First Experience with Nb_3Sn Accelerator Magnets

Giorgio Ambrosio,

with contributions from MQXFA and MQXFB teams

Acknowledgement

- 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, E. Lee, M. Marchevsky, M. Naus, H. Pan, 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
  - A. Ballarino, H. Bajas, M. Bajko, B. Bordini, N. Bourcey, J.C. Perez, S. Izquierdo Bermudez, S. Ferradas Troitino, L. Fiscarelli, J. Fleiter, M. Guinchard, O. Housiaux, F. Lackner, F. Mangiarotti, A. Milanese, P. Moyret, H. Prin, R. Principe, E. Ravaioli, T. Sahner, S. Sequeira Tavares, E. Takala, E. Todesco

High Luminosity LHC (HL-LHC)

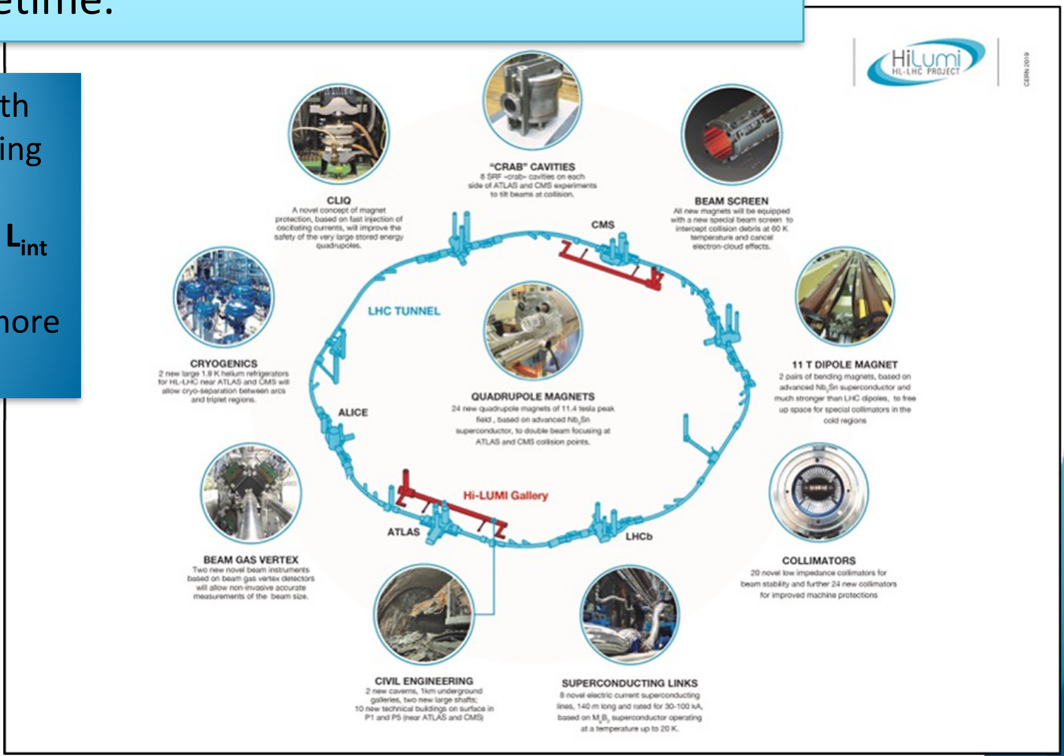
The main objective of HiLumi LHC Design Study is to extend the LHC lifetime by **another decade** and to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

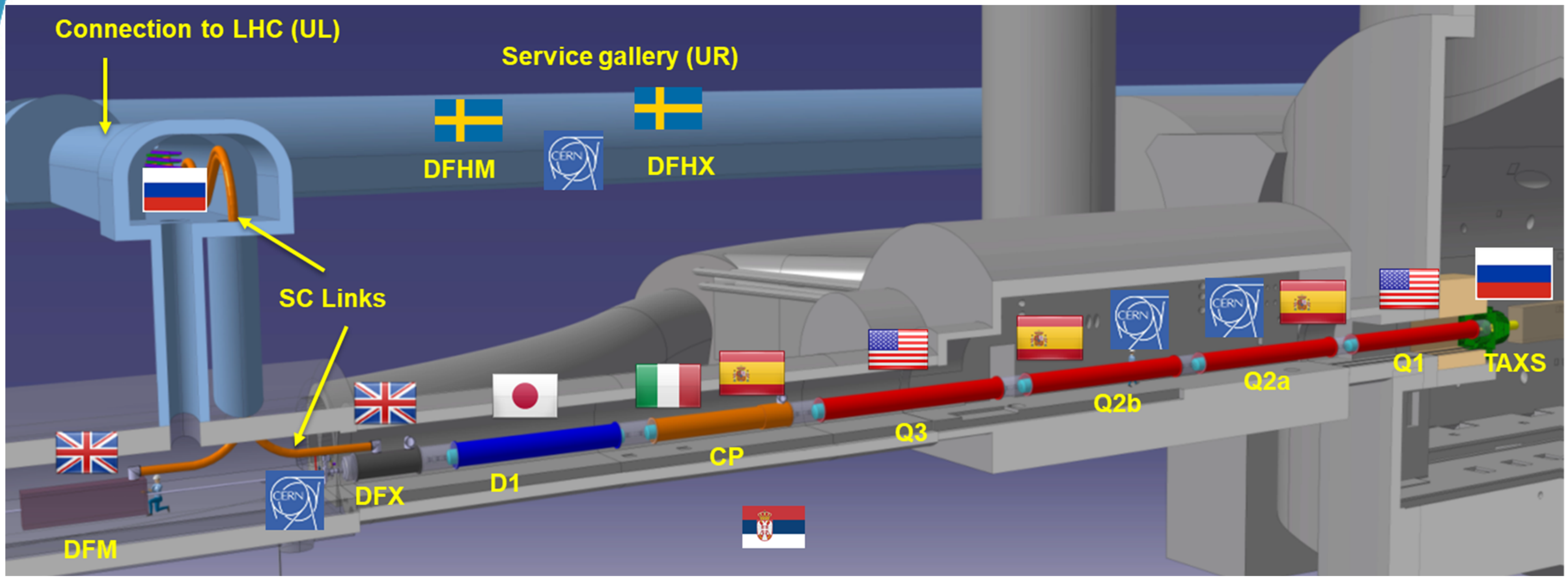
An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016. With same hardware and same beam parameters, by using **engineering margins:**
$L_{peak\ ult} \cong 7.5\ 10^{34}\ cm^{-2}s^{-1}$ and **Ultimate Integrated $L_{int\ ult} \sim 4000\ fb^{-1}$**
LHC should not be the limit, would Physics require more than nominal

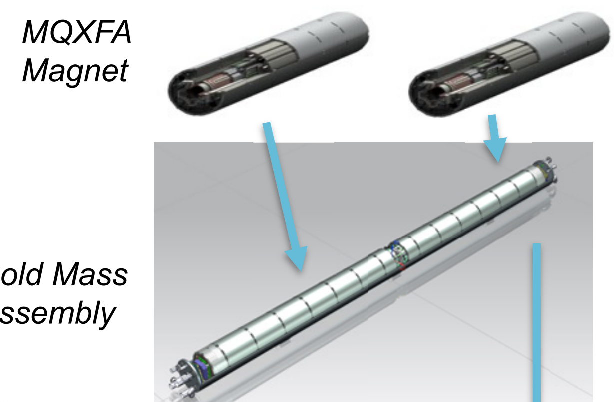
Project approved by CERN Council in June 2016

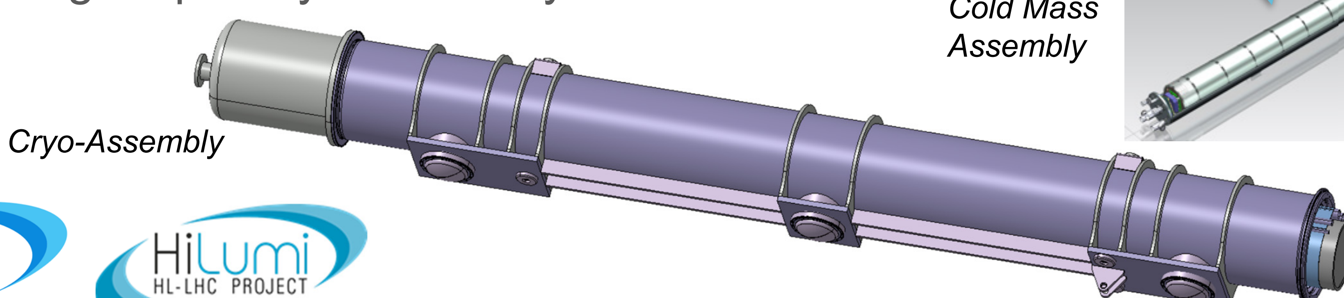


Inner Triplet @ ATLAS and CMS



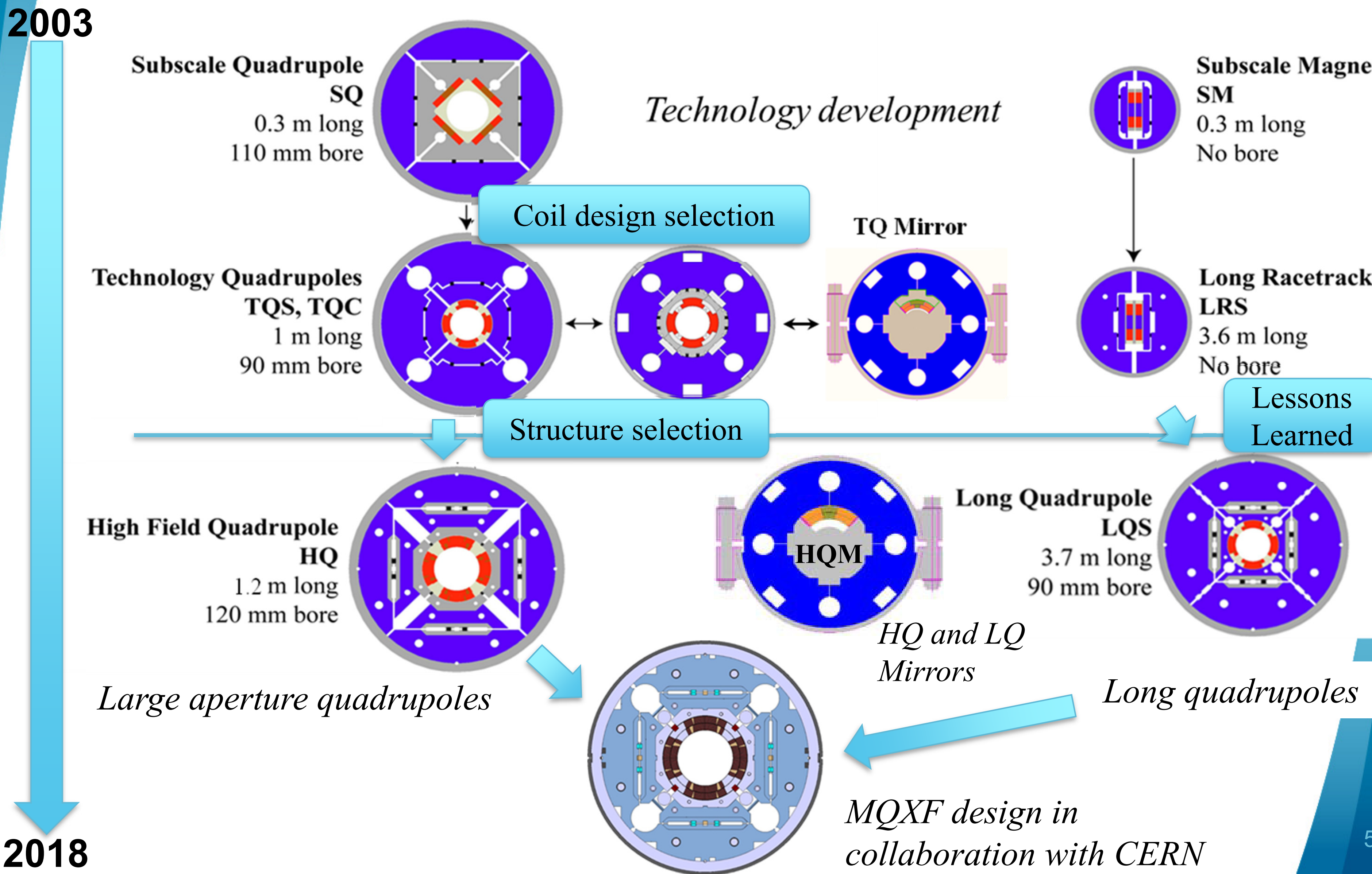
- US-AUP: Q1 and Q3 (8 + 2 spare)
  - 2 magnets per cryo-assembly
- CERN: Q2a and Q2b
  - 1 magnet per cryo-assembly





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

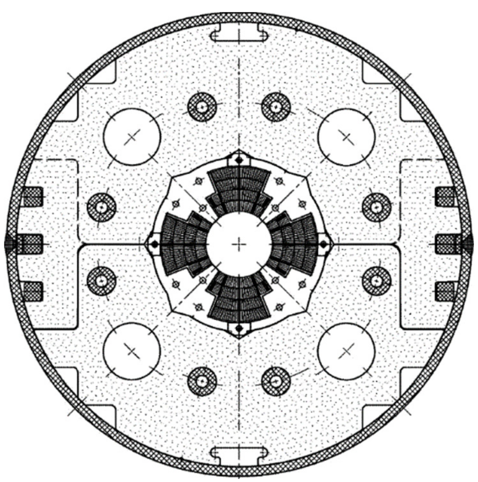


Low-β quadrupole magnets from LHC to HL-LHC

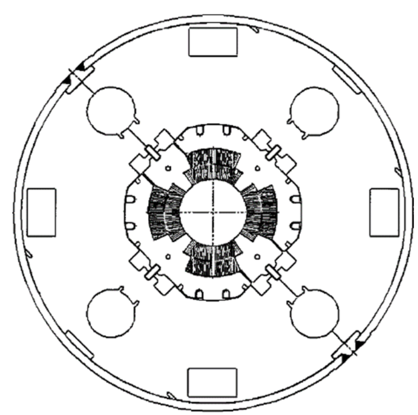
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

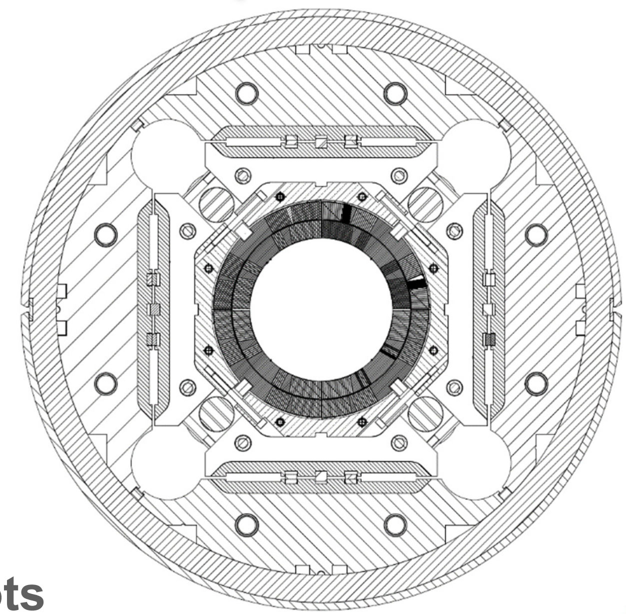
MQXA



MQXB



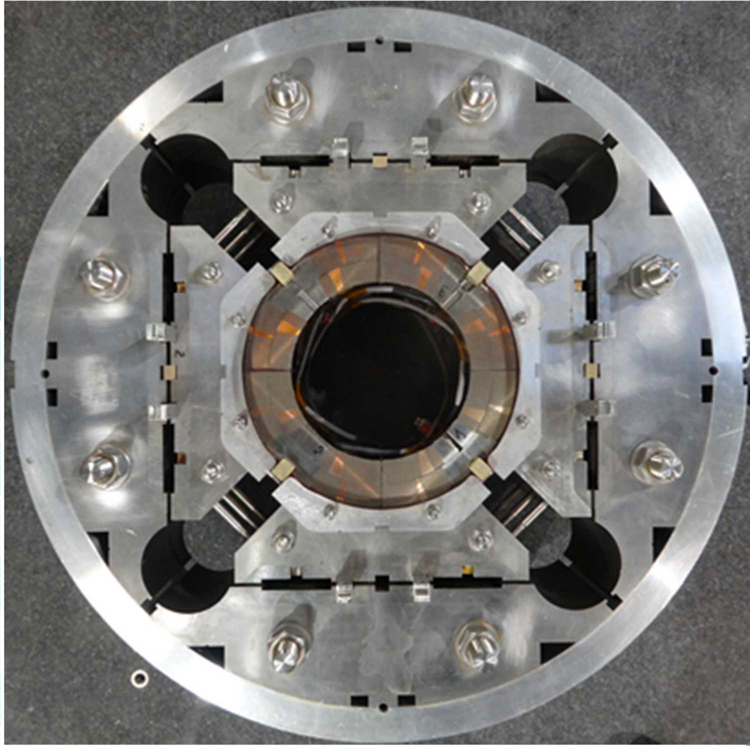
MQXF

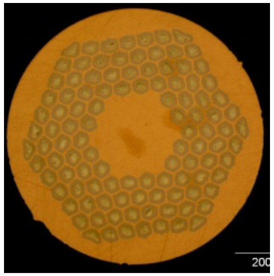


Same scale for all 3 plots

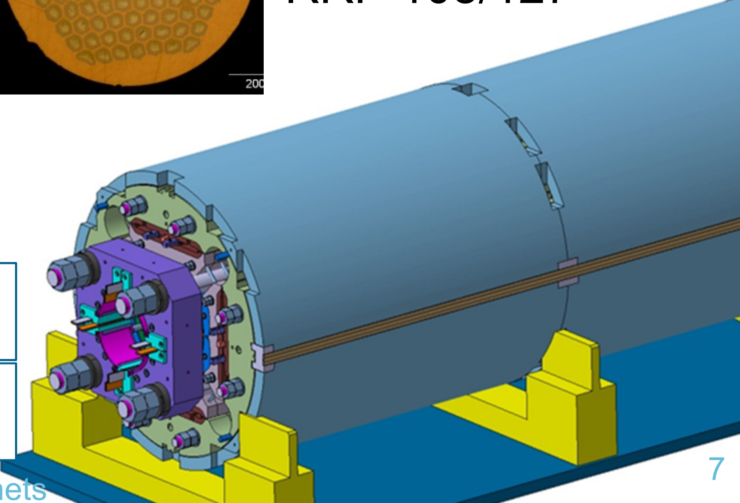
MQXFA/B Design

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

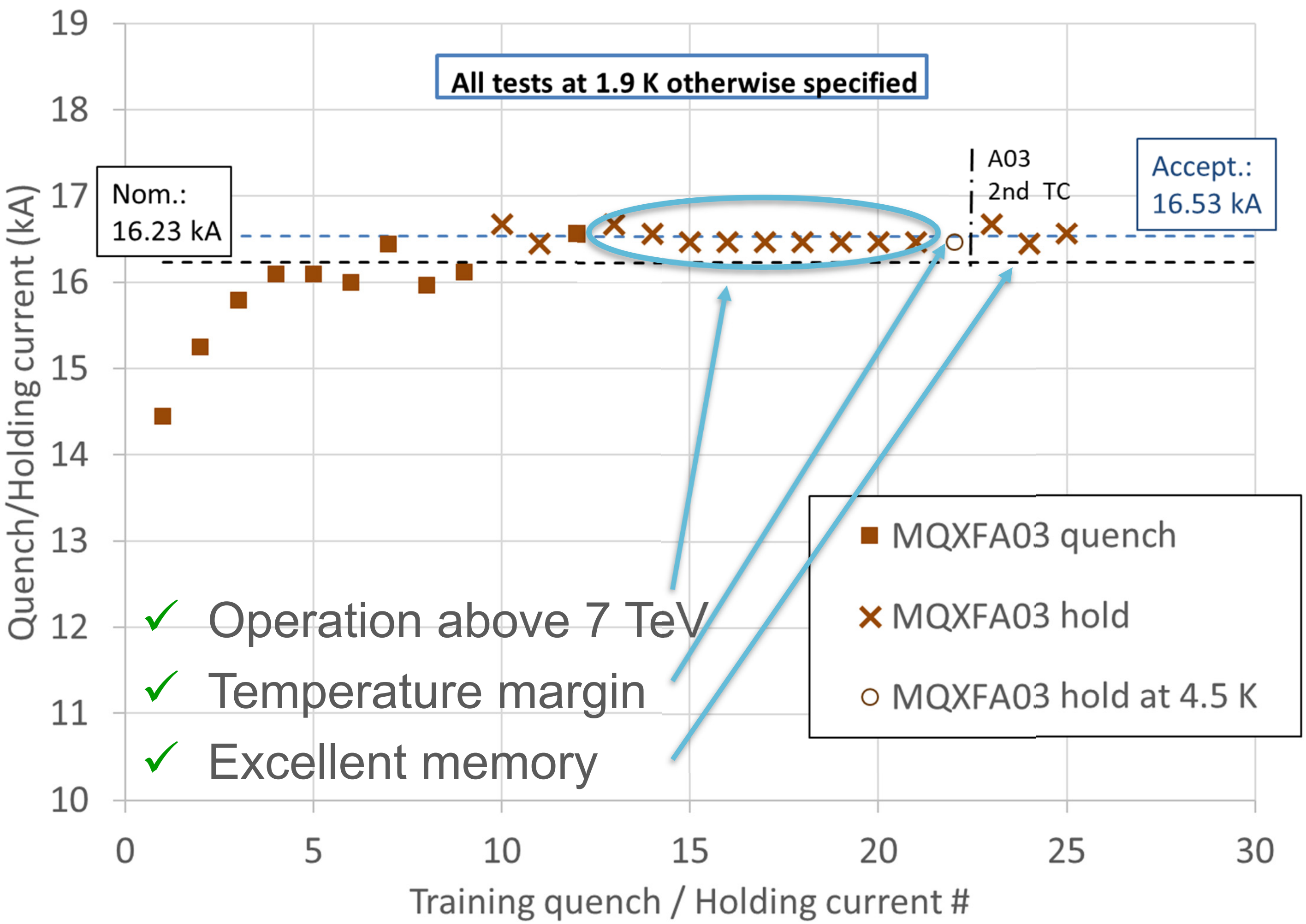


P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

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

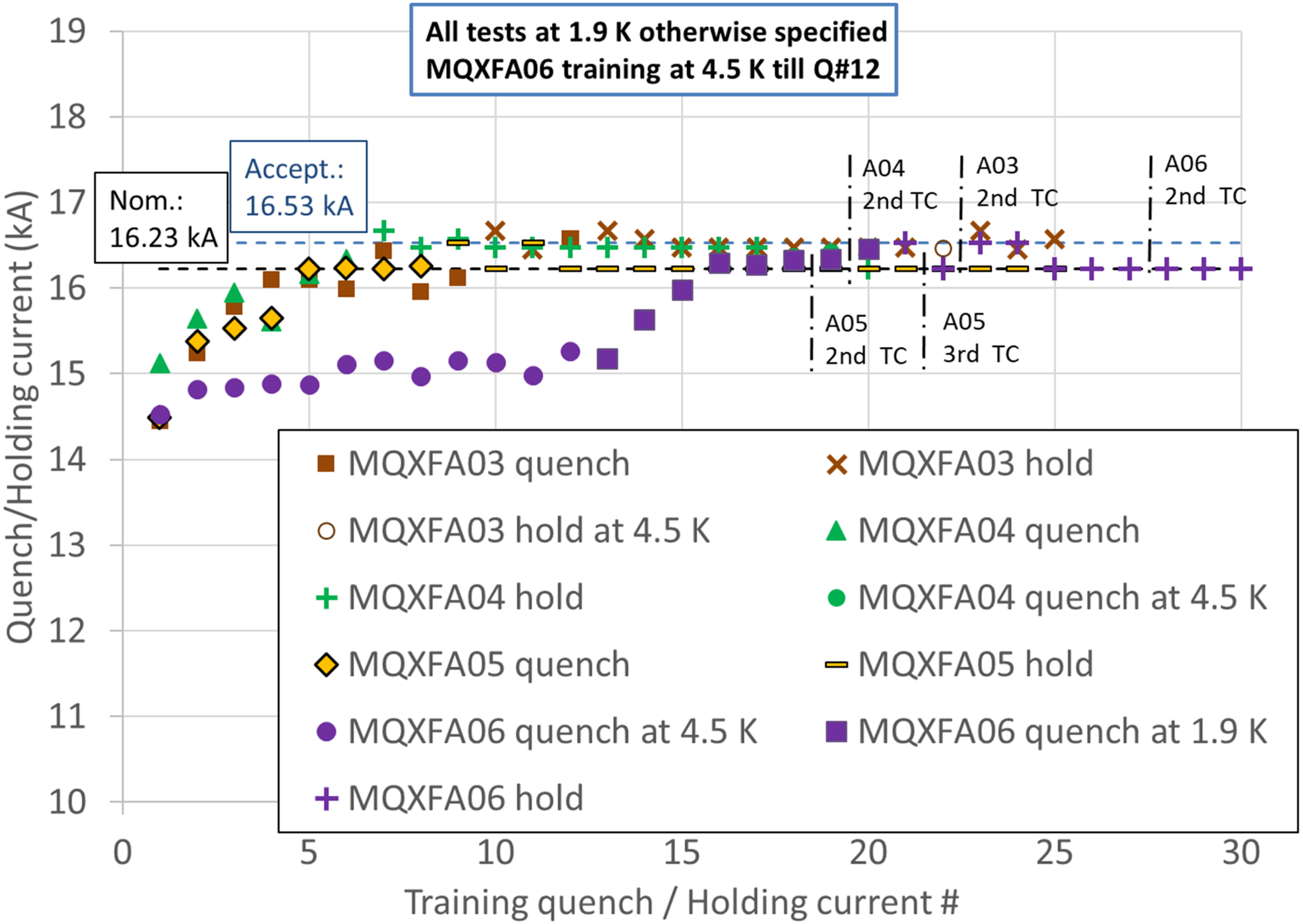
MQXFA Vertical Test

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

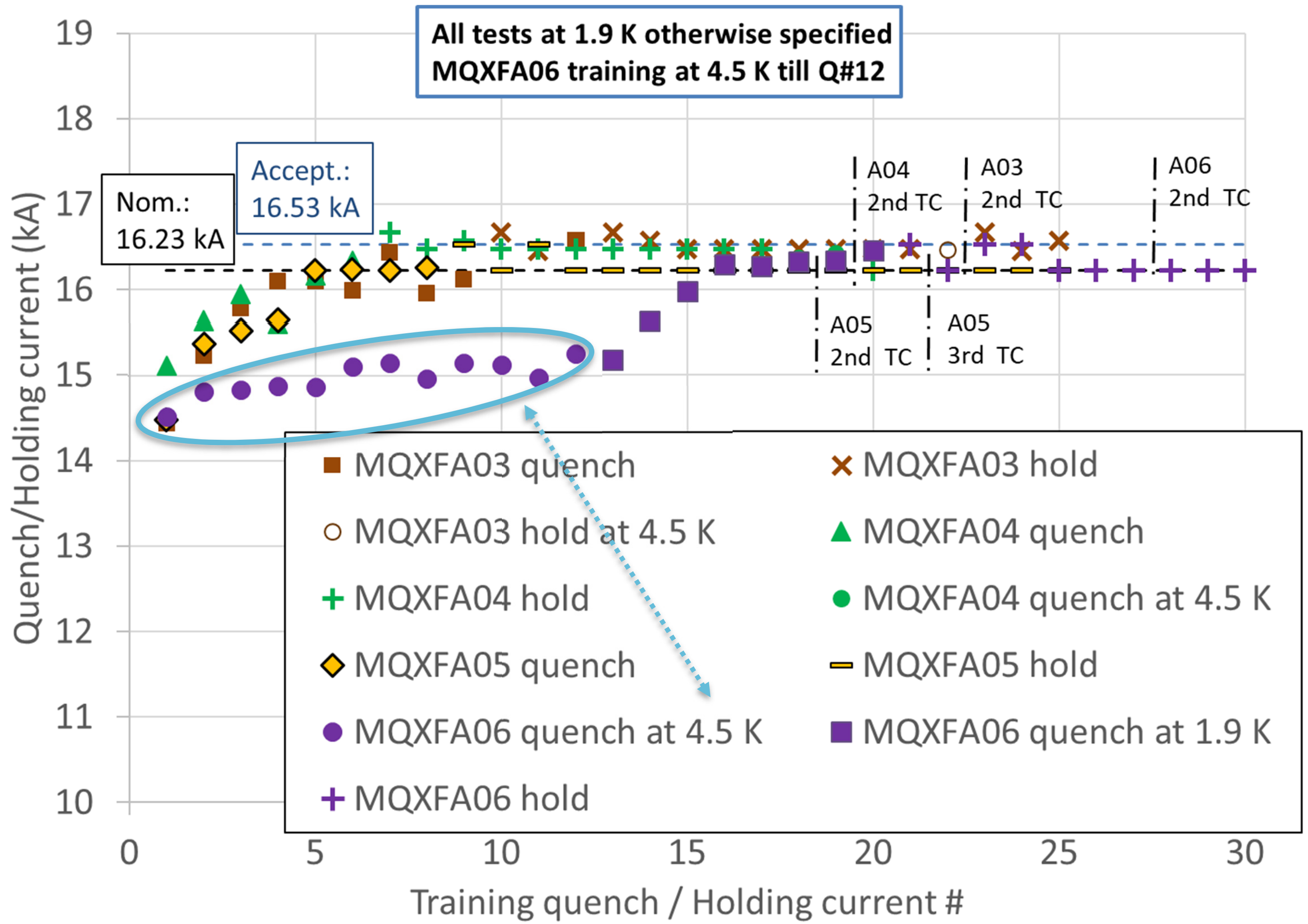


J. Muratore et al., "Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade", IEEE Trans. Appl. Superc. 2021, #4001804

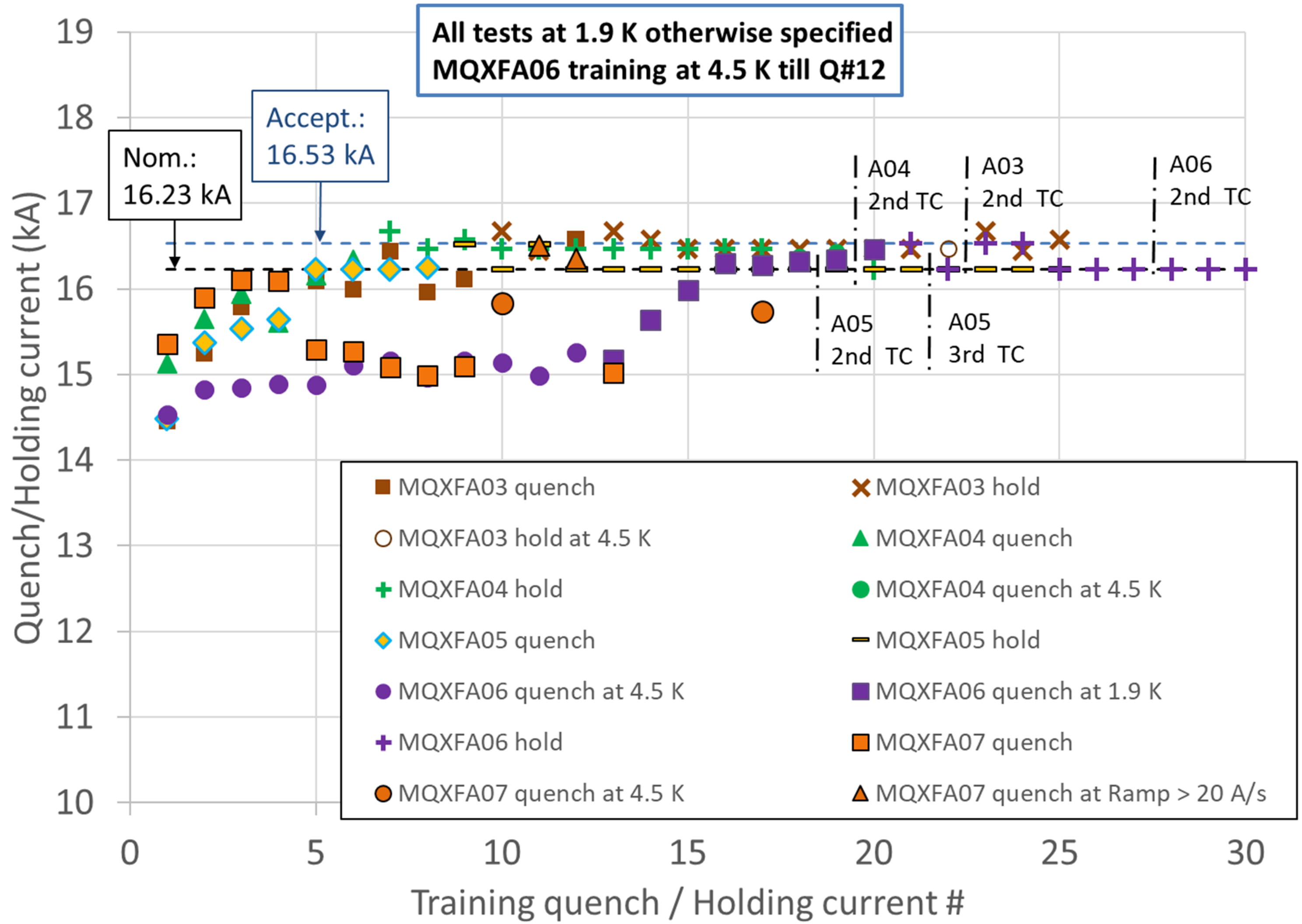
MQXFA03/4/5/6/7 Vertical Test



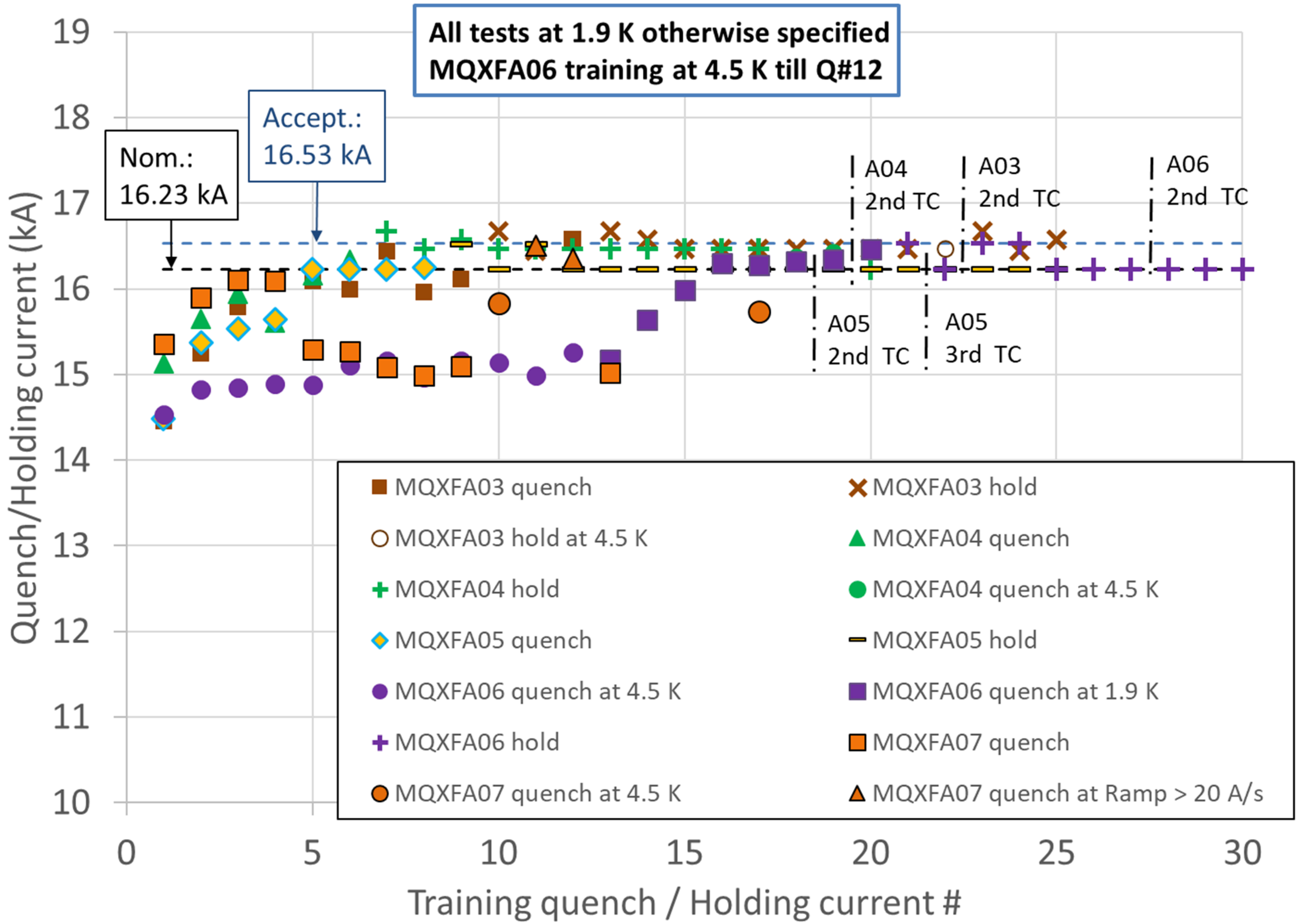
MQXFA03/4/5/6/7 Vertical Test



MQXFA03/4/5/6/7 Vertical Test



MQXFA03/4/5/6/7 Vertical Test



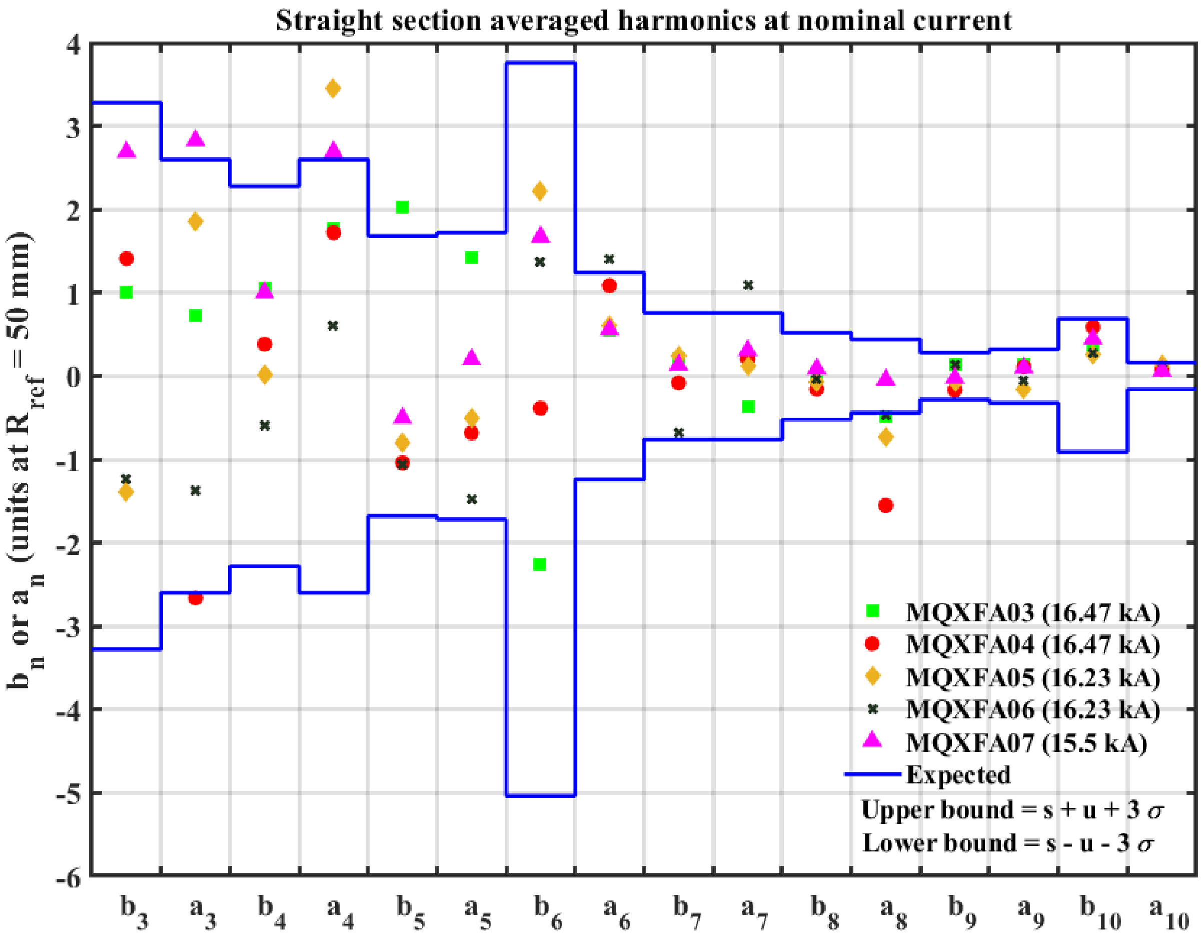
- 4 successful magnets; 5th limited by one coil

Plans for MQXFA07 → MQXFA07b

- MQXFA07 is limited by one coil
- It 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

- AUP Baseline assumes that 4 magnets out of 20 are going to fail the 1st vertical test
- Limiting coil was affected by COVID lockdown
  - 14 weeks stop during fabrication
  - We are going to perform tomography (CERN lead)

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 ✓
  - Temperature margin ✓
  - Training memory ✓
  - Magnetic measurements ✓
  - Splice resistance ✓
  - All electrical requirements ✓
- MQXFA03 and MQXFA04 are being used for the assembly of the 1st LMQXFA Cold Mass

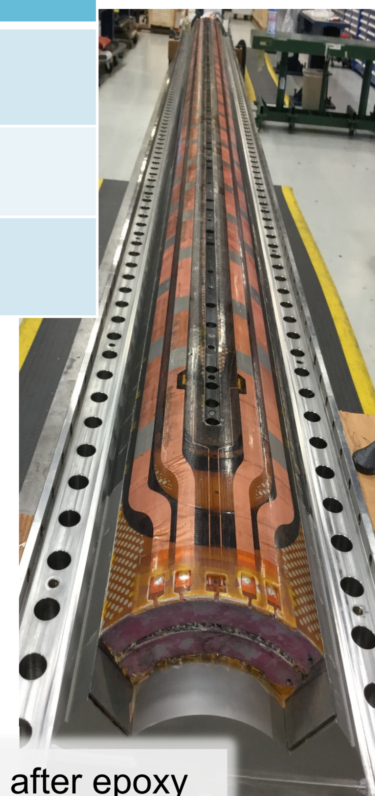
MQXFA Yield Assumptions and Actual

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

	Cable Fabr. & Insulation	Coil Fabrication	Total Coil Yield*	Magnet Vertical Test
Assumption	90%		87.5%	80%
Actual	92.1%	87.2%	84.5%	80%
% complete	73%	55%		25%

* Including magnet assembly and vertical test

Fully assembled magnet



Coil after epoxy impregnation

MQXFB at CERN

- MQXFB magnets are too long for vertical test
- Two MQXFB prototypes have been tested in temporary cryo-assembly:
  - MQXFBP1 was limited around 15 kA due to degradation in the center of a coil
  - MQXFBP2 reached ~nominal current w/o margin
- In both magnets the cold-mass provided additional prestress to the coils;
- ➔ Cold-mass specifications were changed in order to minimize additional prestress
- Assembly of third prototype is in progress

Main Lessons Learned

- LARP used lower Hipot voltages than AUP

→ *Estimate peak voltages as early as possible*

- Design Criteria were not finalized before Prototypes

→ *Finalize Design Criteria (Structural, Electrical, …) as early as possible*

- "Learning curve" with low coil yield was longer than prototyping phase

→ *Equipment changes from short to long coils and larger technician number may negatively affect coil yield in the early phase of production*

US HL-LHC AUP

HiLumi HL-LHC PROJECT

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. Superconductivity, 2021, #4001105

LL: Step before Large Scale Production

- *Before scaling up production by one or two orders of magnitude an intense effort should be spent to develop 2nd generation Nb_3Sn coil fabrication technology for accelerator magnets,*
- Goal: Cost reduction
  - Significant reduction of touch labor.
- Automation may be part of the solution, nonetheless, preparation for this step will require significant effort and extended time.
  - The development of the present technology took about 20 years.

Conclusions

- The fabrication of MQXFA (HL-LHC low-beta) magnets by US-AUP is at peak production rate
- Yields of magnets and sub-components are consistent with AUP assumptions
- **We are demonstrating that Nb_3Sn magnets are a viable option for particle accelerators**
- The development of 2nd generation Nb_3Sn coils & magnets is needed before large scale production