Analysis of the production of MQXFA Low β Quadrupoles for HL-LHC at 50% coil fabrication

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with contributions from the whole MQXFA team

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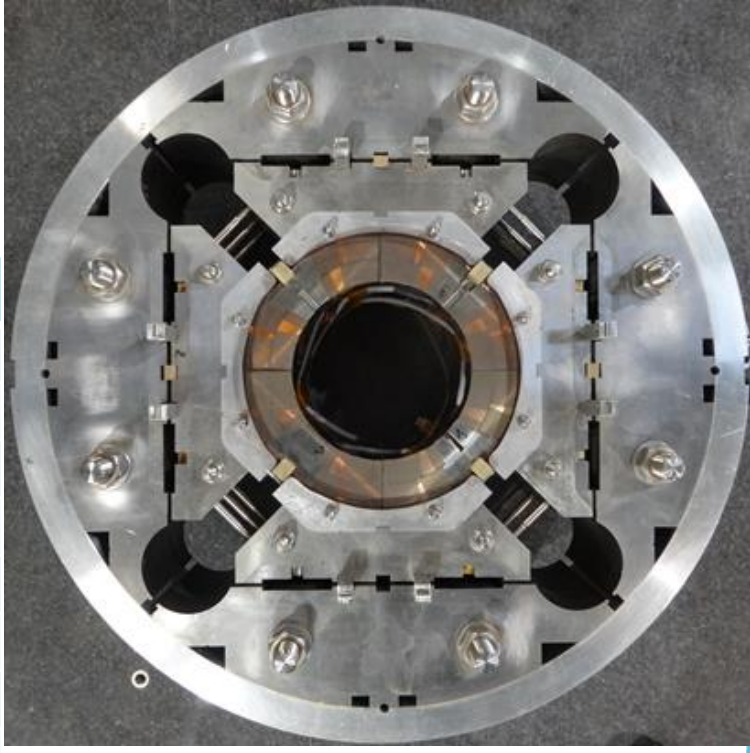
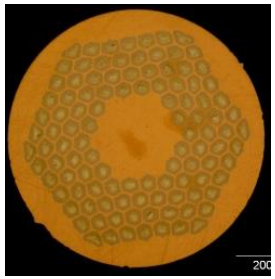
Outline

- Results of Vertical Tests
  - Analysis in progress
- Production Status
  - Lessons Learned
- Conclusions

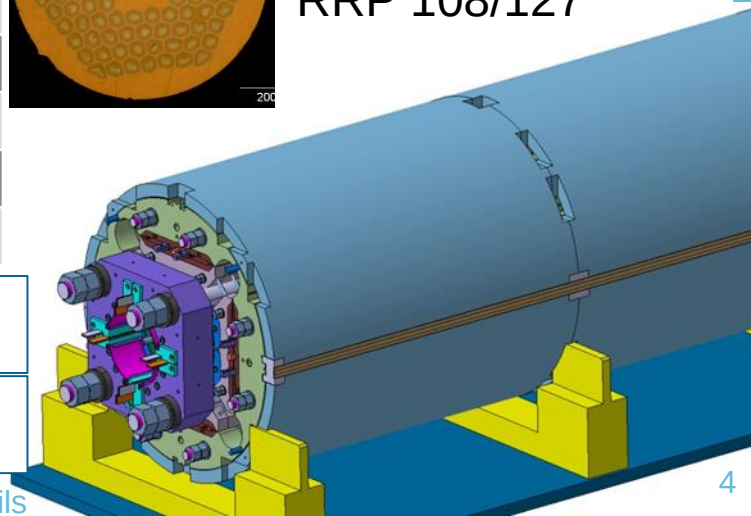
MQXFA/B Design

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

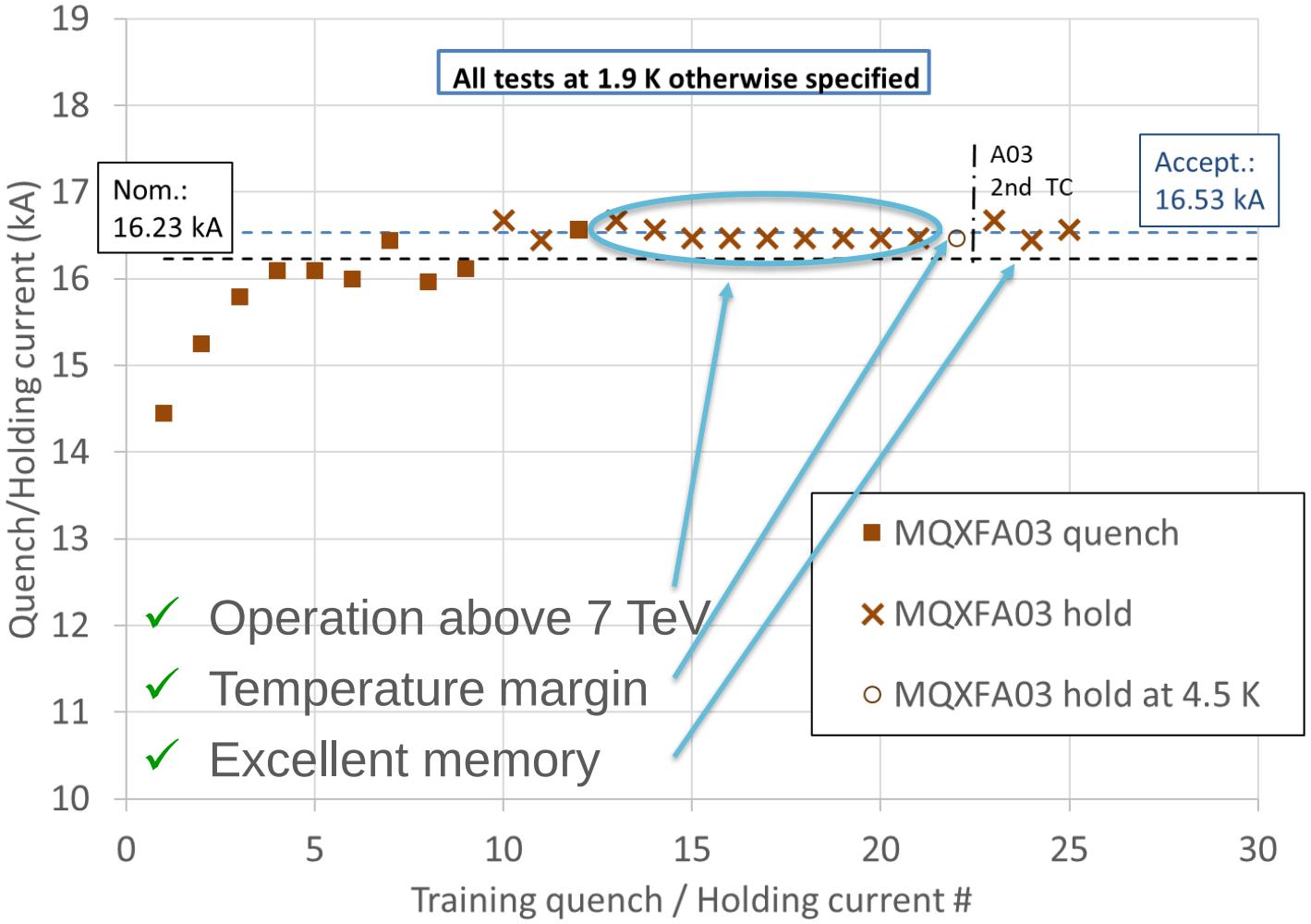


P. Ferracin et al., “Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC ” IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

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

MQXFA Vertical Test at BNL

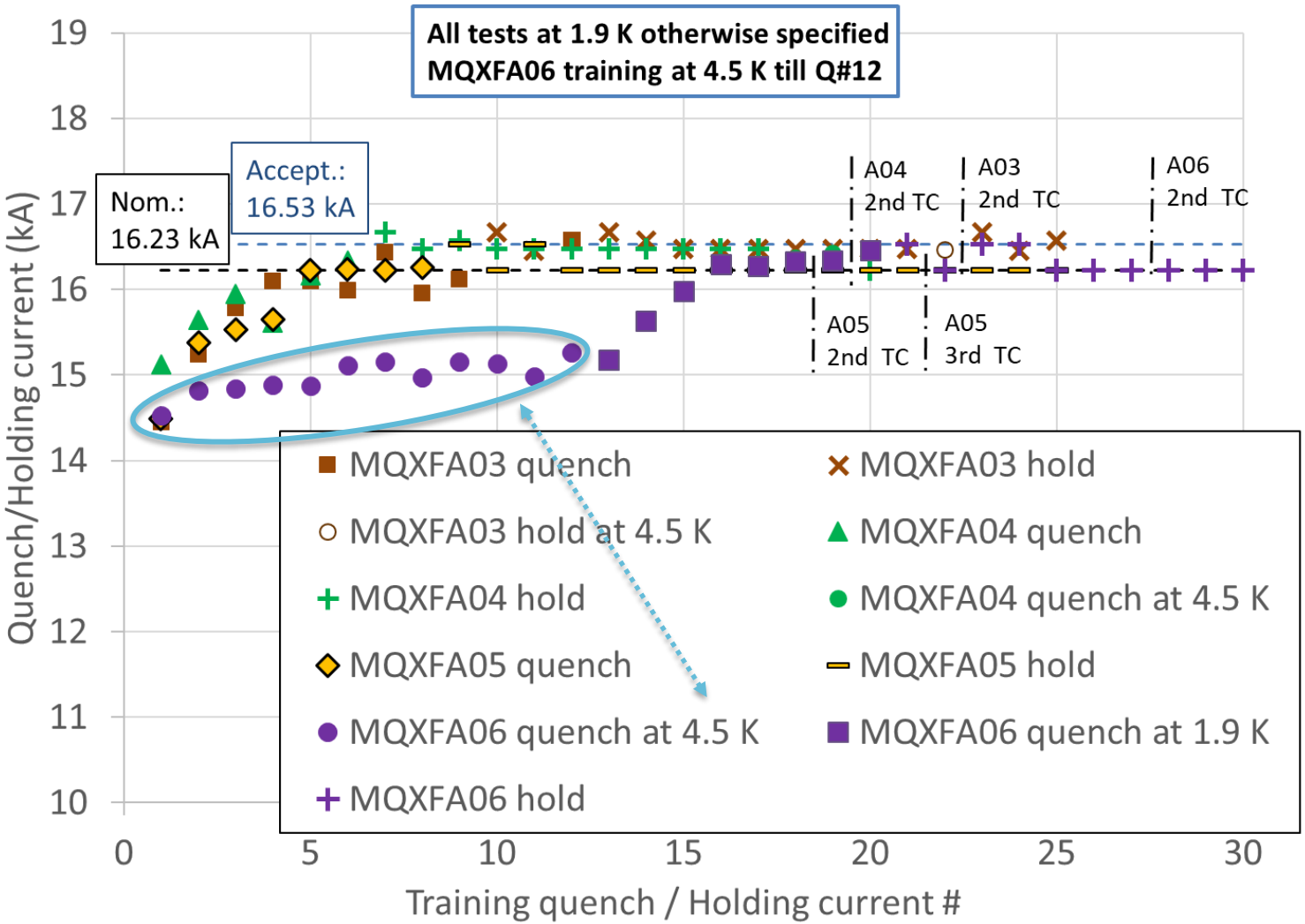
- MQXFA03: 1st pre-series magnet for Q1/Q3



J. Muratore et al., "Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade", IEEE Trans. Appl. Superc. 2021, #4001804

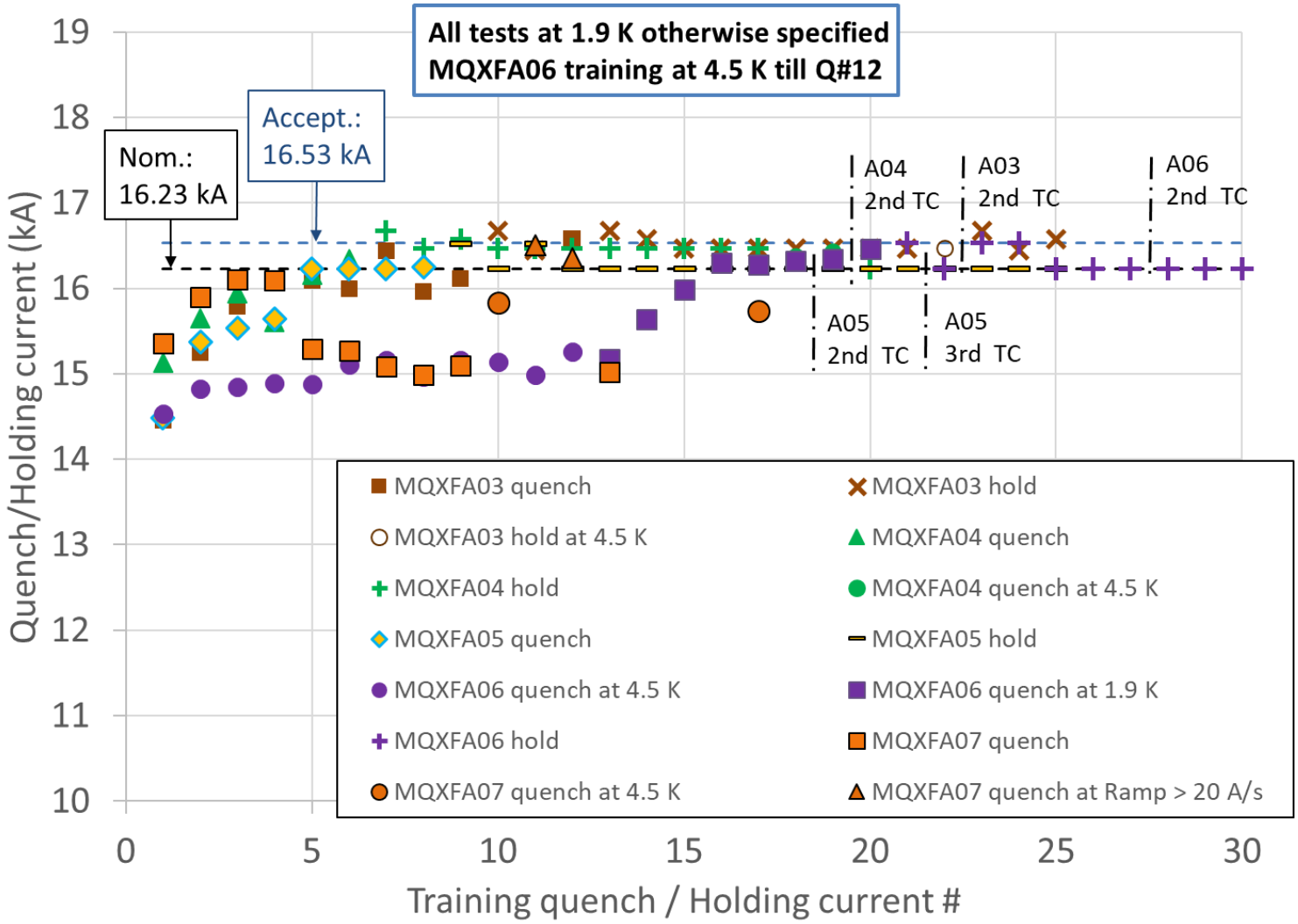
MQXFA magnet being moved to vertical test station at BNL

MQXFA03/4/5/6 Vertical Test



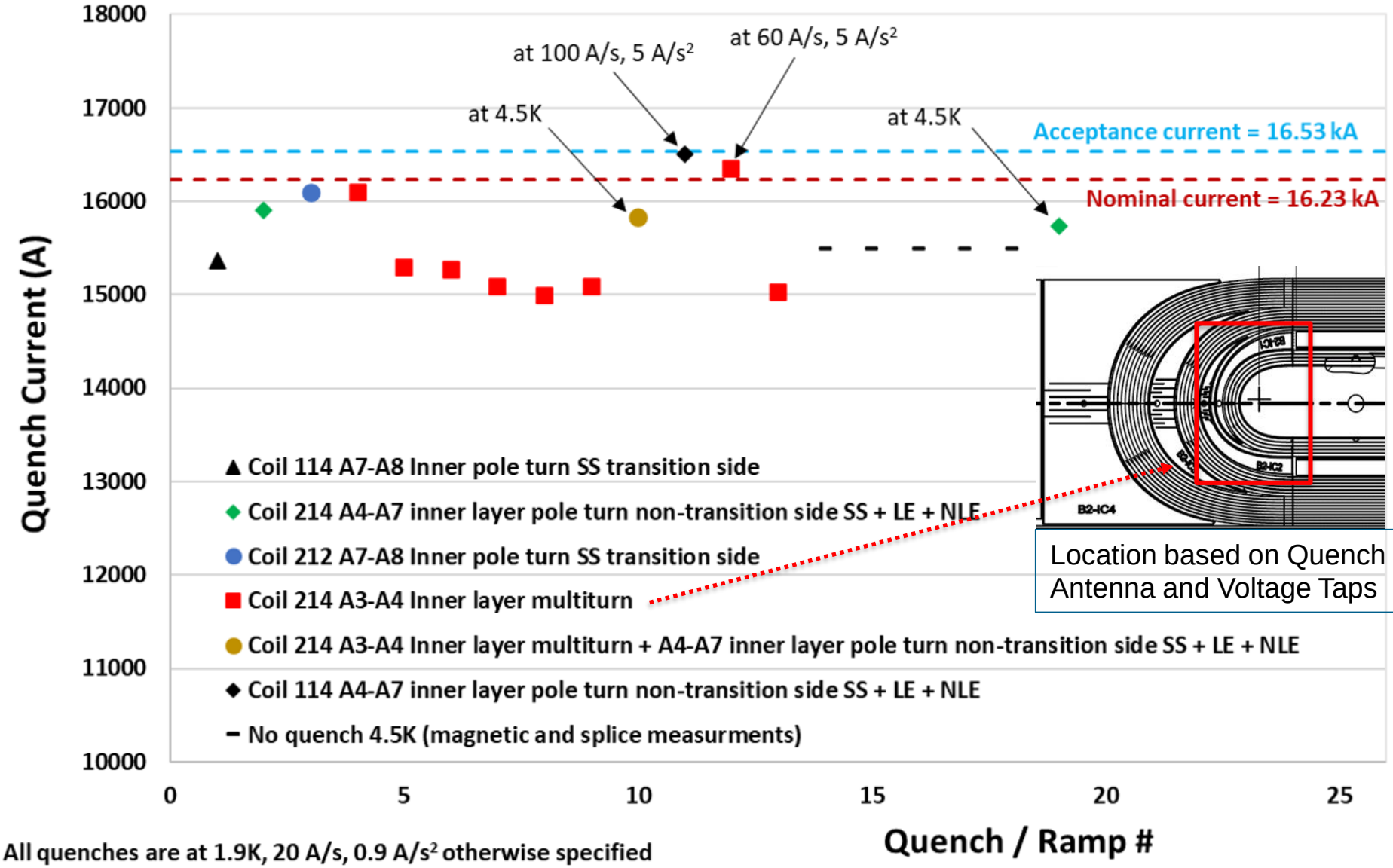
J. Muratore et al., "Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade", IEEE Trans. Appl. Superc. 2021, #4001804

MQXFA03/4/5/6/7 Vertical Test



- 4 successful magnets; 5th limited by one coil

MQXFA07 Training Quenches



Location based on Quench Antenna and Voltage Taps

Courtesy of J. Muratore and A. Ben Yahia

Limitation "Mechanism"

- **Self-field instability** triggered by a **local issue**, likely affecting only some strands, that pushes more current in adjacent strand(s)
  - Field in quenching segment is between 5 and 9.2 T

B. Bordini, et al., IEEE Trans. Appl. Superc., vol. 22, 2012, # 4705804
A. K. Ghosh, IEEE Trans. Appl. Superc., vol. 23, 2013, # 7100407

- Similar mechanism in other magnets:
- MQXFS03 showed a reversible component

H. Bajas et al., "Test Results of the Short Models MQXFS3 and MQXFS5 for the HL-LHC Upgrade", IEEE Trans. Appl. Superc. Vol 28, # 4007006 (2018)

- LARP Long Quadrupole #2 showed "enhanced thermo-magnetic instability" in mid-plane block
  - With flux jumps

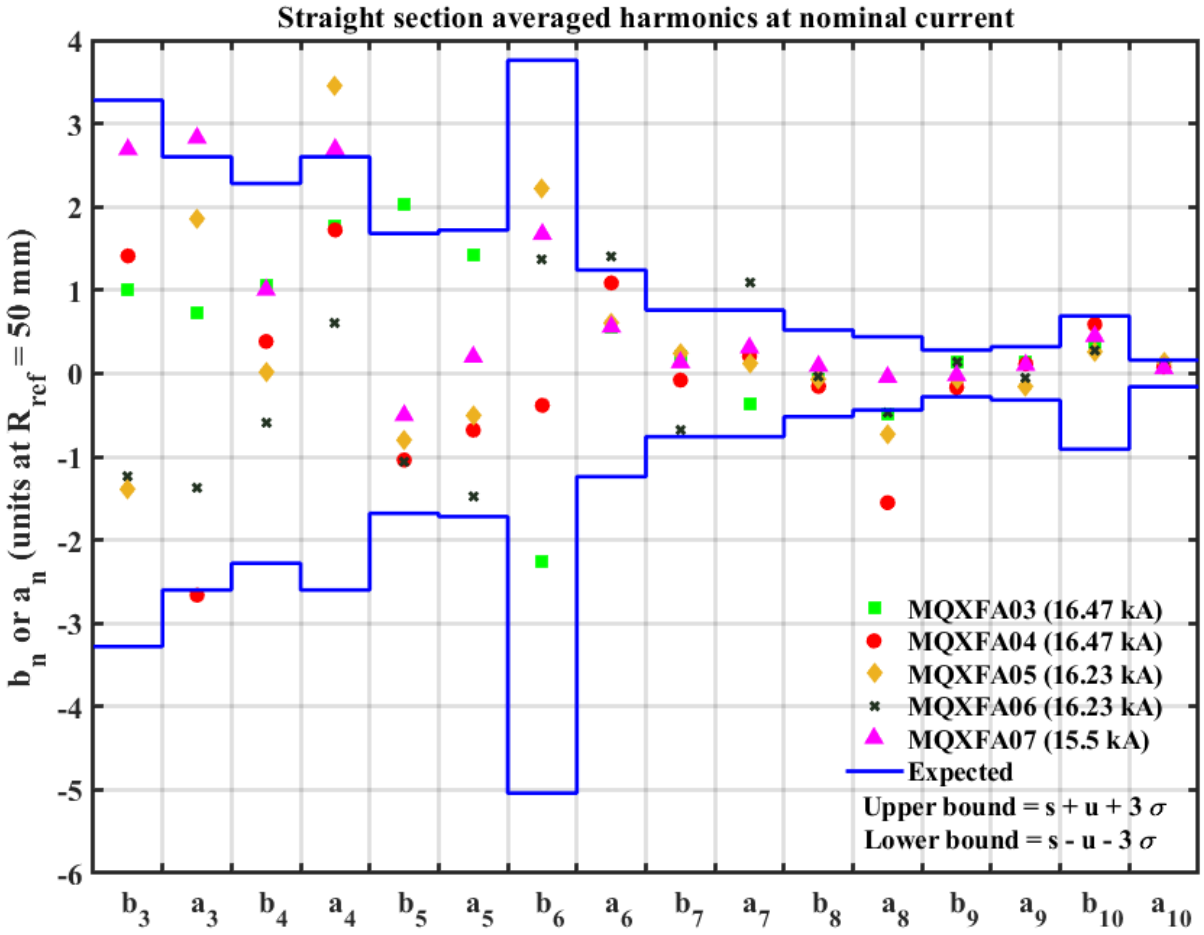
Ref: G. Ambrosio et al., "Progress in the Long Nb_3Sn Quadrupole R&D by LARP", IEEE Trans Appl, Superc. Vol 22, # 4003804 (2012)

Investigation and Plans

- Possible causes of local issue:
  - Some strands popped out during winding, were fixed, popped out overnight and were fixed a second time
  - Limiting coil was affected by COVID lockdown
    - 14 weeks stop after winding & curing of inner layer
  - Axial preload had to be removed in order to fix position of end plate
- We are going to perform CT-scan of both ends (CERN lead*) and micrography analysis
- MQXFA07 will be dis-assembled in order to remove the limiting coil and replace it with a new coil
  - It will be re-assembled and pre-loaded
  - It will be tested in Vertical condition

*Courtesy of S. Sgobba and Bartosz Bulat, CERN

MQXFA03/4/5/6 – Average Straight Section Harmonics at Nominal



Integral harmonics to be measured in Coldmass

Based on short model FQ b6 correction introduced in one coil on MQXFA04 and all subsequent coils: *125 um shift toward midplane*

Magnetic shims used to correct low order harmonics

- Integrated Gradient and Magnetic Length within specs

Vertical Test Summary

- Requirements & Test Goals: **MQXFA03/4/5/6**
  - Hold current at nominal current + 300 A ✓
  - Ramp to/from I_nom at ±30 A/s ✓
  - 100 A/s ramp down w/o quench (max for power supply) ✓
  - Temperature margin ✓
  - Training memory ✓
  - Magnetic measurements ✓
  - Splice resistance (large noise fixed since MQXFA04 test) ✓
  - All electrical requirements ✓
- MQXFA03 and MQXFA04 are being used for the assembly of the 1st LMQXFA Cold Mass

S. Feher, et al., "AUP first pre-series Cryo-Assembly Design Production and Test Overview" - WED-OR2-103-02

Conductor @ FSU, LBNL, FNAL

- Conductor for cables in baseline is ~**90% received**
  - Out of 2500 km
  - Order for additional conductor (8 cables = 160 km) is in progress
- A few issues were successfully addressed by Corrective and Preventive Actions, and audits:
  - Some spools that were reworked received extra lubricant, and impacted cable mechanical stability
- Strand procurement and QC are on schedule
- Cable Fabrication is **74% complete**
  - Out of 104 cables to be fabricated and insulated
  - Yield is **92.2%** (3 rejected, 6 on-hold), vs. 90% assumed
    - Cables on-hold because of strand lubrication issue causing cable mechanical instability
  - ➔ **Lesson Learned: protective oil amount must be controlled**
- Cables are a bit behind schedule w/o impact on coil fabrication

Coil Fabrication @ BNL & FNAL

	Coils at FNAL	Coils at BNL	Total
Accepted*	**22**	**21**	**43**
In Fabrication	6	5	11
Rejected	3	2	5
On Hold	4**	2	6**
Total	**35**	**30**	**65**

- Coil fabrication is **58% complete** (out of 100 coils)
- Coil Fabrication yield is: 86.1%
  - * Accepted for shipment to LBNL for Magnet Assembly
  - ** 1 coil on hold for COVID related issue
- Overall Coil Yield after fabrication, magnet integration & magnet vertical test: **83.5%**
  - **Lessons Learned** from Pre-Series coils included: coil yield lower than assumed, robust electrical design and process

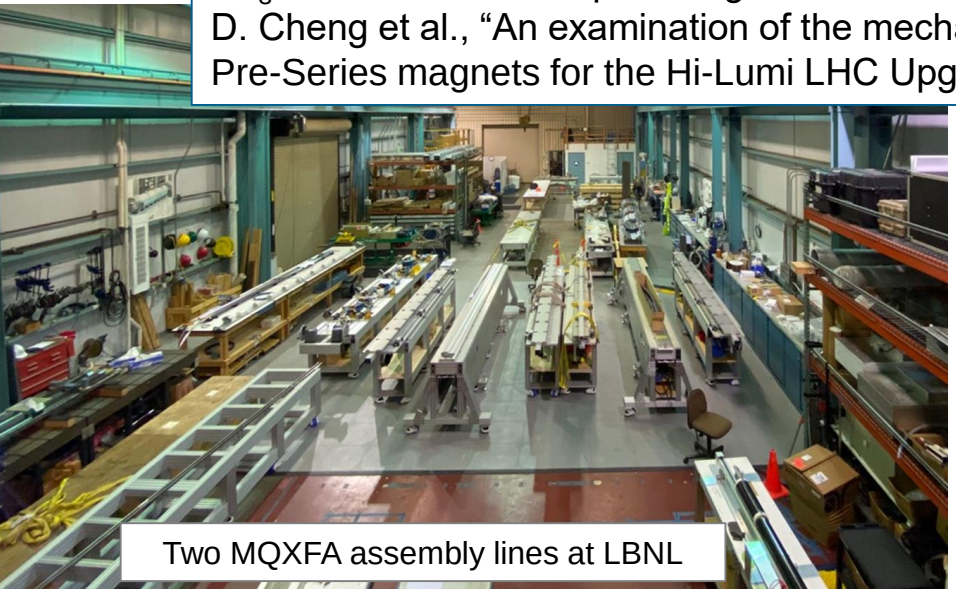
US HL-LHC AUP

G. Ambrosio et al., "Lessons learned from the prototypes of the MQXFA Low Beta Quadrupoles for HL-LHC and status of production in the US", IEEE Trans Appl, Superc. Vol 31, # 4001105 (2021)

MQXFA Structure & Magnet Assembly @ LBNL

- Assembly of MQXFA09 and MQXFA10 are in progress.
  - Both assembly lines are fully operational (staggered mode)
  - MQXFA07 disassembly will start after MQXFA09 is complete
- **Lessons Learned:** tight QC to avoid structure issue.
- **Assembly and pre-load specifications** based on FE analysis, short models and prototypes

P. Ferracin et al., "Assembly and Pre loading Specifications for the Series Production of the Nb_3Sn MQXFA Quadrupole Magnets for the HL LHC" – THU-PO3-112-06
D. Cheng et al., "An examination of the mechanical performance of the 4.5 m long MQXFA Pre-Series magnets for the Hi-Lumi LHC Upgrade" - THU-PO3-112-01



Two MQXFA assembly lines at LBNL

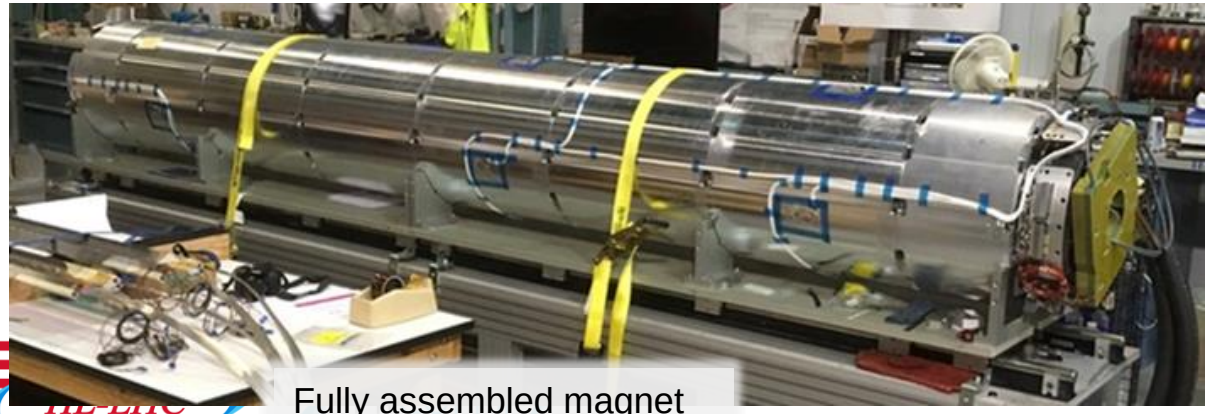
MQXFA shell-yoke assembly in process

MQXFA Yield Assumptions and Actual

- All magnet fabrication steps are at **peak production rate**
- Yield assumptions based on LARP program:

	Cable Fabr. & Insulat.	Coil Fabrication	Total Coil Yield*	Magnet Vert. Test
Yield assumption	90%		87.5%	80%
Actual yield	92.2%	86.1%	83.5%	80%
% complete	74%	58%		25%

* Including magnet assembly and vertical test



Fully assembled magnet

Coil after epoxy impregnation

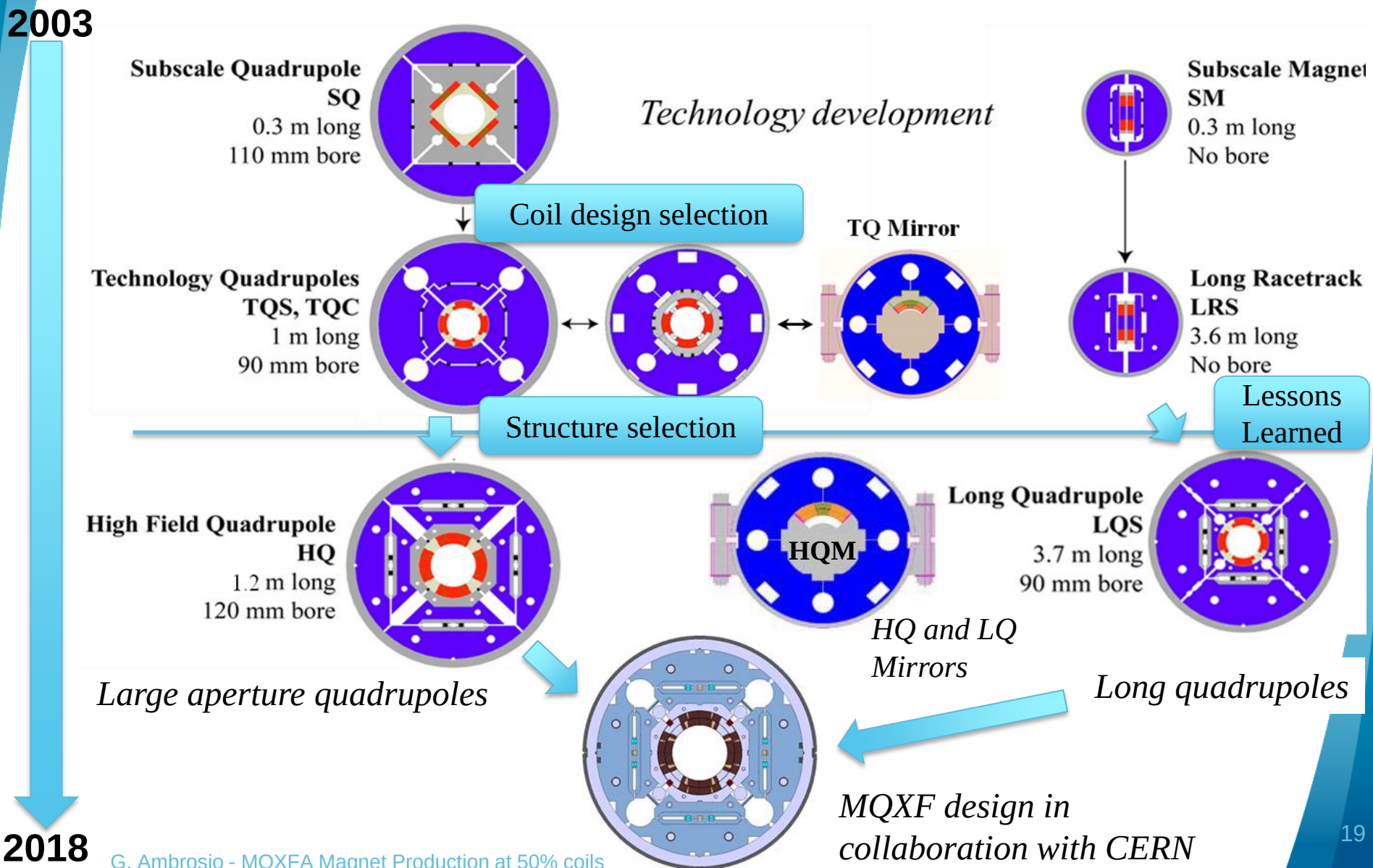
Conclusions

- The fabrication of MQXFA (HL-LHC low-beta quad) magnets by US-AUP has reached peak production rate in summer 2021
- Yields of magnets up to MQXFA07 and sub-components are consistent with AUP assumptions
- Additional conductor and coil parts are under procurement in order to be able to fabricate additional cables and coils if needed
- Last magnet to be completed around end of 2023

Back up Slides

Model Magnet Development Chart (by LARP)

Started from simple configurations directed at basic technology studies and progressed to incorporate all requirements for operation in the accelerator

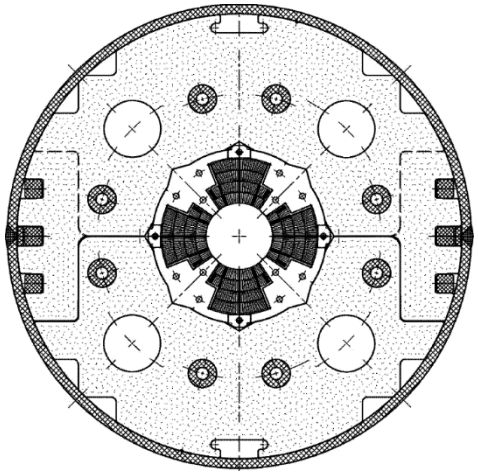


Low-β quadrupole magnets from LHC to HL-LHC

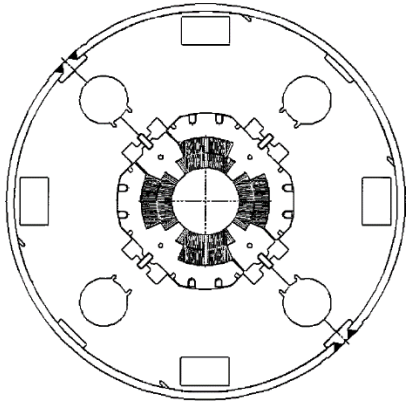
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

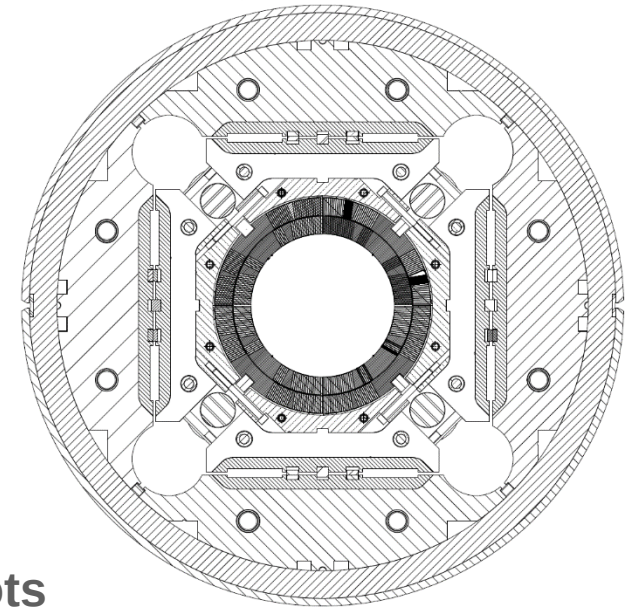
MQXA



MQXB



MQXF



Same scale for all 3 plots