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First results of AUP Nb_3Sn quadrupole horizontal tests

Maria Baldini on behalf of the HL-LHC AUP team

Fermi National Accelerator Laboratory

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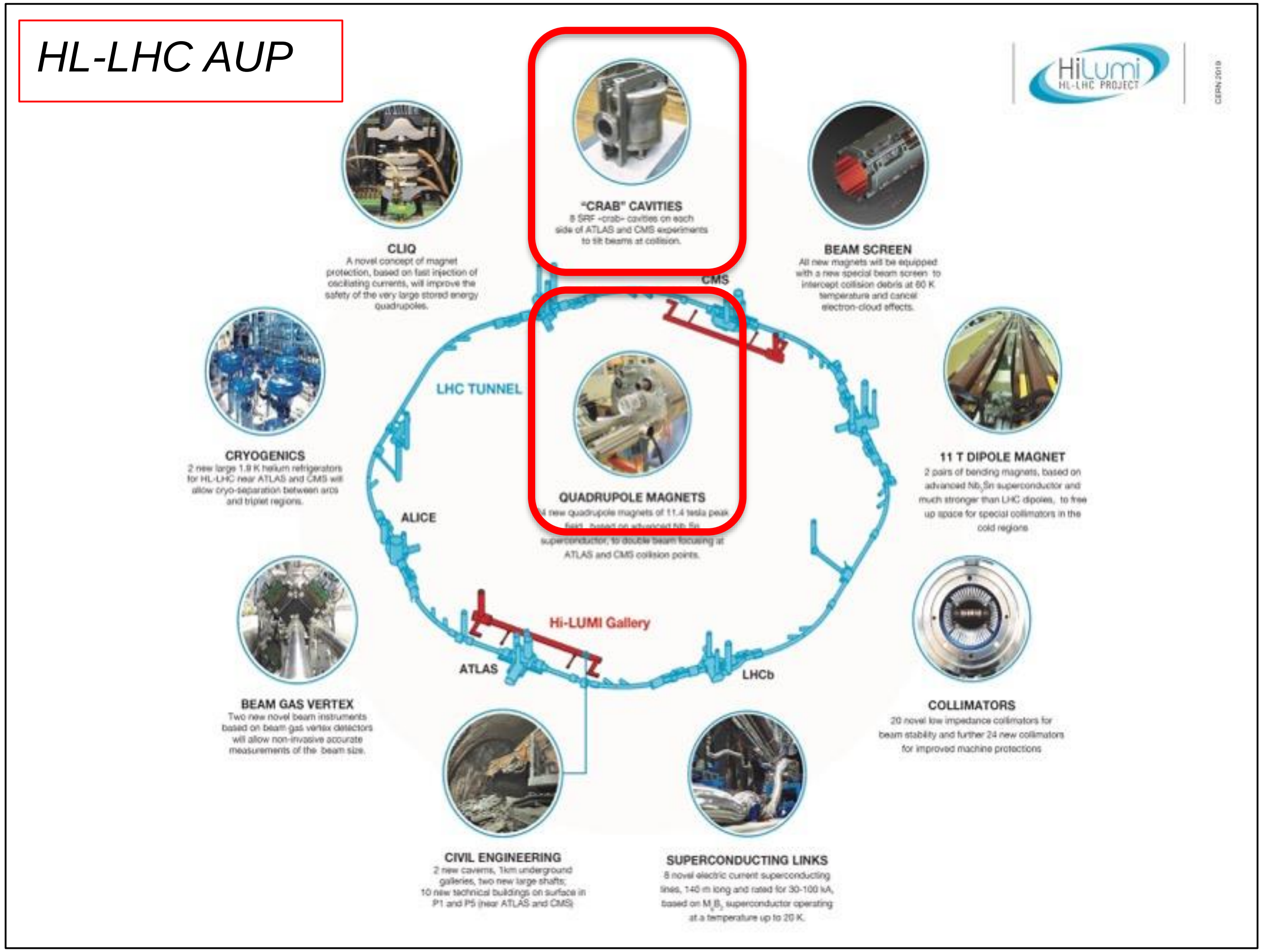
- All the work performed by many technicians across the three labs

Outline

- The HL-LHC AUP project
- A journey from Nb_3Sn strand to Cryo-assembly
- Status of the AUP project
  - MQXFA superconducting magnets
  - Lesson learned
- The first LQXFA Cryo-assembly
  - Quench Test Results and Issues
- Summary and Conclusions

US Contribution to HL-LHC

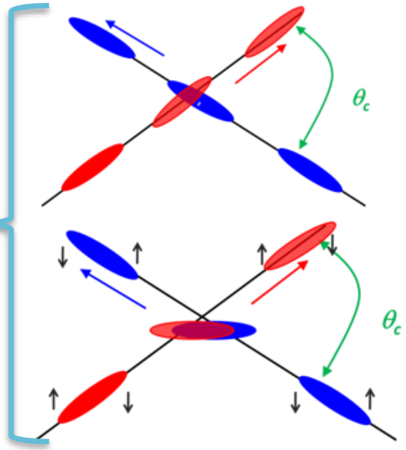


Quad Magnets

$$L = \gamma \frac{f_{rev}\, n_b\, N_b^{\,2}}{4\pi \varepsilon_n \beta^*} R$$

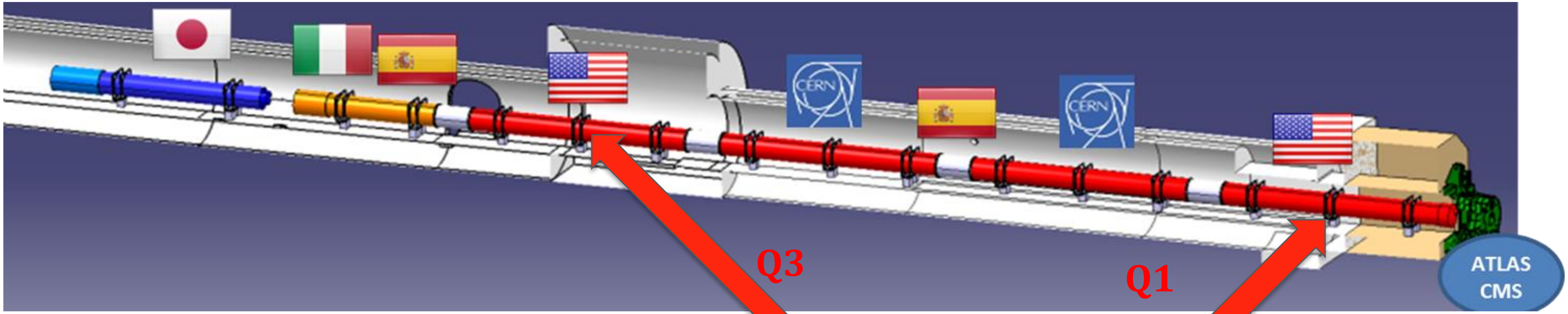
Beam size

Crab Cavities

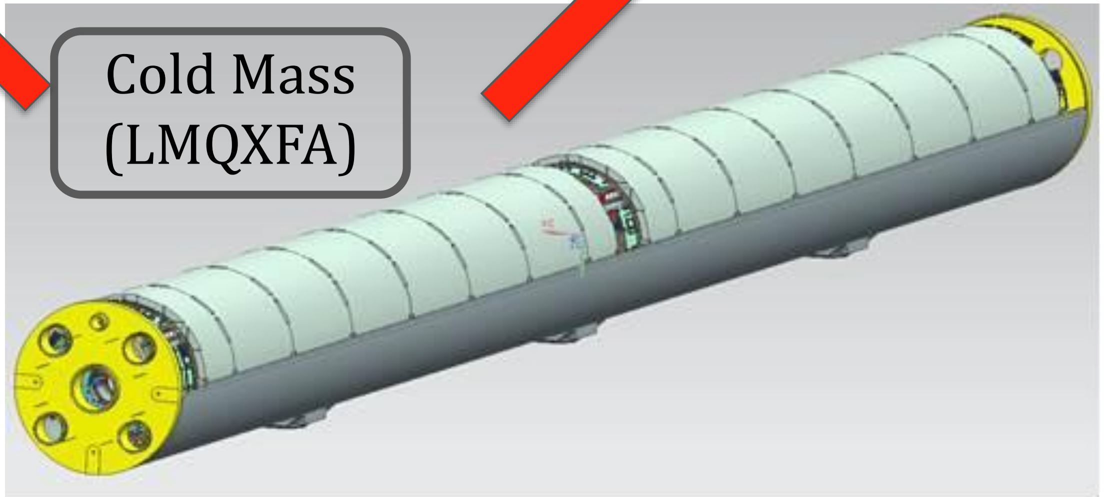


- HL-LHC: from 300 fb^{-1} to 3000/4000 fb^{-1}

MQXFA = US Quadrupoles for HL-LHC



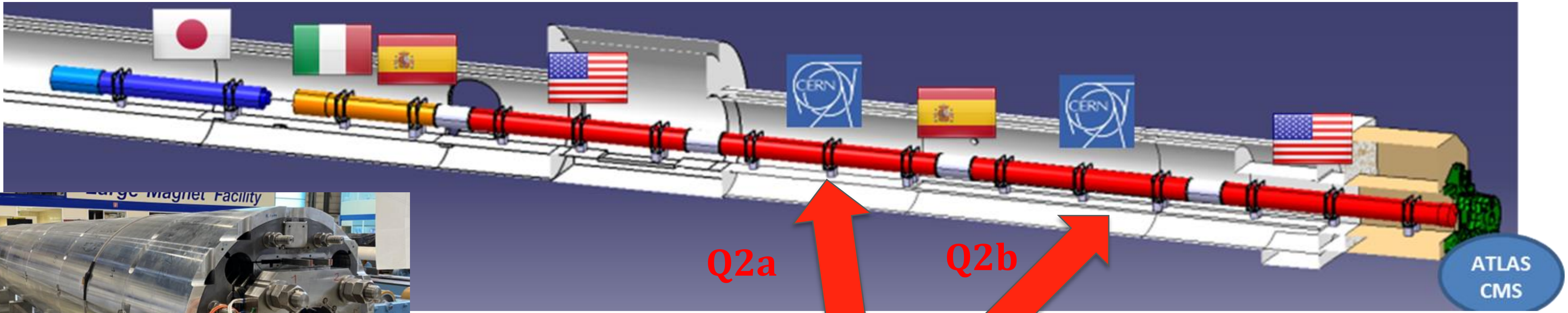
Magnet (MQXFA)

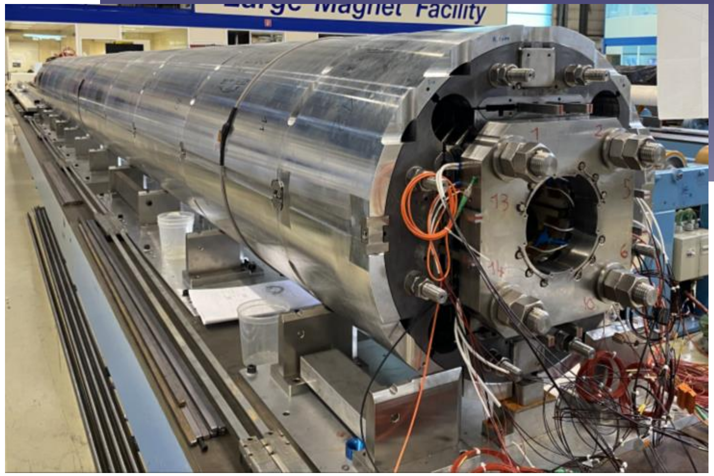


Cold Mass (LMQXFA)

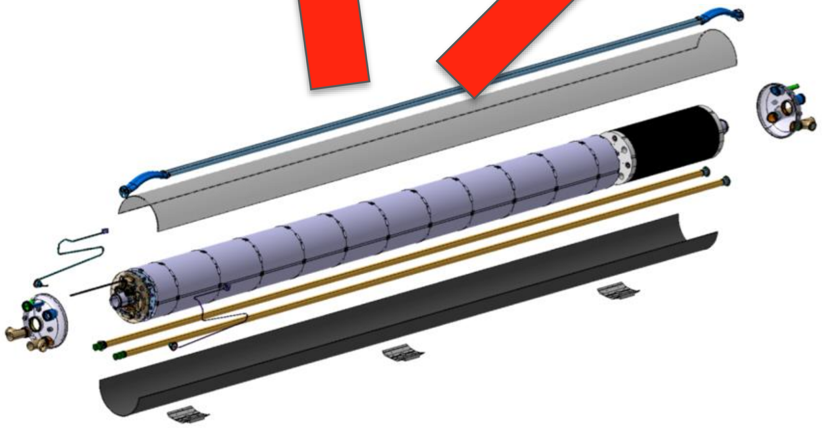
- **20 Magnets/ 10 Cryo-assemblies:**
- 16 magnets for 8 Q1/Q3 to be installed in LHC tunnel and 4 magnets for 2 Q1/Q3 commissioning spares

MQXFB = CERN Quadrupoles for HL-LHC





Magnet (MQXFB)



- **MQXFB Cryo-assembly:**
- 7 m long Nb_3Sn quadrupole
- Same cross section of MQXFA magnet

poster WEPS64

Courtesy of S. Izquierdo

E Todesco *et al*, The High Luminosity LHC interaction region magnets towards series production, *Supercond. Sci. Technol.* 34 053001, 2021

S. I. Bermudez *et al*., "Performance of a MQXF Nb_3Sn Quadrupole Magnet Under Different Stress Level," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-6, Sept. 2022, 4007106

S. I. Bermudez *et al*., "Status of the MQXFB Quadrupoles for the HL-LHC," in *IEEE Trans*Nb_3Sn *actions on Applied Superconductivity*, vol. 33, 5, pp. 1-9, 2023, 4001209.

N. Lusa *et al*., "Towards MQXFB Series Coils," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, 1-8, 2024, 4003408.

The journey: from LARP toward AUP

LARP (LHC Accelerator R&D program) established the necessary technology for low β quadrupole for the HL-LHC from 2004 to 2015

LHC luminosity upgrade studies pointing at the need for higher field, larger apertures and temperature margins → **Nb_3Sn IR Quadrupoles**

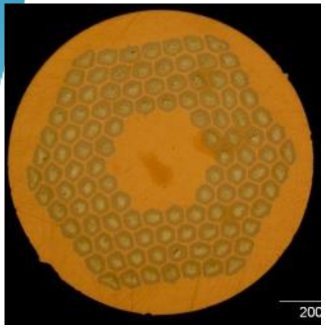
The goal was:

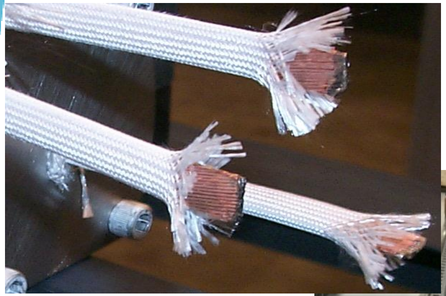
- Investigate the Potential and Challenges of Nb_3Sn Technology
- R&D Phases and main achievements from fundamental technology demonstration to accelerator quality magnets
- *Bridge from proof-of-principle tests to accelerator readiness*

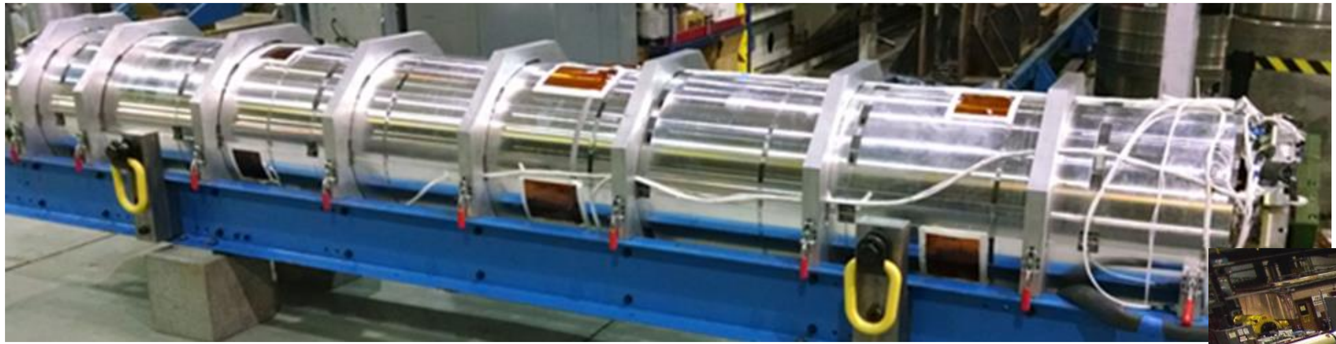
DOE baselined HL-LHC Accelerator Upgrade Project (AUP), coordinating efforts from US Labs (FNAL, BNL, LBNL with contributions from SLAC, JLAB, ODU & FSU)

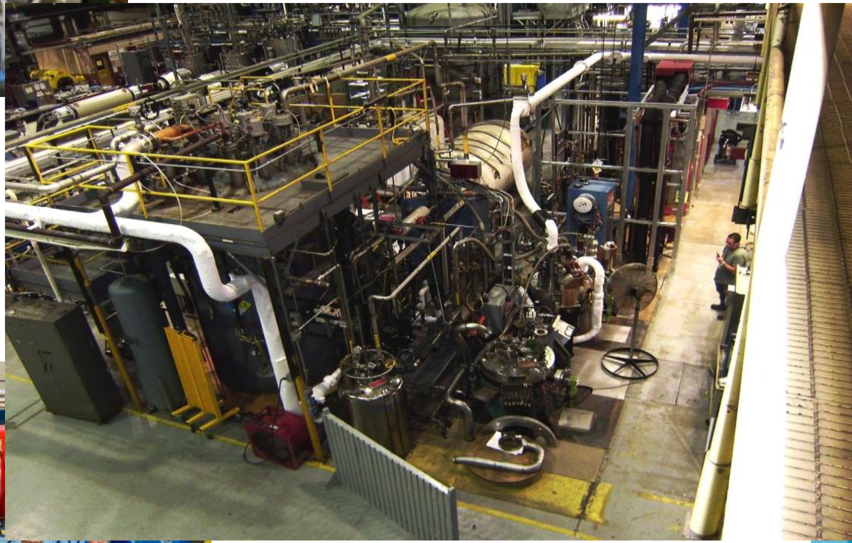
- April 2016: Project approval
- Dec 20: construction approval
- Dec 22: Covid impact and re-baseline

From Nb_3Sn strand to Cryo-assembly

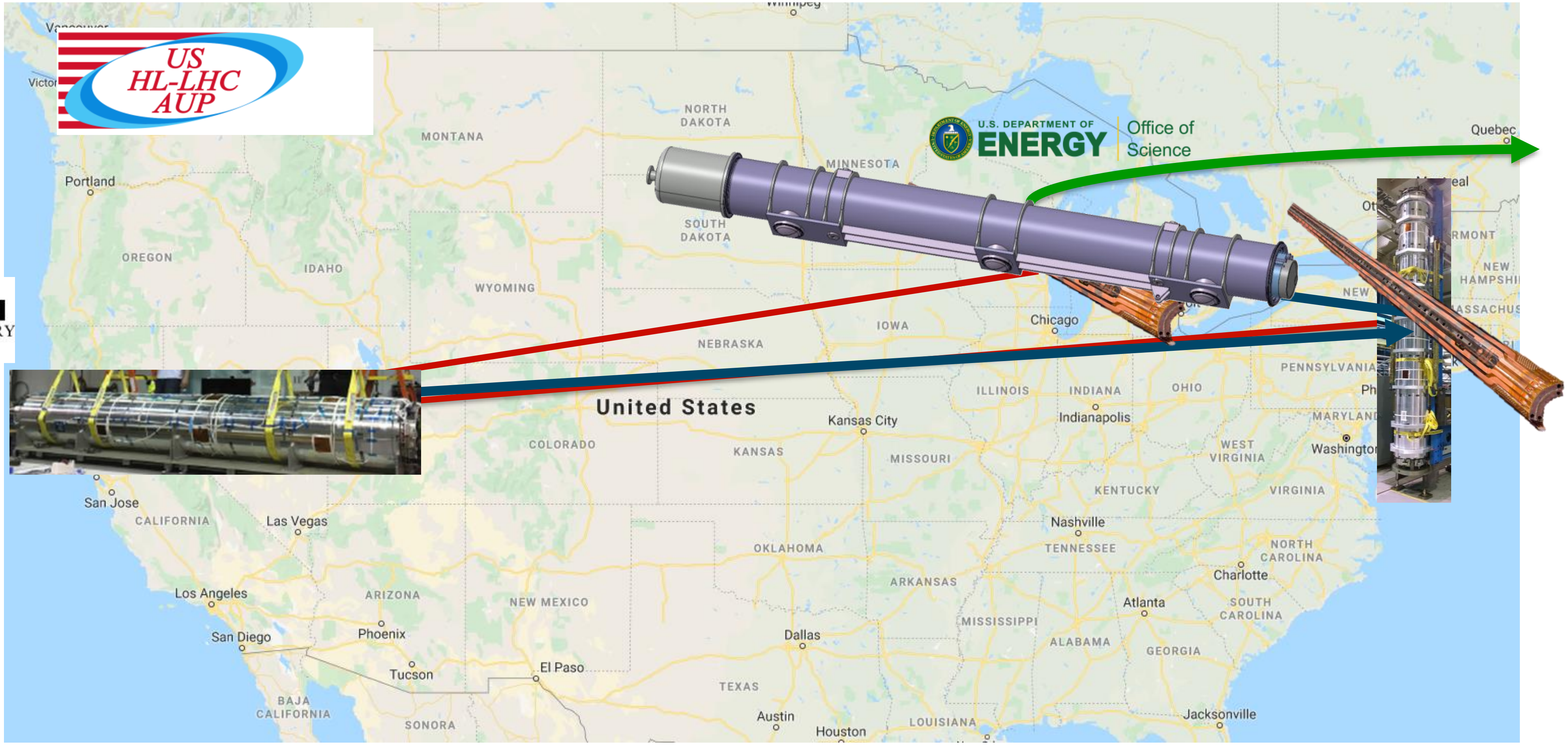








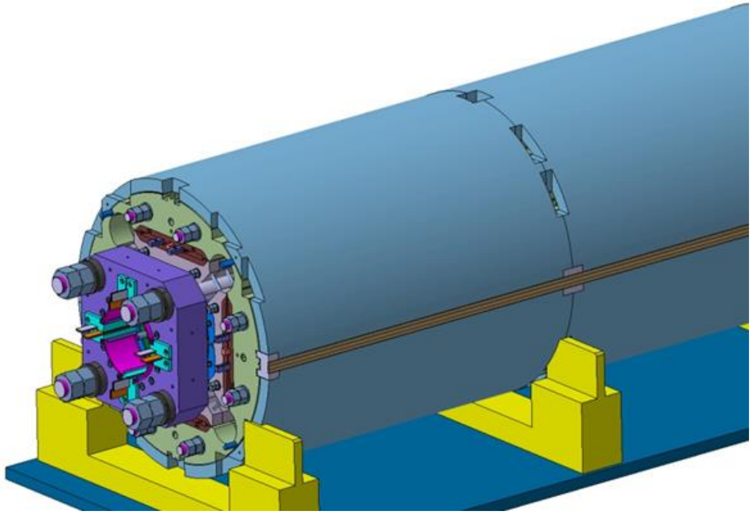
The US-HL-LHC AUP: Cryo-assembly fabrication



Journey across the US fabricating Magnets.

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



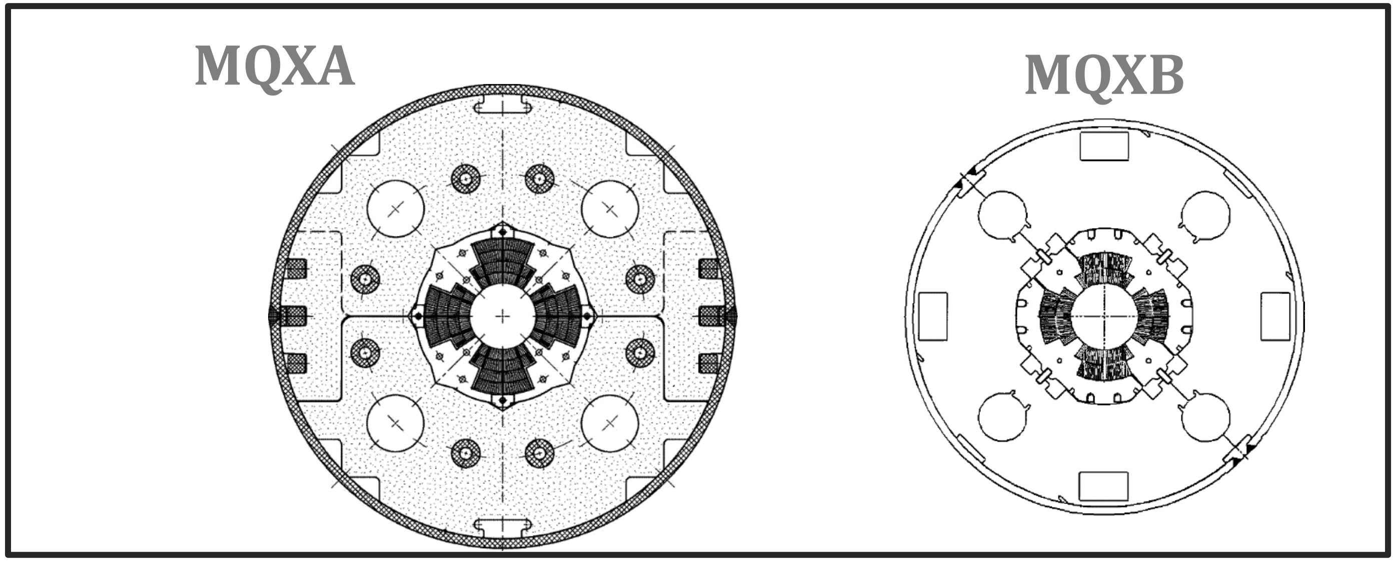
P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

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

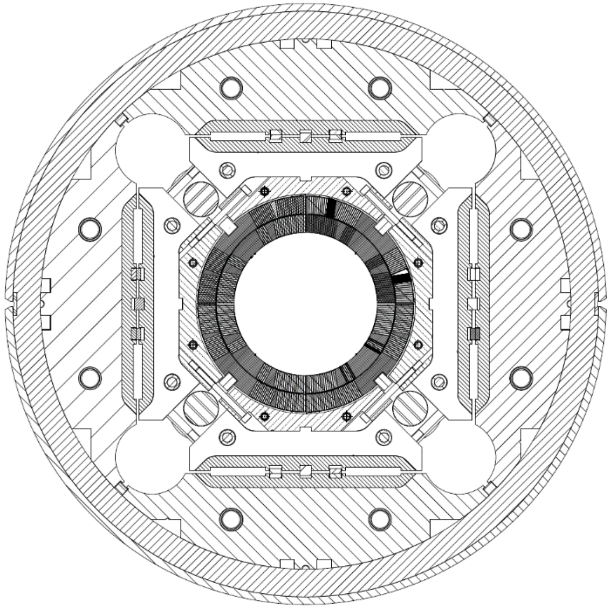
Low-β quadrupole magnets from LHC to HL-LHC

- 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*

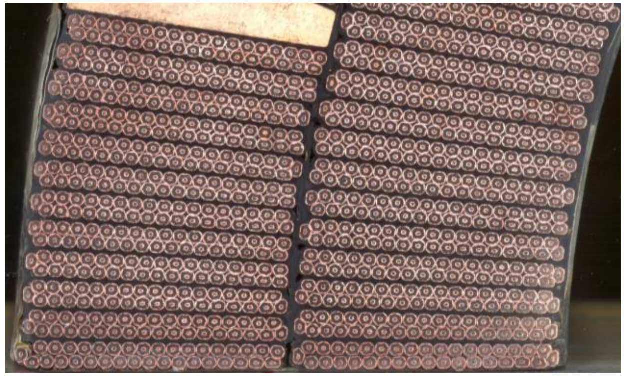


MQXF (HL-LHC)



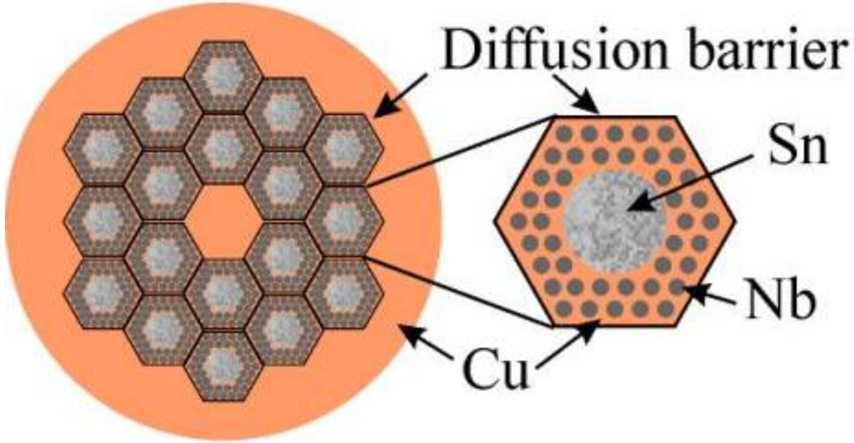
Same scale for all 3 plots

The Nb_3Sb conductor



Potential:

- Nb_3Sn critical temperature and field are about a factor of 2 larger than in NbTi
- Significantly expands the magnet design space: higher field and temperature margin



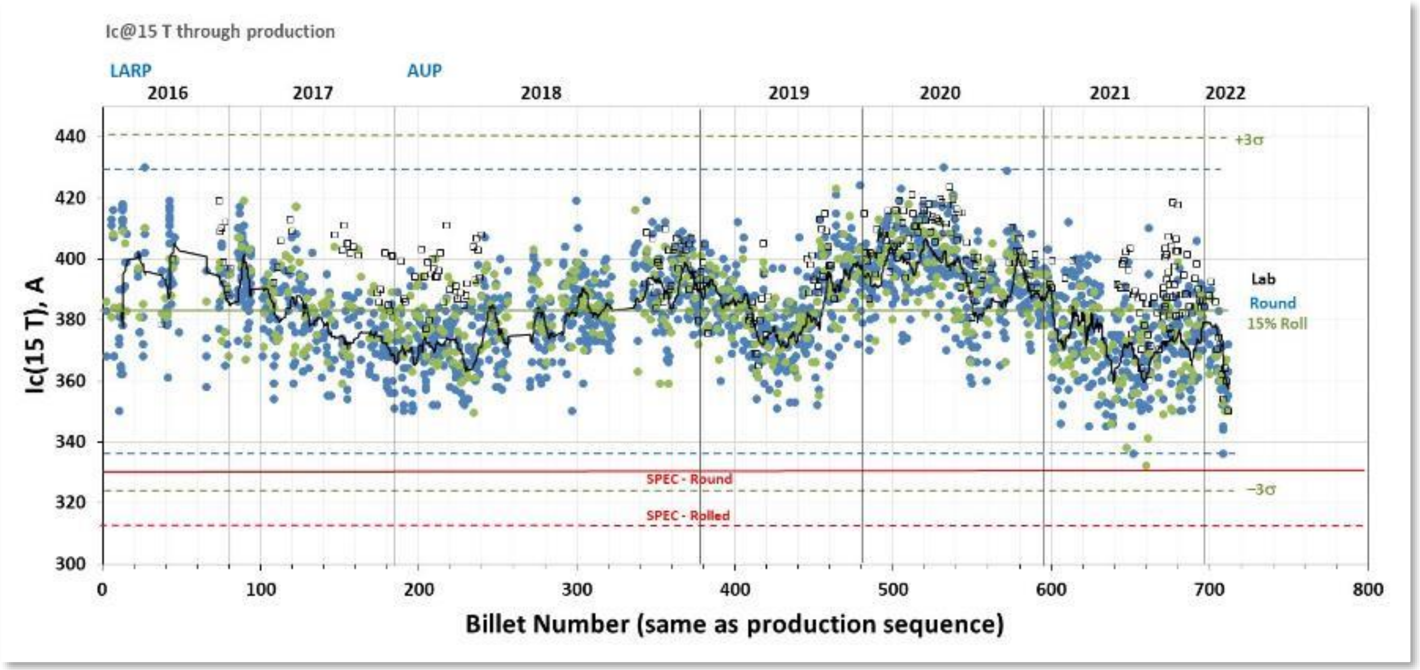
Challenges:

Brittle and strain sensitive
Develop the technology to prevent damage

- Rod Restack Process, RRP 108/127
- Each sub-element has a diffusion barrier.
- Non-Cu J_C up to 3000 A/mm^2 at 4.2 K and 12 T.

Nb_3Sn RRP 108/127 strand

For AUP production: 2080 km di RRP 108/127 (10.4 tons of strands).



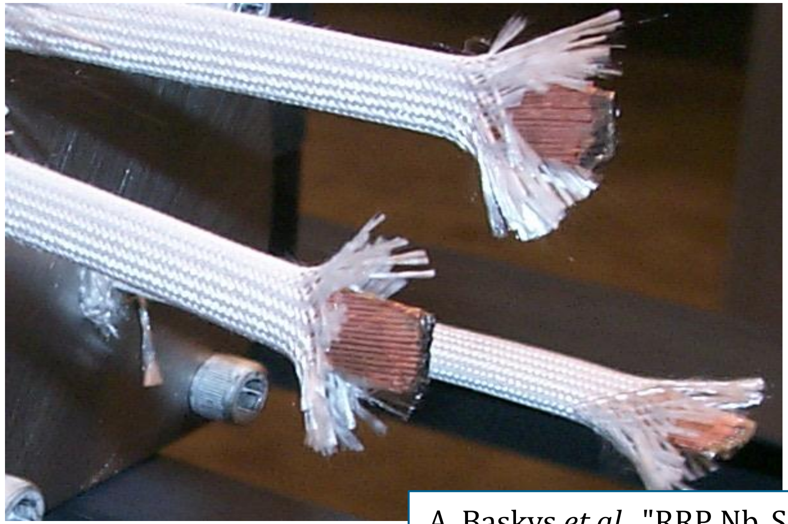
L. D. Cooley et al., Conductor Specification and Validation for High Luminosity LHC Quadrupole Magnets, IEEE Trans. Appl. Supercond., vol. 27 no. 4, pp. 1-5, Jun. 2017.

- The robustness of the RRP strand after rolling is clearly demonstrated here. Very good QC/QA processes were established Example: Ic at 15 T (most sensitive to process variations)
- 1,751 measurements: stable production over 7 years

Cables

To prevent severe damage in cabling/winding: react coils after winding

Main challenge for cable fabrication: Mechanical stability vs sub-element damage



A. Baskys *et al*., "RRP Nb_3Sn Subelement Shear Dependence on Hexagonal Subelement Stack Orientation and the Strand's Position Within a Rutherford Cable," in *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-5, Aug. 2023, 4801605

A. Baskys et al., "Image Analysis Capabilities and Methodologies of Nb_3Sn Rutherford Cables," in *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-6, Aug. 2023, 4800606.

- Peak heat treatment temperature 665 °C.
- New insulation: **fiberglass** sleeve braided on the cable.
- Thickness varies between 100 and 200 µm.

Cable are fabricated at LBNL

We have fabricated well over 50 km of AUP cables.

- 40 strand per cable
- (113 cables, each cable ~470 m)
- Cable fabrication is complete
- Yield > 95%

G. Ambrosio, "Nb_3Sn High Field Magnets for the High Luminosity LHC Upgrade Project," in *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1-7, June 2015, Art no. 4002107.

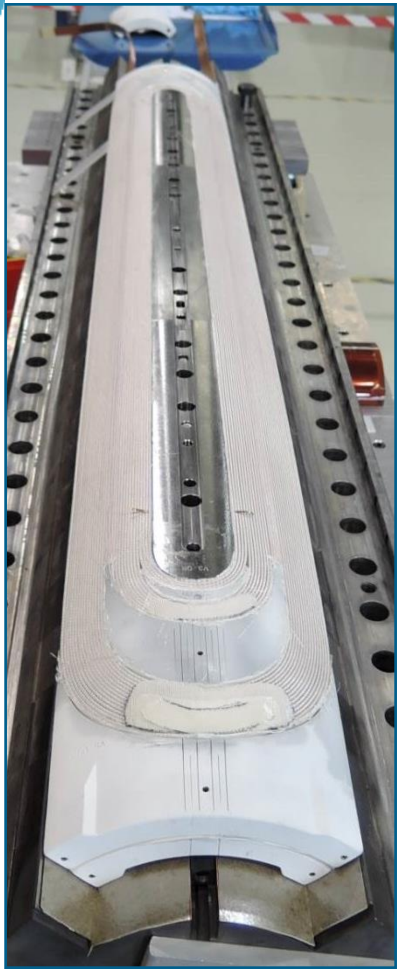
QXFA coils

Fermilab

BROOKHAVEN NATIONAL LABORATORY

After reaction

After winding/curing



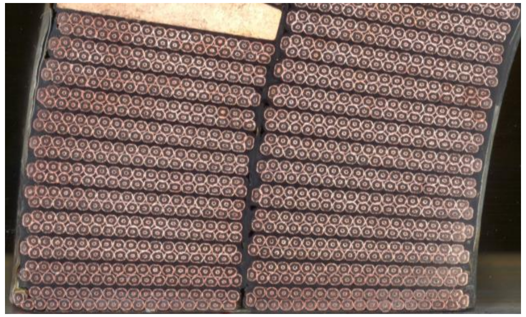
After impregnation

High sensitivity to stress/strain:

- Wind and react (665 C)
- Epoxy impregnation
- New coil part material: Ti Pole

Coil fabrication at FNAL and BNL

- 110 coils fabricated
- BNL fabrication is complete
- FNAL fabrication: one coil left
- Coil fabrication Yield=89.2%



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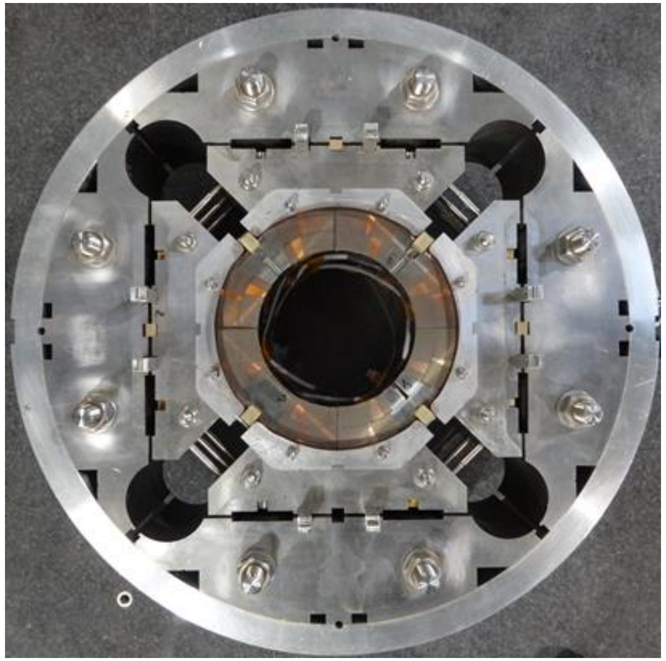
Magnet assembly: Bladder and keys

Magnets are assembled at LBNL: 60% of production

The external shell is entrusted with the coil pre-compressing and the containment of the Lorentz forces.



D. W. Cheng *et al*., "The Challenges and Solutions of Meeting the Assembly Specifications for the 4.5 m Long MQXFA Magnets for the Hi-Luminosity LHC," in *IEEE Transactions on Applied Superconductivity*, vol. 33, 5, 1-5, Aug. 2023, 4003905.

First use of Bladder and Key Technology in Accelerator magnet

- Pre-load applied with water-inflated bladders and keys to lock it in.

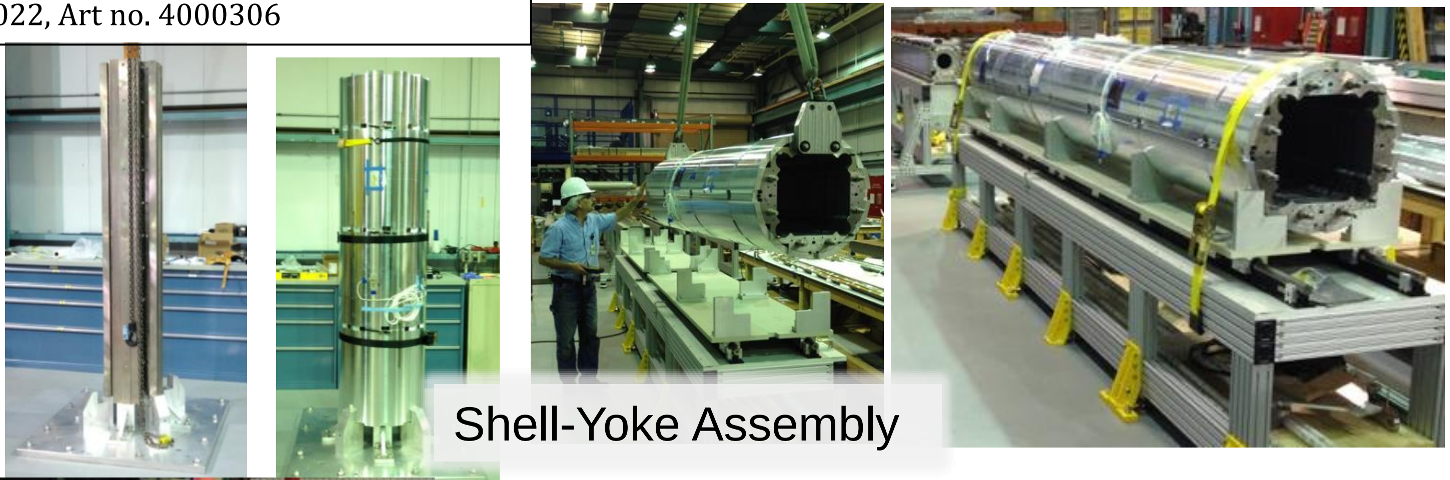
- Aluminum external shell: high thermal contraction determine an increase of the force compressing the coil during cooldown and less rigid structure

- The yokes are split (azimuthally) in quadrant separated by gaps that remain always open. No force coming from the shell is intercepted by any components before getting to the coil.

Magnet fabrication process – a pictorial view

P. Ferracin *et al.*, "Assembly and Pre-Loading Specifications for the Series Production of the Nb_3Sn MQXFA Quadrupole Magnets for the HL-LHC," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-6, Sept. 2022, Art no. 4000306

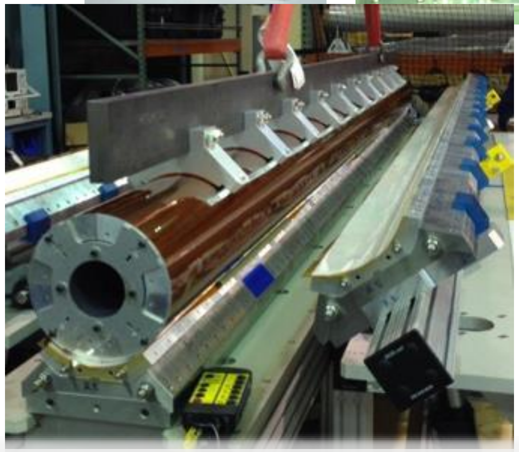
Magnet assembly is performed at LBNL: 2 assembly lines



Shell-Yoke Assembly

Coil Prep

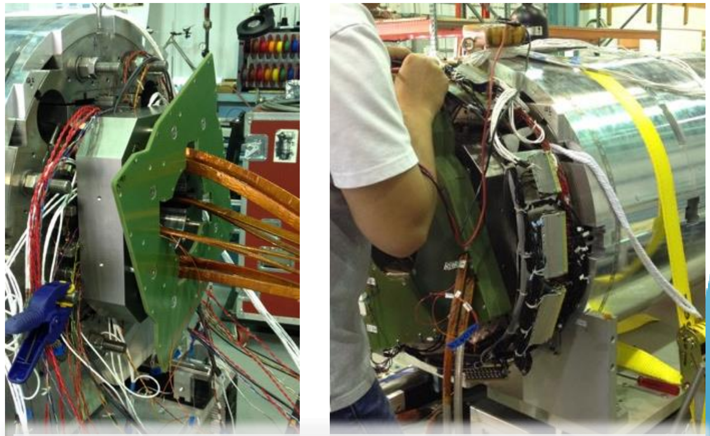
Radial Shim Prep



Final Coil pack assembly

Coil pack Insertion

Preloading



Splicing and Connectorization

MQXFA Vertical Test Summary

- Requirements & Test Goals:
  - Hold current at nominal current (16.23 kA) + 300 A ✓
  - gradient of 132 T/m ✓
  - Training memory after thermal cycle ✓
  - Temperature margin (I nom at 4.5 K) ✓
  - Ramp to/from I_nom at ±30 A/s ✓
  - 100 A/s ramp down w/o quench ✓
  - Field Quality ✓
  - Integrated Gradient ✓
  - Splice resistance ✓
  - All electrical requirements ✓

- Magnets are sent to FNAL for cold mass assembly if they pass all vertical test requirements

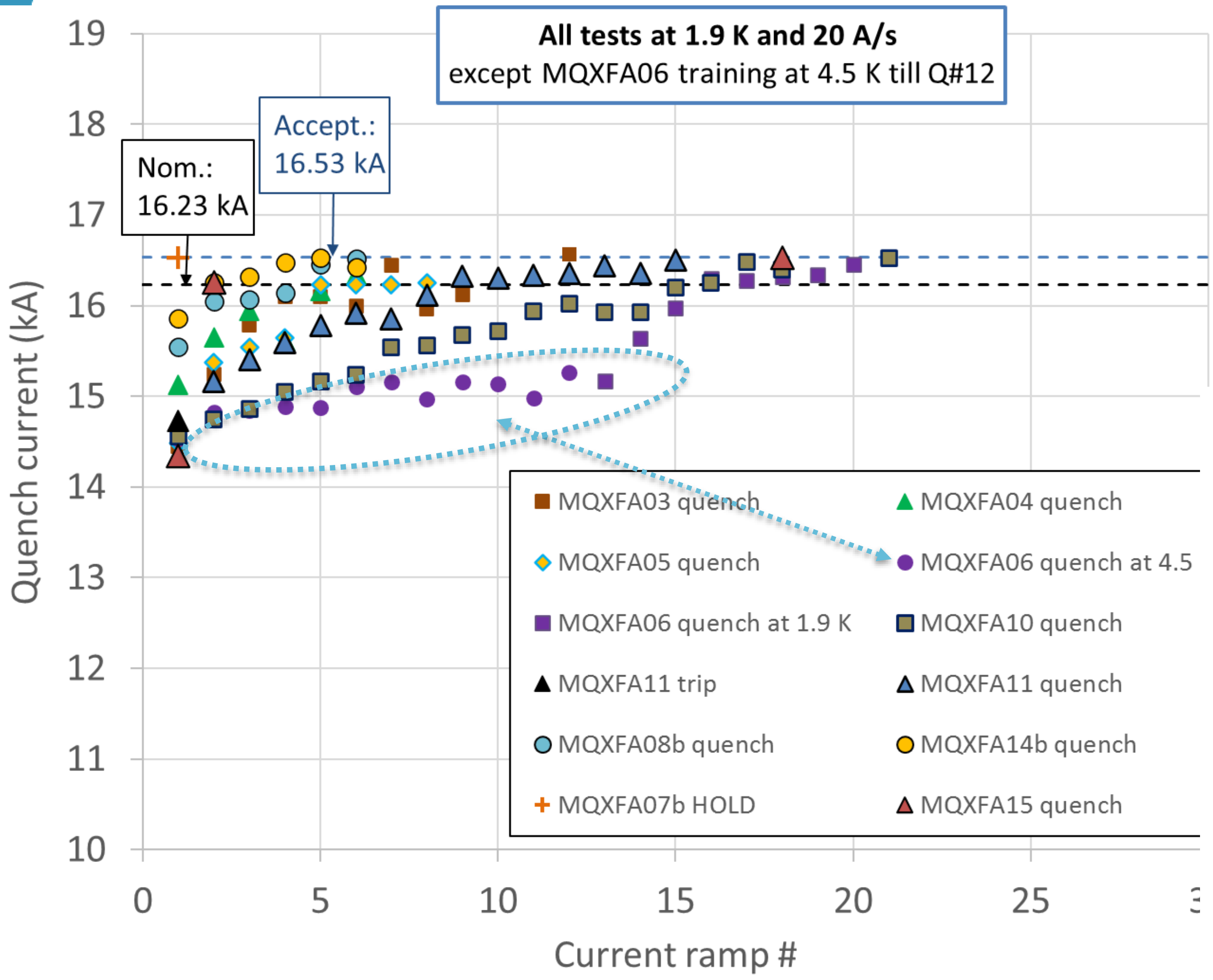
MQXFA magnet being moved to vertical test station at BNL

BROOKHAVEN NATIONAL LABORATORY

Magnet is tested vertically at 1.9 K at BNL

J. Muratore *et al.*, "Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade," in *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-4, Aug. 2021, Art no. 4001804

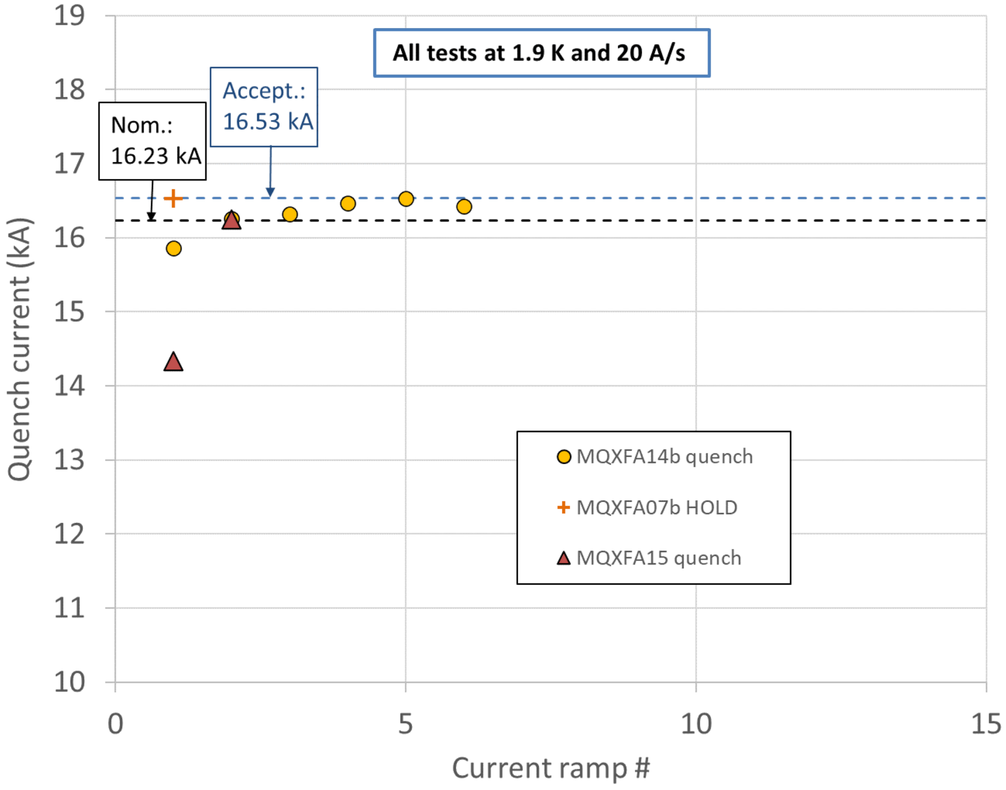
MQXFA Vertical Test Summary



S. I. Bermudez *et al.*, "Status of the MQXFBNb_3Sn Quadrupoles for the HL-LHC," in *IEEE Transactions on Applied Superconductivity*, vol. 33, 5, pp. 1-9, 2023, 4001209.

Lesson learned from MQXFA13 and tests performed on short magnets at CERN

- Increase of azimuthal preload: shorter training in the last 3 magnets



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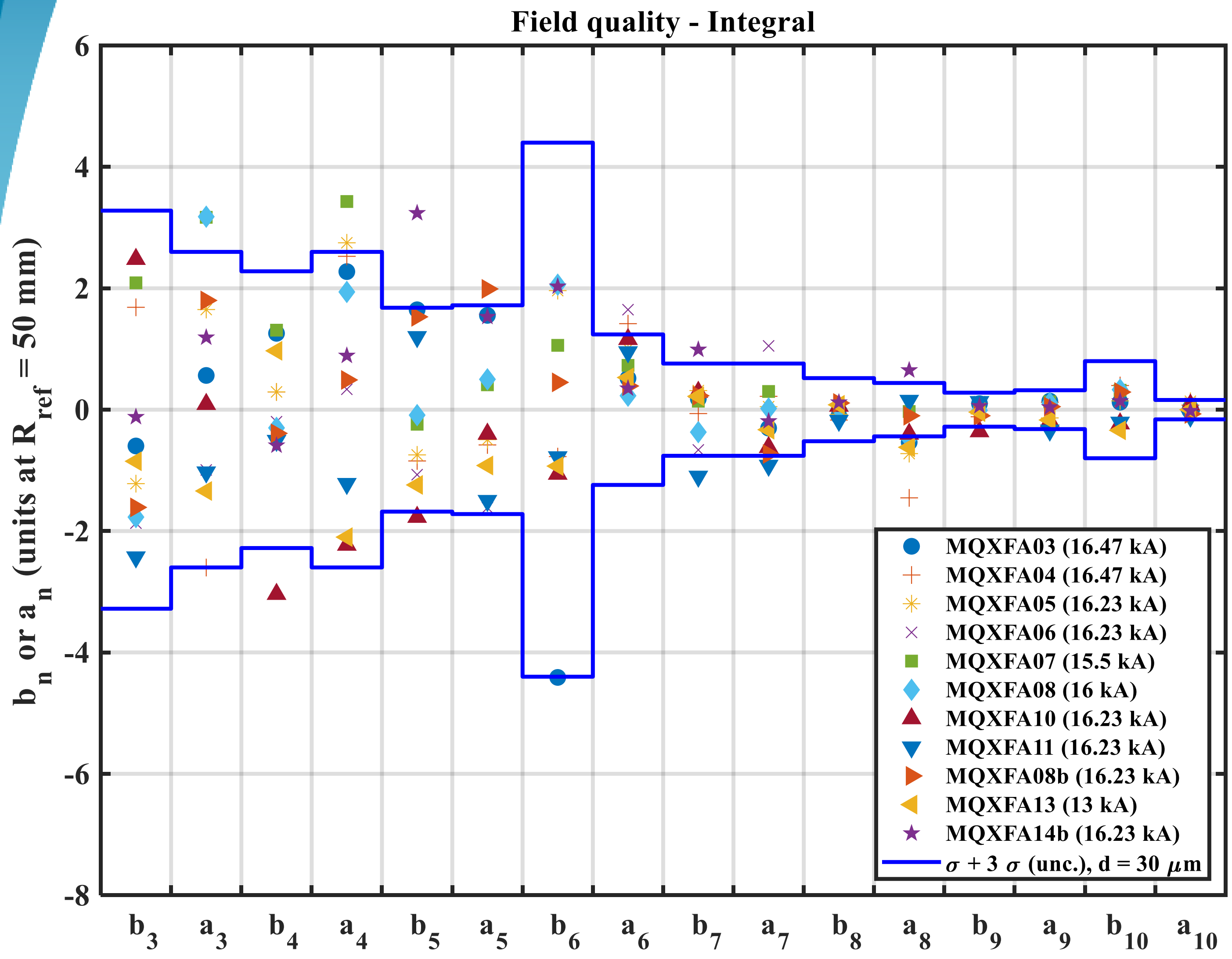
Field quality Integral



- Integral harmonics to be measured in Cro-assembly

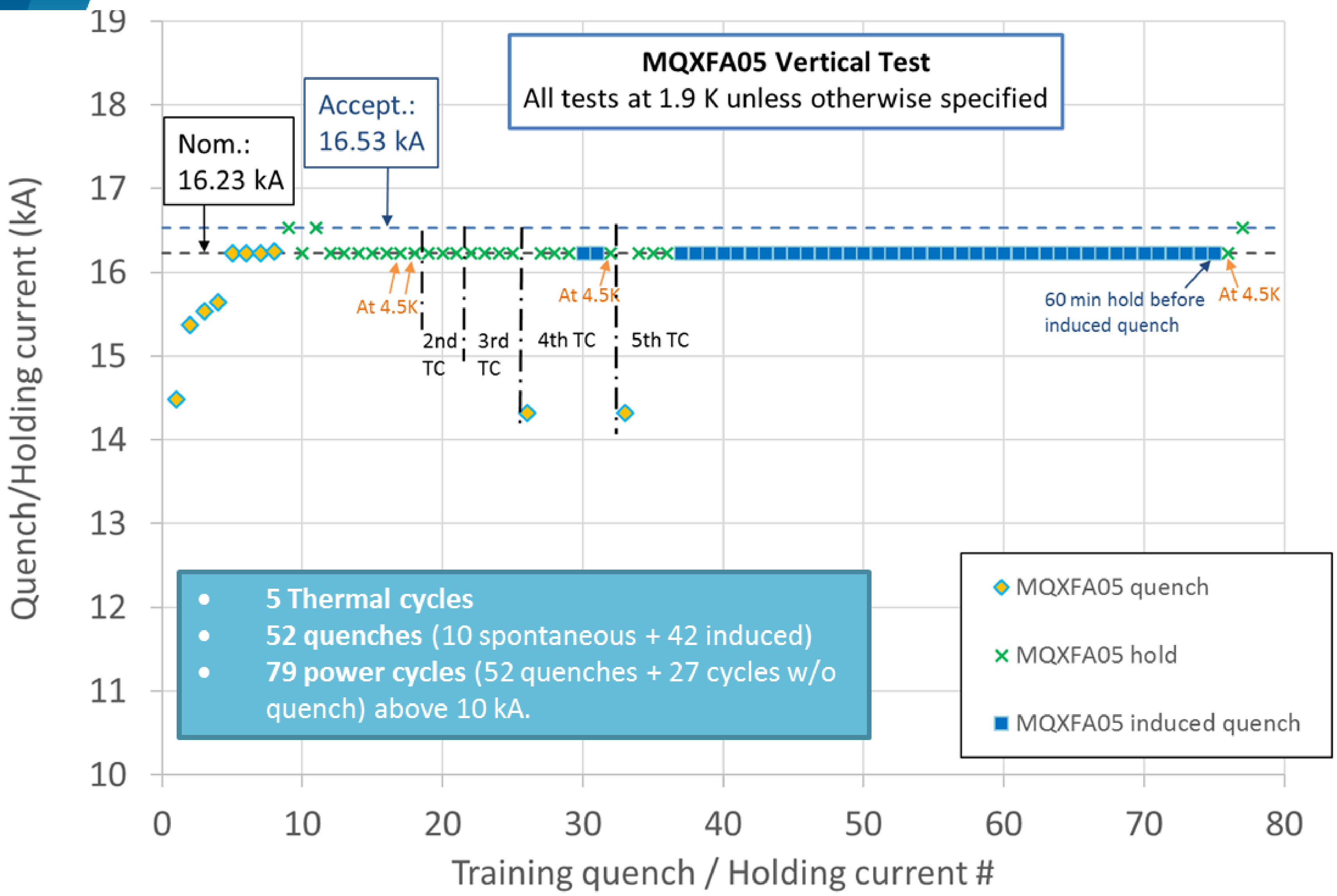
- Based on short model test:
  - b6 correction introduced in one coil on MQXFA04 and all subsequent coils:
  - *125 um shift toward midplane*

- Magnetic shims used to correct low order harmonics

Integrated Gradient and Magnetic Length within targets

A. Ben Yahia et al., "Training performance and magnetic measurements during vertical testing of the MQXFA magnets for HL-LHC", 2023 Magnet Technology Conference (MT-27) Aix-en-Provence, France, September 2023.

US HL-LHC AUP



Endurance

- 5 thermal cycle
- 52 quenches
- 79 power cycle

CERN MAGNETS

MQXFB02

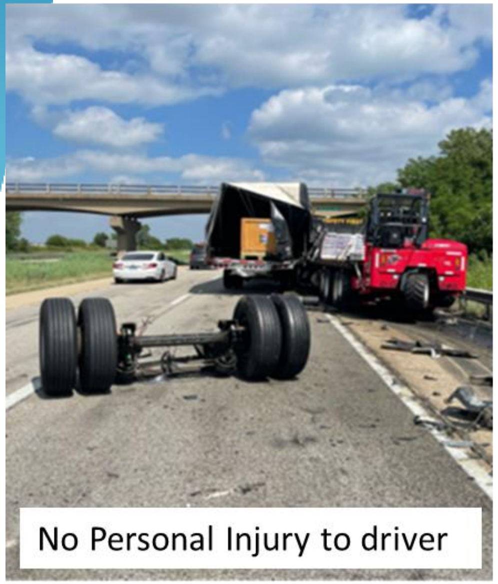
- >500 power cycle
- 4 cooldowns
- 36 quenches

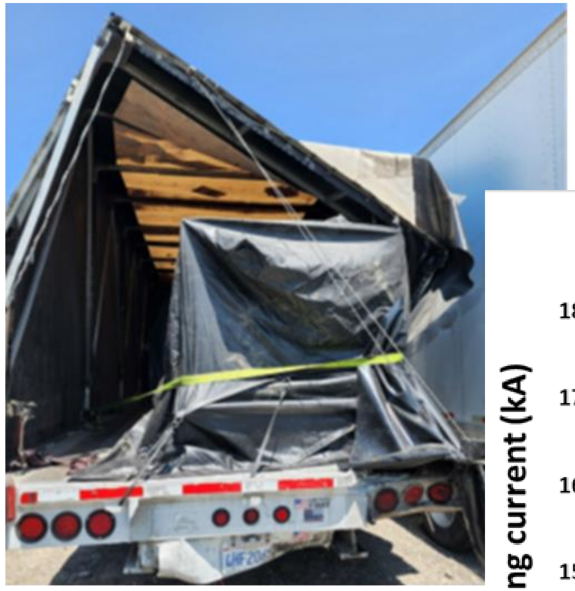
Short model MQXFS7

162 ramps

150 quenches

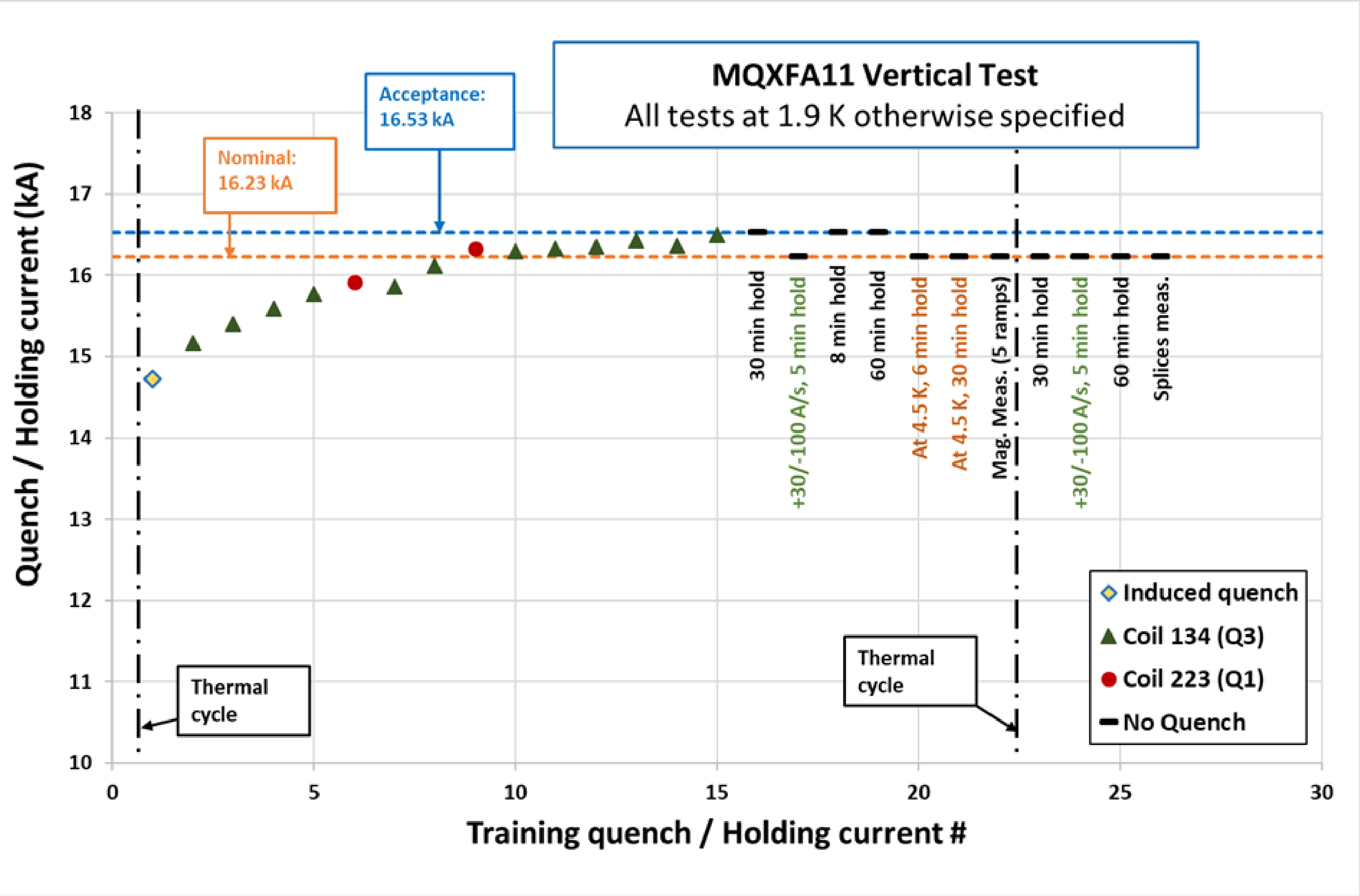
Resilience





10g shock for 5 ms

Courtesy of T. Cruise



MQXFA Status Summary

- Magnets tested in vertical cryostat: 13
- **Met requirements: 10**
- Did not meet requirements: 3
  - Affected by Covid restrictions: 2
  - **Met requirements** after replacing the limiting coil: 2
  - To be tested after replacing the limiting coil: 1

Component	Status
Strand procurement & QC (FNAL, FSU)	~97% complete
Cable fabrication & insulation (LBNL)	99% complete
Coil fabrication (BNL & FNAL)	98% complete
Magnet assembly (LBNL)	~60% complete

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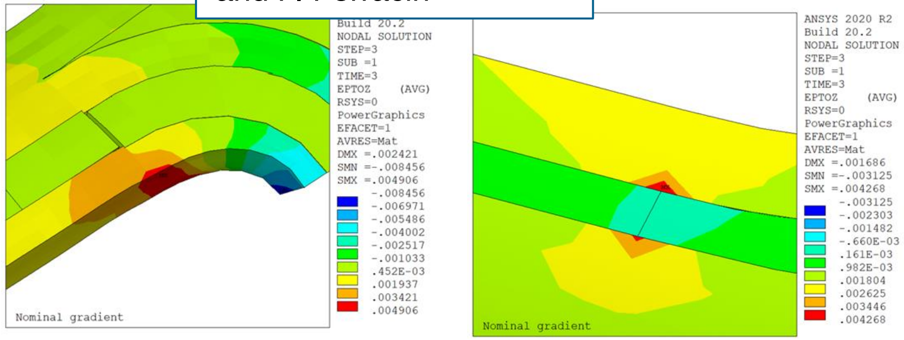
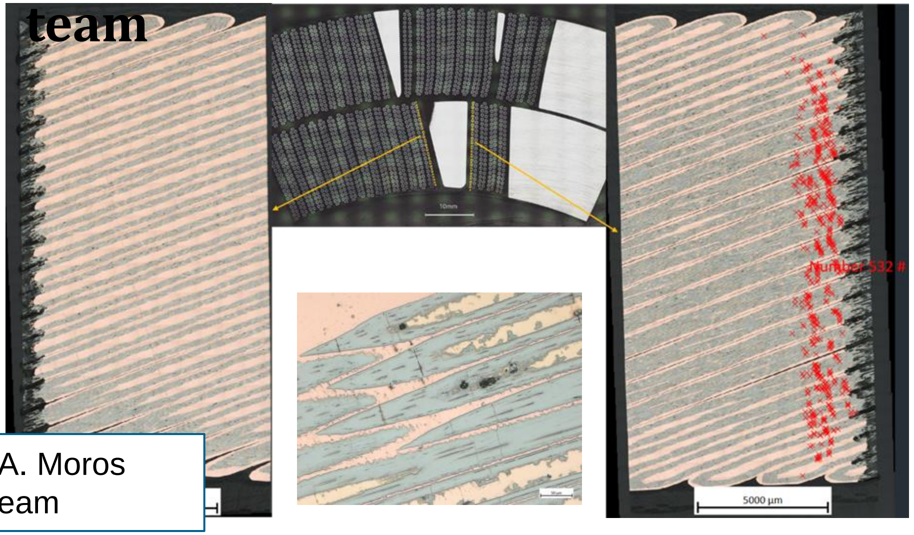
Lesson learned: MQXFA07/08 Possible Damage at Wedge-Spacer Interface

Courtesy of G. Vallone and P. Ferracin



- 3D analysis to identify high stress area
- First observation of broken filaments

CT-scan, dye-penetrant test and metallurgical analysis by CERN team



Courtesy of A. Moros and CERN team

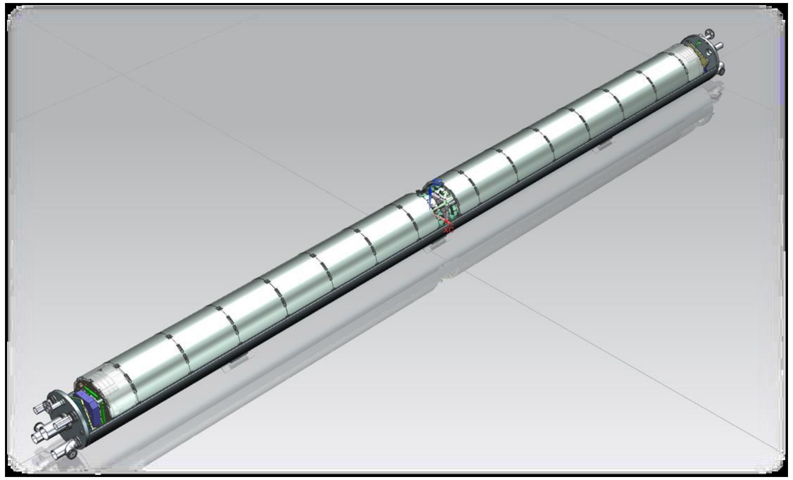
- Magnet fabricated under **Covid restrictions ➔ a coil with less preload**
- 2D FEM analysis was fine
- **At cold** this coil ended up with **less longitudinal preload**
- **At nominal current** tension may develop btw wedge and end-spacer resulting in high **longitudinal strain** (up to **0.4%**) in that location
  - This location is consistent with quench data
  - Effect is larger on the pole block, but also visible on the mid plane block

A. Moros et al., "A Metallurgical Inspection Method to Assess the Damage in Performance-Limiting Nb_3Sn Accelerator Magnet Coils", **IEEE Trans. Appl. Supercond. 33 (2023) 5, 4000208**

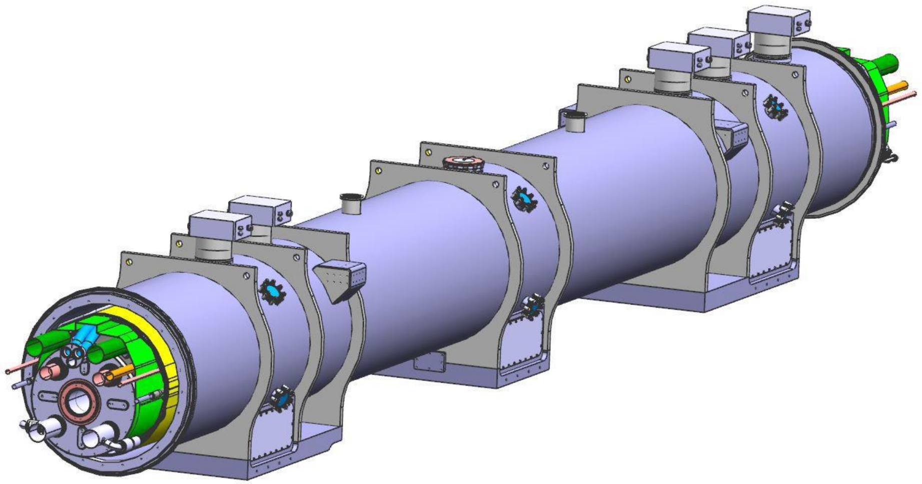
G. Ambrosio et al., "Challenges and Lessons Learned From Fabrication, Testing, and Analysis of Eight MQXFA Low Beta Quadrupole Magnets for HL-LHC", **IEEE Trans. Appl. Supercond. 33 (2023) 5, 4003508**

Cryo-assembly

The **Cold Mass** is the He pressure vessel assembly containing two 4.2 m Nb_3Sn magnets



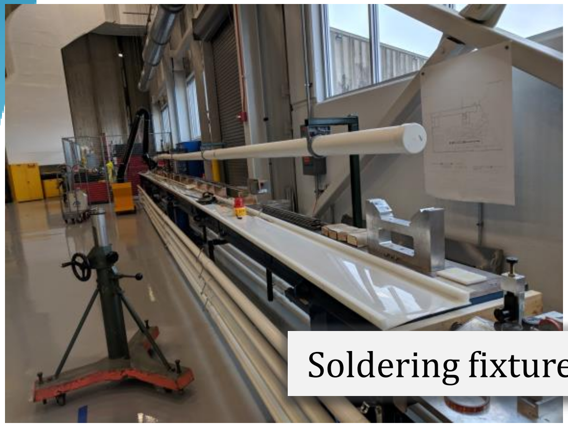
HL-LHC cryo-assembly



- Cold mass + Cryo-assembly fabrication+ Horizontal test is done at FNAL

Cryostat is a CERN design and the procurement of the cryostat and tooling was done by CERN

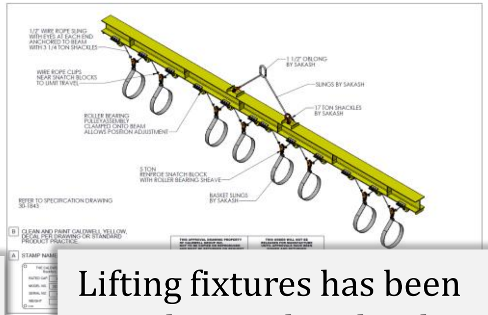
Cold Mass and Cryo-assembly fabrication



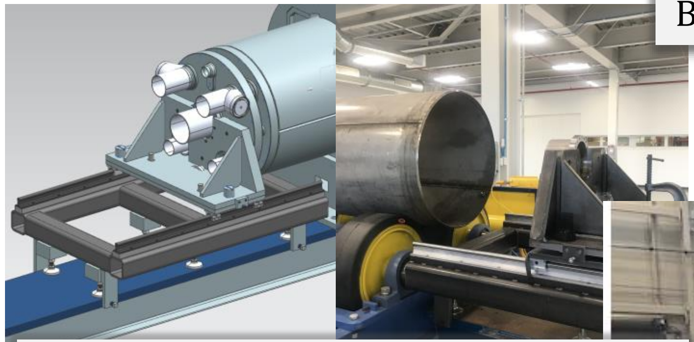
Soldering fixture

Alignment station; clamps and rollers.
Both stations have been aligned

Cold Mass Welding station

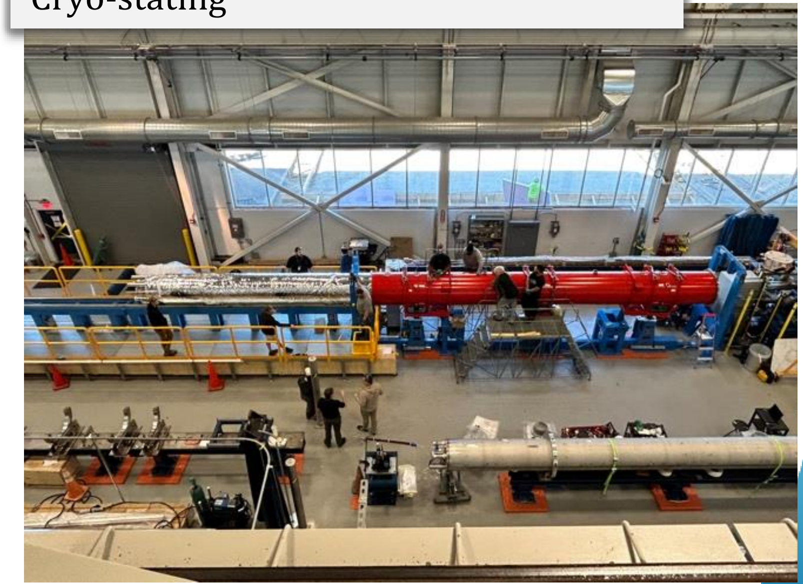


Lifting fixtures has been tested procedure has been written



End cover tooling used for End cover welding tests

Alignment station
Instrumentation station



Cryo-stating

S. Feher *et al.*, "AUP First Pre-Series Cryo-Assembly Design Production and Test Overview," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4005605

Status of Cold Mass (CM) and Cryo-Assembly (CA)

- CA01 was assembled, tested and shipped to CERN (acceptance under way at CERN)
- Assembly of CA02 completed, ready to move to FNAL horizontal test station
- Assembly of CM03 in progress: almost completed
- Assembly of CM04 in progress: shell installation in progress

Completed CM01

R. Rabehl, S. Feher, D. Ramos, T. Strauss and M. Struik, "AUP First Pre-series Cold Mass Installation Into the Cryostat," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4003705

A. Vouris *et al*., "Fabrication of the Fermilab Pre-Series Cold Mass for the HL-LHC Accelerator Upgrade Project," in *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-5, Aug. 2023, Art no. 4002605

Assembly of CA01

Cryo-assembly horizontal test: FNAL stand 4

All cryogenic testing (1.9 K or 4.2 K) are at the FNAL Stand 4 Test Facility, which has been upgraded to be able to accommodate testing LQXFA/B Cryo-assemblies

G. Chlachidze *et al.*, "Fermilab's Horizontal Test Stand Upgrade Overview and Commissioning," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-4, Aug. 2024, Art no. 9500104

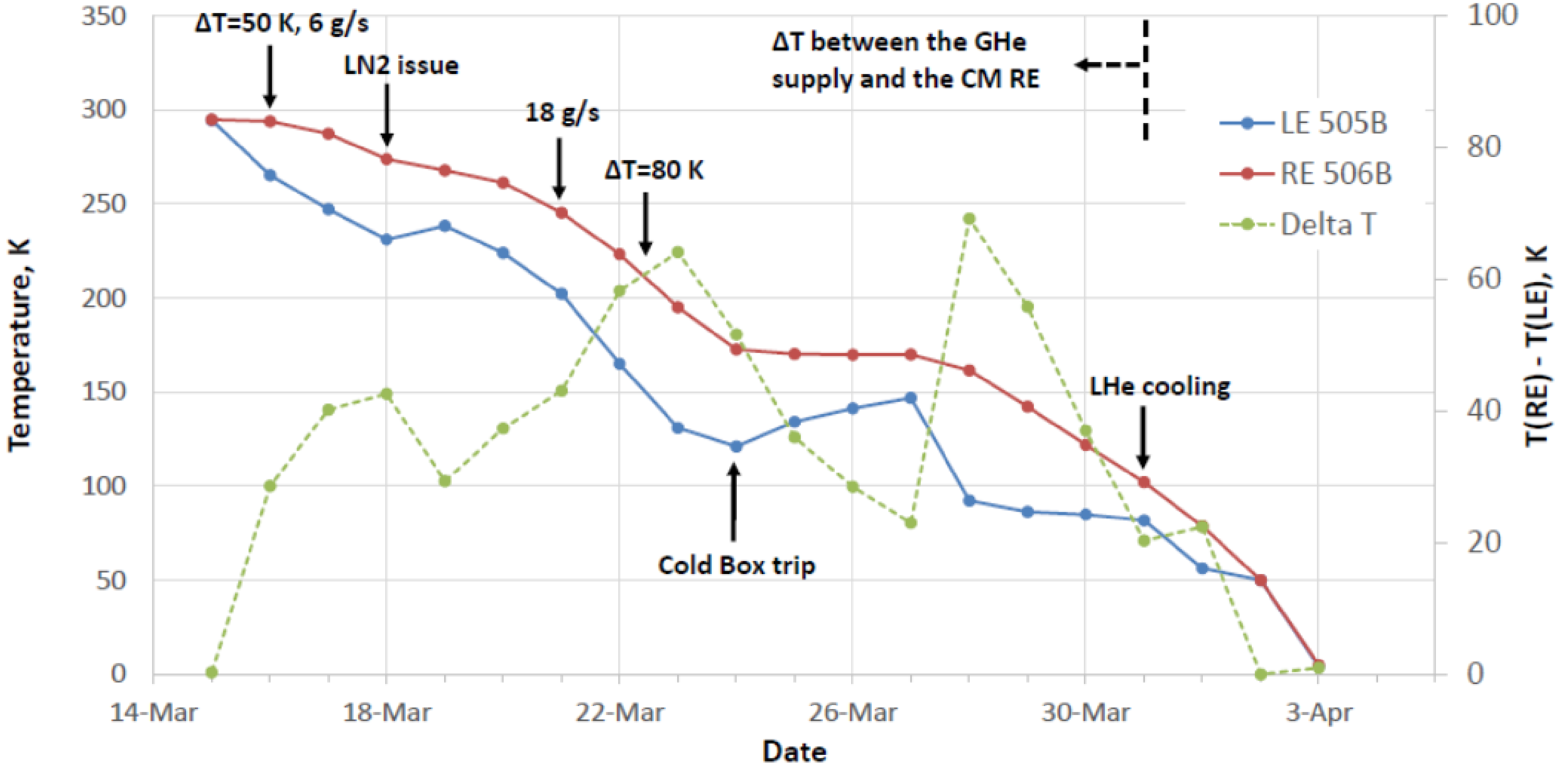
The LQXFA/B-01 Cryo-assembly is the first pre-series cryo-assembly fabricated by HL-LHC AUP: MQXFA03 and MQXFA04 are the magnets in LQXFA/B-01

US HL-LHC AUP

Fermilab

First Thermal-cycle: Cooldown

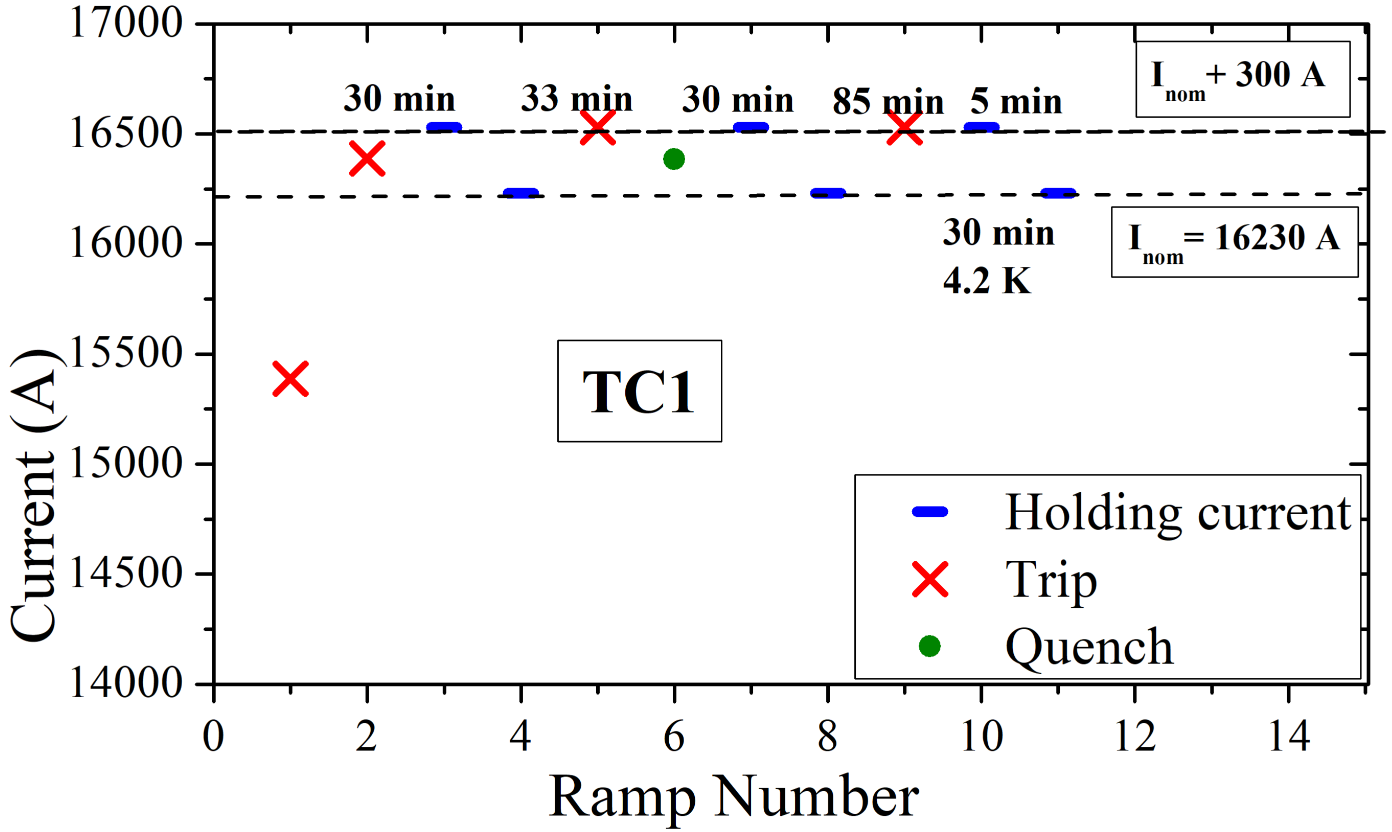
- Cool down started with ΔT requirement of less than 50 K per magnet.
- We kept 80 K difference between cold mass ends.
- Failure of coil to heater hi voltage test at 4.5 K. The magnet can be still safely protected, and this was treated as a non-conformity.



LQXFA TEST REQUIREMENTS

- Maximum temperature gradient of 50 K during a controlled warm-up or cool-down ✓
- Memory: no more than 3 quenches to reach nominal operating current after a thermal cycle. ✓
- Operating at any ramp rate within ±30 A/s. ✓
- not quench while ramping down at 150 A/s from the nominal operating current. ✓
- Continuous steady-state operation at nominal current for 300 min ✓
- Splice resistance must be less than 1.0 nΩ at 1.9 K. ✓

Thermal cycle 1 (TC1) Quench performance

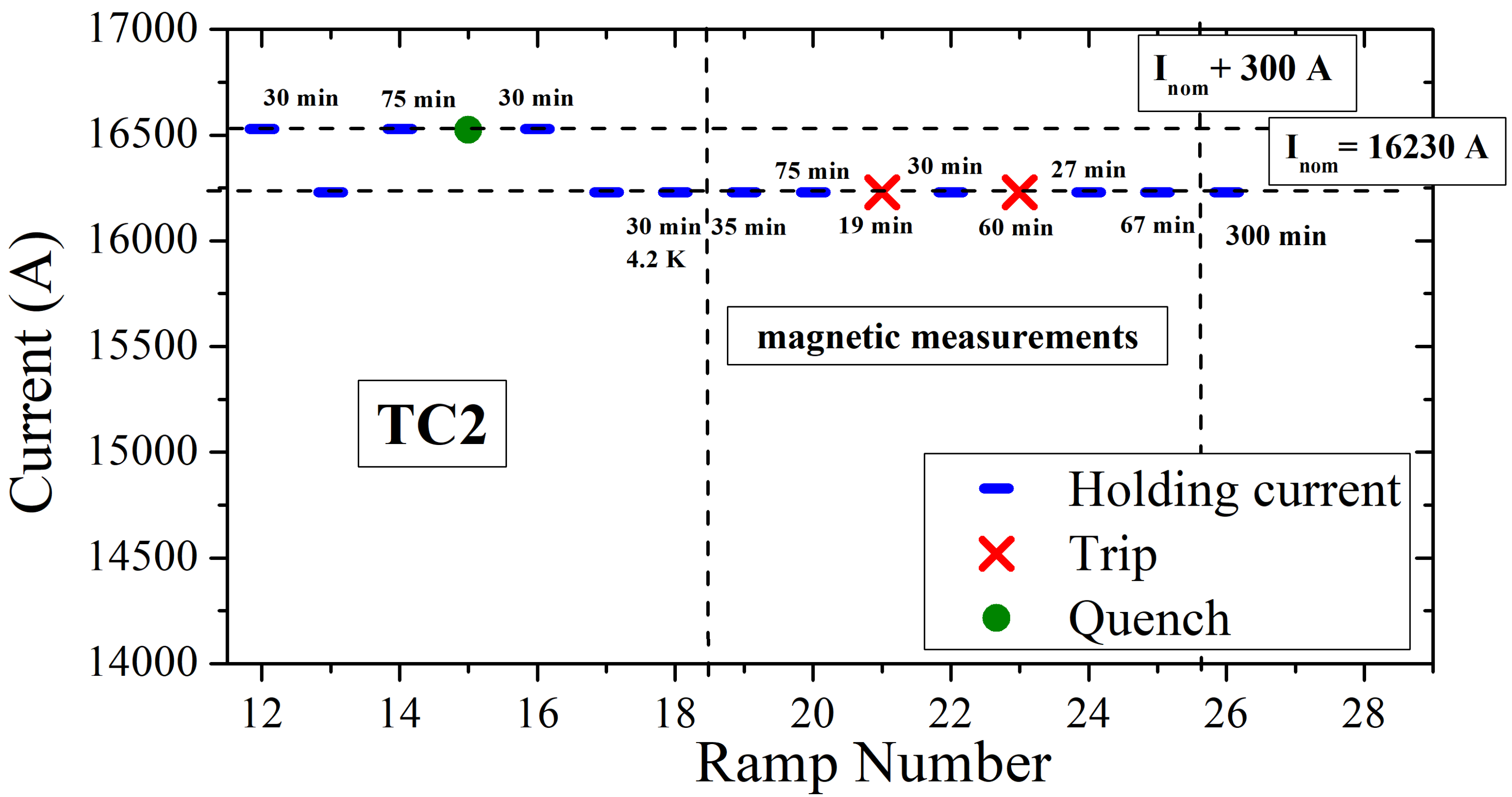


Acceptance current (16530 A) and 30 min at flat top
Nominal current 16230 A and 5 min at flat top

Both magnets in the cold mass reached acceptance current without any spontaneous quenches

- Because of He liquid level instability and threshold settings issues two quenches in one of the SC leads (at 15,245 A and 16,237 A) and some trips
- One Quench in MQXFA04

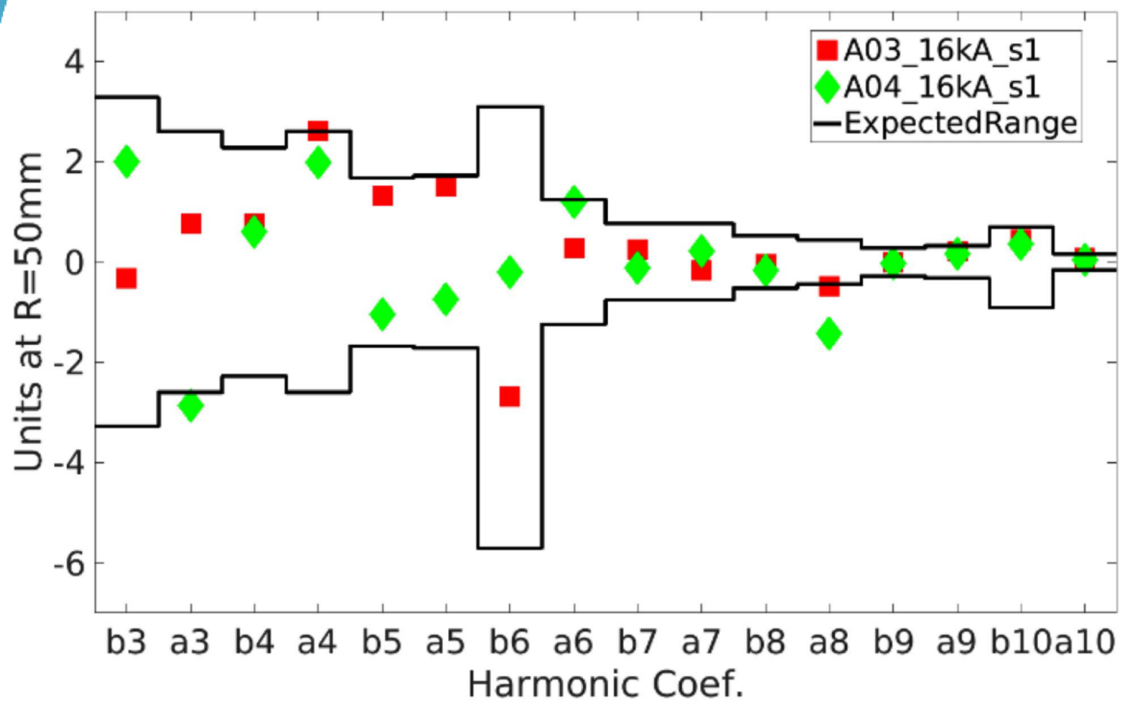
TC2 Quench performance



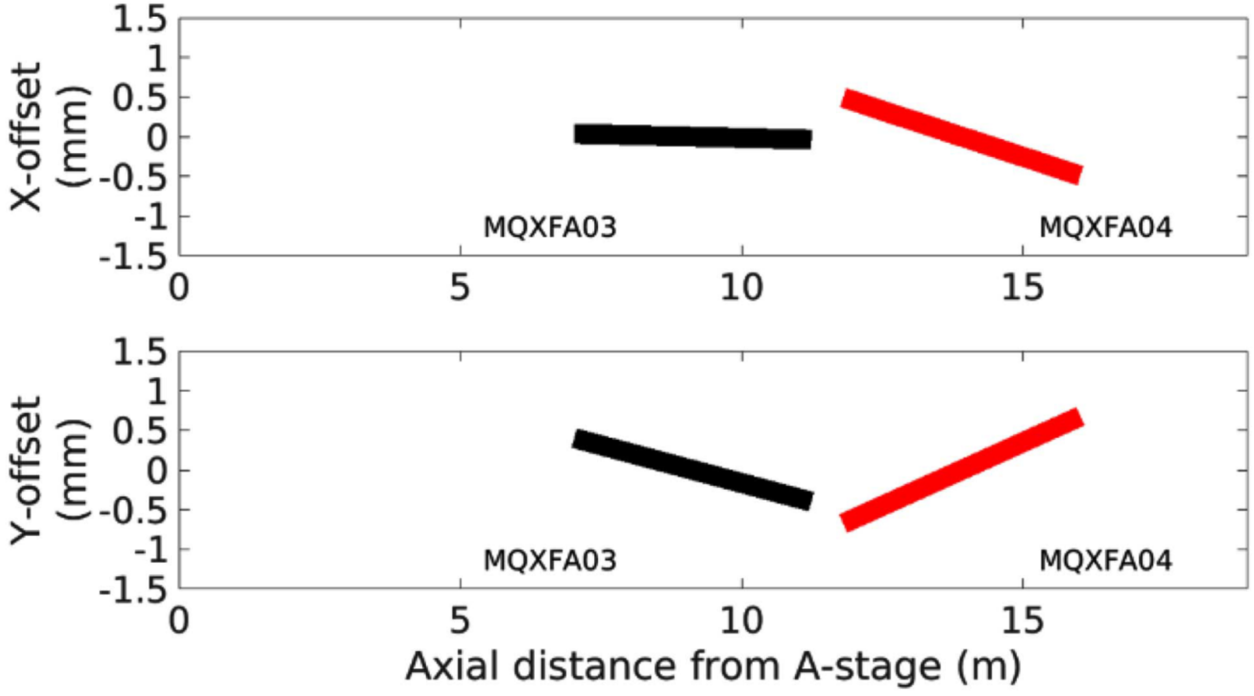
- Magnetic measurements with SSW and 109 mm long rotating coil were performed at 6000 A. 436 mm rotating coil measurements were completed at 1.9 K at nominal current.
- **Issue with liquid level was identified and fixed. Five hours holding test was successfully completed**

M. Baldini *et al.*, "Quench Performance of the First Pre-Series AUP Cryo-Assembly," in *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-4, Aug. 2024, Art no. 4005204

Magnetic measurements

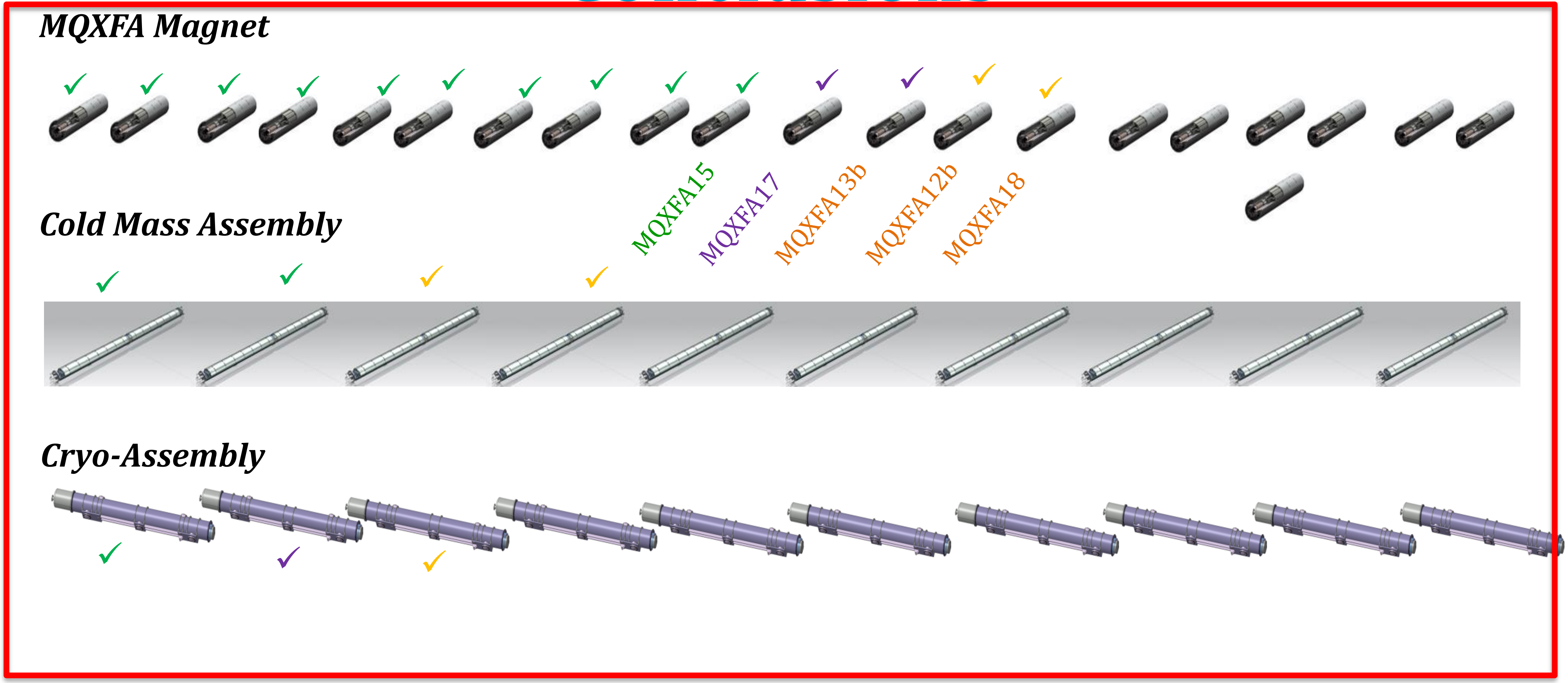


Integral harmonics at nominal operating current (16233A) compared to 3σ range + uncertainty.



The deviation of the magnet ends from the average-axis line was generally within the +/− 0.5 mm of the acceptance criteria, except for A04 which had vertical offsets that exceeded this by about 0.2 mm.

Conclusions



- ✓ Completed, sitting on a shelf or delivered to CERN
- ✓ Under Fabrication
- ✓ Under Test

Slide by G. Apollinari


US
HL-LHC
AUP
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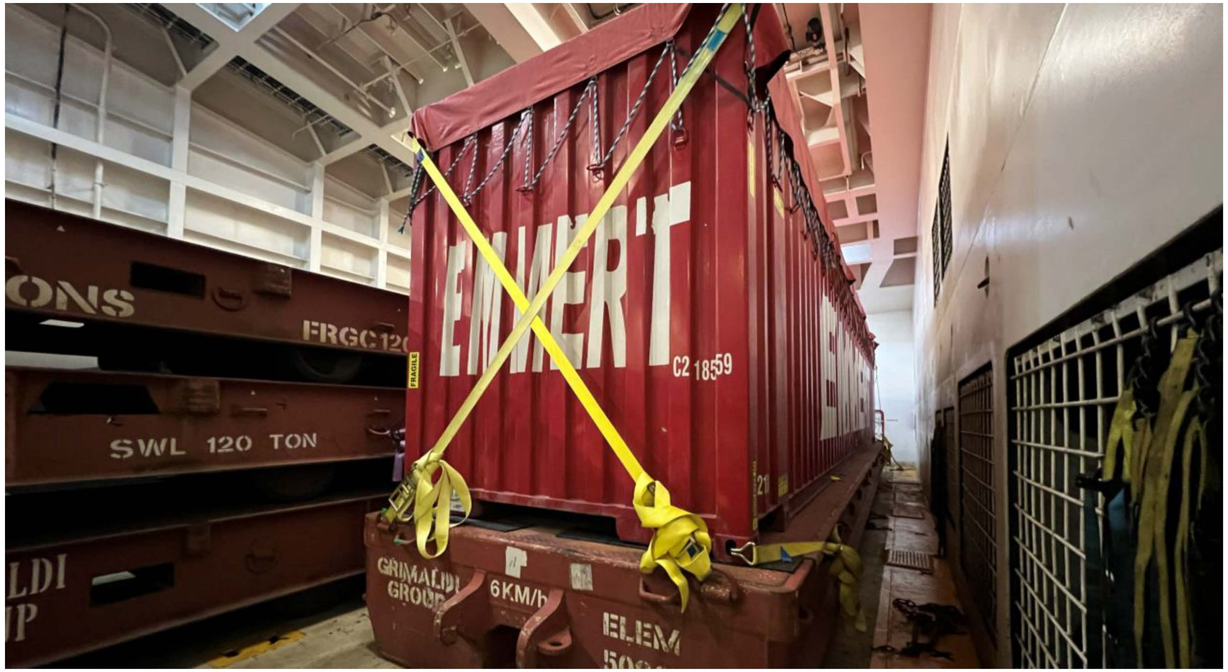
US
HL-LHC
AUP
Fermilab


EMMERT


EMMERT


SWL 120 TON

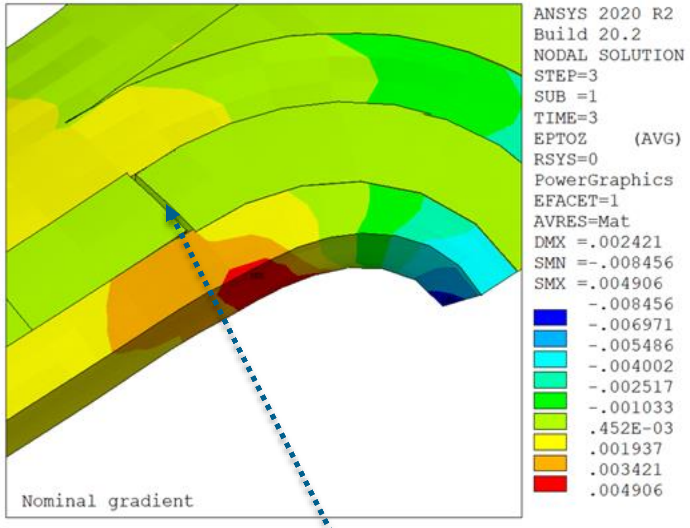

ACL

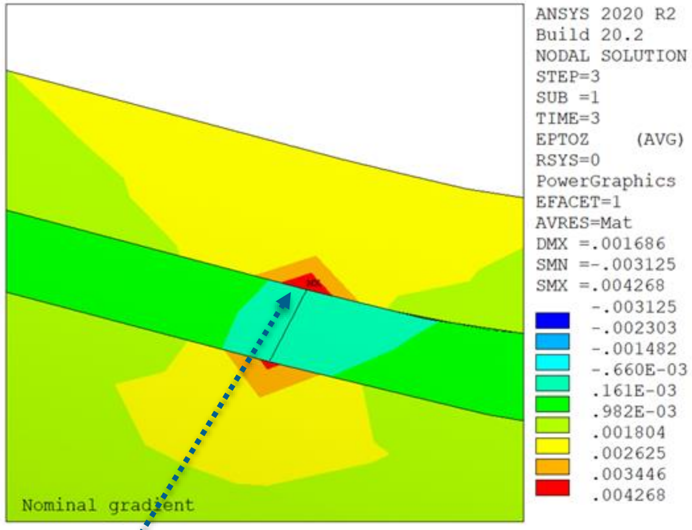

Brookhaven
National Laboratory
BERKELEY LAB

EXTRA SLIDES

Possible Damage at Wedge-Spacer Interface

Courtesy of G. Vallone and P. Ferracin



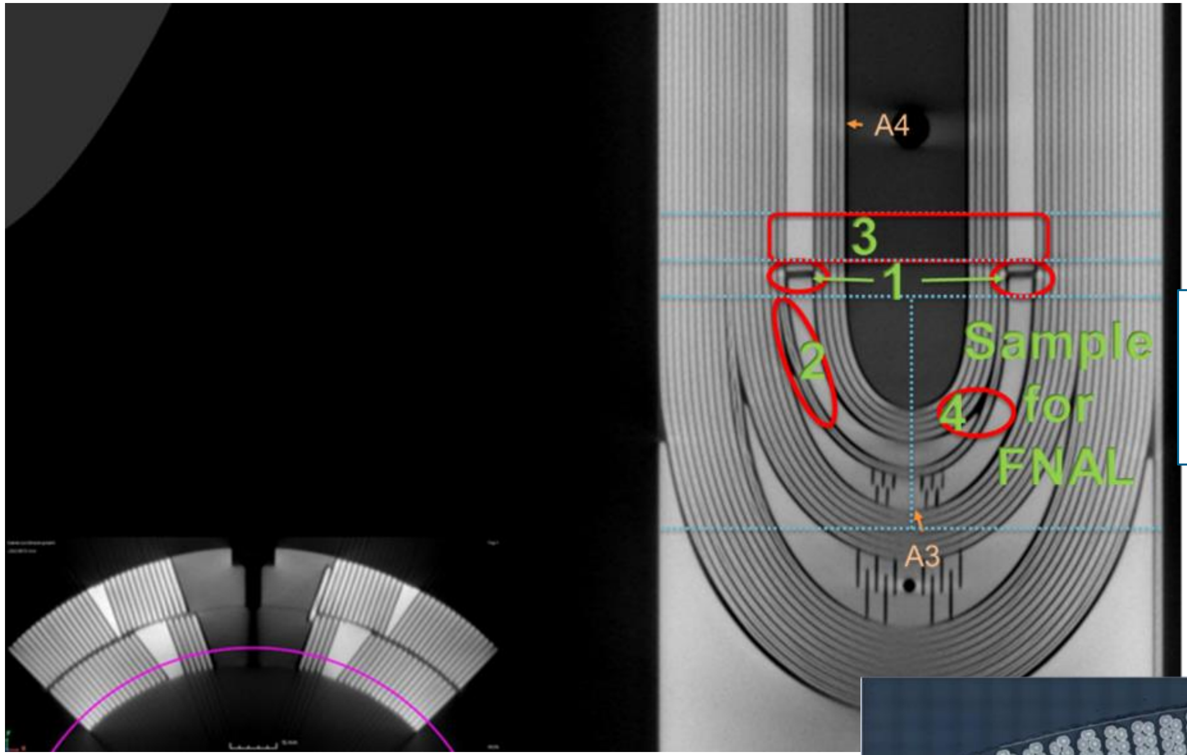


- Magnet fabricated under **Covid restrictions ➔ a coil with less preload**
- 2D FEM analysis was fine
- **At cold** this coil ended up with **less longitudinal preload**
- **At nominal current** tension may develop btw wedge and end-spacer resulting in high **longitudinal strain** (up to **0.4%**) in that location
  - This location is consistent with quench data
  - Effect is larger on the pole block, but also visible on the mid plane block

LL

G. Ambrosio et al., "Challenges and Lessons Learned From Fabrication, Testing, and Analysis of Eight MQXFA Low Beta Quadrupole Magnets for HL-LHC", **IEEE Trans. Appl. Supercond. 33 (2023) 5, 4003508**

Micrographic Analysis of Coil 214 Lead End



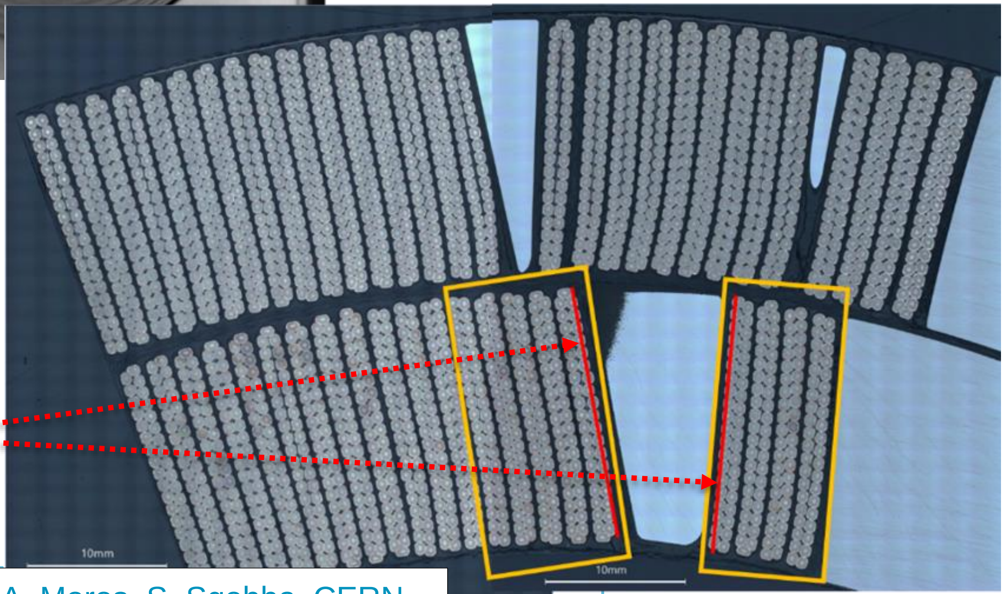
By B. Bulat, CERN

CT-scan, dye-penetrant test and metallurgical analysis by **CERN teams OUTSTANDING!**

A. Moros et al., "A Metallurgical Inspection Method to Assess the Damage in Performance-Limiting Nb_3Sn Accelerator Magnet Coils", **IEEE Trans. Appl. Supercond. 33 (2023) 5, 4000208**

Analysis started with sample #1: wedge-spacer interface

No anomalies found in cross-section #1. Therefore, we did longitudinal sections

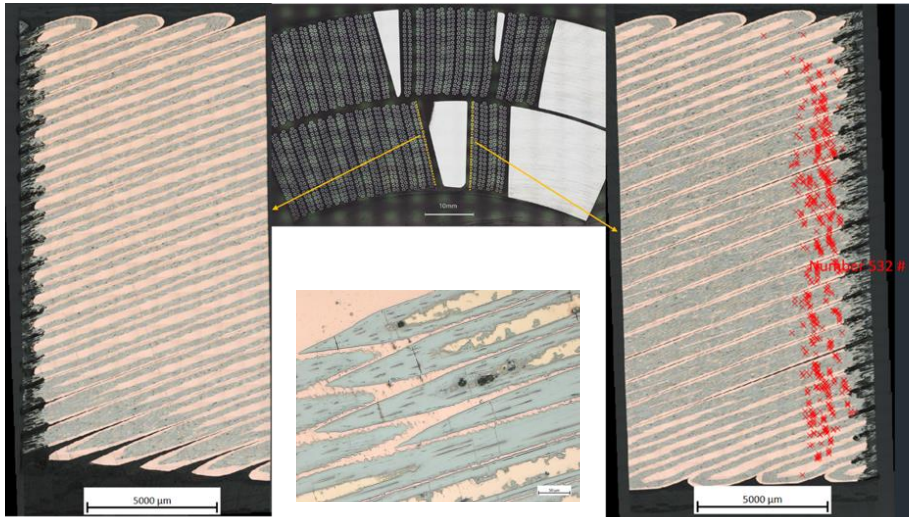


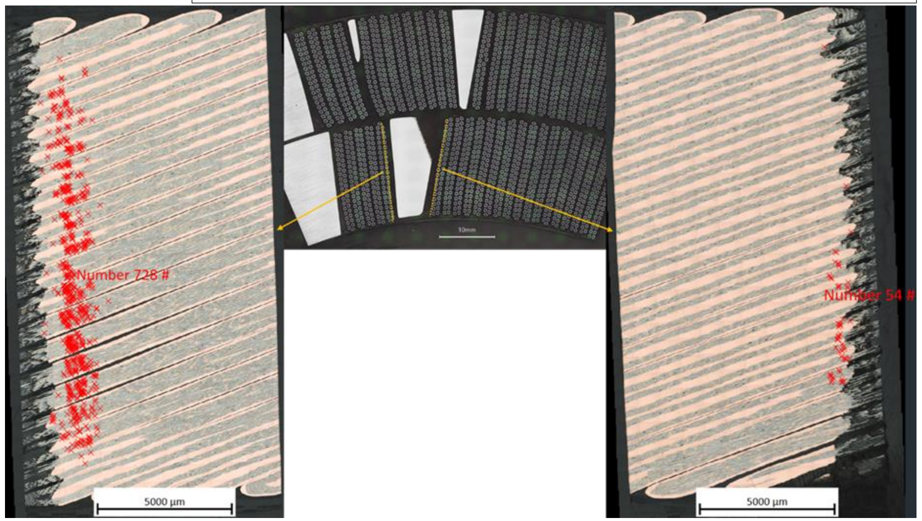
By M. Crouvizier, A. Moros, S. Sgobba, CERN

Metallurgical inspection: the smoking gun!

- Longitudinal cuts on cables adjacent to the end-spacer/copper-wedge transition
  - Localized field of broken filaments (red dots), especially at pole block

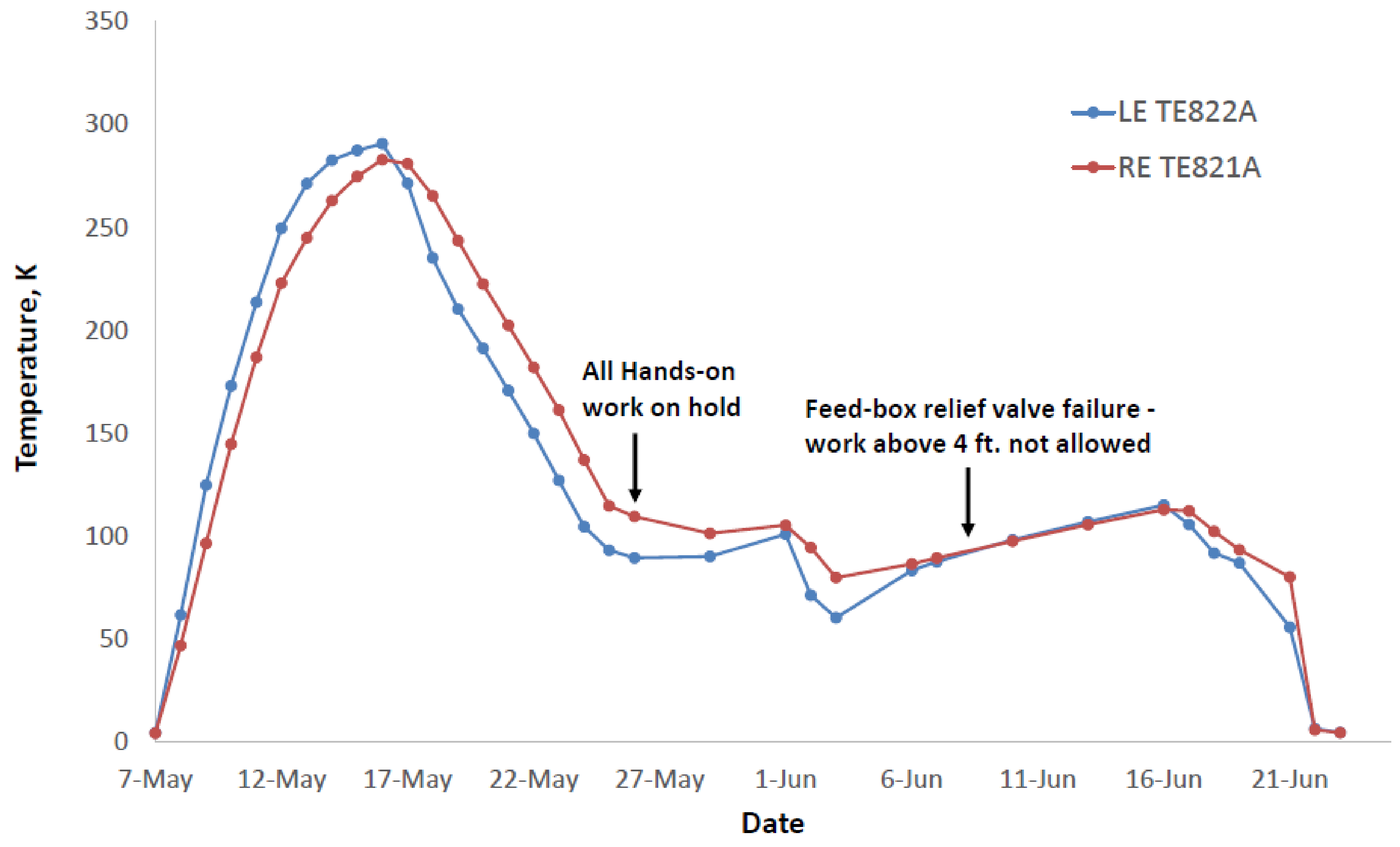
By M. Crouvizier, A. Moros, S. Sgobba, CERN





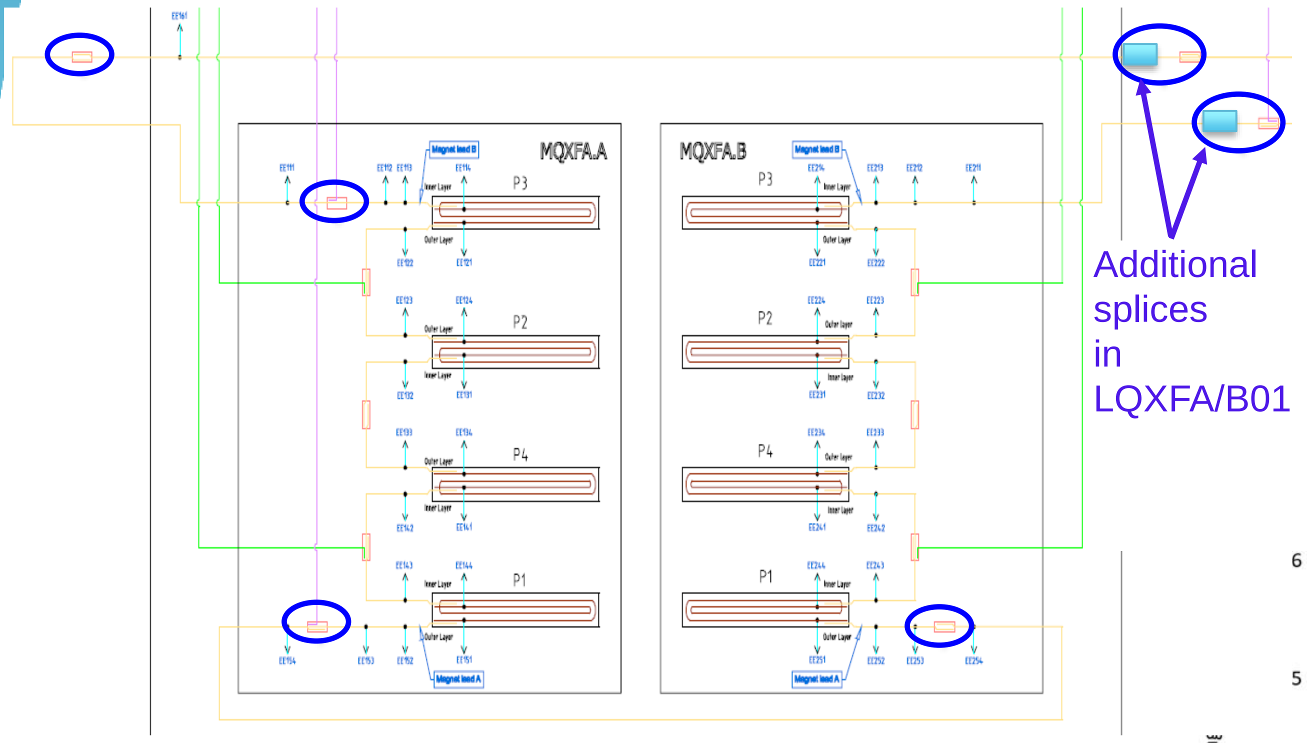
#	Samples adjacent to W-S transition from coil 214 Lead End	Number of cracked filaments
1	Layer-jump side, cable in midplane block, side adjacent to W-S transition	0
2	Layer-jump side, cable in **pole block, side adjacent to W-S transition**	**532**
3	Non-layer-jump side, cable in midplane block, side adjacent to W-S transition	54
4	Non-layer-jump side, cable in **pole block, side adjacent to W-S transition**	**728**
5	Same cable of sample 4, side opposite to the W-S transition	0

Second Thermocycle: Cooldown



SPLICE MEASUREMENTS

First measurement after system verifications were splice resistance measurements at 1.9 K, up to 5 kA.



Additional splices in LQXFA/B01

Leads

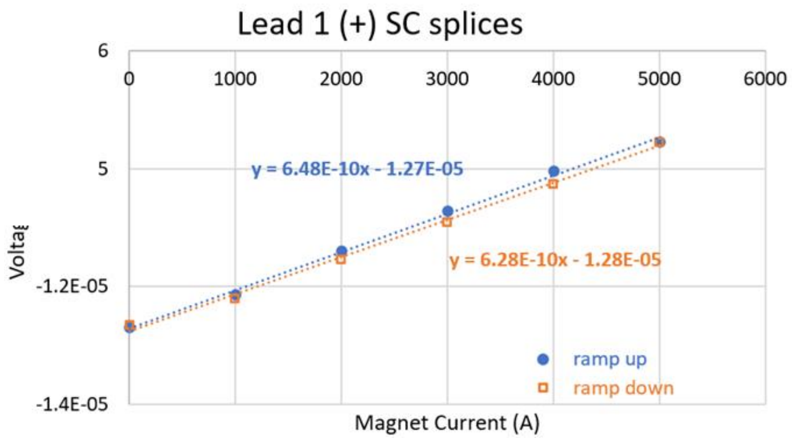
LD+ (nΩ)	LD- (nΩ)
0.6 ± 0.1	0.7 ± 0.1

Magnet A

Pw-lead-to-mag	Bus splice 1	Bus splice 2
0.3 ± 0.1	0.0 ± 0.1	0.0 ± 0.1

Magnet B

Bus splice 3
0.1 ± 0.1



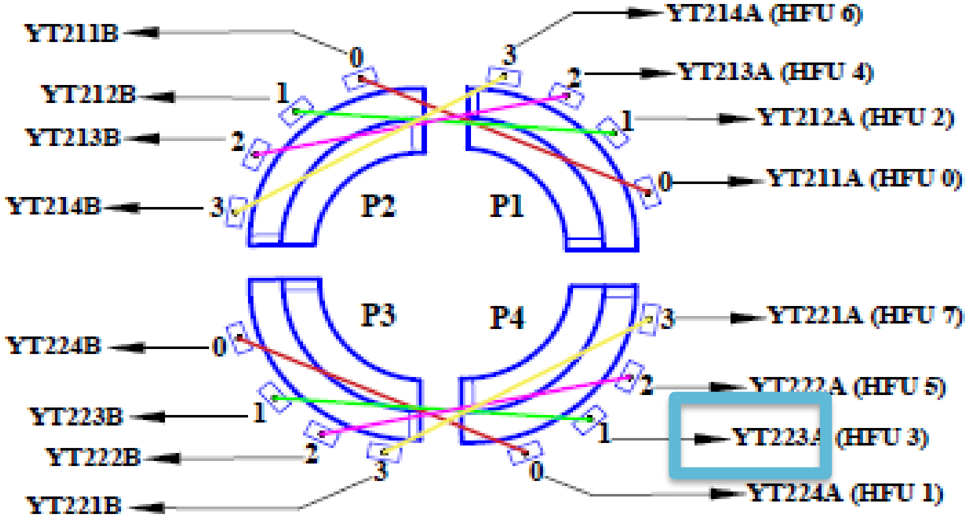
- **Splice resistance must be less than 1.0 nΩ at 1.9 K.**

WARM ELECTRICAL CHECKOUT

MT-28 International Conference on Magnet Technology
Aix-en-Provence, France, 10-15 September 2023

a. High voltage withstands tests (warm He gas can be present)
   i. Coil to Ground **368 V**
   ii. Quench heaters to Coil (coil is grounded) **460 V**

Open YT223 strip heater in MQXFA03. This issue was discovered during LMQXFA cold mass fabrication.

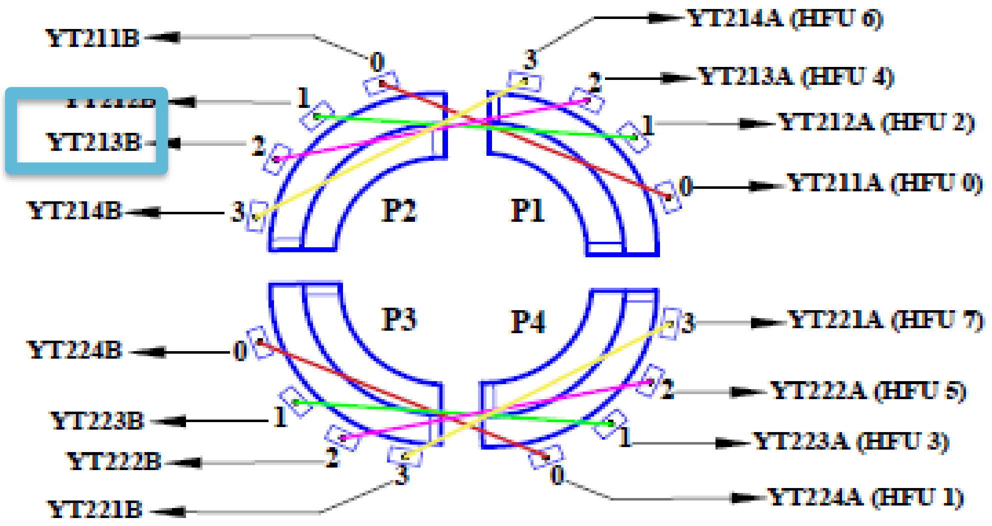


Electrical Design Criteria for HL-LHC Inner Triplet Magnets [EDMS 1963398]

COLD ELECTRICAL CHECKOUT

a. Ground resistance checks of power leads. Measure strip heater resistances
b. High voltage withstands tests at 1.9 K
   i. Coil to Ground **1840 V**
   ii. Quench heaters to Coil (coil is grounded) **2300 V**

YT213 heater to coil hipot failed at 2190 V in MQXFA03
After the breakdown the leakage current was higher.
This heater was isolated



Electrical Design Criteria for HL-LHC Inner Triplet Magnets [EDMS 1963398]