MQXFA Fabrication Status & Schedule

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with contributions from the whole MQXFA team

Acknowledgement

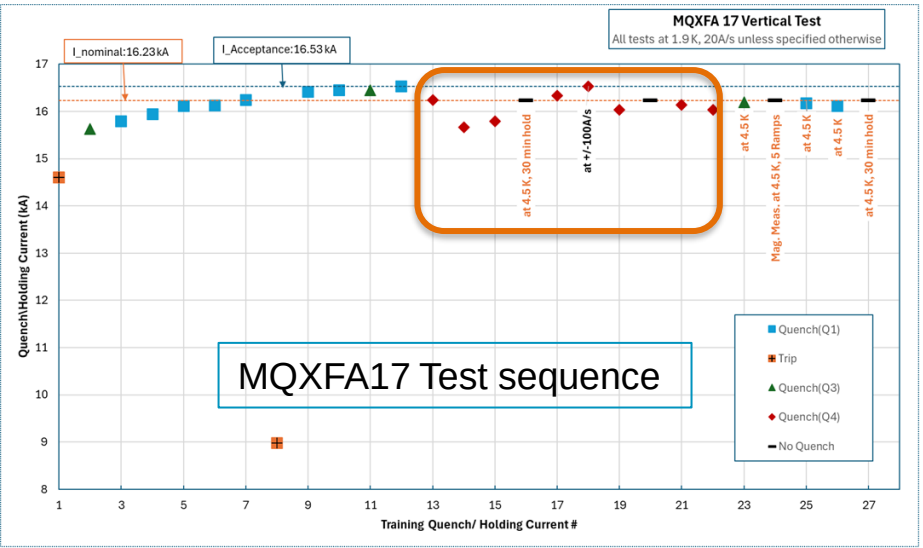
- US HL-LHC Accelerator Upgrade Project (AUP)
  - BNL: K. Amm, M. Anerella, A. Ben Yahia, M. Bornstein, H. Hocker, P. Joshi, F. Kurian, J. Muratore, J. Schmalzle, P. Wanderer
  - FNAL: G. Ambrosio, G. Apollinari, M. Baldini, J. Blowers, R. Bossert, R. Carcagno, G. Chlachidze, J. DiMarco, S. Feher, S. 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
  - LBNL: D. Cheng, J. Doyle, P. Ferracin, L. Garcia Fajardo, E. Lee, M. Marchevsky, M. Naus, I. Pong, S. Prestemon, K. Ray, G. Sabbi, G. Vallone, X. Wang
  - NHMFL: L. Cooley, J. Levitan, J. Lu, R. Walsh
- CERN: HL-LHC Project
  - 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 Weelderen, G. Willering

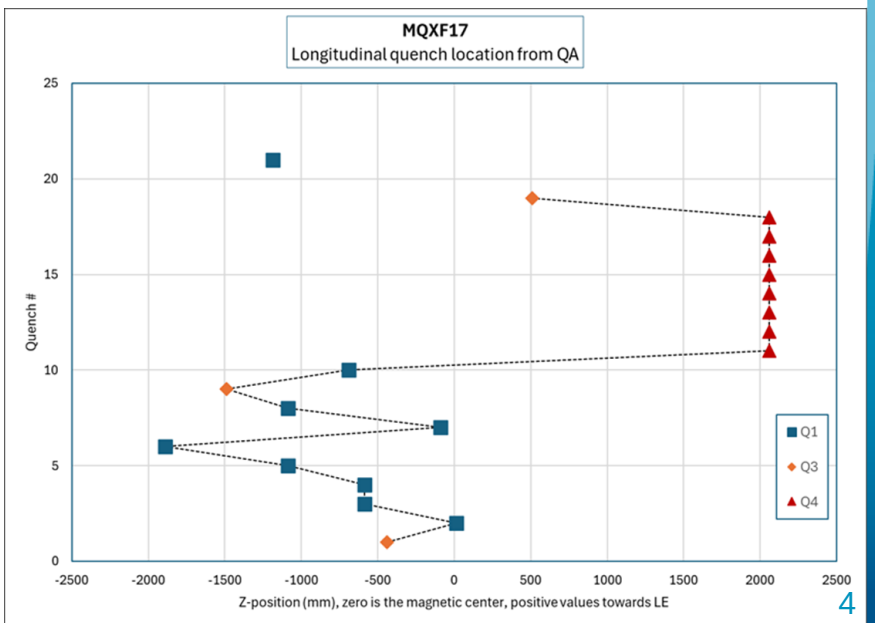
Outline

- **MQXFA17 Analysis**
- Status by Component
- Schedule and Plans

MQXFA17 Analysis I

- MQXFA17 showed detraining and degradation in a single coil during vertical test
  - Quench location (Lead End) similar to MQXFA13
  - Inverse temperature and ramp-rate dependence
- Analysis, in progress, has found:
  - Main factor: **low prestress in the lead end**
  - Possible contributing factor: variations in coil properties



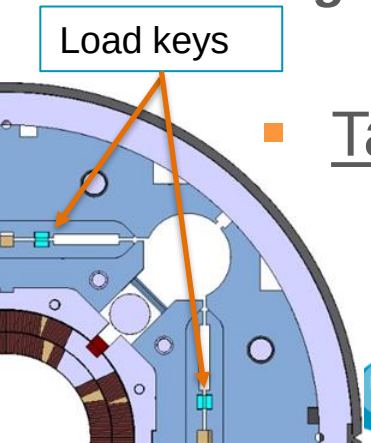


MQXFA17 Analysis II

- Main factor: low prestress in lead end
  - Actual load keys (39 mil) < Target load keys (43 mil)
    - One coil gauge reached max allowable stress (**120 MPa**) during bladder operation.
    - Shell and Coil averages were also close to the max of their spec ranges
  - MQXFA magnet Specs (doc-4009): *"If, with such load key shim targets, the coil stress measured in 2+ strain gauges during the loading or during bladder inflation indicate that the coil stress may reach values above the coil stress spec. during subsequent loading steps or at the end of the loading, **priority should be given to keeping the coil stress within the specs**."*
  - Tapered load shims had not yet been demonstrated

Increased to 135 MPa

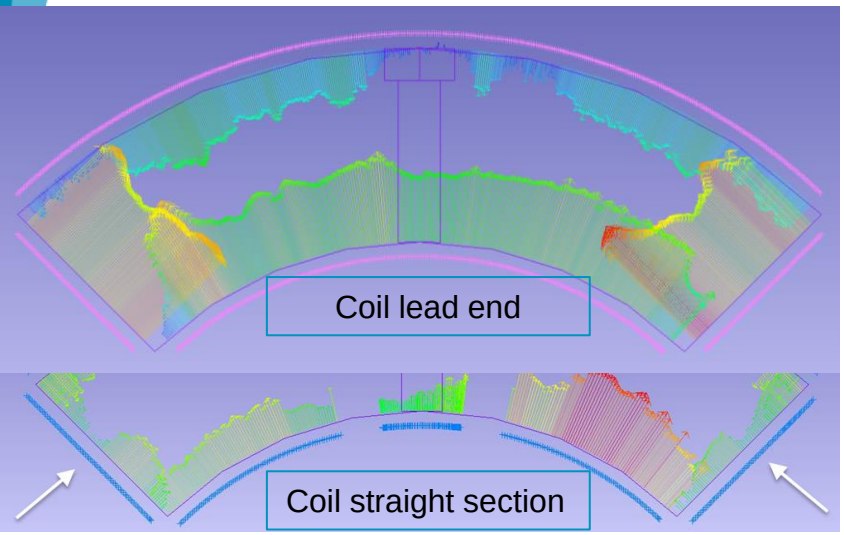
More details in "MQXFA magnet assembly & preload" in **this session**

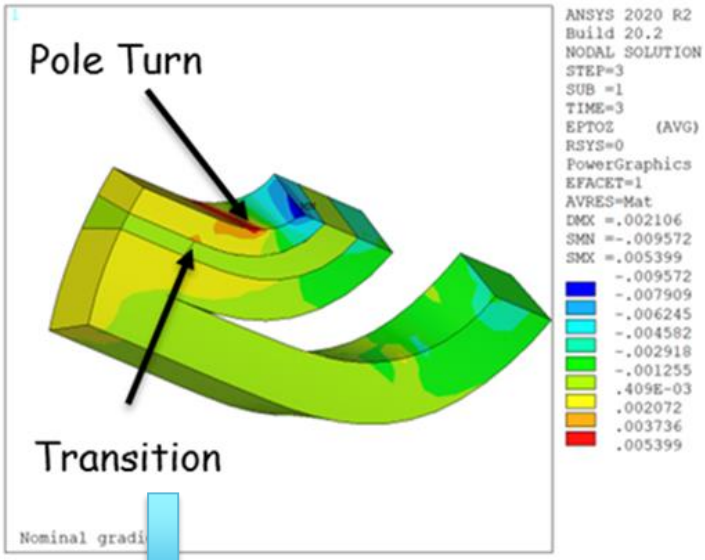


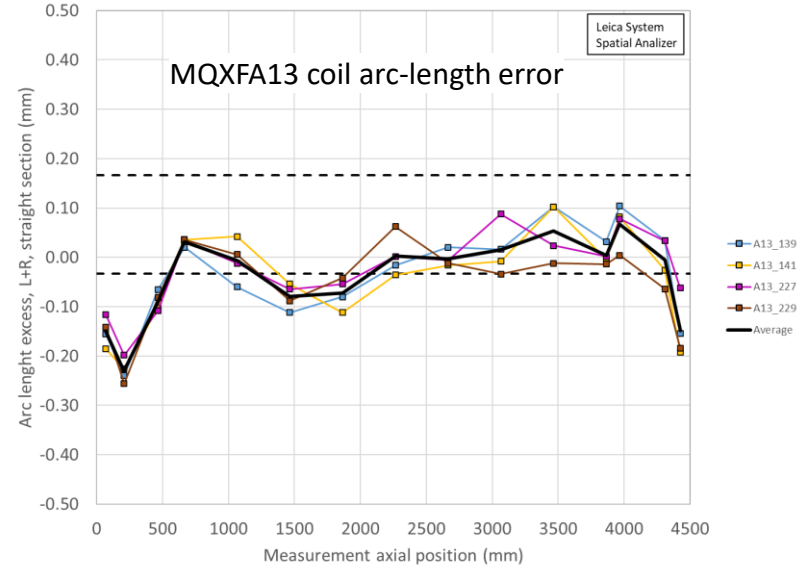
Inserted in MQXFA18/12b/16 and will be used in all future magnets

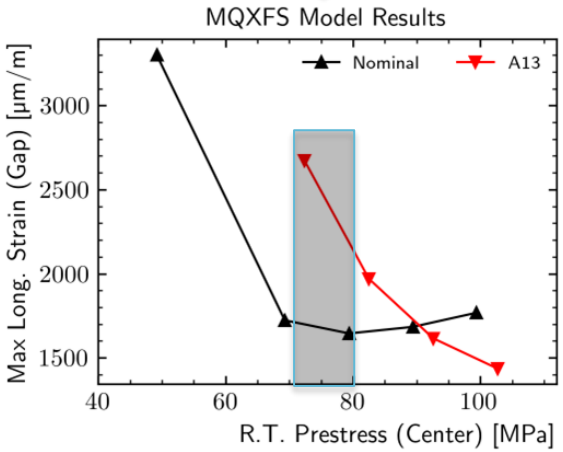
Lessons Learned from MQXFA13/17 test & analysis

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







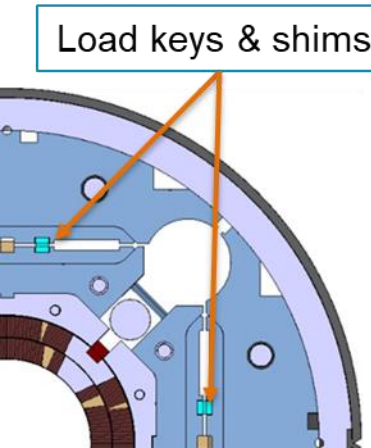


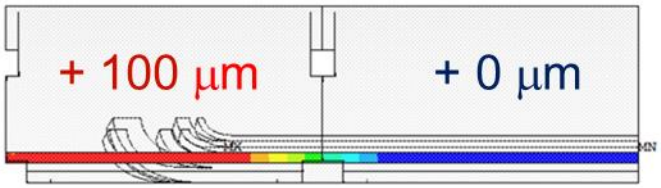
Relative differences are more relevant than absolute numbers because of mesh size and de-bonding assumptions

Courtesy of A. Bartkowska

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
  - Increased target prestress from 80 to 90 MPa
  - 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





Tapered load shims in Lead End

More details in “MQXFA magnet assembly & preload” in **this session**

Limiting Coils

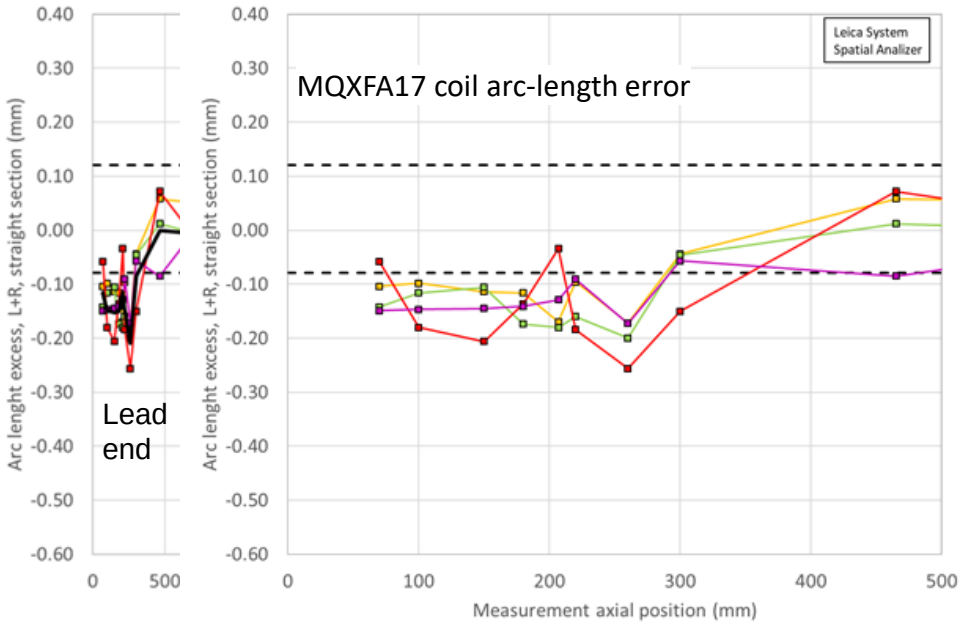
Magnet	Q1	CLIQ + Q2	Q3	CLIQ + Q4
MQXFA03	204	110	202	111
MQXFA04	203	113	206	112
MQXFA05	207	116	209	115
MQXFA06	122	119	211	123
MQXFA07	212	124	**214**	114
MQXFA07b	212	124	218	114
MQXFA08	215	126	**213**	128
MQXFA08b	215	126	219	128
MQXFA10	132	221	131	129
MQXFA11	223	222	134	135
MQXFA13	**227**	139	229	141
MQXFA14b	217	230	143	231
MQXFA15	233	226	220	117
MQXFA17	151	237	152	**239**
MQXFA13b	150	139	229	141

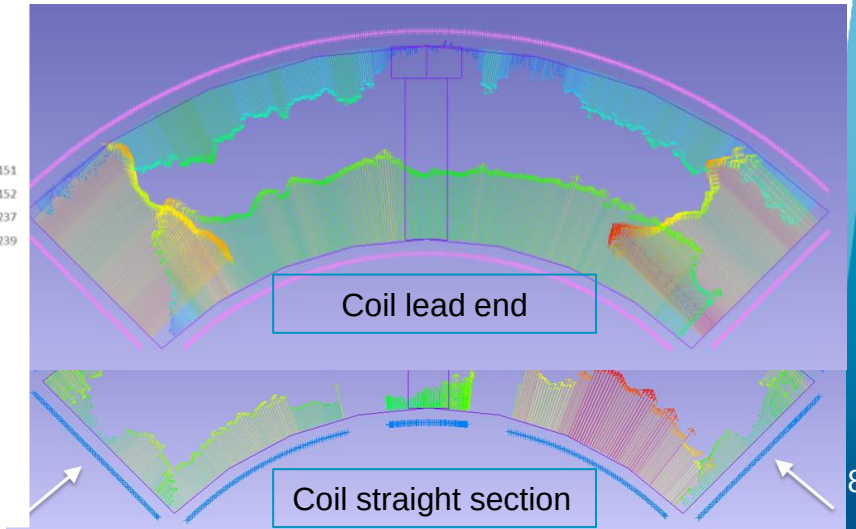
Coil issue caused by small/zero pole-key gaps in this magnet quadrant

Coil issue caused by small (average) arc-length in lead end.

All coils were affected

➔ Why coil 239 failed in MQXFA17?



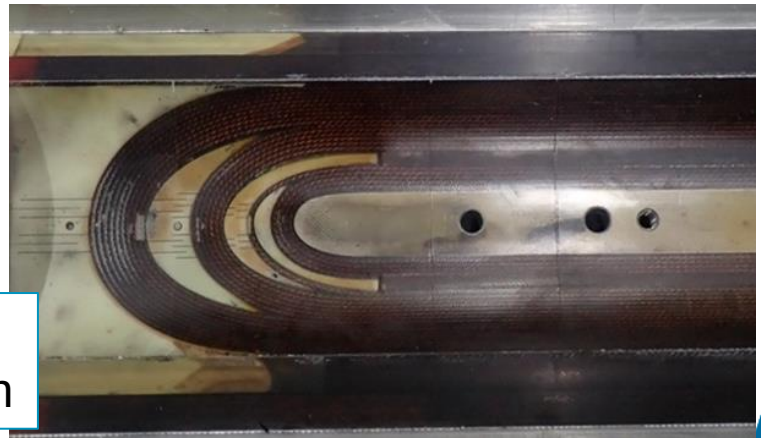


Coil Property Measurement & Simulations

Coils in MQXFA magnets

Magnet	Q1	CLIQ + Q2	Q3	CLIQ + Q4
MQXFA03	204	110	202	111
MQXFA04	203	113	206	112
MQXFA05	207	116	209	115
MQXFA06	122	119	211	123
MQXFA07	212	124	**214**	114
MQXFA07b	212	124	218	114
MQXFA08	215	126	**213**	128
MQXFA08b	215	126	219	128
MQXFA10	132	221	131	129
MQXFA11	223	222	134	135
MQXFA13	**227**	139	229	141
MQXFA14b	217	230	143	231
MQXFA15	233	226	220	117
MQXFA17	151	237	152	**239**
MQXFA13b	150	139	229	141

- Question: *"Are there coil-coil differences that may cause a weakness in some coils?"*
- Measurements:
  - Wedge to end-part gap dimension
  - Bonding strength epoxy-wedge
- Simulations:
  - Impact of gaps dimension & "filled" epoxy properties on strain at wedge-part transition



Coil 239 after epoxy impregnation

Outline

- MQXFA17 Analysis
- **Status by Component**
- **Schedule and Plans**

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

MQXFA at BNL after shipment from LBNL

Coil Status

Coils available (completed, not yet power tested)	38	
Coils in production (at Fermilab)	1	
Coil rejected during fabric., magnet integr. & test		13
Coil on hold after fabric., magnet integr. & test		16
Coils to be recovered from on-hold – future issues	1	
Coils needed for magnets not yet tested (10)	- 40	
Expected coils balance	**0**	

- Two risks for additional coils in Risk Register
  - Risk of coil issues during magnet test
  - All other coil issues (mostly magnet assembly)

Conductor Status

- Strand Inventory:
  - Available strands for **one MQXFB** (~800 m) cable
  - Incoming strand:
    - for **3 MQXFA cables** (~500 m) by end of October
    - for **2 MQXFA cables** by January 2026 (maybe earlier)
- Cable inventory is empty:
  - Planning to make one MQXFA cable in Nov./Dec.
  - We may make 2 more cables in first quarter of 2025

Coil Parts

Coil Parts	Qt. in inventory
Pole	3
End Parts	3
Wedges	16
QH Trace	4
NbTi Cable	13
Insulation Components	3

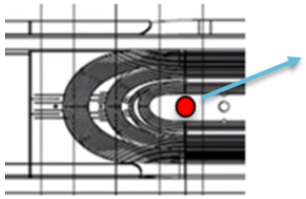
Under procurement	Qt.	Status
CERN End Parts Coating	14+ sets	In coating process at the vendor
MQXFA QH Trace	2	Under fabrication at CERN

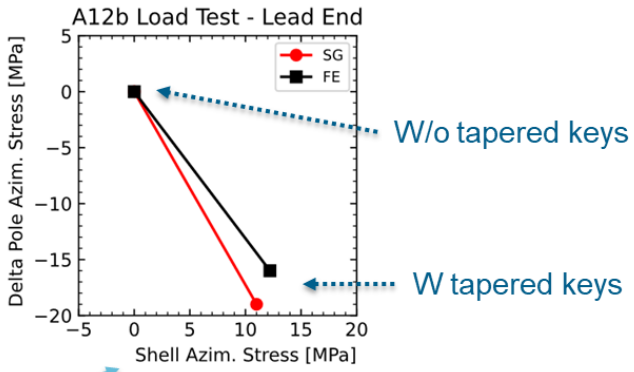
MQXFA Structures and Assembly

- Structure procurement is complete (except a few spare parts).
- Magnet assembly is at peak production with two assembly lines fully operational
- 20 MQXFA magnets assembled (MQXFA03-18, 7b, 8b, 13b, 12b):
  - MQXFA12b: used to test insertion of tapered load shims
    - Tapered load shims were inserted in the Lead End at ½ preload and removed to test the procedure.
    - Data from additional gauges were analyzed ➔ very good agreement with FE
- FMEA through all magnet assembly travelers to address integration issues (first round done, second in progress)

More details in “MQXFA magnet assembly & preload” in **this session**

Delta stress on gauges @ pole tip: measured (SG) vs computed (FE)





Plans and Schedule

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

- Working Schedule
  - August update:

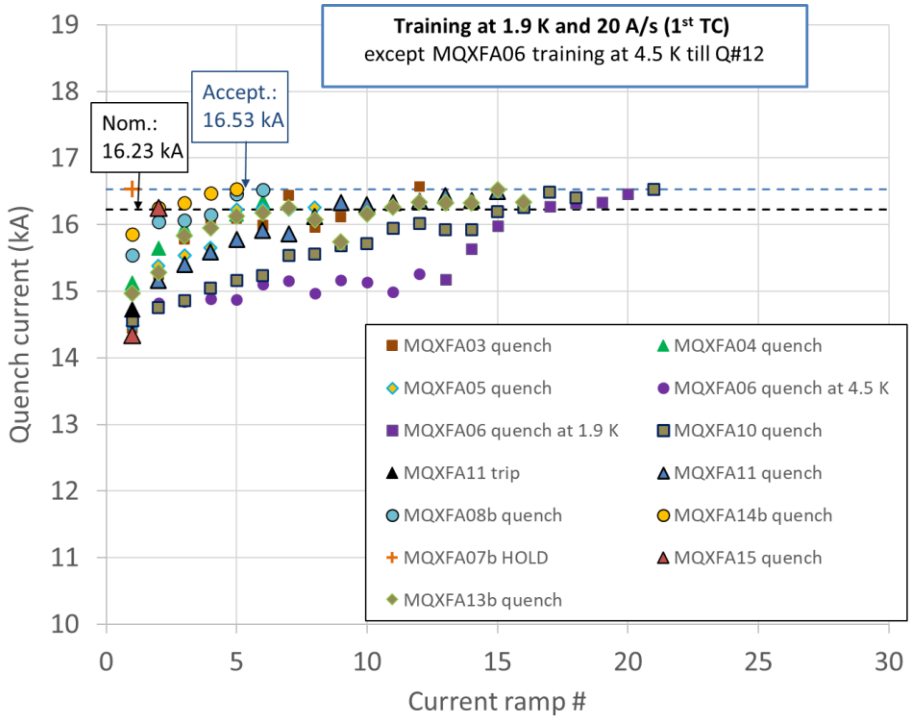
Magnet Assembly	P6 Schedule	
P6 Label	Start	Finish
MQXFA-12b	2-Feb-24	9-Sep-24
MQXFA-16TLS	9-Sep-24	10-Oct-24
MQXFA-R4/17b	23-Aug-24	21-Nov-24
MQXFA-19	27-Jun-24	12-Dec-24
MQXFA-20	15-Oct-24	28-Jan-25
MQXFA-21	26-Nov-24	11-Mar-25
MQXFA-22	15-Jan-25	22-Apr-25
MQXFA-23	27-Feb-25	28-May-25
MQXFA-24	10-Apr-25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

Magnet Tests

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

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 the Endurance Test
    - 7 thermal cycles (5 vertical + 2 in CA02), 53 quenches, 87+ power cycles
  - MQXFA11 demonstrated resilience (after highway crash)



All magnets that showed limited test performance during vertical test were identified during the first thermal cycle (TC).
➔ All magnets will be tested vertically, with only one TC to be within budget.

MQXFA magnet being moved to vertical test station at BNL

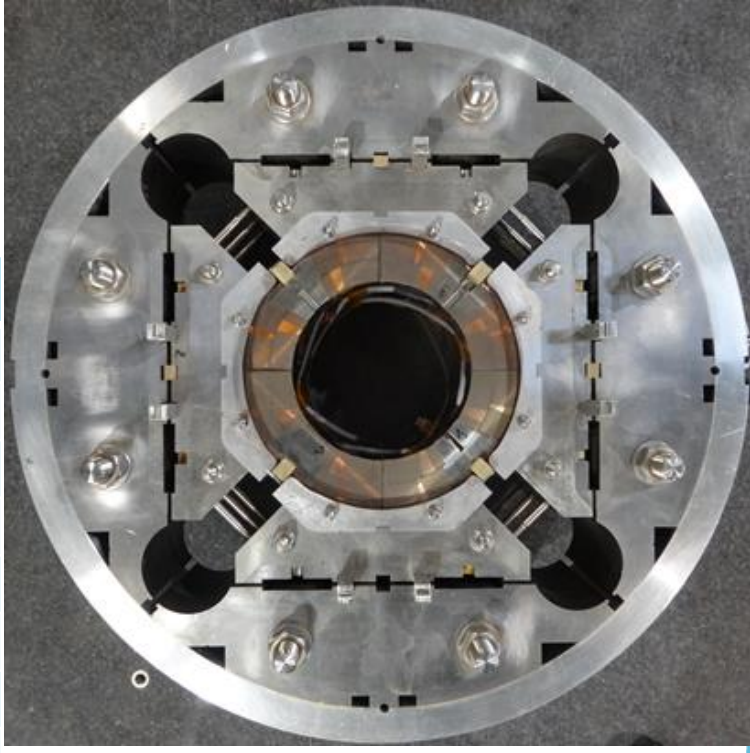
MQXFA Summary

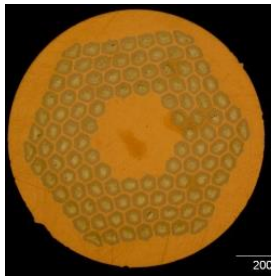
- 11 magnets met requirements, 10 more to go
  - 3 magnets that did not meet requirements were repaired by changing one coil and met requirements.
  - All magnets will be vertically tested
- Major procurements are complete
- Last coil is in fabrication at Fermilab
- Strands in inventory for up 5 coils (6 max)
- Coil parts in inventory for up ~3 coils
- 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 by next HL-LHC Collaboration Meeting

Back up Slides

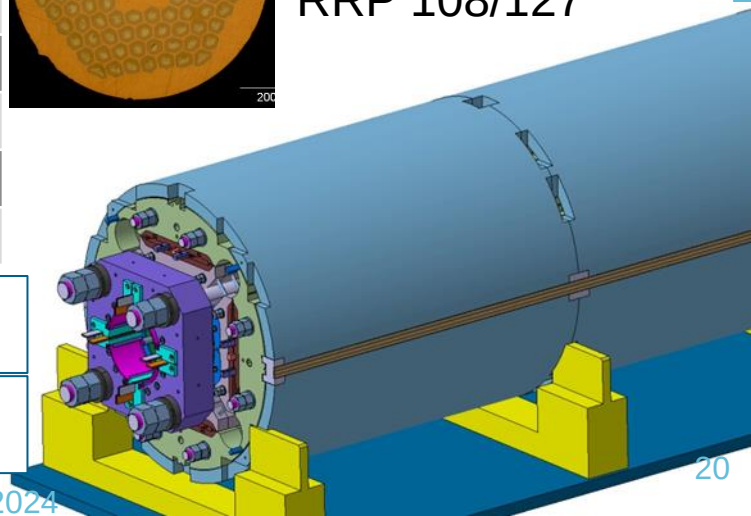
MQXFA/B Design

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





Nb_3Sn Conductor
RRP 108/127



P. Ferracin et al., “Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC ” IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

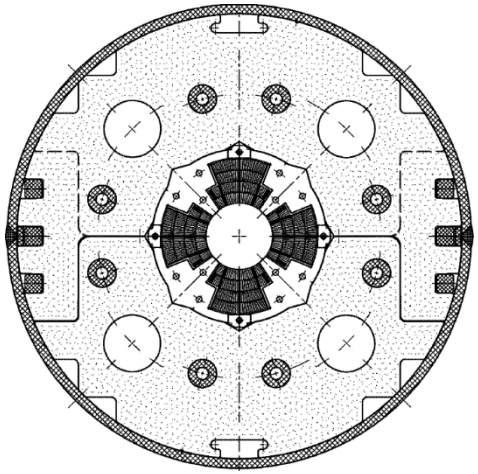
G. Ambrosio et al., “First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC” NAPAC16, FERMILAB-CONF-16-440-TD

Low-β quadrupole magnets from LHC to HL-LHC

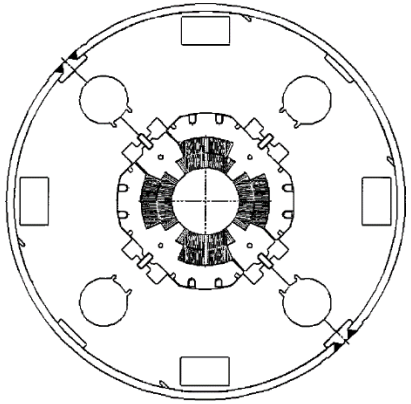
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

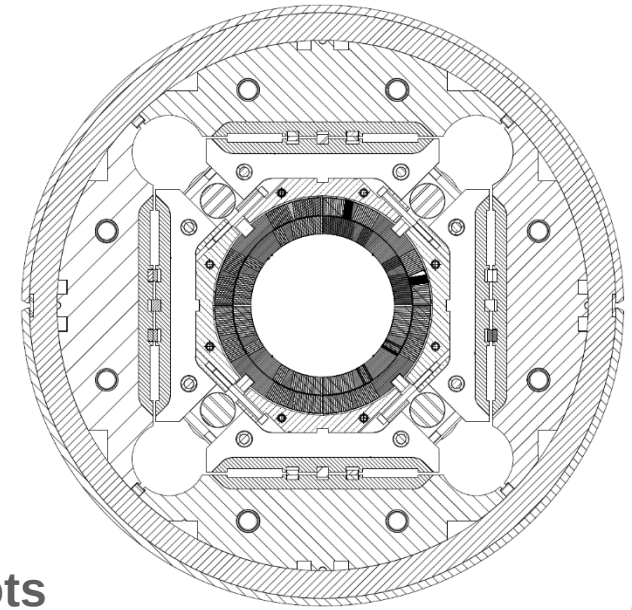
MQXA



MQXB

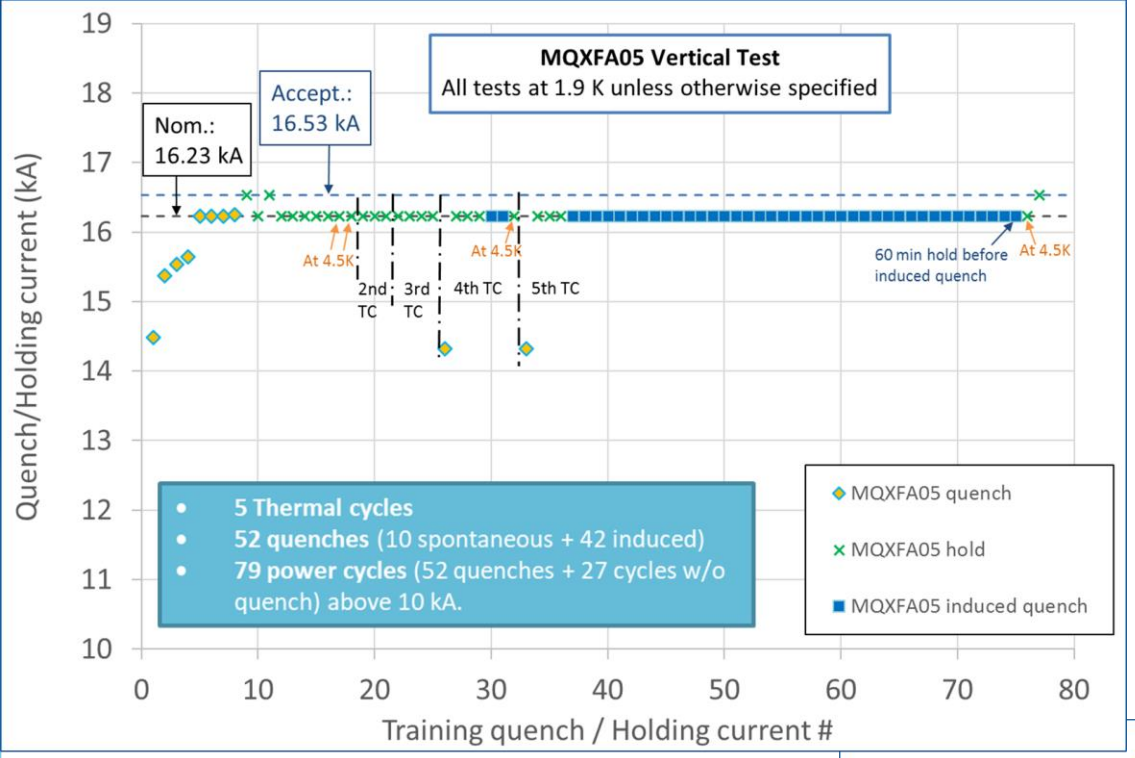


MQXF



Same scale for all 3 plots

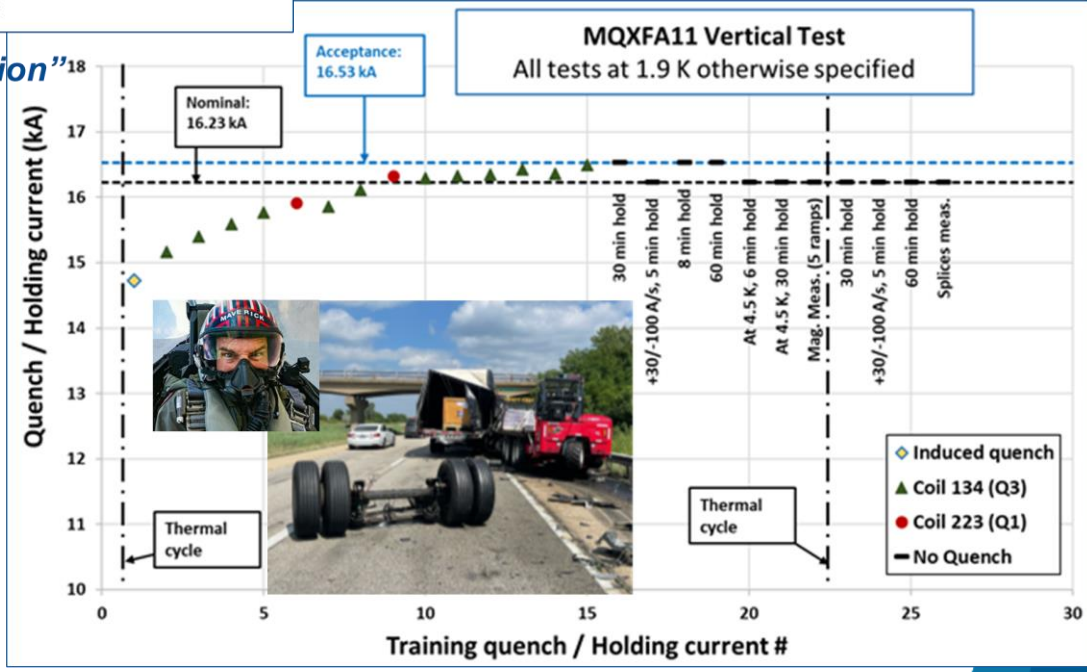
"Endurance" & "Resilience" Demonstrations



MQXFA05 *"Endurance Demonstration"*

All magnets that met requirements demonstrated **very good memory** and **temperature margin**:

I_nom @ 4.5 K



MQXFA11 *"Resilience Demonstration"*