Fermilab

US HL-LHC AUP

HiLumi HL-LHC PROJECT

April 17, 2026

US HL-LHC cryo-assemblies at FNAL – testing and lessons learned

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U.S. DEPARTMENT of ENERGY Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

FERMILAB-SLIDES-25-0317-TD

A U.S.-produced cryoassembly for the high-luminosity upgrade to the Large Hadron Collider is moved from the testing facility at Fermilab in preparation for shipment to CERN, on Sept. 25, 2023. Credit: Ryan Postel, Fermilab

Outline

Testing HL-LHC magnets reveal no significant issues

Testing HL-LHC Cryo-assemblies at FNAL

Facility, magnet features, main measurements and results

Lessons Learned

After testing three cryo-assemblies; includes issues encountered

Based on presentations at MT29 and EUCAS 2025 conferences

https://inspirehep.net/files/3b567113c7569f7e014312fb1d72499f
https://inspirehep.net/files/839717ce17352dbeedeba1a331339020

01

Testing magnets/cryo-assemblies for HL-LHC

HL-LHC upgrade

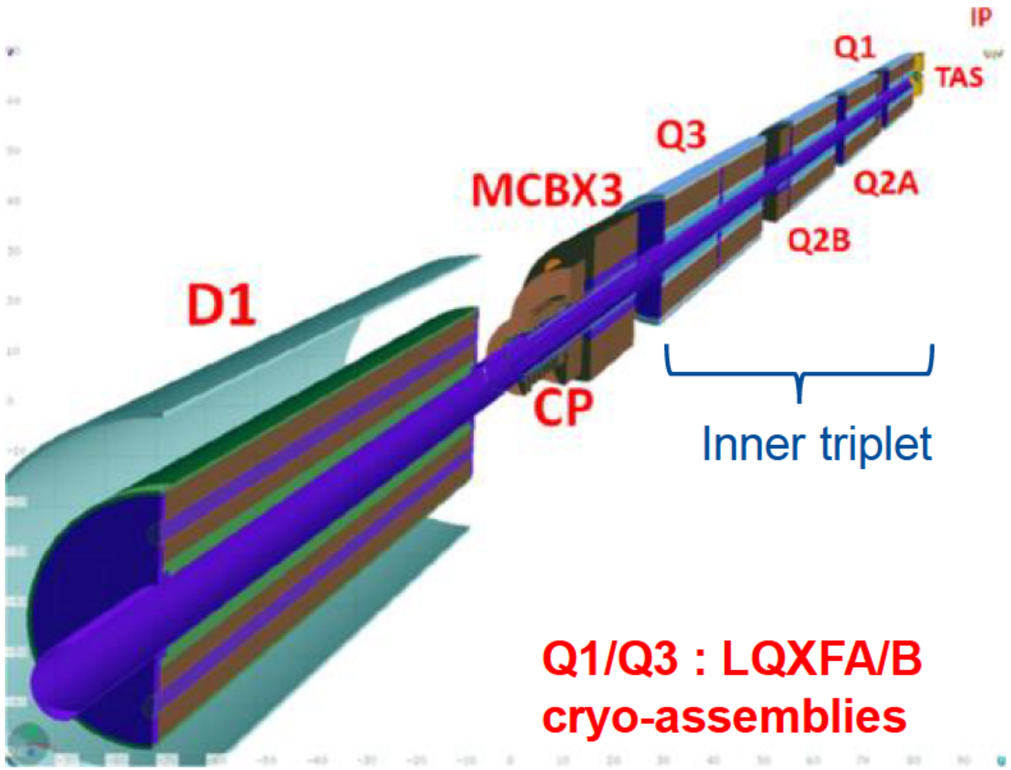
At CERN

On the accelerator side, one of the most impactful upgrades will be the brand-new final focusing systems just before the proton or ion beams arrive at the interaction points. In the new "inner triplets", particles will slalom in a more focused and compacted way than ever before towards collisions inside the detectors.

To achieve the required focusing strength, the new quadrupole magnets will use Nb_3Sn conductors for the first time in an accelerator. Nb_3Sn will allow fields as high as 11.5 T, compared to 8.5 T for the conventional NbTi bending magnets used elsewhere in the LHC. As they are a new technology, an integrated test stand of the full 60 m-long inner-triplet assembly is essential – and work is now in full swing.

The inner-triplet string will remain an installation on the surface at CERN and is expected to operate until early 2027. Four identical assemblies will be installed underground in the LHC tunnel from 2028 to 2029, during Long Shutdown 3. They will be located 20 m away on either side of the ATLAS and CMS interaction points.

Computer model of HiLumi LHC inner triplet with correctors MCBX/CP and D1 dipole.



Q1/Q3 : LQXFA/B cryo-assemblies

Q2A/Q2B cryo-assemblies

https://cerncourier.com/a/cern-gears-up-for-tighter-focusing/

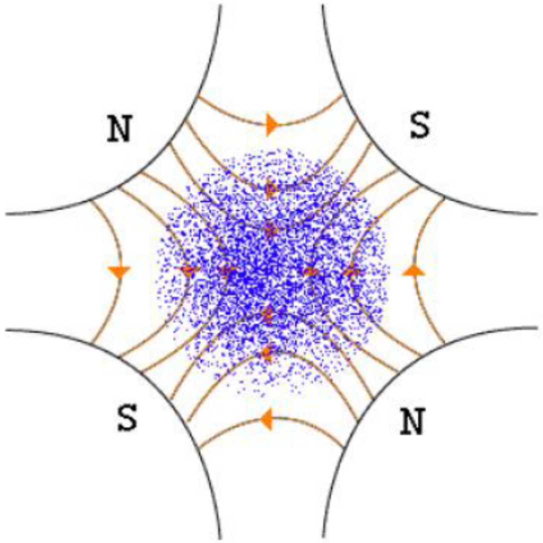
Phys. Rev. ST Accel. Beams **18**, 051001 – **Published 6 May, 2015** https://uspas.fnal.gov/materials/11ODU/Lecture5_Magnet_Design.pdf

https://arxiv.org/pdf/2203.06723

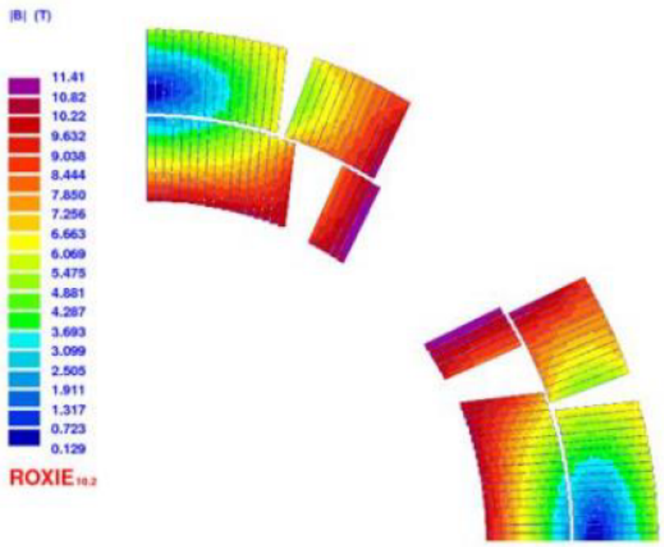
(M/L)QXF(A/B) – HL-LHC quads

Quadrupoles magnets have four poles (four coils)

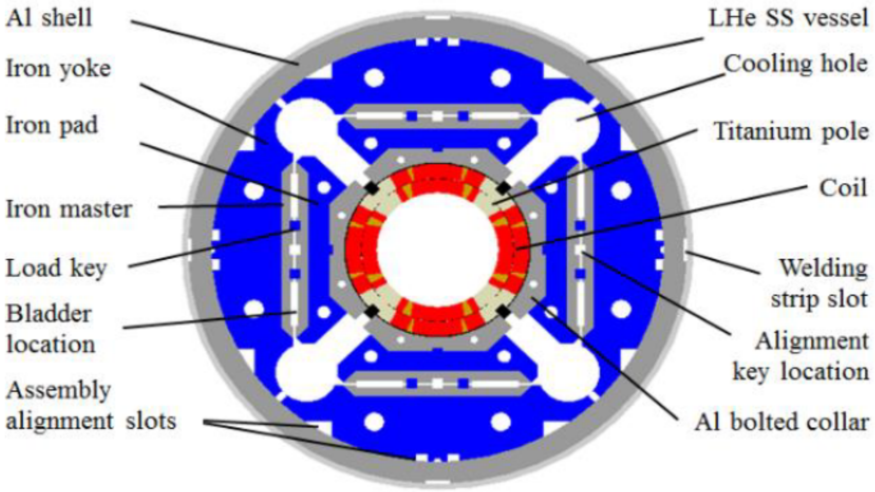
Quadrupole field drawing



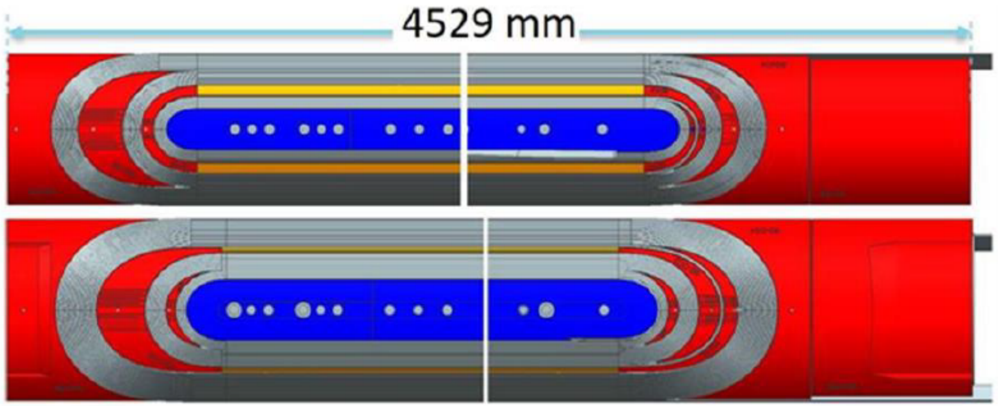
Cross-section of a MQXF coil (magnetic field at 16.47 kA)



Cross-section of a MQXF magnet



QXFA Coil inner layer (top) and outer layer (bottom) showing main components: Nb_3Sn cable (in grey), plasma coated stainless steel end parts (in red), copper wedges (in orange), titanium pole pieces (in blue).



Test Facility Overview at FNAL – IB1

by Vlad Nikolic

Vertical Magnet Test Facility (VMTF): 4 m deep, 0.65 m diameter up to 30kA

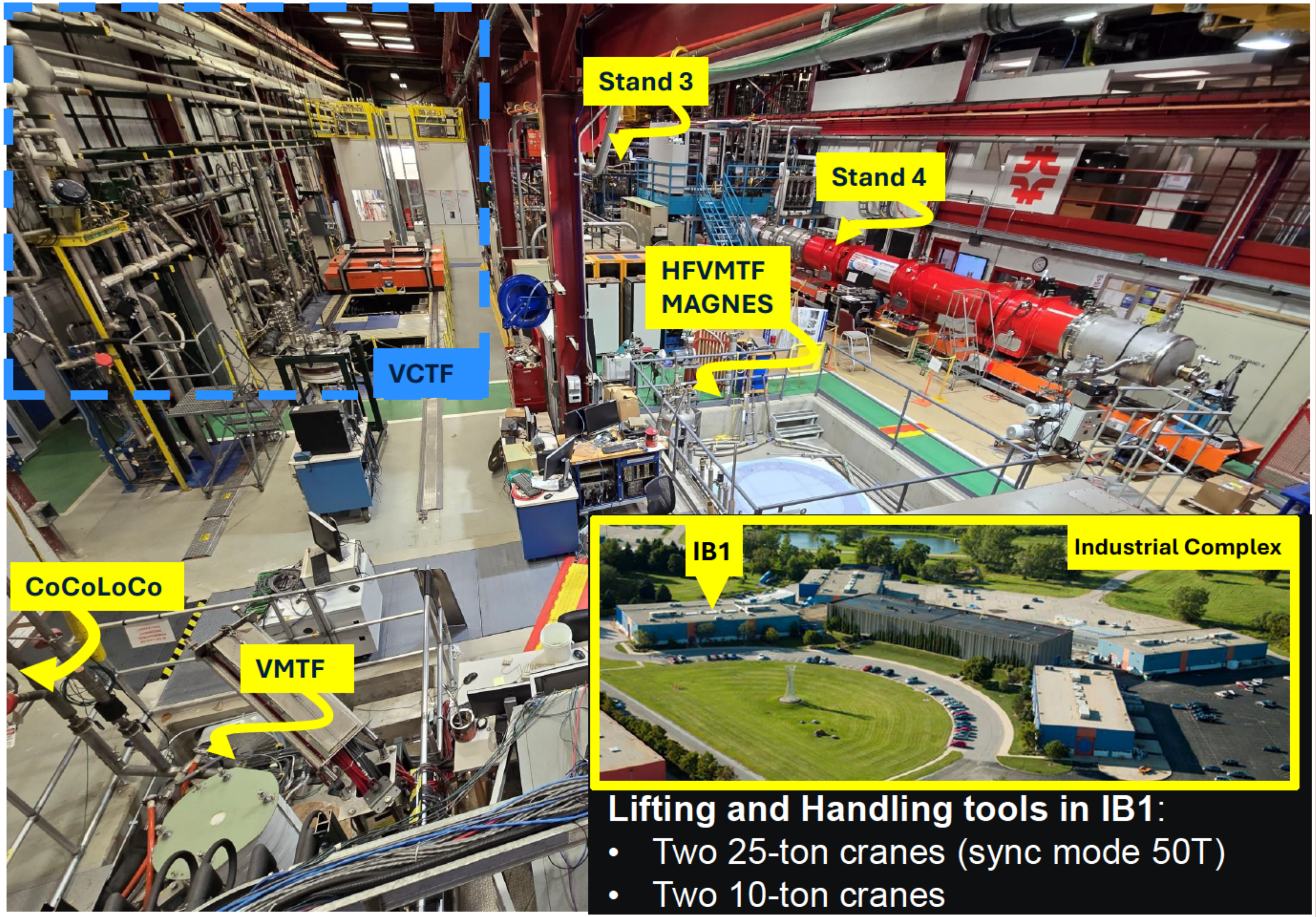
High Field Vertical Magnet Test Facility (HFVMTF): 3m deep, 1.3m diameter up to 24kA

Stand 3: 1 m deep, 0.5 m diameter up to 10 kA

Stand 4: Interface for horizontal cryostat up to 18kA

CoCoLoCo: conduction cooled low-cost facility

VCTF-3 cryostats : 4 m deep, 0.7 m diameter (**used for cavity testing**)

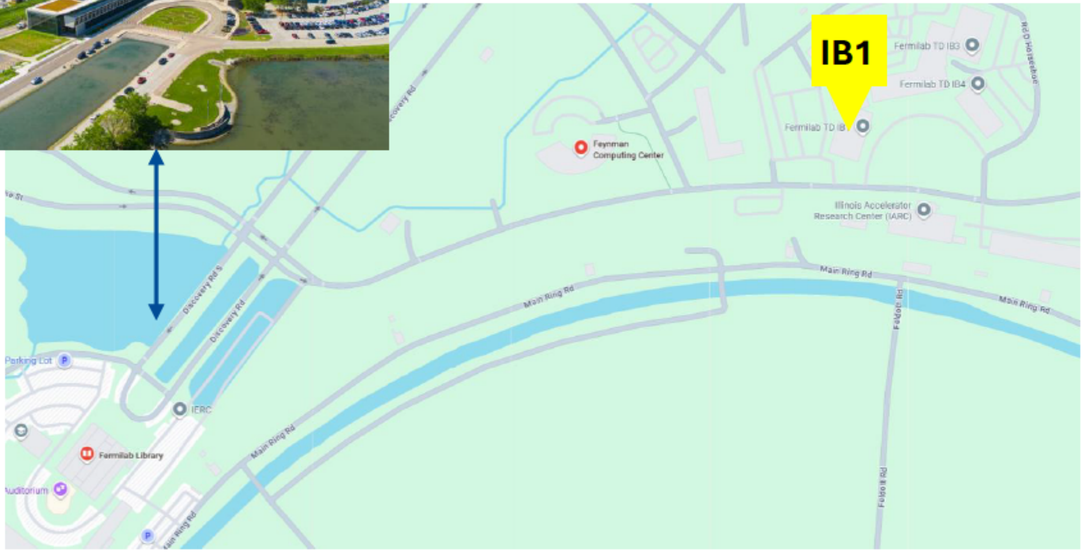


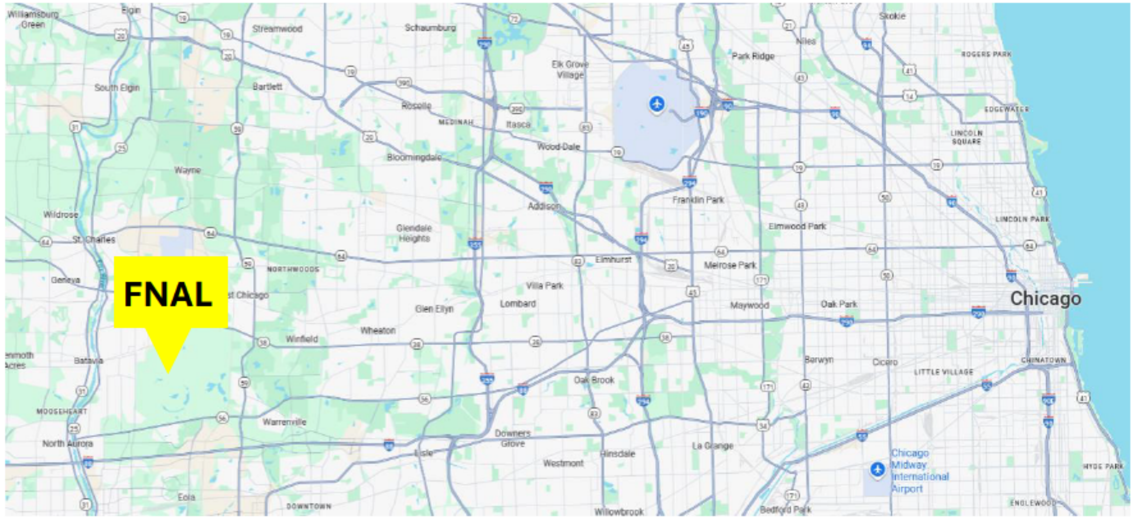
Lifting and Handling tools in IB1:

- Two 25-ton cranes (sync mode 50T)
- Two 10-ton cranes

Location of test facility

At FNAL





Cryo-assemblies for HL-LHC

By US HL-LHC AUP

The US High-Luminosity LHC Accelerator Upgrade Project (AUP) is responsible for delivering cryo-assemblies for the Q1/Q3 quadrupole optical components of the High Luminosity LHC (HL-LHC) at CERN. Each of them contains two magnets.

Three cryo-assemblies (CA) tested at FNAL

- LQXFA/B01 (CA01), LQXFA/B02 (CA02), LQXFA/B03 (CA03)
- Fabricated under the AUP collaboration
  - Coil production: BNL and FNAL
  - Magnet assembly: LBNL
  - Single magnet testing (quench training): BNL
  - Cold mass and cryo-assembly fabrication: FNAL
  - Cryo-assembly testing: FNAL

There are total of 10 cryo-assemblies to be fabricated and delivered to CERN, some to be tested at CERN (not FNAL).

So far five CAs have been delivered to CERN!

CA01 at the FNAL Horizontal Test Stand

CA02 during installation

CA03 at the FNAL Horizontal Test Stand

LQXFA/B01 Test

… and cryo-assembly

- LQXFA/B01 - the first Q1/Q3 cryo-assembly for the HL-LHC was successfully tested at Fermilab in 2023
  - ***M. Baldini et al., MT28 conference, FERMILAB-CONF-24-0052-TD***
- LQXFA/B01 test served as a final commissioning of the upgraded horizontal test stand (Stand 4) at Fermilab
  - Some test stand capabilities, including controlled cooldown/warmup, helium recovery after a quench, operation at higher pressures were commissioned with a cryo-assembly for the first time

LQXFA/B01 cryo-assembly at Stand 4

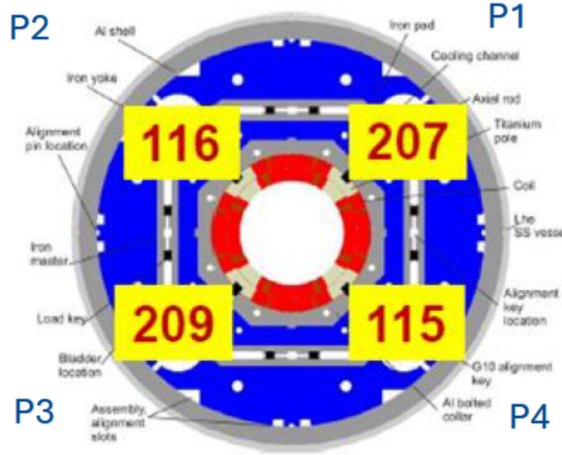
LQXFA/B02 & LQXFA/B03 Cryo-assemblies

All magnets used in LQXFA/B02 and LQXFA/B03 were previously tested at BNL

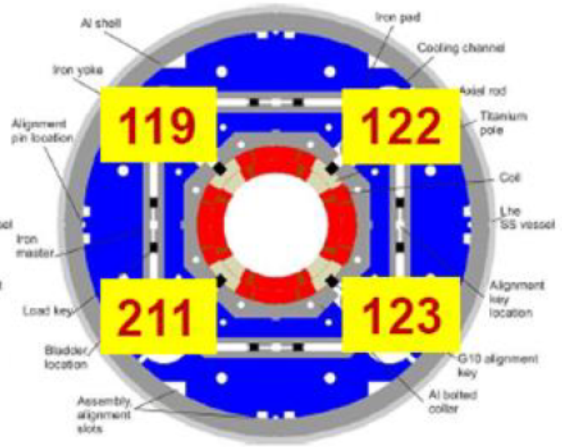
Quadrant numbering

Coil number

LQXFA/B02



MQXFA05

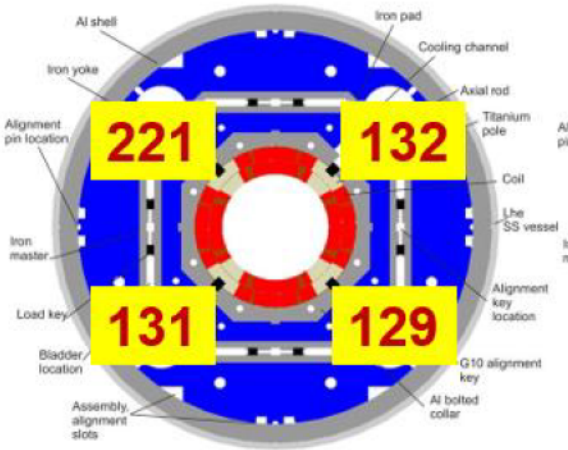


MQXFA06

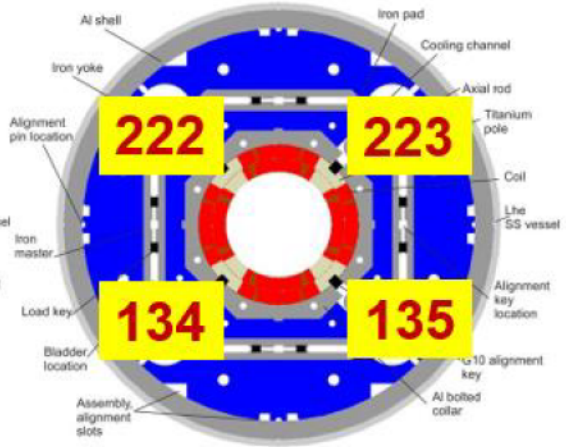
Magnet name

Cryo-assembly name

LQXFA/B03



MQXFA10



MQXFA11

FERMI NATIONAL ACCELERATOR LABORATORY

LQXFA/B's electrical connections

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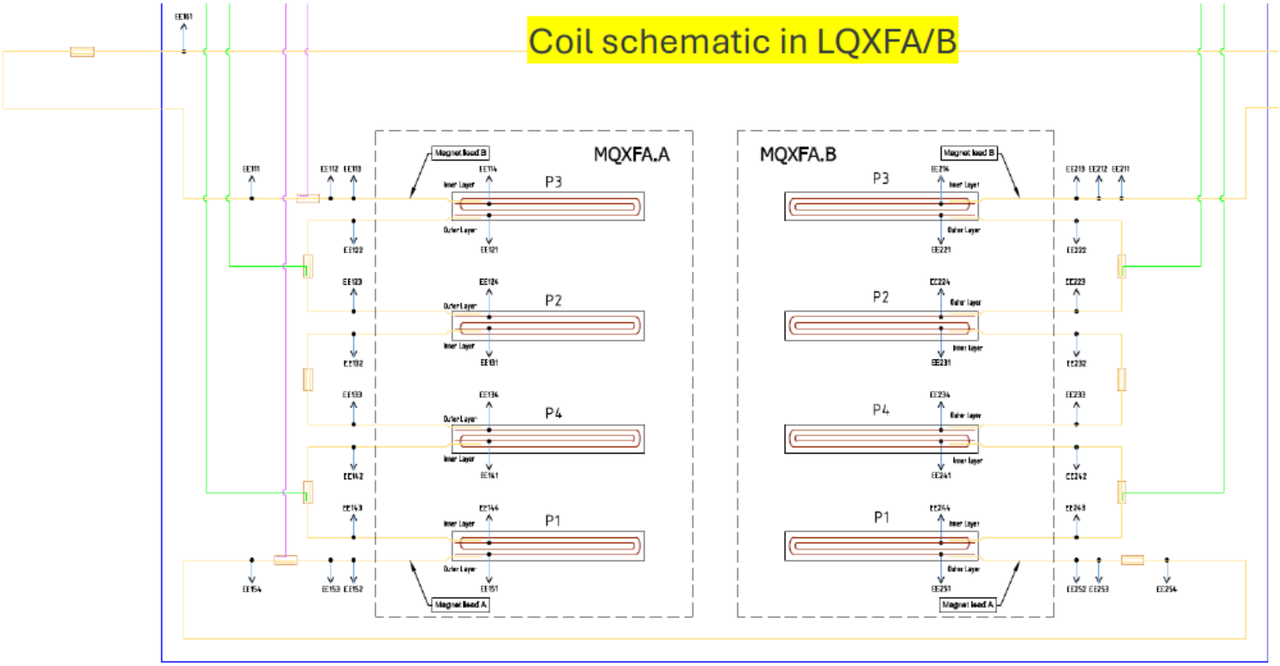
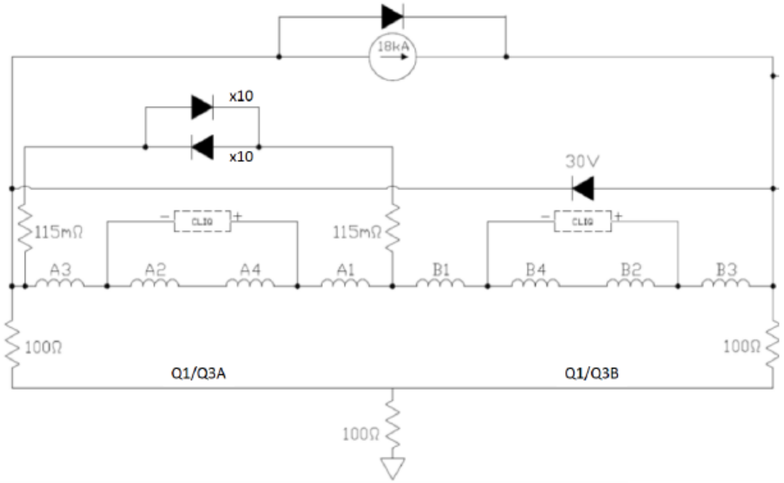


- Quench protection includes CLIQ & Strip heaters on the outer coils
- No external energy extraction is used



Cryo-assembly hook up to the power supply

Controlled cooldown & warmup

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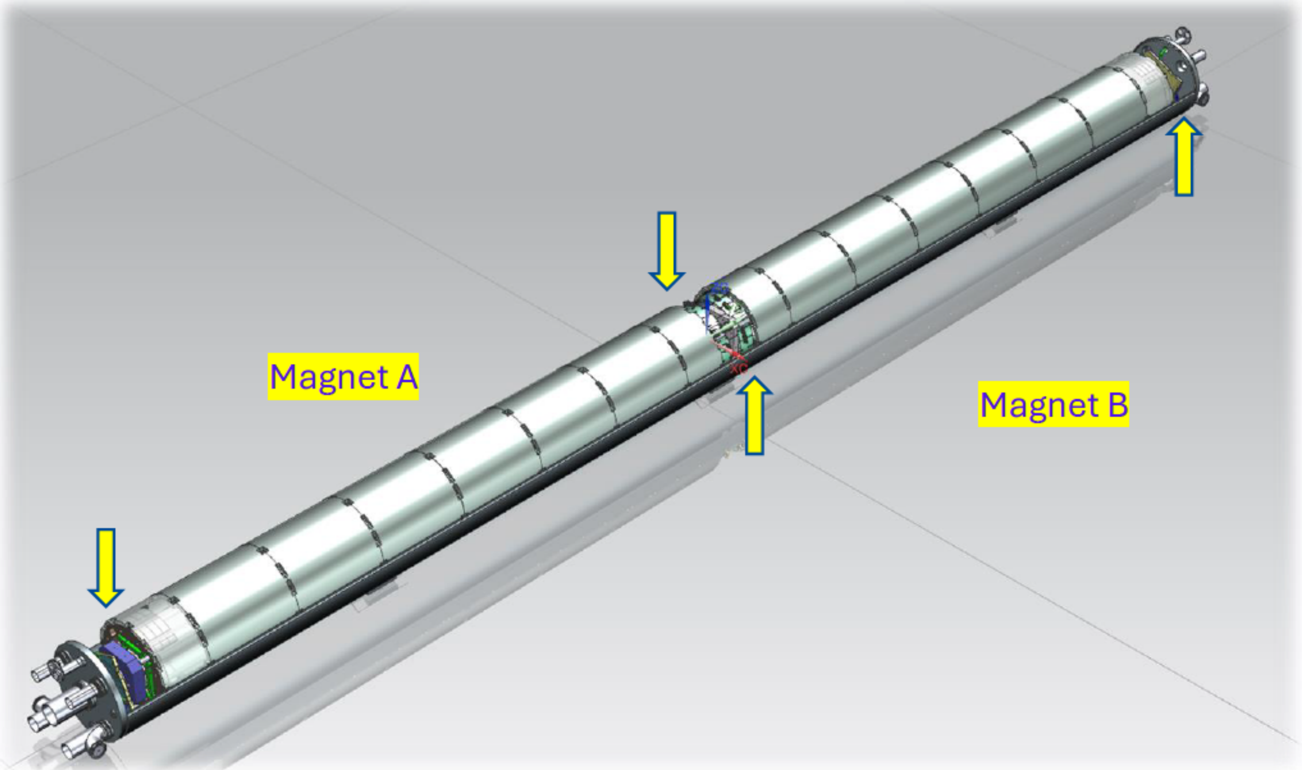
- The maximum temperature difference between the ends of each magnet should not exceed 50 K
  - For monitoring of the temperature gradient, Fermilab installs temperature sensors on both ends of each magnet



Controlled cooldown & warmup (2)

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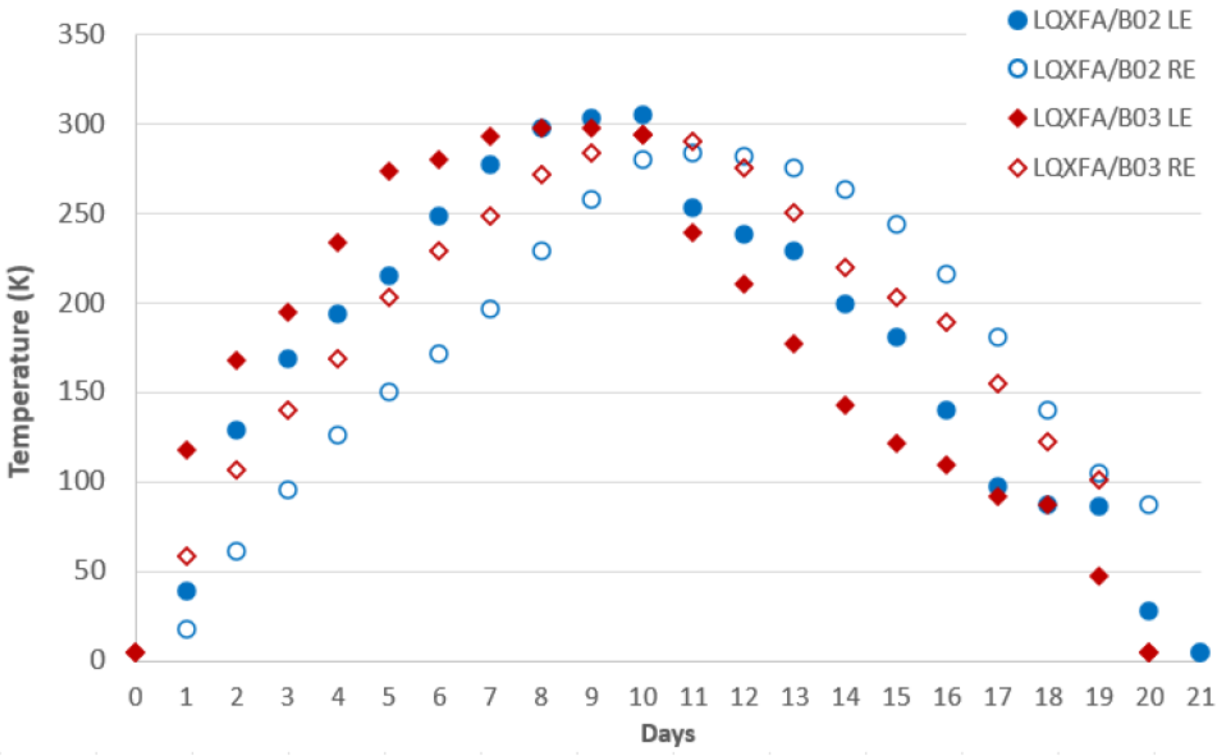
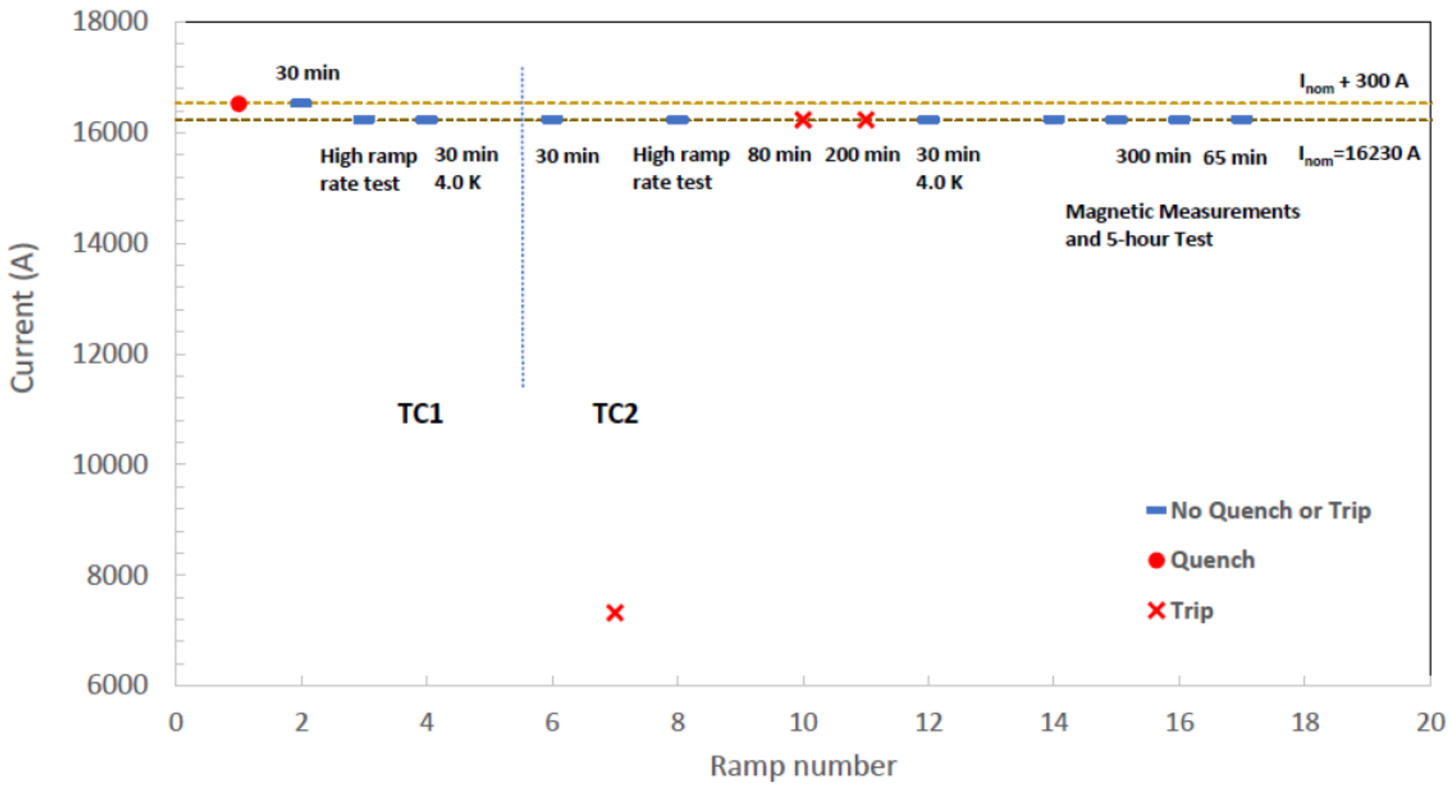
- Uninterrupted controlled warmup and cooldown takes about 20 calendar days
  - The limited mass flow of the helium gas (16-18 g/s) explains long cooldown and warmup
  - For further improvement, the existing heat exchanger and sub-cooler must be replaced



LQXFA/B02 Quench Performance

Individual magnets are first tested at BNL, including quench training

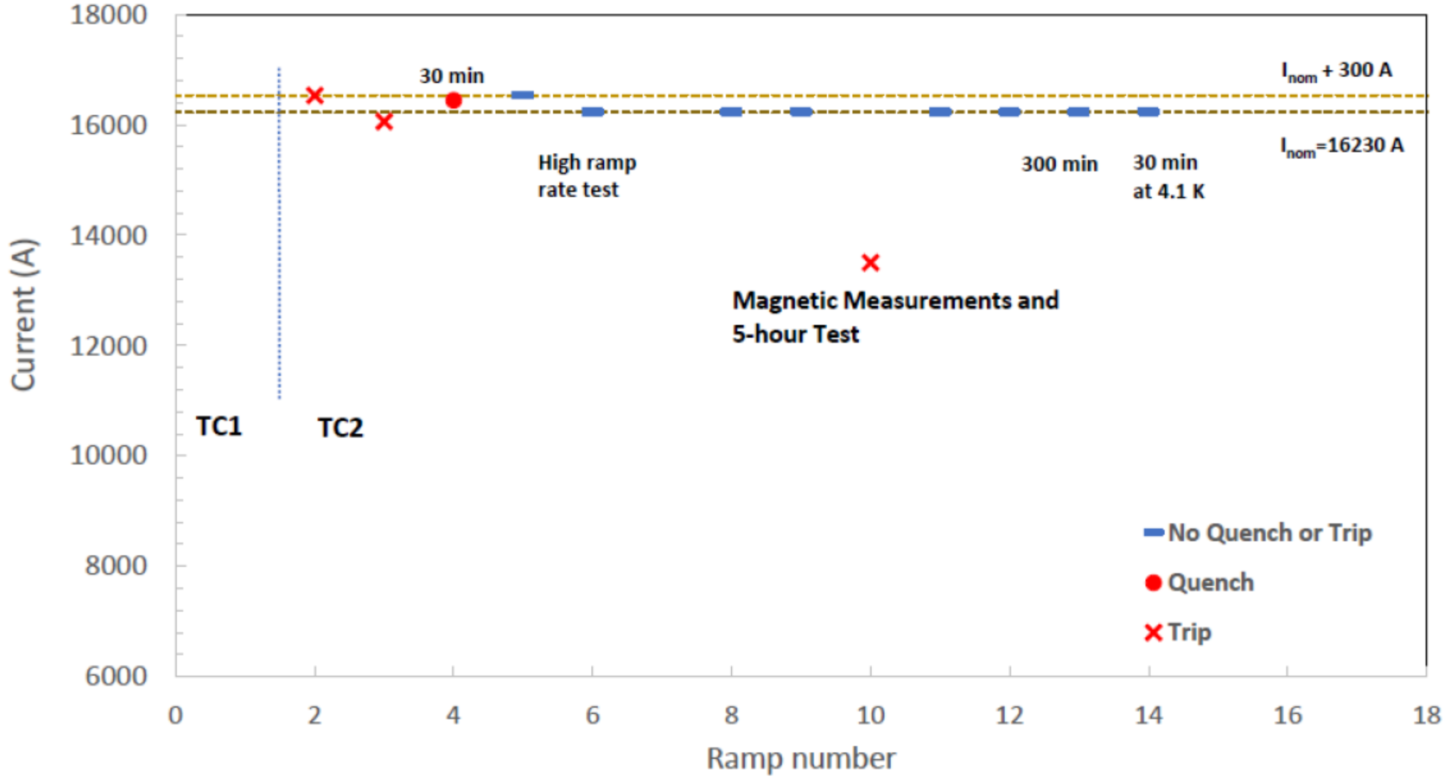
- Reached the acceptance current in one quench
  - After a thermal cycle, reached the nominal current without a quench
  - The issue with the power supply induced trips at the nominal current was resolved with adjusting the quench detection thresholds



LQXFA/B03 Quench Performance

Individual magnets are first tested at BNL, including quench training

- No power tests in TC1 due to a breakdown observed in the coil-to-ground insulation. The insulation fault was investigated and then repaired at Stand 4
  - In TC2, the acceptance current was reached in the first ramp, but cooling issues in the water-cooled flexible power leads caused a trip



Successful testing of the cryo-assemblies

Results were reported earlier*

Only one or no quench per magnet

After quench training of individual magnets at BNL

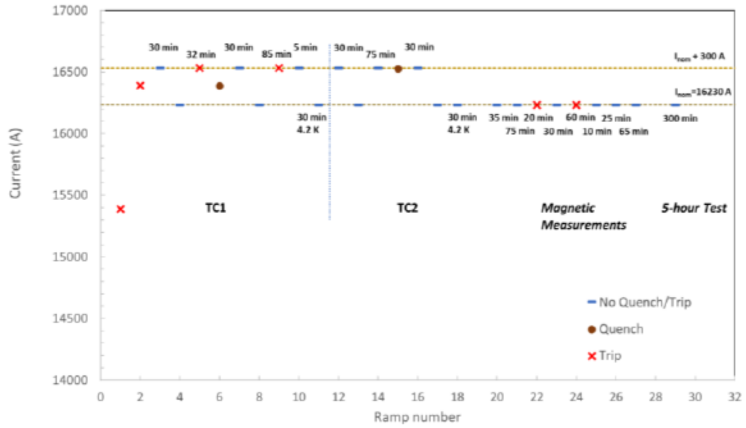
No performance decline after thermal cycles

Acceptance requirements were largely met, including on magnetic field; CAs were accepted

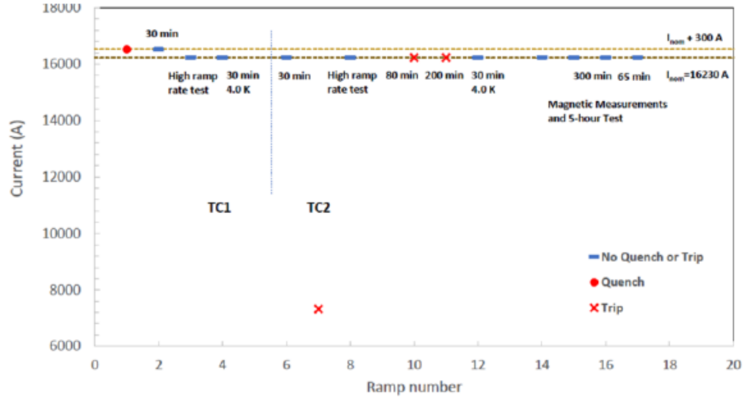
Unintended trips still occur though rarely

Those were dominated by cryogenics in CA1 and by power supply “spikes” afterwords

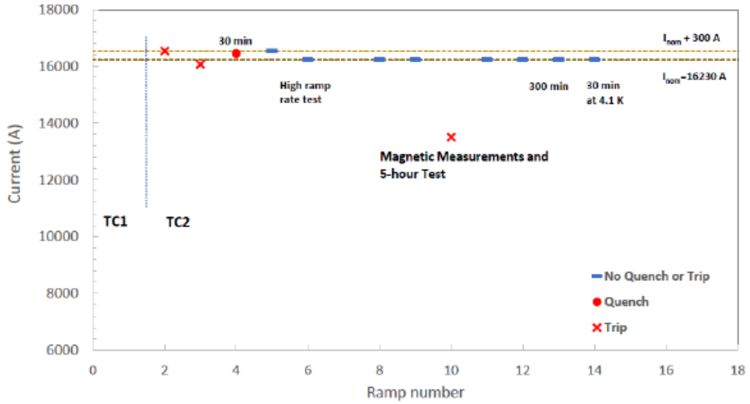
CA01



CA02



CA03



*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, doi: 10.1109/TASC.2024.3358777

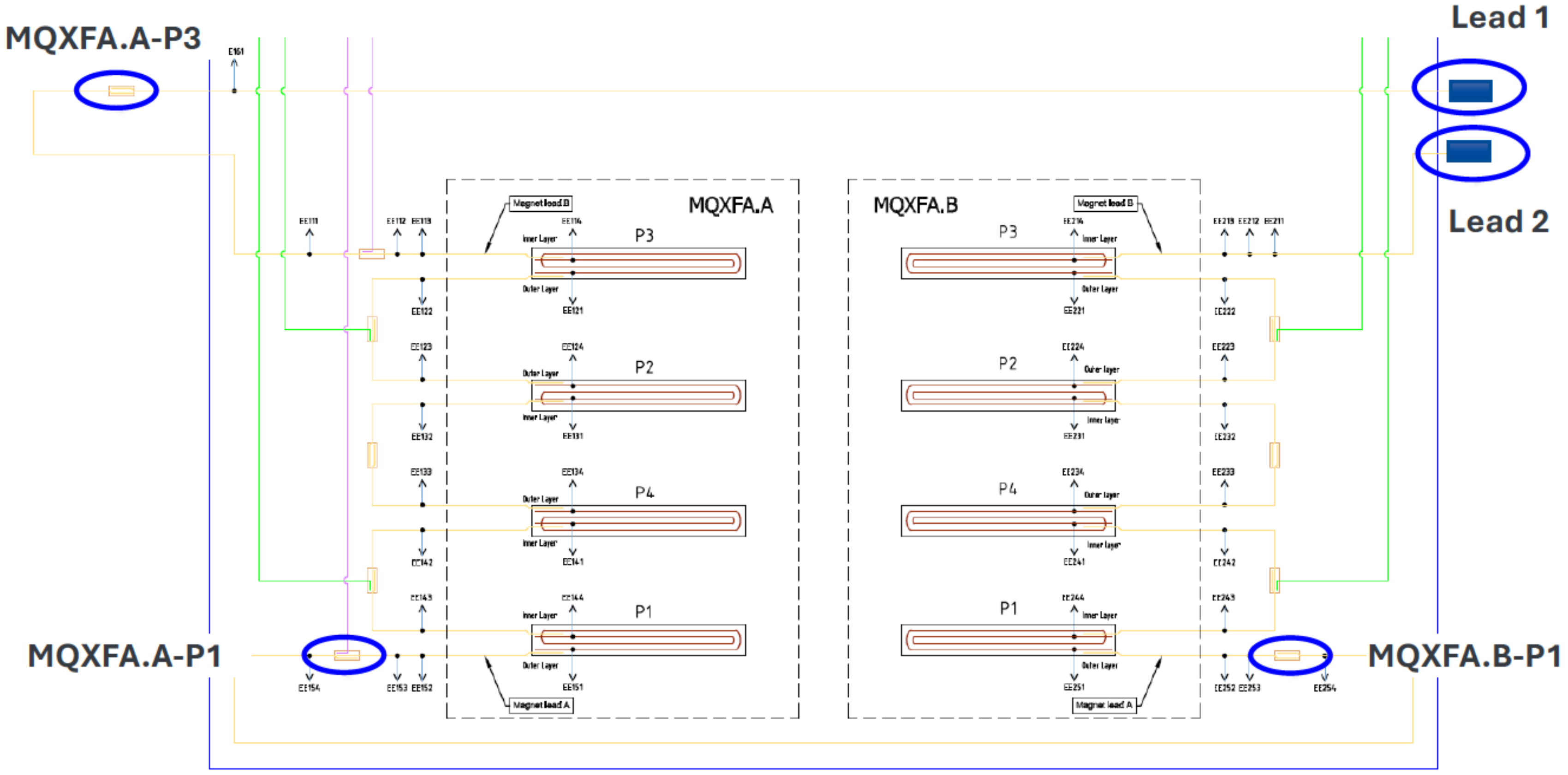
*J. DiMarco et al., "Magnetic Measurements and Alignment Results of LQXFA/B Cold Mass Assemblies at Fermilab," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4000205, doi: 10.1109/TASC.2023.3337202.

*G. Chlachidze et al., "Test results of the LQXFA/B02 and LQXFA/B03 cryo-assemblies for the High Luminosity LHC upgrade," presented at MT29, to be published.

Splice resistance measurements

Should be under 1 nΩ

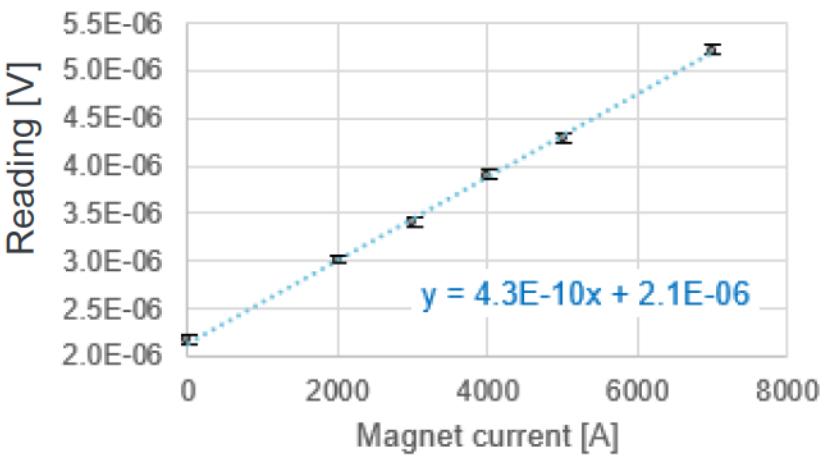
- Splice resistances at 1.9 K were measured for currents up to 8000 A (stairsteps ramping up and down)
  - We measure only NbTi-NbTi splices made at Fermilab



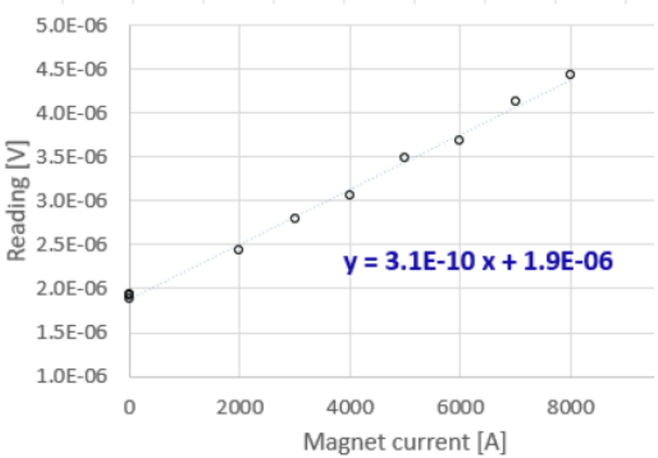
Splice measurements (2)

All measured splices in all cryo-assemblies met the acceptance requirements

MQXFA.B-P1 splice in LQXFA/B02



MQXFA.A-P3 splice in LQXFA/B03



Splice	[Unit]	Required	LQXFA/B02	LQXFA/B03
Lead 1	nΩ	< 1	0.35	0.45
Lead 2	nΩ	< 1	0.38	0.29
MQXFA.B-P1	nΩ	< 1	0.43	0.35
MQXFA.A-P1	nΩ	< 1	0.02*	0.1*
MQXFA.A-P3	nΩ	< 1	0.77	0.31

*This indicated a real technical problem with the magnet setups

Measurement uncertainties are within 0.06 nΩ

Main magnetic measurements

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- The distance between the two magnet axial centers at nominal current (16 230 A, a.k.a. NOC)

	[Unit]	Required at NOC	Measured at NOC
LQXFA/B01	mm	4,775 ± 5	4,772
LQXFA/B02	mm	4,775 ± 5	4,776
LQXFA/B03	mm	4,775 ± 5	4,778

Measurement uncertainty is ~ 1 mm

- The integral strength measured at nominal current with both rotating coil and SSW

[Tm / m]

Two magnets

	Magnets	[Unit]	Required at NOC	RC meas.	RC meas.	SSW meas.
LQXFA/B01	MQXFA03	T	556.9	559.70	1119.65	1119.1
	MQXFA04	T	556.9	559.95		
LQXFA/B02	MQXFA05	T	556.9	562.28	1124.15	1123.06
	MQXFA06	T	556.9	561.87		
LQXFA/B03	MQXFA10	T	556.9	561.56	1122.71	1121.49
	MQXFA11	T	556.9	561.15		

RC – rotating coil

SSW – Single Stretched Wire

Measurement uncertainty is ~0.12/0.25 T for RC and typically ~0.2 T for SSW although some biases exist too

- The maximum fringe field at 10 mm from the outer surface of the cryostat

	[Unit]	Required	LQXFA/B01	LQXFA/B02	LQXFA/B03
Fringe Field at NOC	mT	<50	2.5	2.8	3.6

- Multipole-expansion contributions beyond the main quadrupole field were measured to be within few 10^{-4} in all magnets

More material about magnet test results

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https://indico.cern.ch/event/1421594/contributions/5979257/attachments/2941400/5167908/Production%20testing%20of%20MQXFA%20magnets.pdf

https://lss.fnal.gov/archive/2022/slides/fermilab-slides-22-209-td.pdf

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 33, NO. 5, AUGUST 2023 4003508

Challenges and Lessons Learned From Fabrication, Testing, and Analysis of Eight MQXFA Low Beta Quadrupole Magnets for HL-LHC

Giorgio Ambrosio, Kathleen Amm, Michael Anerella, Giorgio Apollinari, Gonzalo Arnau Izquierdo, Maria Baldini, Amalia Ballarino, Christian Barth, Anis Ben Yahia, James Blowers, P. Borges De Sousa, R. Bossert, Bartosz Wojciech Bulat, Ruben H. Carcagno, Daniel W. Cheng, G. Chlachidze, Lance Cooley, Mickael Crouvizier, Arnaud Devred, Joseph DiMarco, Sandor Feher, Paolo Ferracin, Jose Ferradas Troitino, Laura Garcia Fajardo, S. Gourlay, Henry M. Hocker, Susana Izquierdo Bermudez, Piyush Joshi, Steven T. Krave, Elizabeth Marie Lee, Jeremy W Levitan, Vito Lombardo, Jun Lu, Maxim Marchevsky, Vittorio Marinozzi, Alice Moros, Joseph F Muratore, Michael Naus, Alfred Nobrega, T. Page, Ian Pong, J.C. Perez, Soren Prestemon, Katherine L Ray, GianLuca Sabbi, Jesse Schmalzle, J. Seyl, Stefano Sgobba, S. Stoynev, T. Strauss, Ezio Todesco, Daniele Turrioni, Giorgio Vallone, R. Van Weelderen, P. Wanderer, X. Wang, and Miao Yu

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022 9001407

Magnetic Measurements of HL-LHC AUP Cryo-Assemblies at Fermilab

J. DiMarco, P. Akella, G. Ambrosio, *Member, IEEE*, D. Assell, M. Baldini, G. Chlachidze, S. Feher, W. Ghiorso, J. Nogiec, V. Nikolic, S. Stoynev, T. Strauss, M Tartaglia, P. Thompson, D. Walbridge, and X. Wang

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 5, AUGUST 2024 4900606

Effect of CLIQ on Training of HL-LHC Quadrupole Magnets

S. Stoynev, G. Ambrosio, K. Amm, J. DiMarco, S. Feher, P. Ferracin, V. Marinozzi, S. Prestemon, and A. B. Yahia

02

Lessons Learned

Test stand (TS4) commissioning took time…

… and a cryo-assembly

The horizontal test stand was refurbished – it was previously used for testing the first generation LHC IR cryo-assemblies

- Preliminary commissioning of systems were performed through a “zero-magnet” test
  - electronics and acquisition systems
  - power and auxiliary systems
  - protection components
  - test stand cryogenic system (partially)
- Commissioning of the upgraded test stand required an actual cryo-assembly present
  - to find and fix tolerance inconsistencies
  - to accommodate observed irregularities (hardware, software, electronics) or intrinsic magnet features
  - to make it work as part of the bigger cryogenic distribution system
  - to make it work with other cryo-users, including high-priority ones like PIP-II cavity testing
  - to exercise controlled cooldown/warmup operations; and helium recovery after quench/trip

*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, doi: 10.1109/TASC.2023.3341985.

*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, doi: 10.1109/TASC.2024.3379173.

LQXFA/B01 Test Challenges

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- Liquefying capacity of the cryogenic plant was not sufficient for a continuous operation of Stand 4 at 1.9 K
- Instability in the liquid helium supply line caused several high current trips due to a sudden drop of the LHe level in the 4.5 K Feed Box
- The dynamic heat load to the 4.5 K Feed Box was found unexpectedly high. To survive high current ramps, we had to elevate the liquid helium level in the Feed Box, increasing the liquid helium consumption
- The old heat exchanger and the sub-cooler - the vessel containing the liquid nitrogen bath, are limiting our capabilities for a fast cooldown and warmup

- After the first test, various improvements have been made to increase the capability of the horizontal test facility

Cryo-plant operations

The cryo-facility is a blend of modern and vintage components

- Since 2024 we have a new fully operable cryo-plant
    - We still need the old cryo-plant to get to 600 l of LHe per hour
    - Only with the two plants we could operate continuously at 1.9 K
    - Unexpectedly high dynamic heat load led to large LHe consumption
- Gas bubble formations affected TS4 cryo-operations
    - We had to learn how the rest of the cryo-plant piping network affected TS4 testing
    - Bubbes in He-supply lines caused the LHe level to drop – some segments needed to be isolated to avoid the problems
- Addition of sensors (temperature, pressure) for better control
- New logic for automated recovery after quench
    - Still manual operation, 95 % done
    - Waiting for corrected interface between cryogenic and power supply PLCs
- Optimizations for cooling down/warming up

This is between CA01 and CA02

Resolved after CA01 testing

Resolved during CA01 testing

After CA01

Not yet completed (post CA03)

Continued in all CAs

Modern and vintage

There are inherited limitations

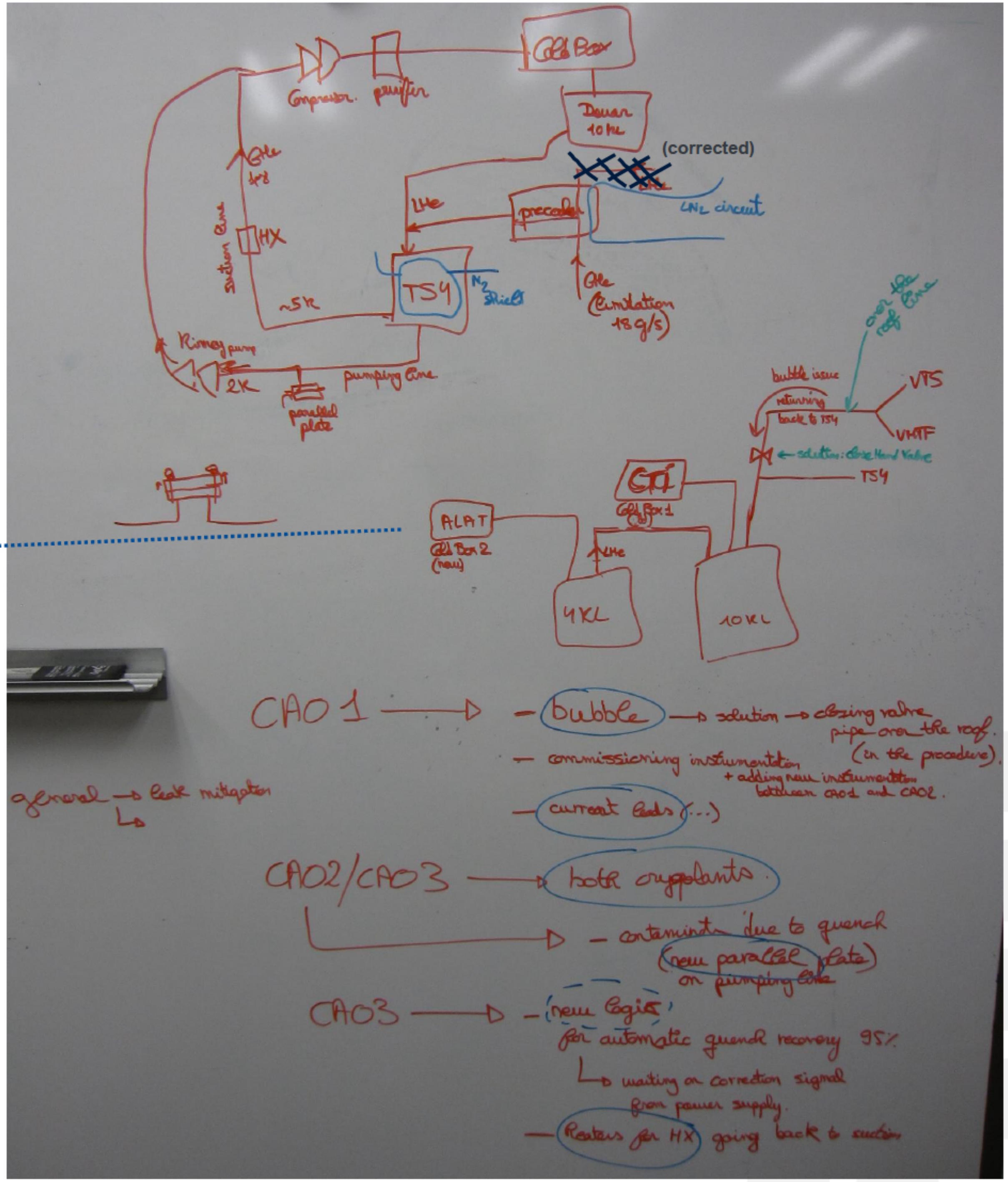
- Most of the infrastructure is still many 10s of years old
  - It is sometimes challenging to operate a modern facility along the vintage one (still quite reliable!)
- Single He-flow entrance to CA
  - The test stand set up is such that cooling/warming lines are coming from one CA side only ("lead end")
- Limited gas flow – no fast cooldown or warmup
  - Mostly due to the sub-cooler pipe-lines, the He gas flow is limited to 18 g/s
  - The sub-cooler is a repurposed Tevatron sub-cooler, **not designed for TS4**
- The heat exchanger in the He return was freezing
  - Temperature regulated heaters added to the He return lines — *After CA01*
  - Reengineered temperature control to further limit freezing of the heat exchanger — *After CA02*
- Lead-joint repair was necessary to normalize LHe operations
  - Newly designed copper fixture implemented, >15x dynamic heat load reduction — *After CA01*
- Relieve (parallel plate) valve faulted after a quench, no automatic detection
  - Two of those valves replaced by modern, more reliable, ones — *After CA02*

New liquefier from Air Liquide Advanced Technologies (ALAT)

It was commissioned in 2023 and started operation at full capacity in 2024. Liquid helium production rate doubled from 300 to 600 liter/hr when "old" and "new" liquefiers are running in parallel, and the LHe storage volume increased from 10,000 to 14,000 liters

Unofficial cryo-summary

by Maria Barba (FNAL cryo-engineer)



Space considerations

Too much or too little are drawbacks

- Building where the horizontal test stand is
  - Premium space, sometimes tight, other activities around
  - Most extensive leak/vacuum tests were deferred to the fabrication area (another building)

After CA01

- Tolerances
  - Test stand and cryo-assembly interconnect elements don't match perfectly due to fabrication tolerances
  - There is limited space to work and fix the issues, we learn to spot them as early as possible
  - In retrospect – more the interfaces, more the troubles
- Engineering and implementations
  - Tough to come up with easy spatial solutions (providing as much space as possible)
  - Due to nearly impossible spatial puzzle a voltage tap is wrongly placed resulting in a wrong splice resistance measurement (too low)

Pin-pointed in CA03

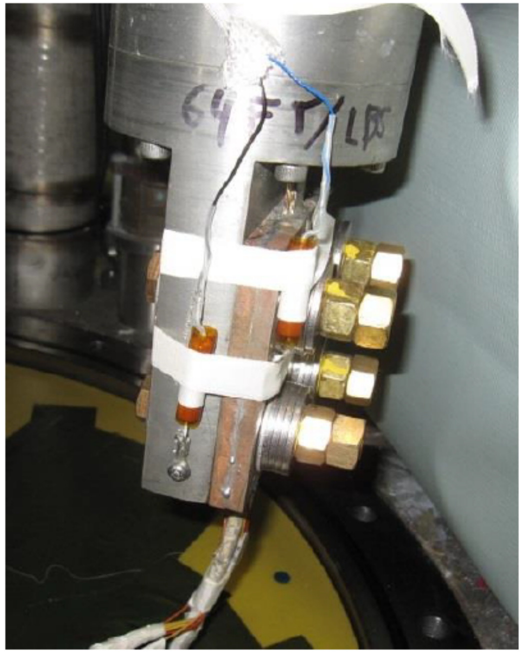
- Wire insulation problem
  - Too much extra length of the VT wire bundle created clutter in already crowded area
  - A wire got caught out of the terminal protection box, then welding damaged insulation

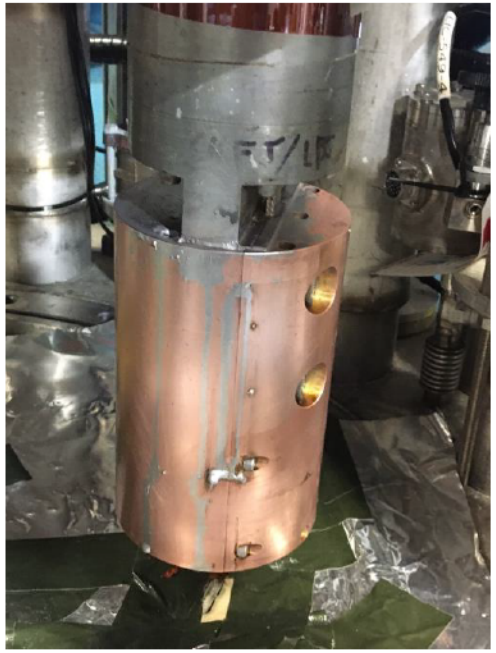
In CA03

Some of the issues encountered

Since resolved

A wire loop was found trapped outside of a protection box





The original lead joint (left) and the modified lead joint (right)

Eventually, excessive heat from welding of the nearby metal cover flange damaged the electrical insulation

Power supplies

The same system* was used for testing the first degeneration LHC IR cryo-assemblies

- The system of six modules (150 kW each) can provide up to 30 kA, it's over 20 years old
  - It is well maintained and serviced; repairs were needed but only occasionally
- Noise in the system
  - The system is not without noise, there are "features" (spikes)
  - The vast majority of spikes is well handled by the quench detection system
  - We did have to adjust some detection thresholds and validation times — *In CA01*
- Trips
  - "Features" were detected and taken care of — *In CA01*
  - Some intermittent spikes were difficult to catch and investigate, some were related to the magnets themselves (as observed in testing of individual magnets too)
  - One spike type was hard to comprehend (also intermittent) — *In CA03*
  - Spikes forced us to gradually loosen some detection thresholds, in a safe manner — *In CA02, CA03*

*R. Carcagno et al., "New 30 kA power system at Fermilab and its use for measuring the effects of ripple current on the performance of superconducting high field magnets," in IEEE Transactions on Applied Superconductivity, vol. 15, no. 2, pp. 1520-1523, June 2005, doi: 10.1109/TASC.2005.849153.

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Quench detection (QD)

Newly developed, DQD+AQD based*

A lot of detection channels available – 64 digital and 20 analog

- Versatile and robust system
  - It gives a lot of options and handles in safe environment, high degree of redundancy
- DQD
  - All detection channels have current-dependent thresholds
  - It took efforts to adjust thresholds, unintended trips occurred
  - Due to power supply and signal processing issues some channels were dropped or thresholds increased
  - Still well overprotected – the main detection channels of the cryo-assembly, bucked half-magnets for each magnet, are now triggering at 250 mV while we started with 150 mV (above 8 kA)
- AQD
  - AQD are the independent back up, thresholds are set manually
  - They allow much less control than digital ones, similar issues with threshold adjustments
  - Apart from “leads”, we only use two (bucked) channels from AQD now

*A. Galt et al., "A Quench Detection and Monitoring System for Superconducting Magnets at Fermilab," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-4, Sept. 2022, Art no. 9500404, doi: 10.1109/TASC.2022.3155492.

Magnetic measurements

We expect those to "just work"

- Single Stretched Wire system
  - A well-respected vendor could not provide quality wire (very specific) for the system
  - A vendor known for quality of specific wires was chosen later

After CA01

- Rotating coil system – brand new set up
  - Mock-up testing did not reveal issues, but that set up had limitations
  - At high current, magnets cold, running for long time – multiple issues became apparent
    - Additional resistance to rotation at high magnetic current, coupling becoming loose
    - DAQ (encoder) triggers lost
    - Disruptions in the laser-tracker-based motion control system (including due to frost/moisture)
    - Memory buffer overflow

Solved in CA01

  - Buffer overflow problems returned in CA02 and even CA03 (partially) with longer tests

Solved in CA03

- The real culprit: lack of dedicated system integration and "contingency" in the final conditions
  - Enough time, no pressure – hardly the case
  - Alternative and back-up systems/duplicates (evaluation and separation of issues); there was no plan "B"

*J. DiMarco et al., "Magnetic Measurements and Alignment Results of LQXFA/B Cold Mass Assemblies at Fermilab," in IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4000205, doi: 10.1109/TASC.2023.3337202.

Conclusions

Testing HL-LHC magnets reveal no significant issues

CERN celebrated the arrival of the first cryo-assembly for the HL-LHC with a ceremony on Dec. 18 (2023). From left: Oliver Brüning, CERN, HL-LHC project leader; Mike Lamont, CERN, director for accelerators and technology; and Giorgio Apollinari, Fermilab, head of the U.S. HL-LHC Accelerator Upgrade Project. Photo and captioning: CERN

Full test stand and systems commissioning require the real test object (CA)

From mechanical, through cryogenics, to electronics and even shifting testing priorities

Cryogenics is (almost) everything

Many issues we encountered revolved around cryogenics and limitations stemming from the nature of cryogenic conditions

The AUP is delivering to CERN

No significant issues with cryo-assemblies and magnets, schedule is tight but workable, collaboration with CERN is strong

PERFECT is enemy of GOOD-ENOUGH

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, through the US LHC Accelerator Upgrade Project (AUP).

Spare

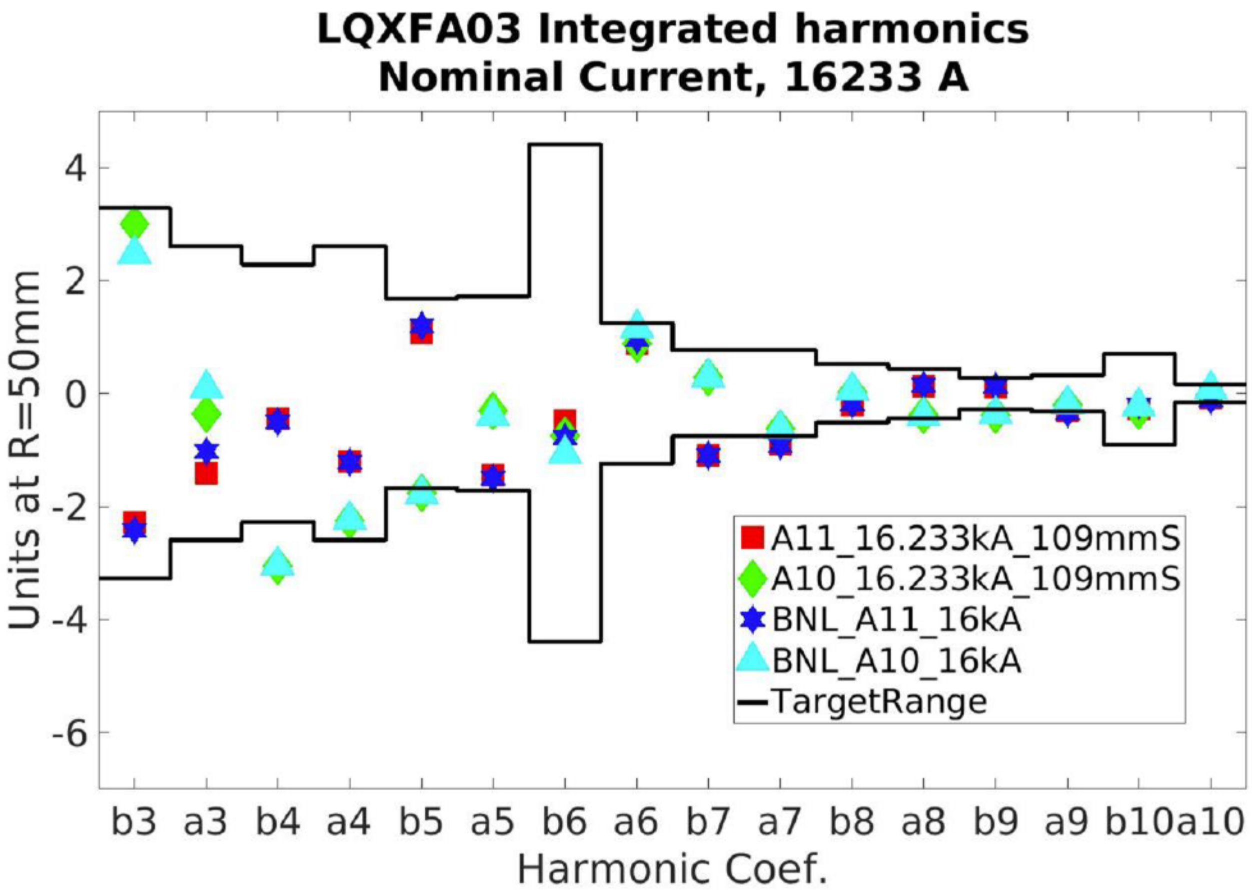
Field harmonics:

- If $\frac{\partial B_z}{\partial z} = 0$

  Maxwell gives $\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = 0$, $\frac{\partial B_y}{\partial y} + \frac{\partial B_x}{\partial x} = 0$

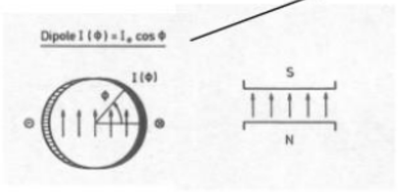
and therefore the function $B_y + iB_x$ is analytic

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} \qquad (x,y) \in D$$

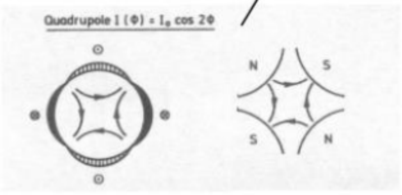


$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} = C_0 + C_1(x+iy) + \ldots \qquad (x,y) \in D$$

- Each coefficient corresponds to a "pure" multipolar field

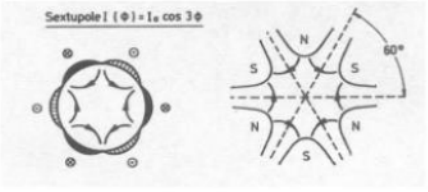


A dipole



A quadrupole

[from P. Schmuser et al, pg. 50]



A sextupole

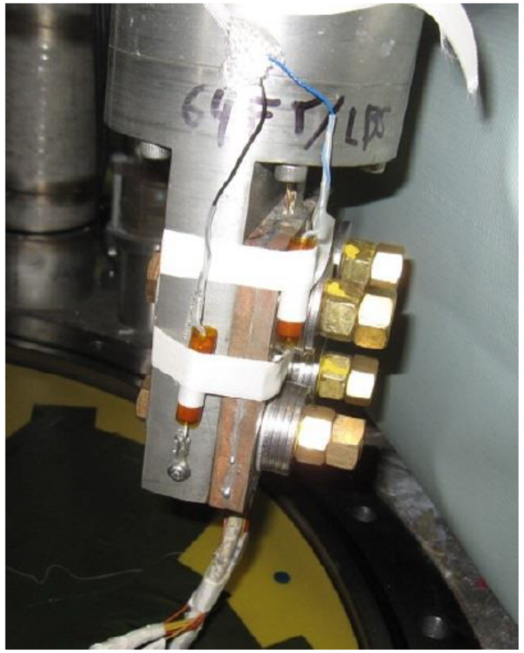
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

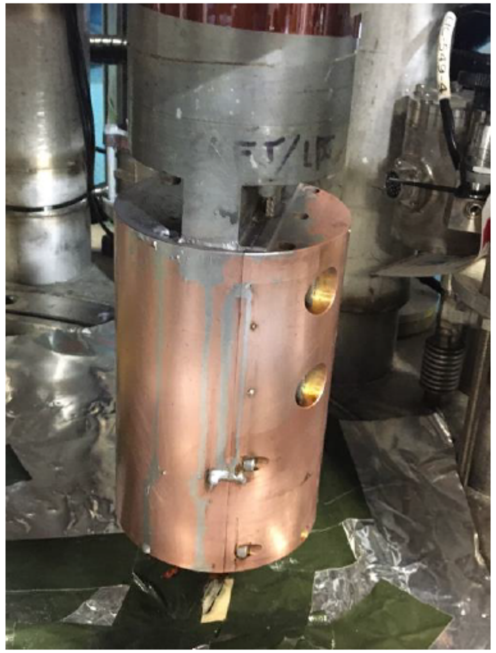
(for details, see reference material; there are US and EU notations…)

https://indico.cern.ch/event/440690/contributions/1089751/attachments/1143438/1638603/U5rr.pdf

Spare

New copper fixture and
a mock-up of the existing flag

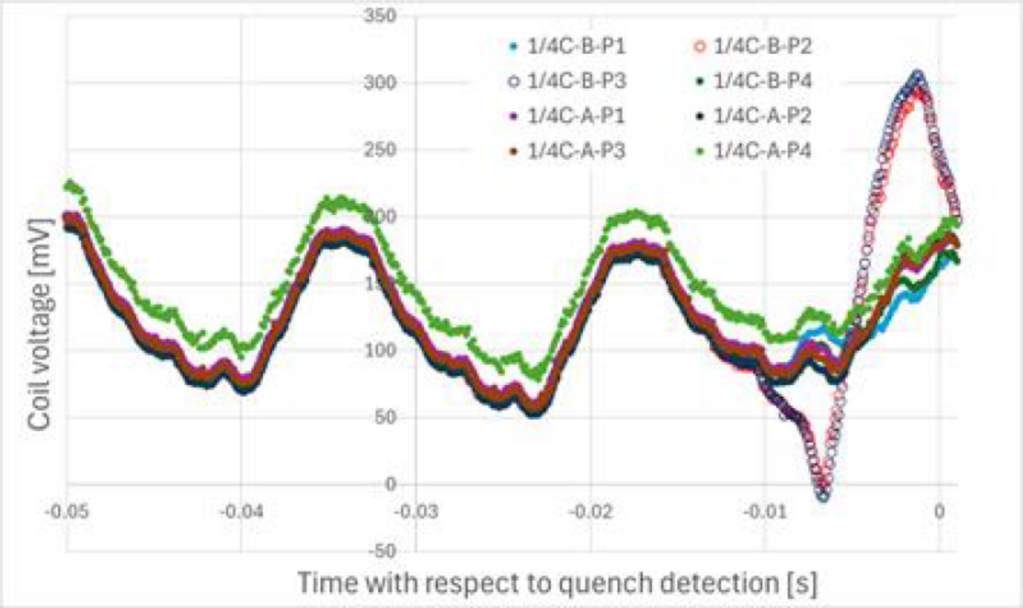




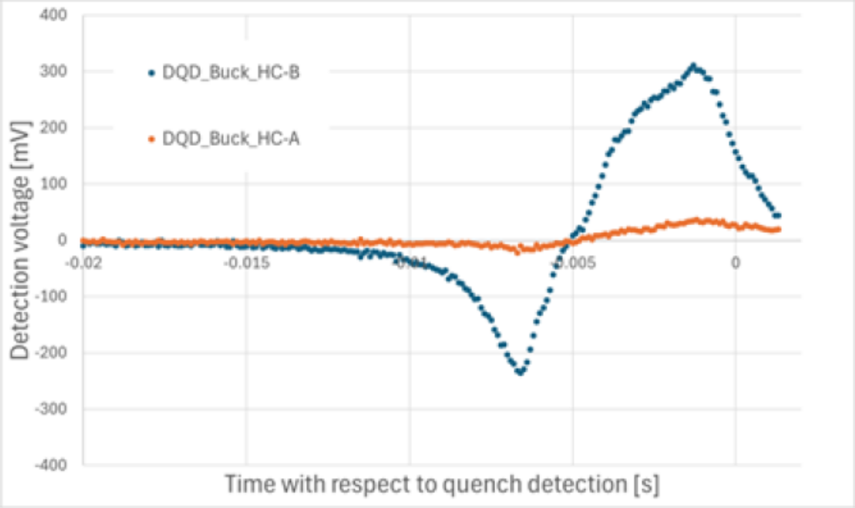
The original lead joint (left) and
the modified lead joint (right)

Spare

Unfiltered voltages on individual coils



Detection channels



This led to a trip (likely cased by coil/part movement)

Larger thresholds take care of this example, but not if magnitude becomes sufficiently higher

Fermilab

FermiFORWARD

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