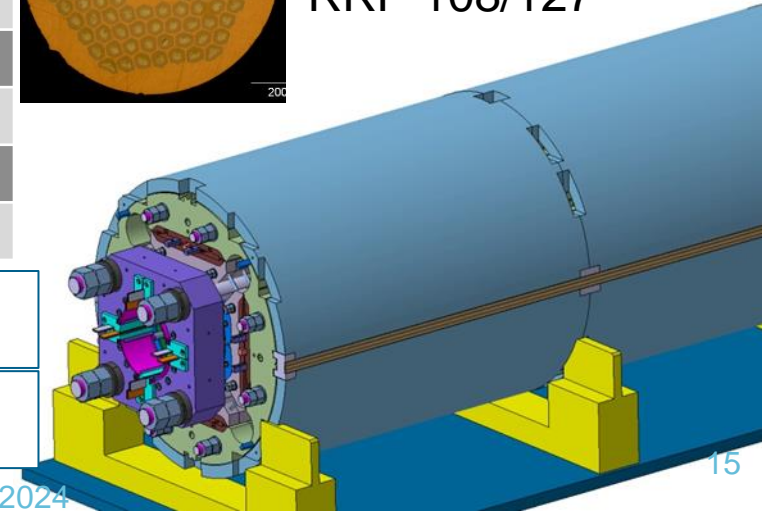


MQXFA/B Design

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.2
Nominal current	kA	16.23
Peak field at nom. current	T	11.3
Stored energy at nom. curr.	MJ/m	1.15
Diff. inductance	mH/m	8.26
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4



Nb₃Sn Conductor
RRP 108/127



P. Ferracin et al., "Development of MQXF, the Nb₃Sn Low-β Quadrupole for the HiLumi LHC" IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

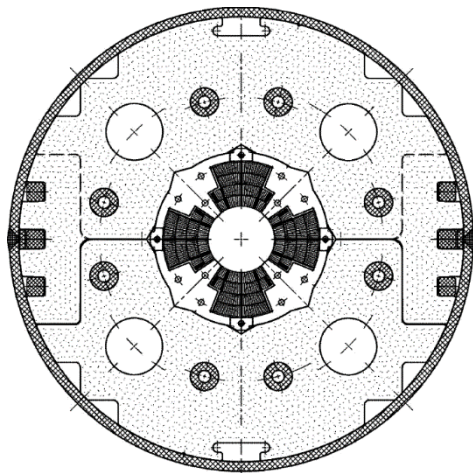
G. Ambrosio et al., "First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC" NAPAC16, FERMILAB-CONF-16-440-TD

Low- β quadrupole magnets from LHC to HL-LHC

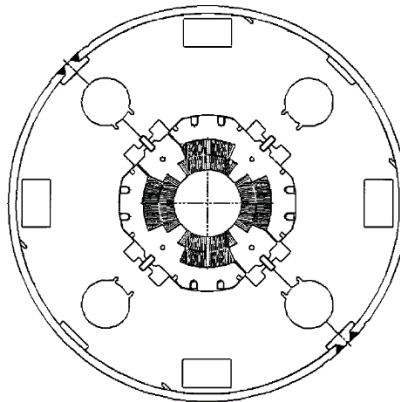
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- **~4 times** the e.m. forces in straight section
- **~6 times** the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

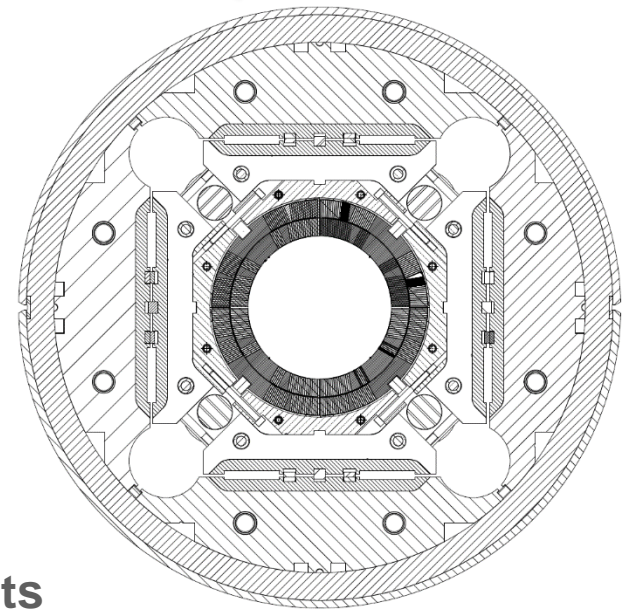
MQXA



MQXB



MQXF



Same scale for all 3 plots