# MQXFA fabrication status and schedule

*Giorgio Ambrosio,*

*with contributions from the whole MQXFA team*

# Acknowledgement


- US HL-LHC Accelerator Upgrade Project (AUP)
  - BNL: K. Amm, M. Anerella, A. Ben Yahia, H. Hocker, P. Joshi, F. Kurian, J. Muratore, J. Schmalzle, , P. Wanderer
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# Outline

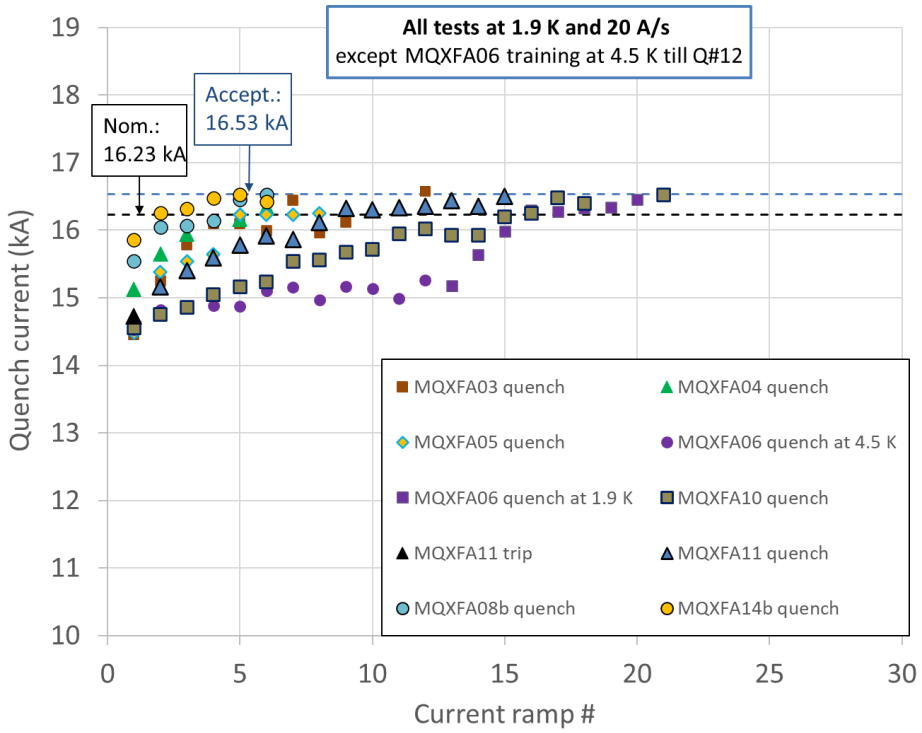
- The Big Picture
- **Status and Inventory of each component**
- Additional magnet
- Conclusions

| Component | Status | Actual yield | Yield in Baseline |
|---|---|---|---|
| Strand procurement | 98% complete | - | - |
| Cable fabrication & insulation | 98% complete | **95.5%** | 91% |
| Coil fabrication | 96% complete | **88.7%*** | |
| Coil yield due to magnet integration & test | - | **84%**** | |
| Total coil yield | - | **74.5%** | 75.5% |
| Magnet assembly | ~50% complete | | |
| Magnet yield after vertical test | 11 tests | **82.8%**** | 83.3% |

# The Big Picture

## MQXFA magnets

- Tested: 11
- Met Requirements: 8
- Did not meet requir.: 3
- Waiting for test: 1
- Being assembled: 2





MQXFA at BNL after shipment from LBNL

# Conductor Procurement & QC

- Conductor delivery:
  - **~98% conductor received** (out of 260 km, including LARP proc.)
  - Last shipment (40 km) expected in September 2023
  - Some spools that were reworked received extra lubricant, and impacted cable stability (see next slide)
- Status
  - Strand verification 98% complete
  - Cable qualification 100%
  - Witness Sample tests ~94%
- Inventory (after BL components are complete):
  - **60 km** of strand to be received by B-OST (replacement)
  - Dates under discussion, possibly ~end of 2024

# Cable Fabrication & Insulation

- Cable Fabrication & Insulation Status:
  - Fabricated: 111 (+ 4 from LARP)
  - To be fabricated: 2
- Cable yield:
  - Yield is **95.5%** (4 rejected, 2 on-hold), vs. 91% assumed in Baseline
    - Some cables (5) were on-hold because of strand lubrication issue causing cable mechanical instability
      - Coil fabrication teams (at FNAL and BNL) were able to fix all popped strands and wind 4 coils
- Inventory (after BL components are complete):
  - **6 cables** (1 of them with excessive oil issue)

# Coil Parts

- All procurements have been completed
  - With the exception of some parts that were rejected
- Inventory (after BL components are complete):
  - Full set for **6 coils** after receiving repaired/re-fabricated parts

| Coil Parts | Qt. in inventory |
|---|---|
| Pole | 4 + 3 (30 parts for another 3 coils are being repaired/refabricated at vendor) |
| End Parts | 6 + 1 (2 parts for another 1 coil need to be recoated) |
| Wedges | 26 |
| QH Trace | 3 + 10 (Quarantined) |
| S2 glass components | 6 |

# Coil Fabrication at FNAL & BNL

- Coil fabrication is **95% complete** (out of 106 coils)

| | Coils at FNAL* | Coils at BNL | Total | Baseline |
|---|---|---|---|---|
| **Accepted after fabr.** | **42** | **41** | **83** | |
| In Fabrication | 2 | 5 | 7 | |
| Rejected | 4 | 3 | 7 | |
| On Hold | 6 | 3 | 9 | |
| **Total** | **54** | **52** | **106** | **106** |
| **Fabrication Yield** * | | | **88.7%** | |

*The actual yield includes the sum of the probabilities of using coils on hold (i.e. 2 coils with 50% probability of being used = 1 coil approved for use).

- Coil fabrication yield was lower in first years of production
  - For instance: ~80% in October 2020
- Effect of *learning curve* is visible in ~second half of coil fabrication
- Similar improvement is expected in coil yield for integration & test

# Overall Coil Yield

- Final coil yield will depend on yield after magnet integration and test
- Improvement due to *learning curve* is expected
  - More coils will be needed if expectation is not met

| | After Integration | After Vertical Test | Total | Baseline |
|---|---|---|---|---|
| Rejected | 2 | 3 | 5 | |
| On Hold | 5 | 0 | 5 | |
| **Accepted after Test** [1] | | | **32** | 80 |
| **Integration & Test Yield**** | | | **84.0%** | |
| **TOTAL Coil Yield** | | | **74.5%** | **75.5%** |

**MQXFA07 and MQXFA08 coils and magnets were fabricated under Covid restrictions. AUP project was re-baselined assuming that 66% of MQXFA07 and MQXFA08 limited performances were due to the impact of Covid restrictions. These issues assumed to be Covid impact were not included in the actual yield.
This yield assumes recovery of 33% coils on hold after integration and test

# Coil Inventory

- Inventory (after 20 magnets):
- Some coils on hold are expected to be used
  - Low risk coils
  - A few coils previously on hold have already been used
  - Some coils previously on hold are in MQXFA15
- Other coils on hold will remain in inventory
  - Mid and high risk coils
- If needed, more coils may be fabricated using cables and parts in inventory, and budget in risk register for labor

# MQXFA Structure Proc. & Magnet Assembly

- Procurement of main parts is complete
- Two assembly lines at LBNL are fully operational
  - staggered mode
- 15 magnets have been assembled
  - 11 tested (8 successful, 2 reworked, 1 to be reworked)
  - 2 disassembled for NCRs
  - 1 preload adjustment based on lessons learned from MQXFA13
  - 1 ready for test (MQXFA07b)
- Assemblies of MQXFA16 and MQXFA17 are in progress.
- FMEA performed for Magnet Assembly Travelers

More details on **Thursday** in MQXFA, magnet assembly and preload by Dan Cheng

Two MQXFA assembly lines at LBNL

MQXFA shell-yoke assembly in process

# Plans and Schedule

- Plans for magnet assembly:
  - MQXFA07b is at BNL for test
  - MQXFA15 preload adjustment in ~3 weeks after MQXFA16 is complete
  - MQXFA16 & MQXFA17 have high priority for test in CA05 (no vertical test)
  - MQXFA13b and MQXFA12b after them
  - MQXFA09 was retired
    - 2 coils and structure reused in other magnets
    - ➔ last magnet = MQXFA23
- Working Schedule
  - August update:

| Magnet Assembly | P6 Schedule | |
|---|---|---|
| P6 Label | Start | Finish |
| MQXFA-16 | 8-Aug-23 | 11-Oct-23 |
| MQXFA-17 | 20-Sep-23 | 22-Nov-23 |
| MQXFA-18 | 15-Dec-23 | 23-Feb-24 |
| MQXFA-19 | 2-Feb-24 | 5-Apr-24 |
| MQXFA-20 | 15-Mar-24 | 17-May-24 |
| MQXFA-21 | 26-Apr-24 | 1-Jul-24 |
| MQXFA-22 | 10-Jun-24 | 13-Aug-24 |
| MQXFA-23 | 23-Jul-24 | 25-Sep-24 |
| *MQXFA-R3* | *16-Oct-24* | *26-Dec-24* |
| *MQXFA-R4* | *27-Nov-24* | *11-Feb-25* |

# Additional MQXFA magnet

- Negotiation in progress for acceptance by CERN of CA01 with an additional magnet
  - MQXFA24
- Coil fabrication could start tomorrow (after BCR is approved) because we have cables and coil parts in house
- But it would **“empty” the inventory**
- Therefore, we will have to add cables, coil parts, structure components and possibly strand (?)

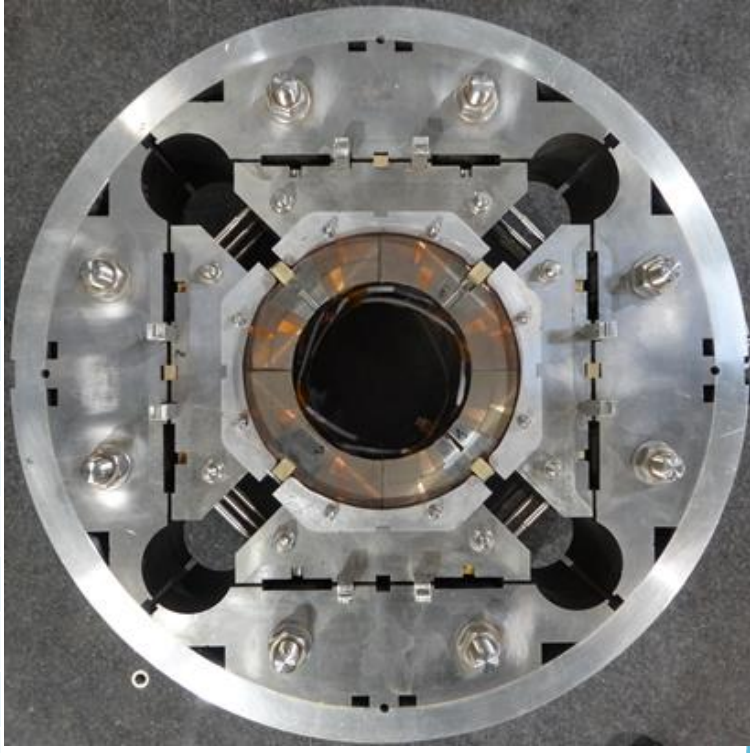
# Conclusions

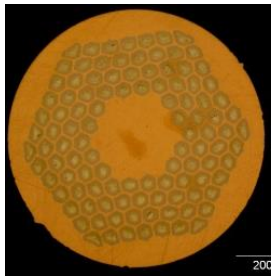
- The fabrication of MQXFA magnets by US-AUP is at peak production rate.
  - Strand procurement, Cable fabrication, Coil fabrication are almost complete
  - Magnet assembly is close to 50% complete
- Three magnets out of eleven did not meet requirements during vertical test. Lessons were learned and changes implemented.
  - Magnet yield is expected to increase
- Cable yield is higher than starting assumption, whereas coil yield is lower. Baseline was changed accordingly.
  - Inventory for 6+ additional coils
- Last magnet to be completed around beginning of 2025

# Back up Slides

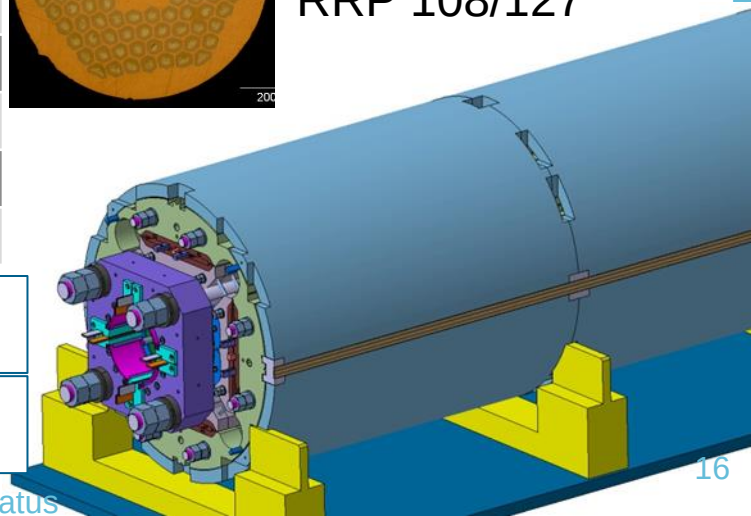
# MQXFA/B Design

| 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

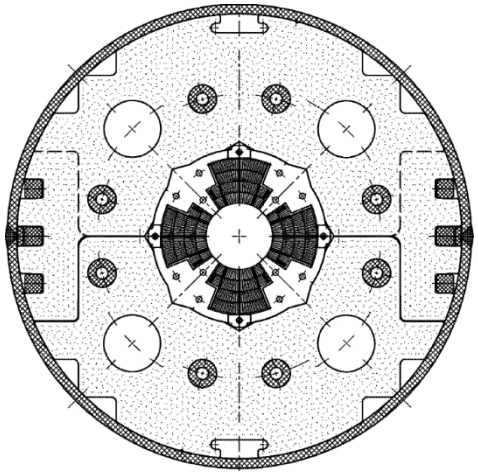
G. Ambrosio et al., “First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC” NAPAC16, FERMILAB-CONF-16-440-TD

# Low-β quadrupole magnets from LHC to HL-LHC

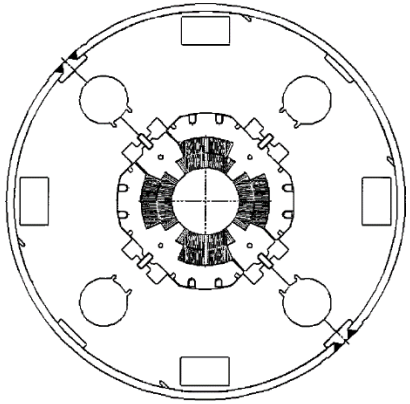
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

*State of the art quadrupoles at the time of LHC construction*

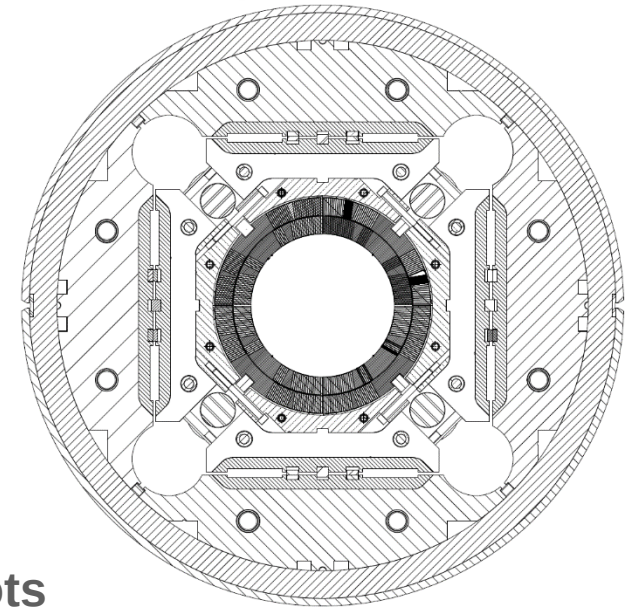
**MQXA**



**MQXB**



**MQXF**



**Same scale for all 3 plots**

# Status Summary

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  - For instance: ~80% in October 2020
- Effect of learning curve visible in ~second half of coil fabrication
- Similar impact expected in coil yield for integration & test

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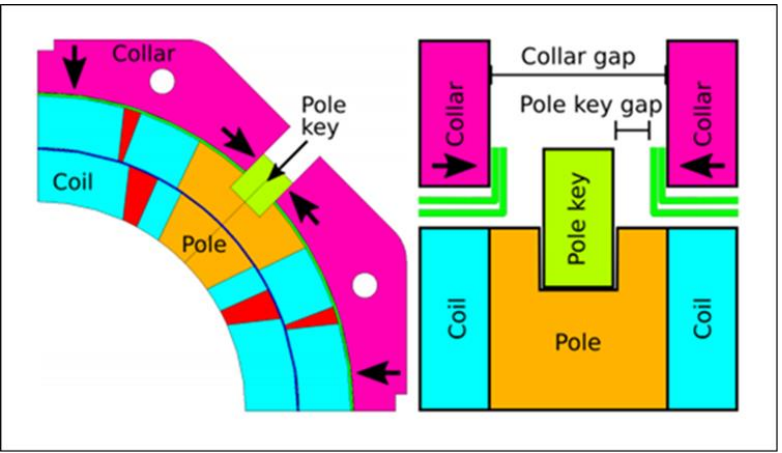
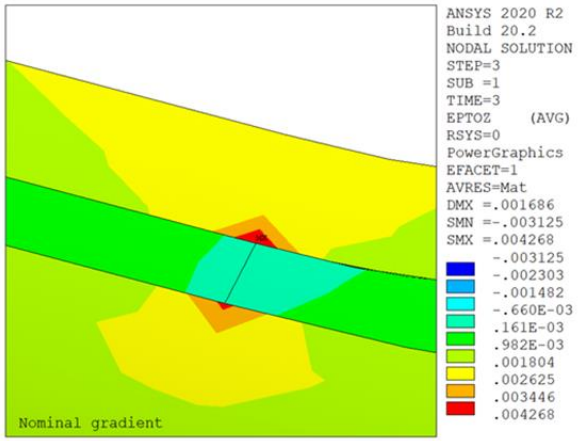
# Lessons Learned from MQXFA07/08 NCR

- MQXFA07 and MQXFA08 non-conformity analyses are complete (AUP doc-4293 & 4776; EDMS# 2777612)
  - "Smoking gun" (broken $Nb_3Sn$ filaments) was found through metallographic analysis by CERN team
- Lessons learned:
  - Asymmetry during assembly may be looked-in by prestress
  - 2D asymmetry may cause poor preload in the ends
  - COVID restrictions contributed to these issues
- All causes have been addressed for future magnets




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 NCR

- MQXFA13 investigation is in progress
  - metallographic analysis to be performed at CERN
- Main suspect: Small arc-length in the ends of all coils caused low pre-load and high strain in the ends.
  - Limiting coil had smallest arc-length of all tested coil
- Preventive actions:
  - Increased the maximum allowable stress during preload: from 110 to 120 MPa
  - Target for minimum loading key size based on coil dimensions

More details on **Thursday** in MQXFA, magnet assembly and preload by Dan Cheng