Horizontal Test Results of LQXFA/B01

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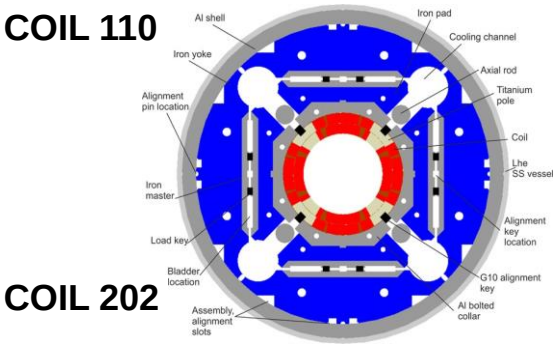
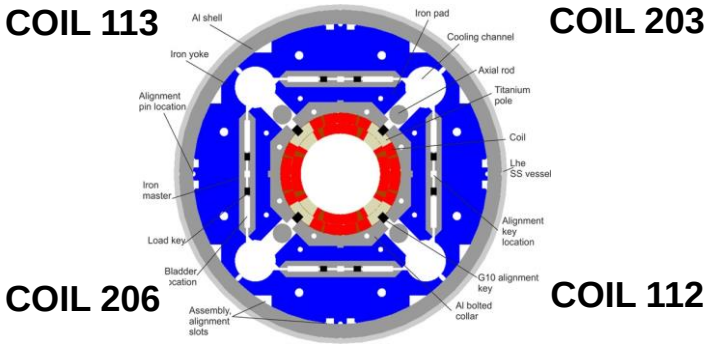
Fermilab
Oct 5, 2023

LQXFA/B01

- LQXFA/B01 - the first pre-series cryo-assembly with MQXFA03 and MQXFA04 magnets previously tested at BNL

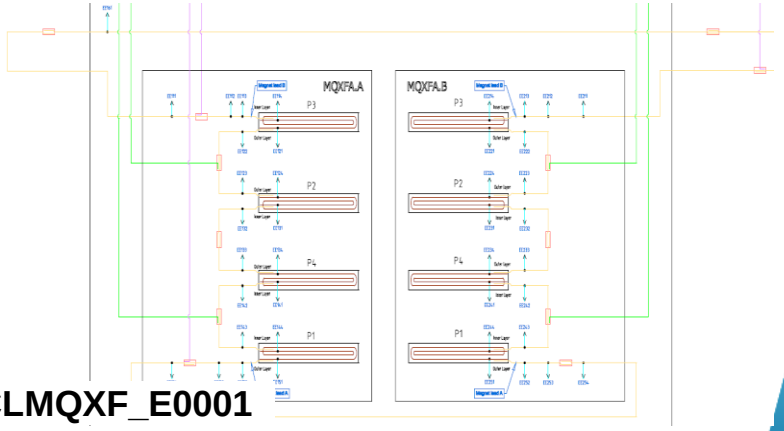


MQXFA03



MQXFA04

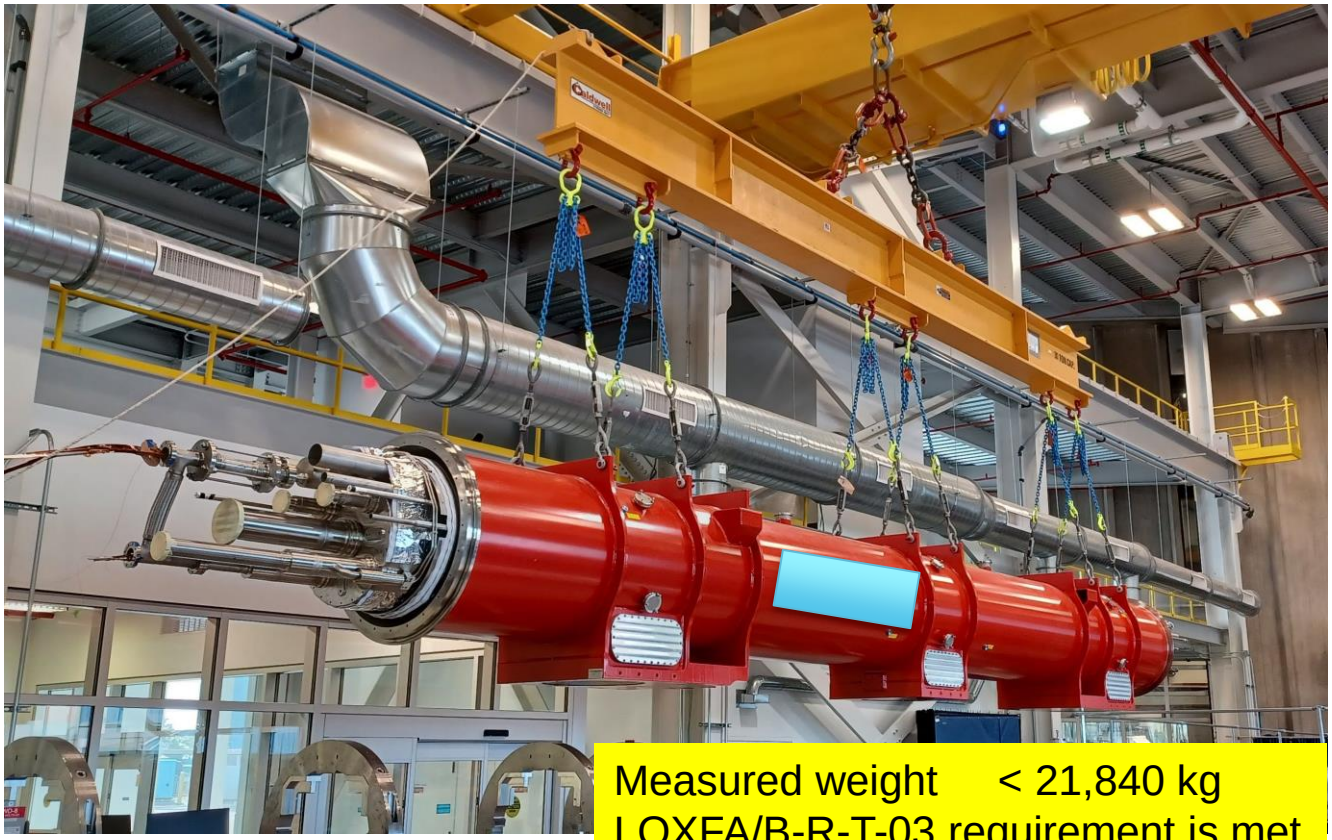
- Voltage taps used only for quench detection
- Strip heaters on the outer coil layer
- Dump delayed for 1000 ms/ then completely removed



LHCLMQXF_E0001

LQXFA/B01 cryo-assembly

- Cryo-assembly weight was measured in July 2022
  - More precise measurement will be done after all the local piping extensions are removed



Measured weight < 21,840 kg
LQXFA/B-R-T-03 requirement is met

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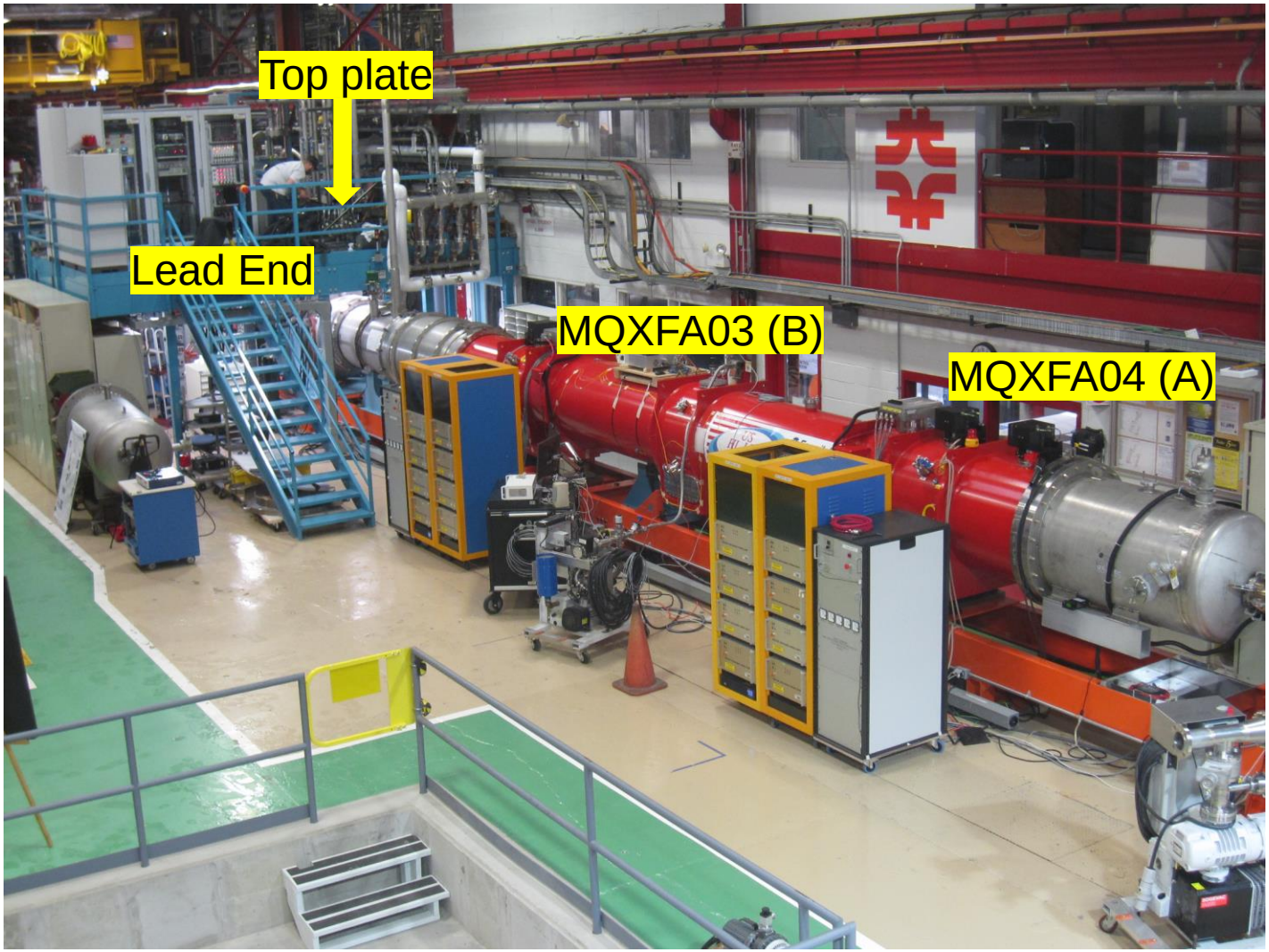
LQXFA/B01 at Fermilab's horizontal test stand



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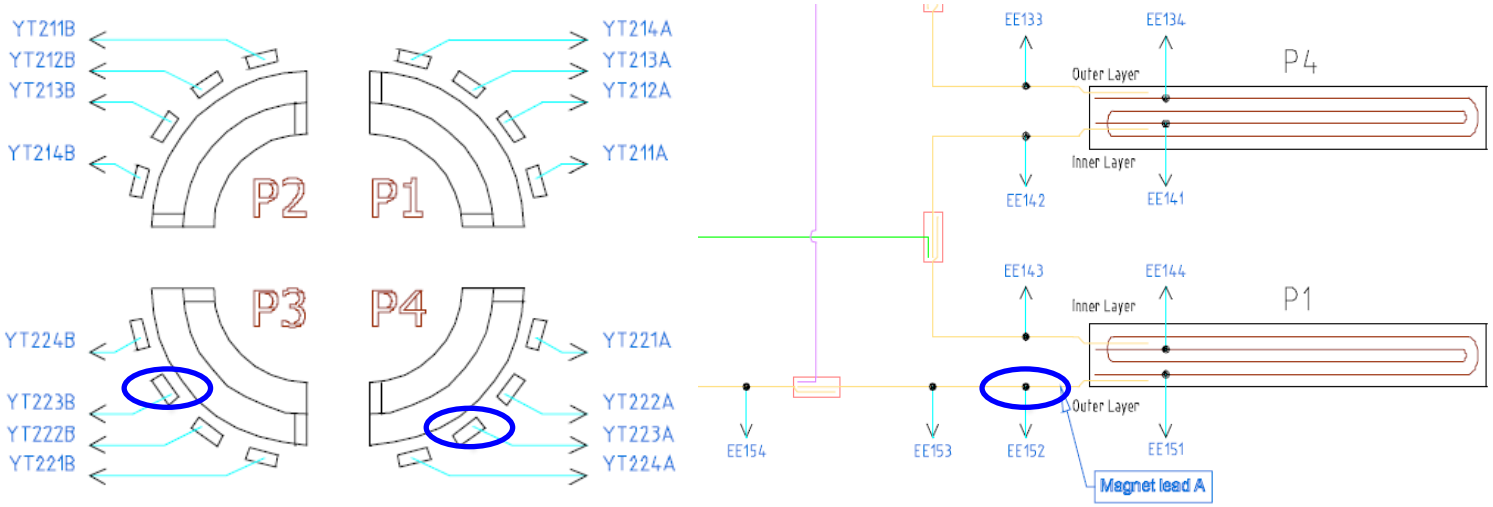
Initial Electrical Checkouts

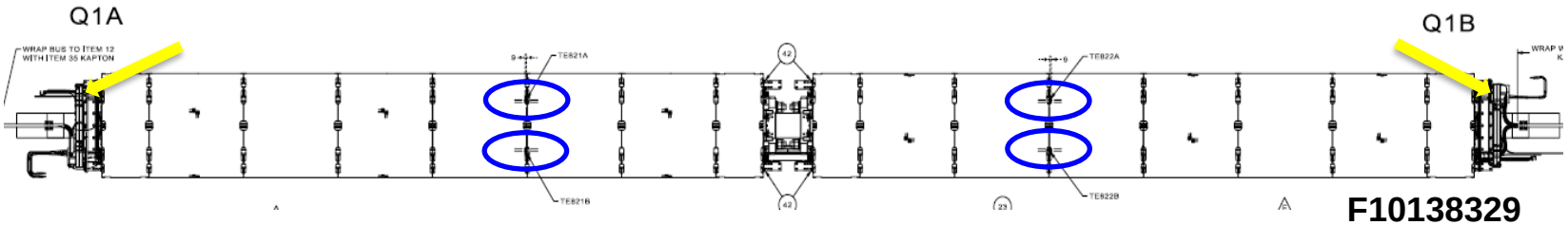
- Cryo-assembly was received at the test facility with one open heater (YT223 in MQXFA03) and one open voltage tap EE152



- Room temperature insulation (Hipot) tests: no failures
  - Coil-to-structure at 2.5 kV for Top plate leads w/o magnets
  - Coil-to-ground at 368 V
  - Quench heater-to-coil at 460 V

Magnet temperature sensors

Platinum RTDs 505/506 are installed on the CM ends



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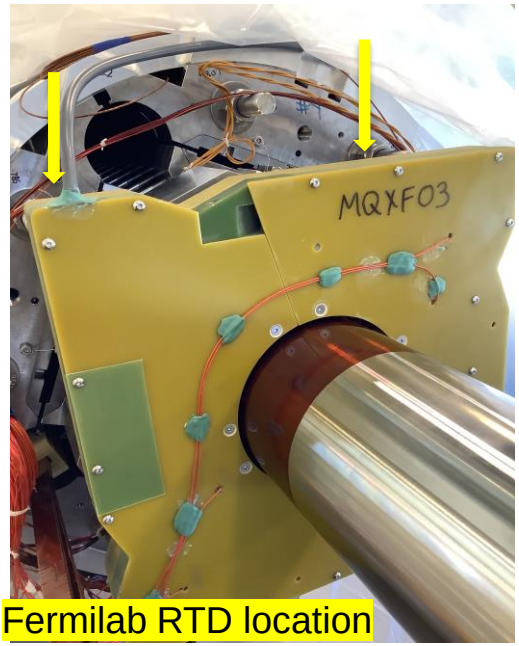
Cernox TE821

Cernox TE822



Fermilab RTD location

CERN RTD location

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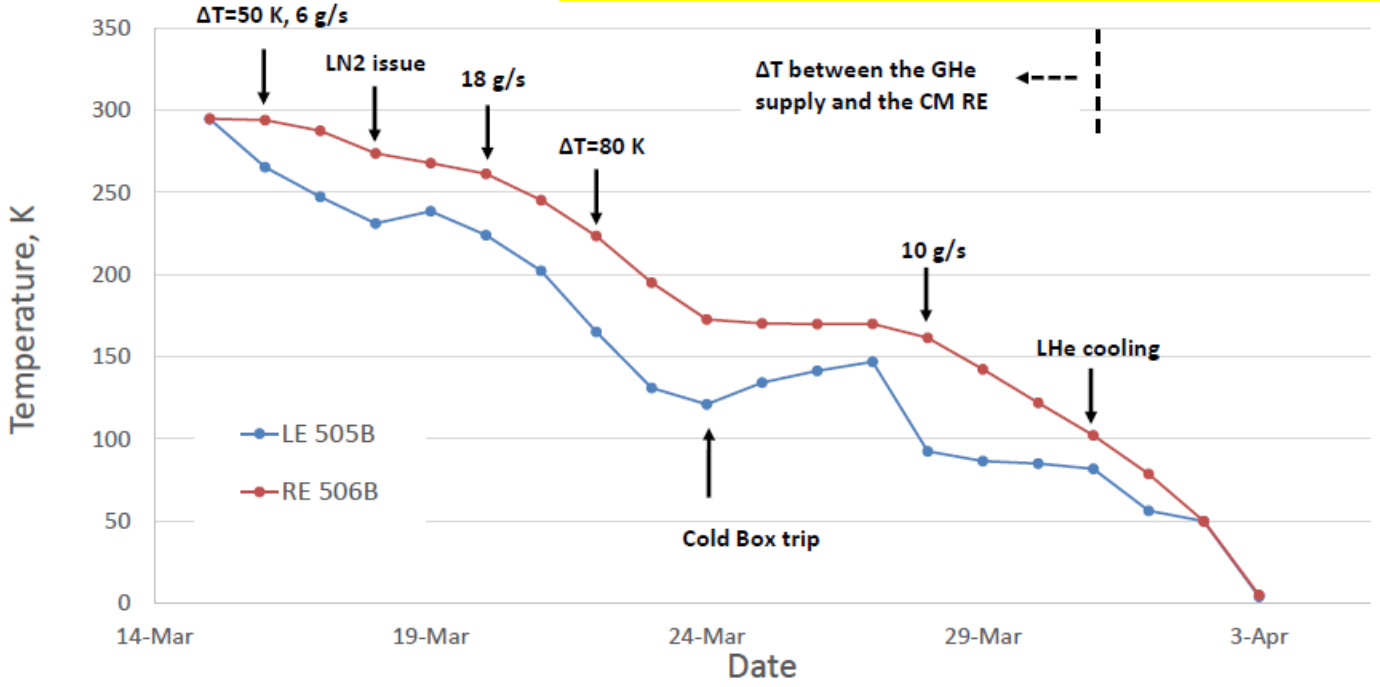
LQXFA/B01 controlled cooldown

- 19 days of cooldown: Mar 15 - Apr 3
  - About 5 days of downtime due to various issues
  - First week running with the 50 K temperature difference across the cold-mass
  - GHe mass flow rate varied from 5 g/s to 18 g/s

Platinum RTDs 505/506 are installed on the CM ends



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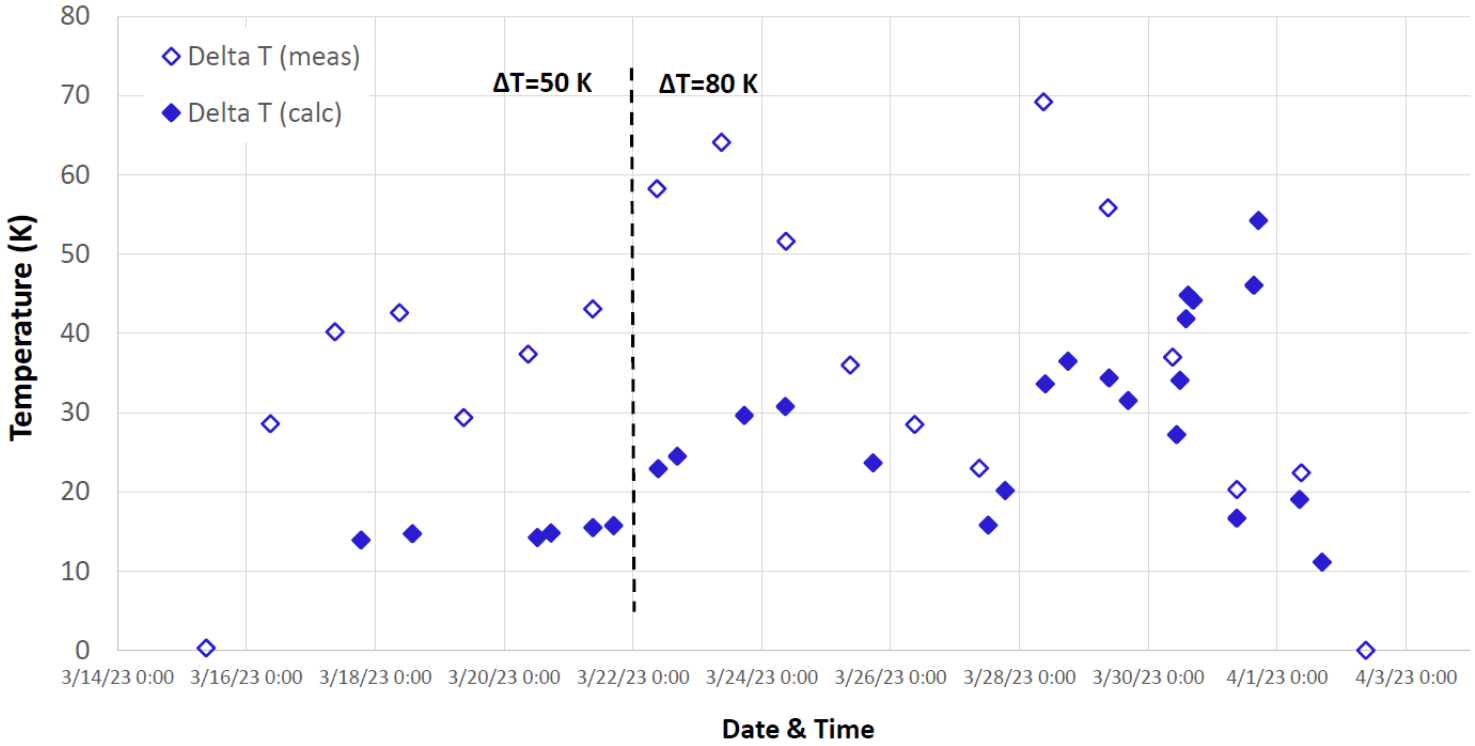
LQXFA/B01 Controlled cooldown (2)

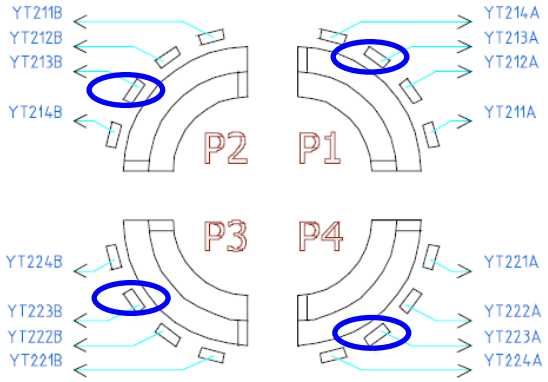
- ΔT requirement between the GHe supply and the CM RE changed from 50 K to 80 K
  - Delta T (meas) - difference between the temperature readings of the RTD sensors 505/506 located on the magnet ends
  - Delta T (calc) is based on the magnet resistance measurements



Cold Electrical Checkouts

- Coil-to-ground at 1840 V
- Quench heater-to-coil Hipot at 2300 V

Test Item	Resistance to GND/Coil	Target HV (V)	Current Threshold(μA)	Ramp Time (s)	Arc Sense Setting	Voltage Lead Location	Return Location	Max Ramp Current (μA)	Leakage Current(μA)	Success?	Type of Failure Arc or BreakDown	Breakdown V + Current
YT111 & YT112	>60Mohms	2300	10	230	1	P221 A-B	CLIQ Lead (Coil Grounded)	2.7	0.0	YES		
YT113 & YT114	>60Mohms	2300	10	230	1	P222 A-B	CLIQ Lead (Coil Grounded)	5.3	0.0	YES		
YT121 & YT122	>60Mohms	2300	10	230	1	P223 A-B	CLIQ Lead (Coil Grounded)	3.7	0.0	YES		
YT123 & YT124	>60Mohms	2300	10	230	1	P224 A-B	CLIQ Lead (Coil Grounded)	4.7	0.0	YES		
YT211 & YT212	>60Mohms	2300	10	230	1	P225 A-B	CLIQ Lead (Coil Grounded)	4.0	0.0	YES		
YT213	>60Mohms	2300	10	230	1	P226 A	CLIQ Lead (Coil Grounded)			NO	Breakdown	2190V (>10mA)
YT214	>60Mohms	2300	10	230	1	P226 B	CLIQ Lead (Coil Grounded)	2.9	0.0	YES		
YT221 & YT222	>60Mohms	2300	10	230	1	P227 A-B	CLIQ Lead (Coil Grounded)	3.2	0.0	YES		
YT224	>60Mohms	2300	10	230	1	P228 B	CLIQ Lead (Coil Grounded)	2.3	0.0	YES		



MQXFA03: YT213A/B heater failed the Hipot test around 2190 V

- No dead short to coil or ground, small current leakage at 200 V
- Dummy load is used instead of YT213

No degradation of the heater to coil and heater to ground insulation observed after the thermal cycle

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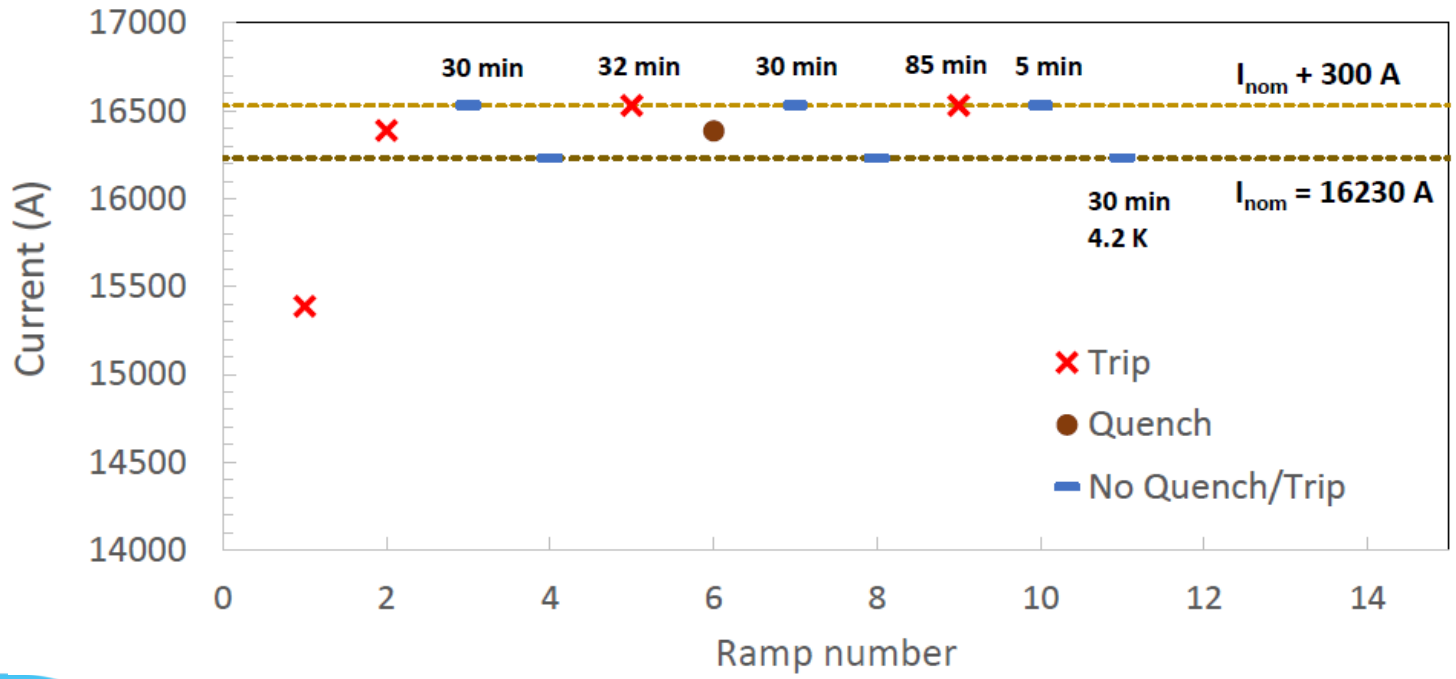
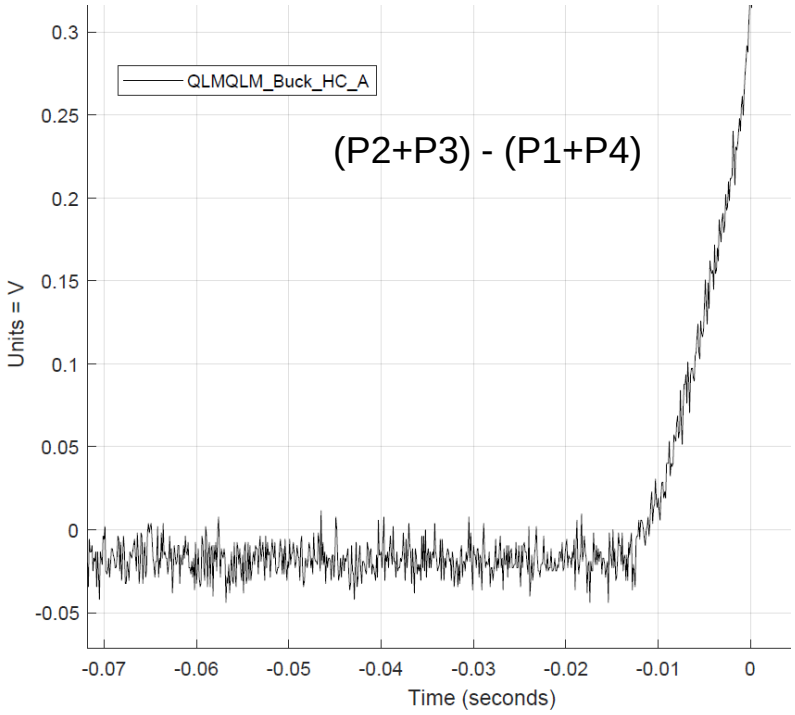
LQXFA/B01 Quench Performance in TC1

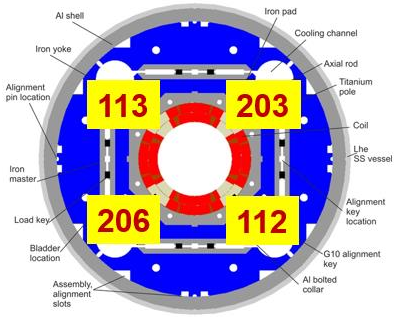
- Acceptance current Inom+300 A was reached w/o a quench
  - LMQXFA-R-T-28, LMQXFA-R-O-05 requirements are met
  - Two trips in the test stand leads - one of the Cu-SC lead joints in the top plate assembly exhibited high resistance, the LHe level adjustments were required
- Two attempts of the holding current test
  - First trip at Inom+300 A=16530 A caused a minor detraining

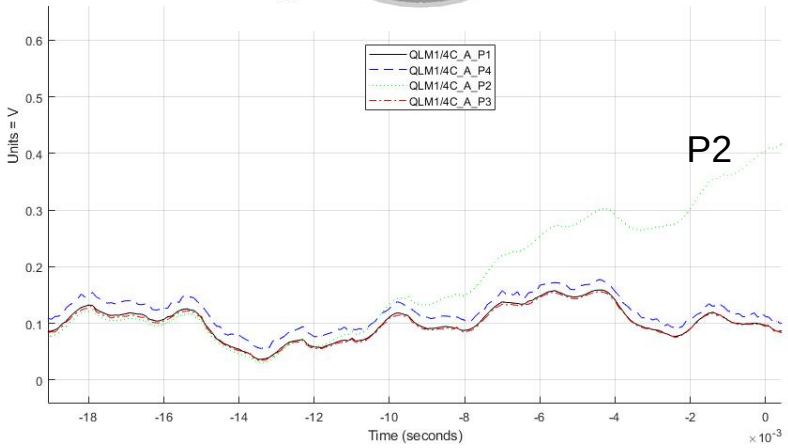


Quench #1 in TC1

- Only one spontaneous quench in magnets
  - Quench at 16386 A, in MQXFA04 (Magnet A), coil 113 (P2)
  - Quench Integral 27.35 MIITs (w/o external energy extraction)

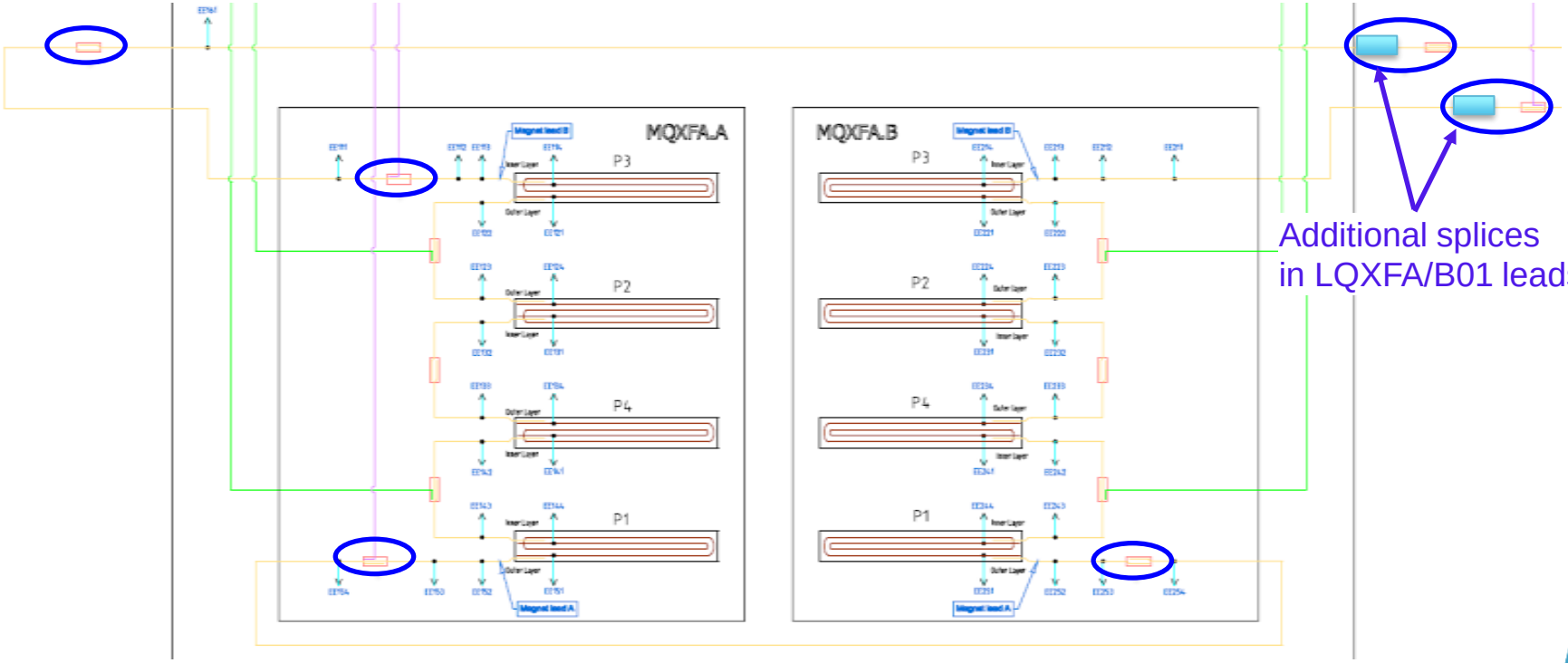






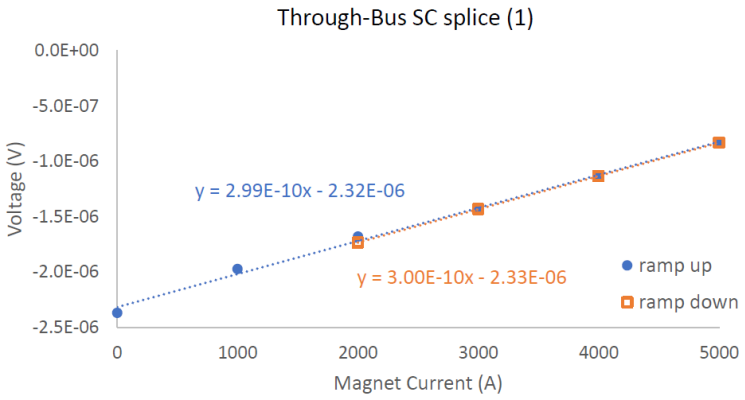
Splice measurements

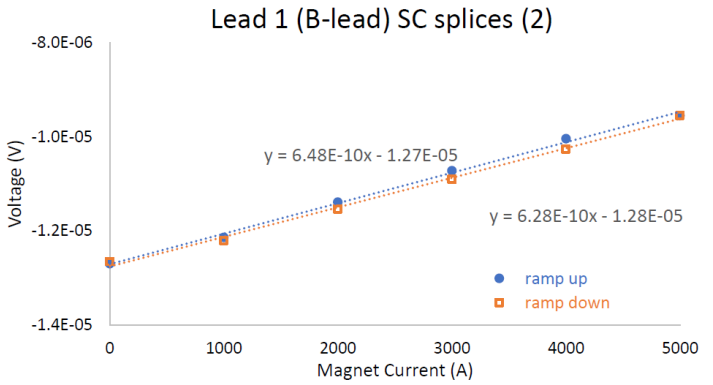
- Two additional splices were made in LQXFA/B01 power leads to add extra length for testing at Fermilab (and CERN)
  - Lead length w/o the additional splice is sufficient for the tunnel installation at CERN

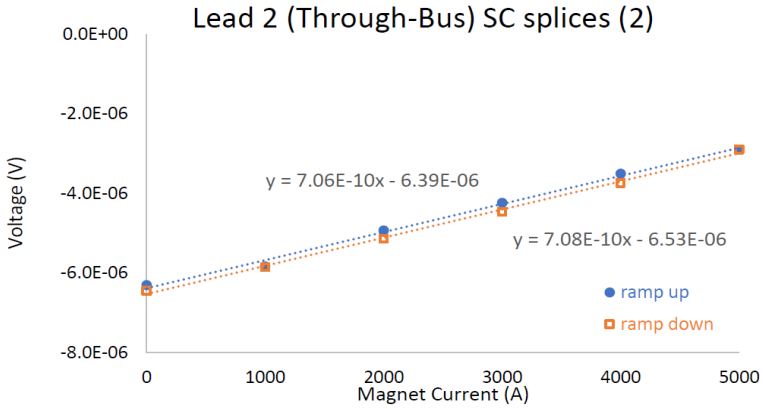


Splice measurements (2)

- Splice measurements were made at 1.9 K for currents up to 5 kA
  - 8-channel MUX system based on Keithley 2182A Nanovolt Meter
- Two-splice segments are measured ~0.7±0.1 nΩ, and single splice segments - less than 0.3±0.1 nΩ







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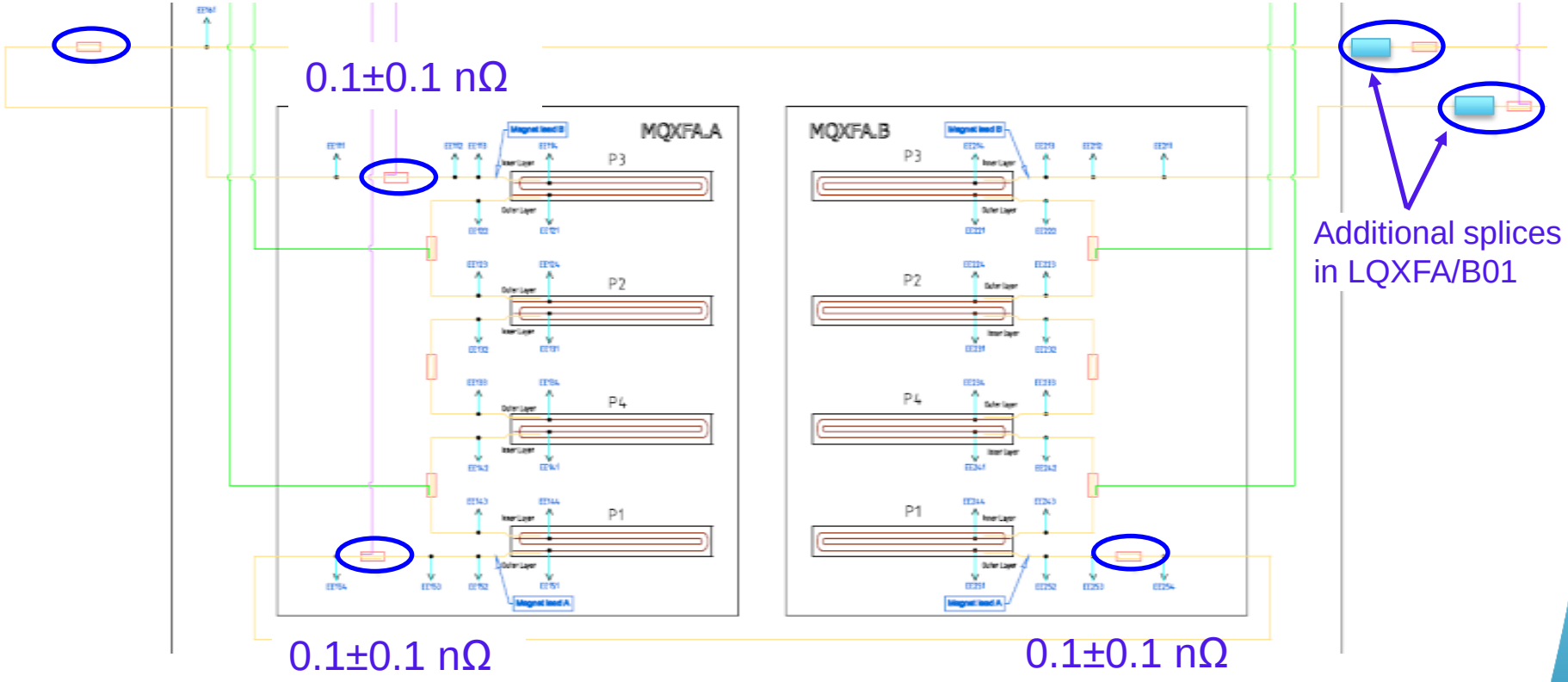
Splice measurements (3)

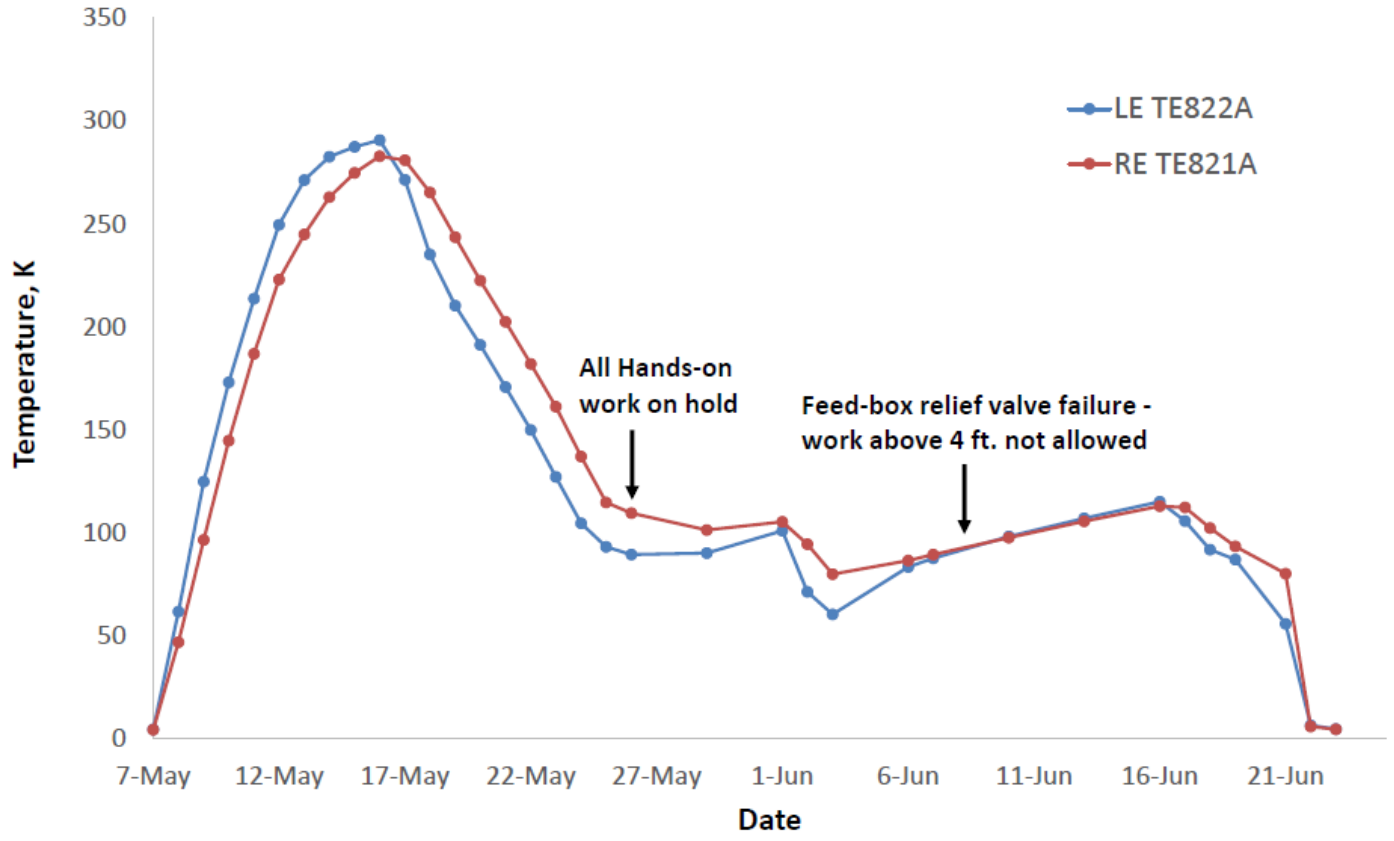
- Splices resistance values well below the required 1 nΩ
  - LMQXFA-R-O-03 requirement is met



Warmup and cooldown for TC2

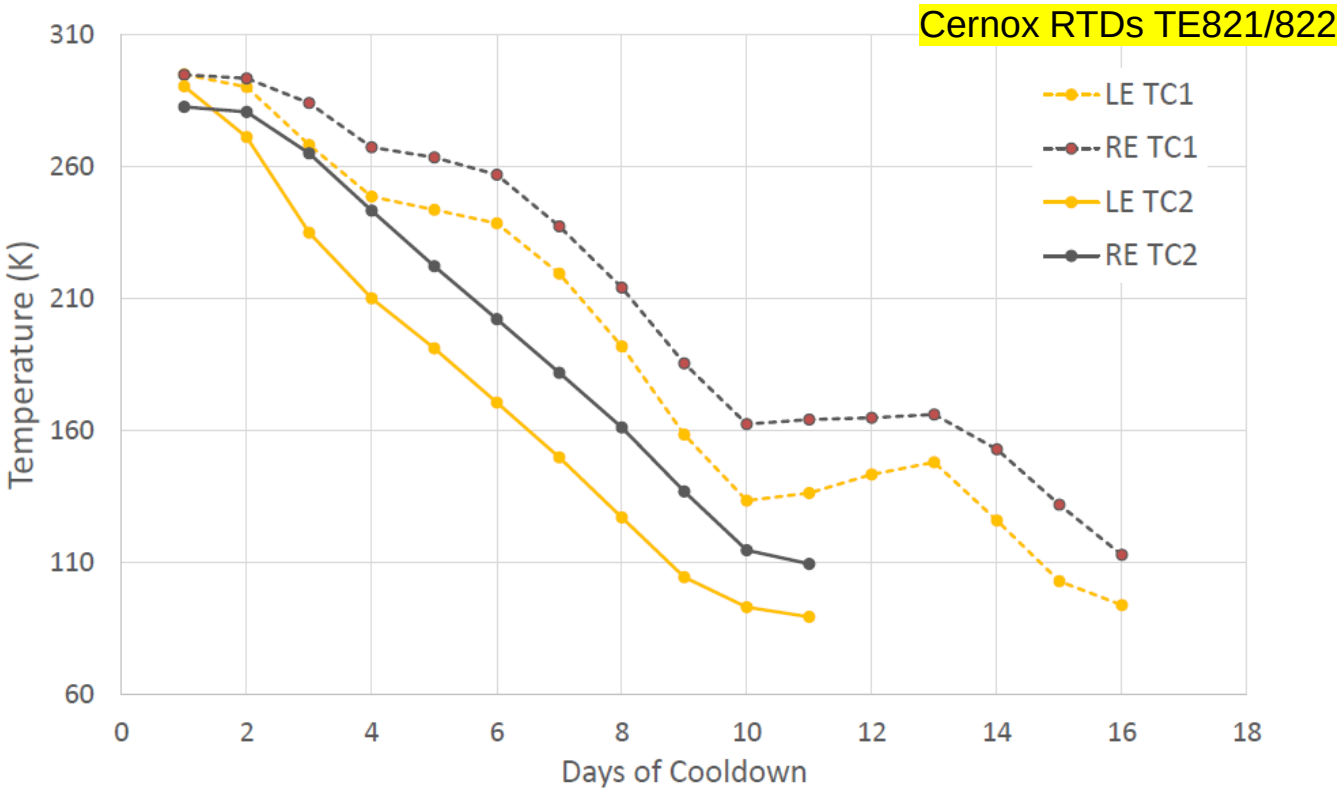
- Controlled warmup just over 1 week. Cooldown was interrupted few times

Cernox RTDs TE821/822 installed in the CM shell openings



Cooldown in TC1 and TC2

- First cooldown used for optimizing the controlled cooldown parameters
  - Two weeks are expected for 1.9 K cooldown. Further improvement requires upgrade of the heat exchanger in the Helium return line



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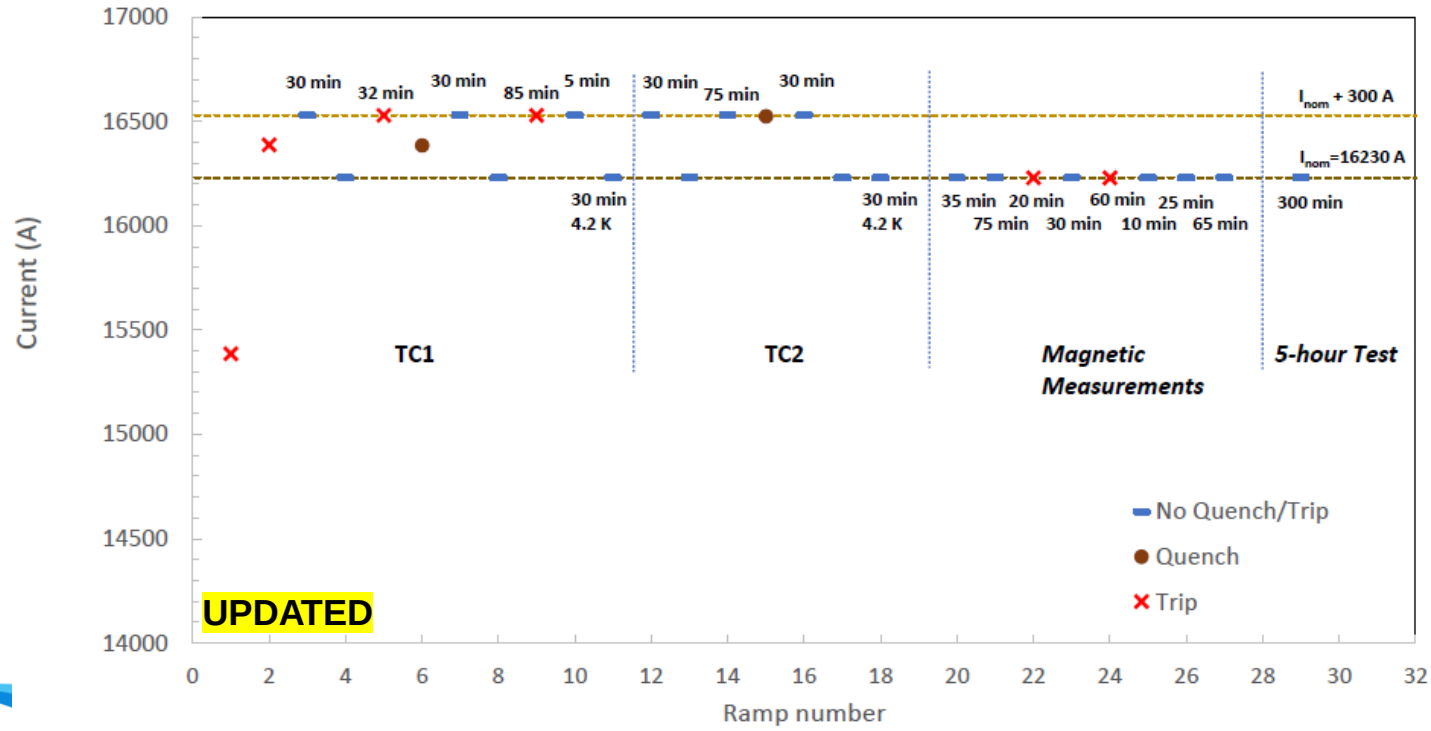
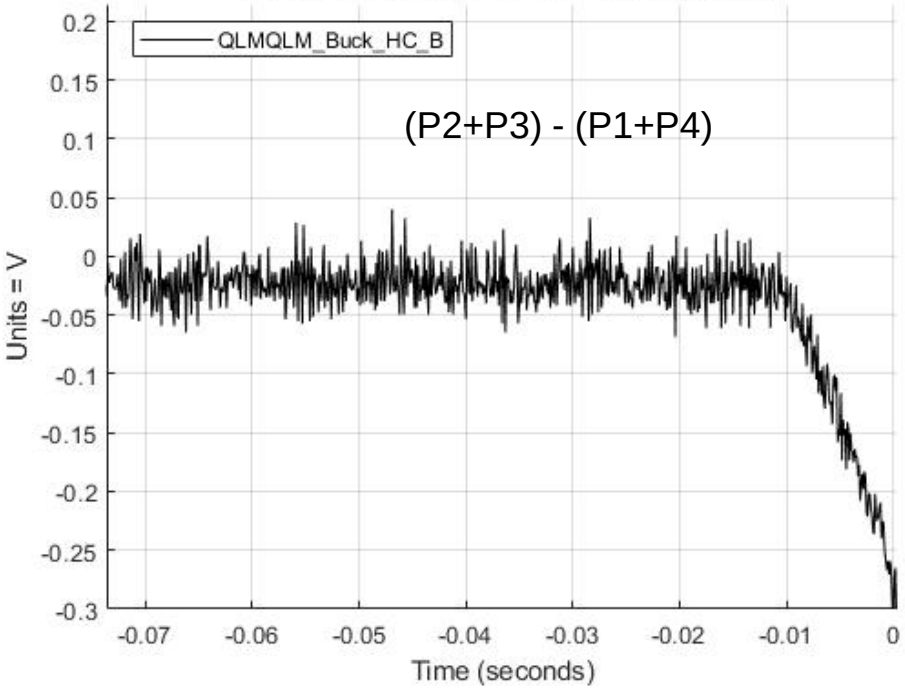
LQXFA/B01 Quench Performance in TC2

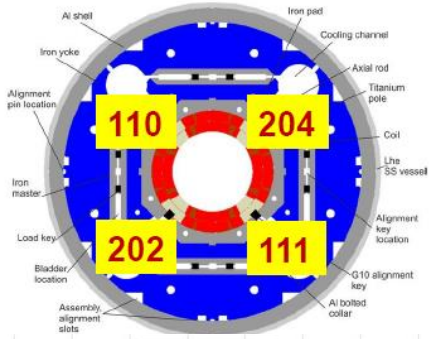
- The acceptance current reached w/o a quench
  - Only one spontaneous quench in TC2, see details on the next slide
  - High ramp rate test was successful (30 A/s ramp up & 150 A/s down)
  - LMQXFA-R-T-22 requirement is met
- The holding current test failed in 75 min due to the LHe stability issue (no trip thanks to PLC interlock modification)

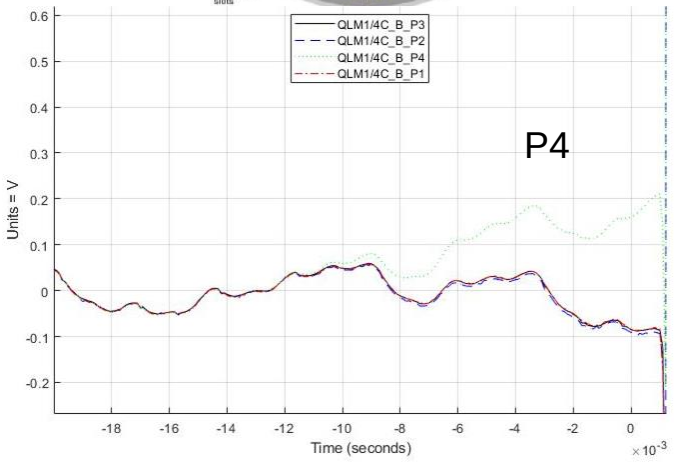


Quench #2 in TC2

- Only one spontaneous quench in magnets
  - Quench at 16525 A, in MQXFA03 (Magnet B), coil 111 (P4)
  - Quench Integral 27.36 MIITs (w/o external energy extraction)

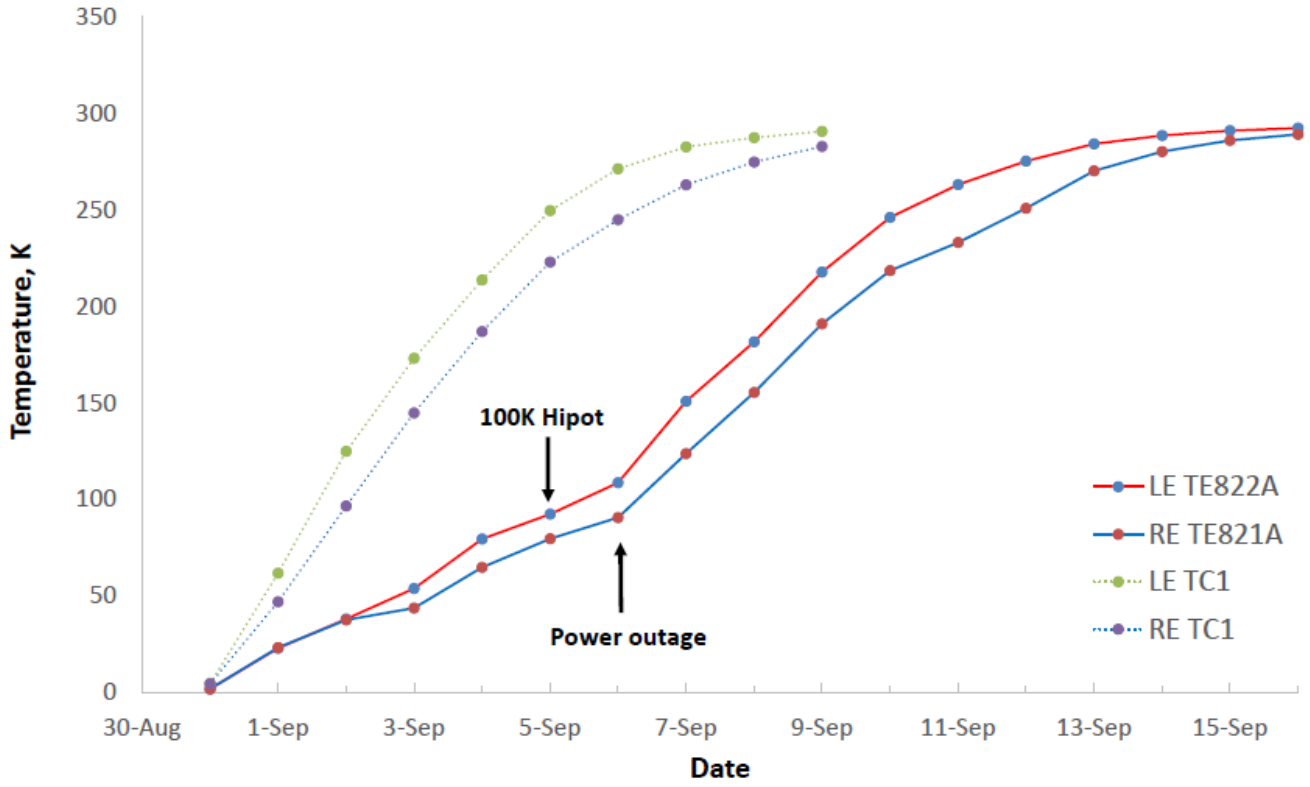






Final Warmup

- Final warmup started on Aug 31st
  - Slow start due to the hipot test at 100 K and short power outage

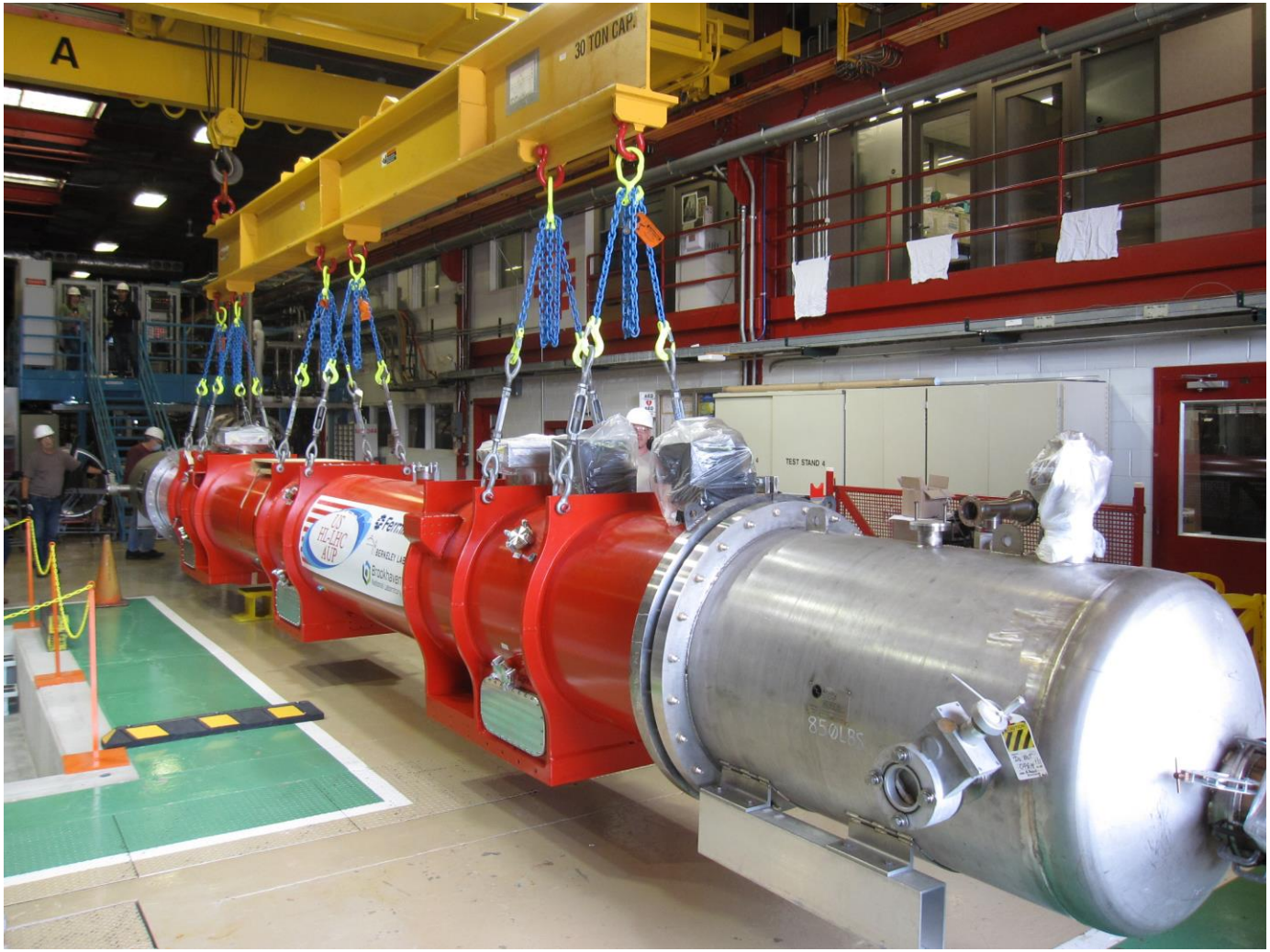


LQXFA/B01 Quench Summary

- Ramp rate not changing during the ramp up and down

Event N.	Date (dd.mmm.yy)	Time (hh:mm)	Type	Temperature (K)	Ramp rate (A/s)	I_1 (A)	I_2 (A)	Coil	Segment	V_{thre} (V)	Validation (ms)
1	21-Apr-23		P	1.9	20	15387					
2	24-Apr-23		P	1.9	20	16388					
3	26-Apr-23		R	1.9	20	16530					
4	26-Apr-23		R	1.9	30	16230					
5	27-Apr-23		P	1.9	20	16530					
6	28-Apr-23	11:18	T	1.9	20	16386		113		0.150	4
7	4-May-23		R	1.9	20	16530					
8	4-May-23		R	1.9	30	16230					
9	5-May-23		P	1.9	20	16530					
10	6-May-23		R	1.9	20	16530					
11	6-May-23		R	4.2	30	16230					
12	13-Jul-23		RW	1.9	20	16530					
13	17-Jul-23		RW	1.9	30/150	16230					
14	18-Jul-23		RW	1.9	20	16530					
15	18-Jul-23	17:25	TW	1.9	20	16525		111		0.150	4
16	20-Jul-23		RW	1.9	20	16530					
17	20-Jul-23		RW	1.9	30/150	16230					
18	21-Jul-23		RW	4.2	20	16230					
19	25-Jul-23		RW	1.9	20	16230					
20	3-Aug-23		RW	1.9	20	16230					
21	4-Aug-23		PW	1.9	20	16230					
22	7-Aug-23		RW	1.9	20	16230					
23	9-Aug-23		PW	1.9	20	16230					
24	11-Aug-23		RW	1.9	20	16230					
25	14-Aug-23		RW	1.9	20	16230					
26	16-Aug-23		RW	1.9	20	16230					
27	31-Aug-23		RW	1.9	20	16230					

LQXFA/B01 lifting at Fermilab's test facility



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Summary

- The first pre-series cryo-assembly LQXFA/B01 successfully tested at Fermilab's horizontal test stand
  - The test facility upgrades successfully commissioned with a cryo-assembly for the first time
  - Liquid level instabilities and power supply issues, as well as Lab-wide safety pause made the commissioning and test longer than expected
  - The cryogenic issues were identified and fixed, allowing the completion of the horizontal test
- LQXFA/B01 test goals are achieved
  - Magnets survived a maximum temperature gradient of 50 K during a controlled warm-up or cool-down
  - The acceptance current reached w/o a quench in both test cycles
  - High ramp rate test requirements are met
  - Splice resistance requirements are met
  - Nominal current was successfully held for 5 hours

Backup Slides

LMQXFA	Threshold	LMQXFA-R-T-22	25. Requirement LMQXFA-R-T-22: The LMQXFA quench performance requirements must meet or exceed the MQXFA magnet quench performance requirements[5]. (a) After a thermal cycle to room temperature, the cold mass should attain the nominal operating current with no more than 3 quenches per magnet (MQXFA-R-T-17) (b) The cold mass must not quench while ramping down at 150 A/s from the nominal operating current (MQXFA-R-T-18)	Reference: Cold Mass Assembly Traveler [1], Pre-series Test Plan [11]	Feher	LQXFA/B01 test report section 5.3
LMQXFA	Threshold	LMQXFA-R-T-28	34. LMQXFA-R-T-28: LMQXFA cold mass shall be capable of continuous steady-state operation at nominal current in pressurized static superfluid helium (HeII) bat at 1.3 bar and at a temperature of 1.9K.		Feher	LQXFA/B01 test report section 5.3
LMQXFA	Objective	LMQXFA-R-O-02	8. Requirement LMQXFA-R-O-02: The common magnetic axis of the two-magnet system should be determined with respect to cold mass fiducials with accuracy of ±0.2 mm to both nodal points. The common average MQXFA field angle with respect to cold mass fiducials should be measured with accuracy better than 0.5 mrad. The magnetic length and the nodal points of each of the two MQXFA magnets in the cold mass need to be known within ±1 mm accuracy relative to external fiducials.	Reference: SSW technique described in Cold Mass Assembly Traveler [1]	Feher	LQXFA/B01 test report section 6.1
LMQXFA	Objective	LMQXFA-R-O-03	16. Requirement LMQXFA-R-O-03: The busbars will include maximum four internal splices. Each splice resistance target value must be less than 1.0 nΩ at 1.9 K. A target value at room temperature will also be specified after the completion of the prototype program. An acceptance threshold will be defined after the completion of the short model program.	Reference: Pre-series Test Plan [11]	Feher	LQXFA/B01 test report section 6.1
LMQXFA	Objective	LMQXFA-R-O-05	27. LMQXFA-R-O-05: After a thermal cycle to room temperature, LMQXFA cold mass should attain the nominal operating current with no more than 2 quenches.		Feher	LQXFA/B01 test report section 5.3
LQXFA	Threshold	LQXFA/B-R-T-03	3. Requirement LQXFA/B- R-T-03: The total weight of the whole cryostat assembly including the cold mass must be ≤ 22 500 kg.	Reference: LQXFA/B cryo-assembly Traveler [19]	Feher	LQXFA/B01 test report section 2.