



MQXFA Vertical test results - AUP

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*12th HL-LHC Collaboration Meeting
Sept. 21st, 2022*



Chronology of MQXFA Tests at BNL

Seven AUP MQXFA quadrupoles tested at the BNL Vertical Test Facility:

- MQXFA03
 - 11-Nov to 19-Dec 2019.
 - Test Successful.
 - MQXFA04
 - 24-Aug to 7-Oct 2020.
 - Test Successful.
 - MQXFA05
 - 5-Mar to 19-May 2021.
 - Test Successful.
 - MQXFA06
 - 14-June to 2-July 2021.
 - Test Successful.
 - MQXFA07
 - 11-Aug to 25-Aug 2021
 - Quench performance was limited by one coil.
- 11th Collaboration Meeting
- MQXFA08
 - **22-Oct 2021 to 11-Feb 2022.**
 - **Quench performance was limited by one coil.**
 - MQXFA05 – Endurance test
 - **21-Mar to 31-May 2022.**
 - **Test Successful.**
 - MQXFA10
 - **15-June to 9-Aug 2022.**
 - **Test Successful.**
- Today

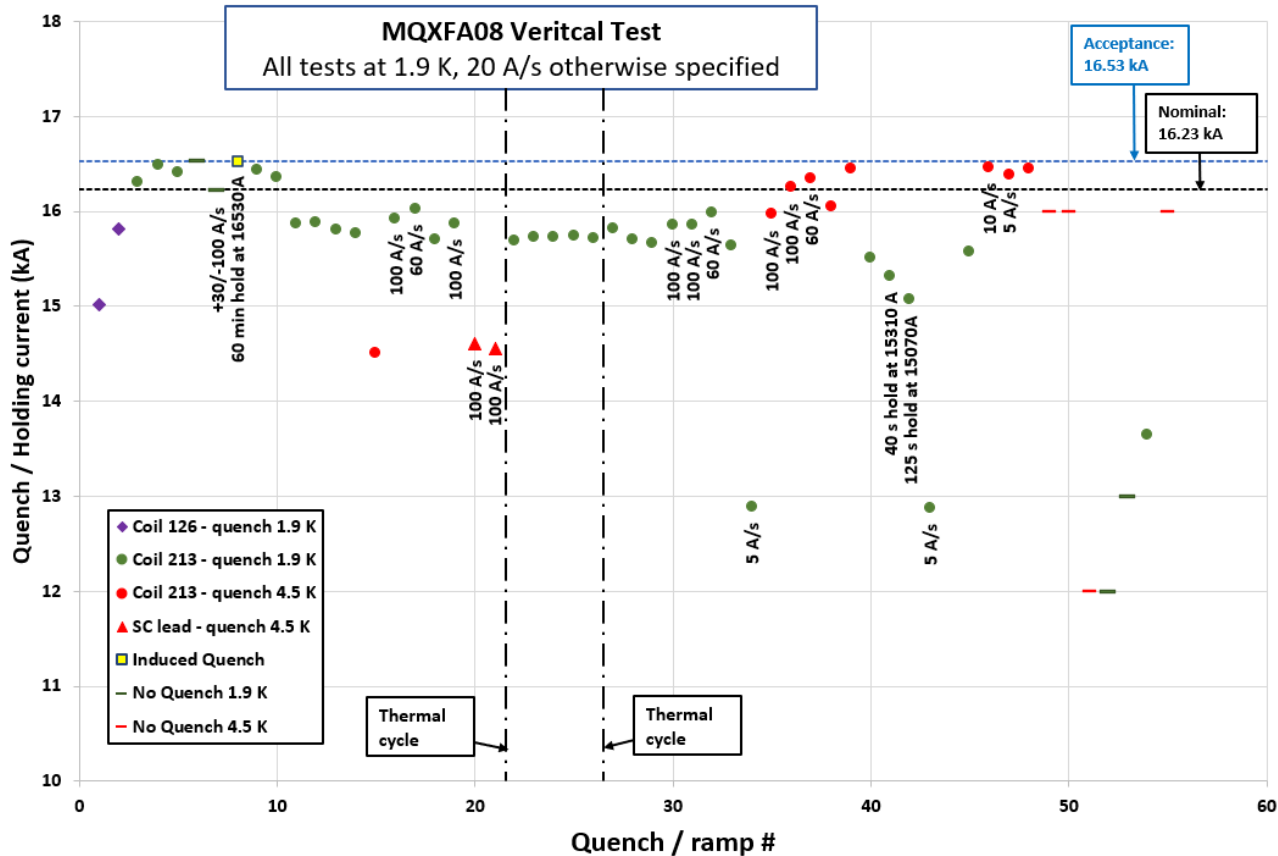
MQXFA08



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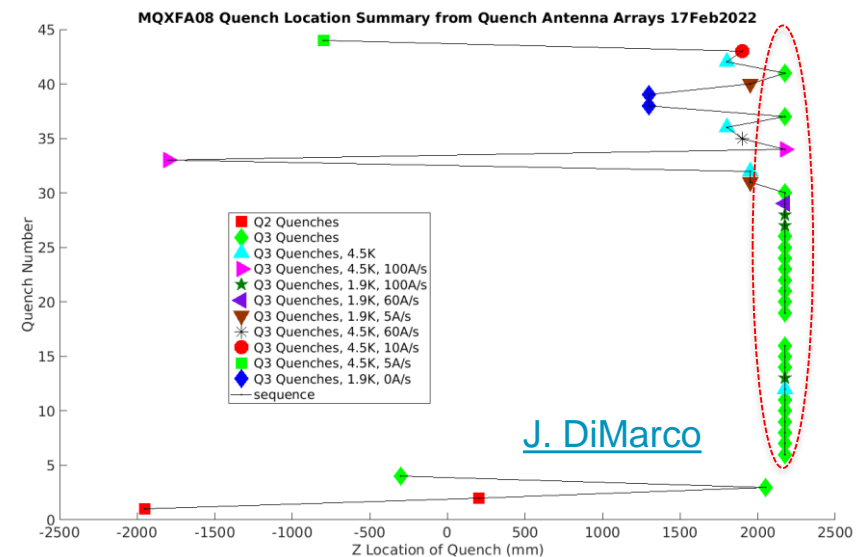
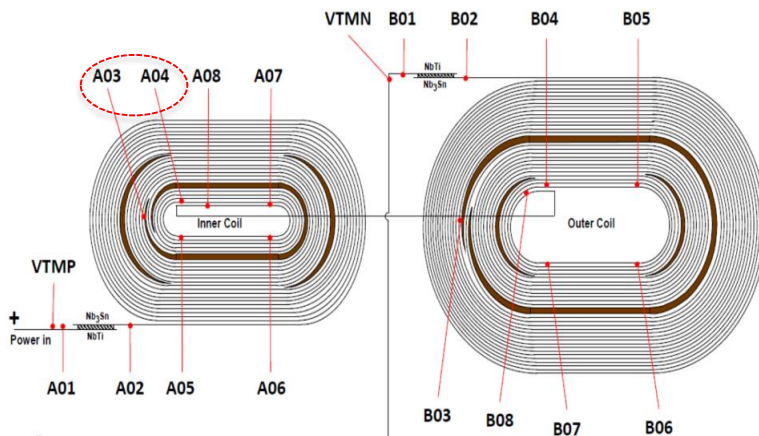
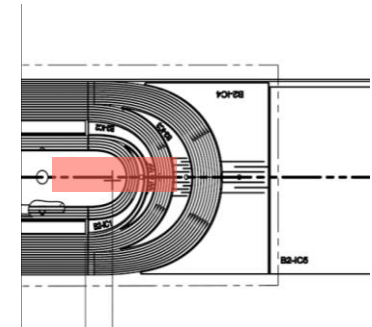
MQXFA08

- Reached acceptance (16.53 kA) after 5 quenches at the beginning.
- During the hold at 16.53 kA, a PS shutoff triggered the QD inducing a quench in the magnet.
- Subsequently, the magnet exhibited detrainning with the quench current settling at 15.7 kA initially.
- Coil 213, in quadrant 3, was the limiting coil.



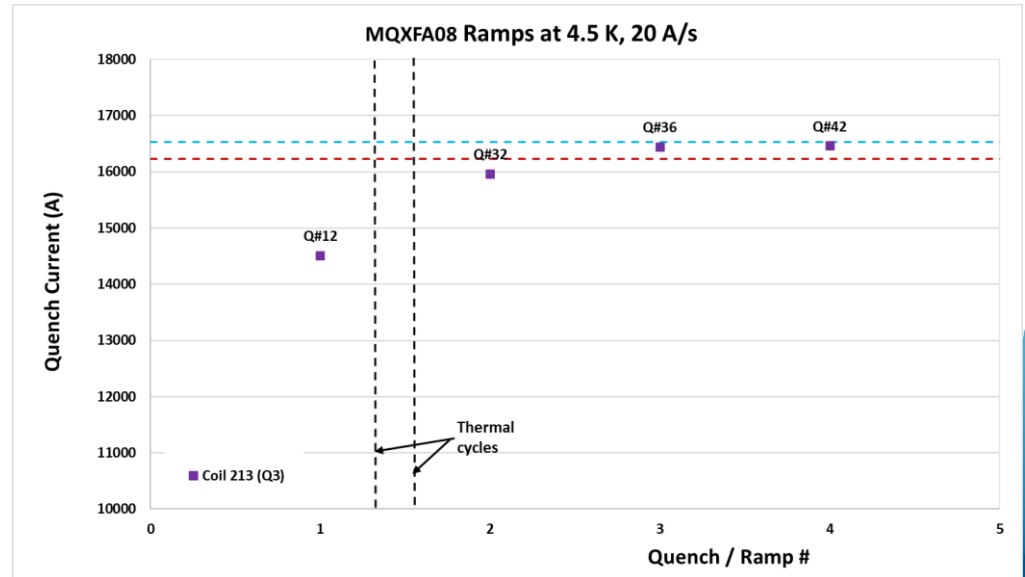
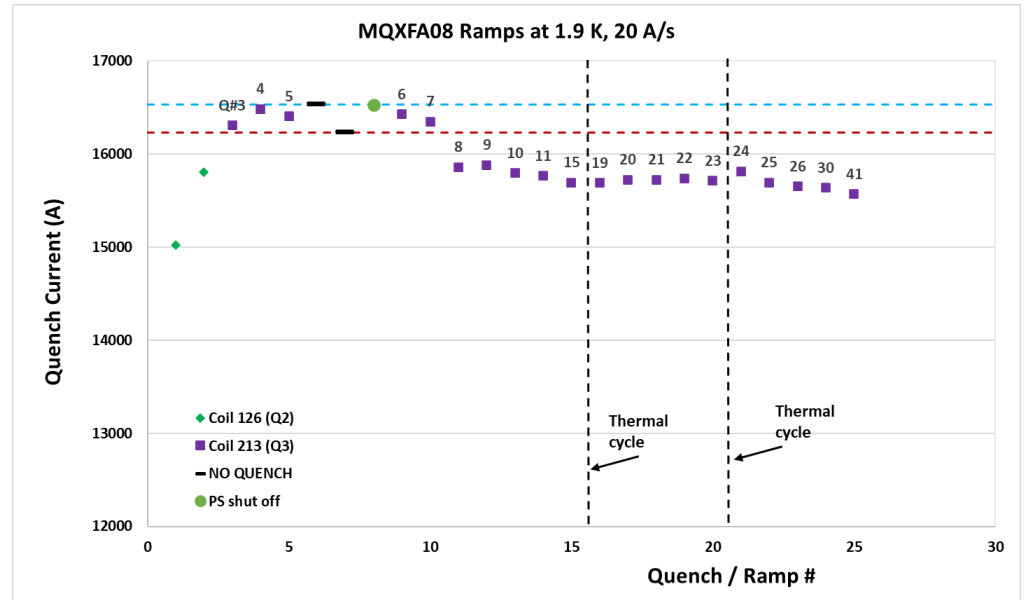
MQXFA08 – quench location

- All limiting quenches were located in coil 213 in the lead end.
- Occurred in A3-A4.
- Only few of the ramp $\neq 1.9$ K, 20 A/s showed a movement of the quench location.



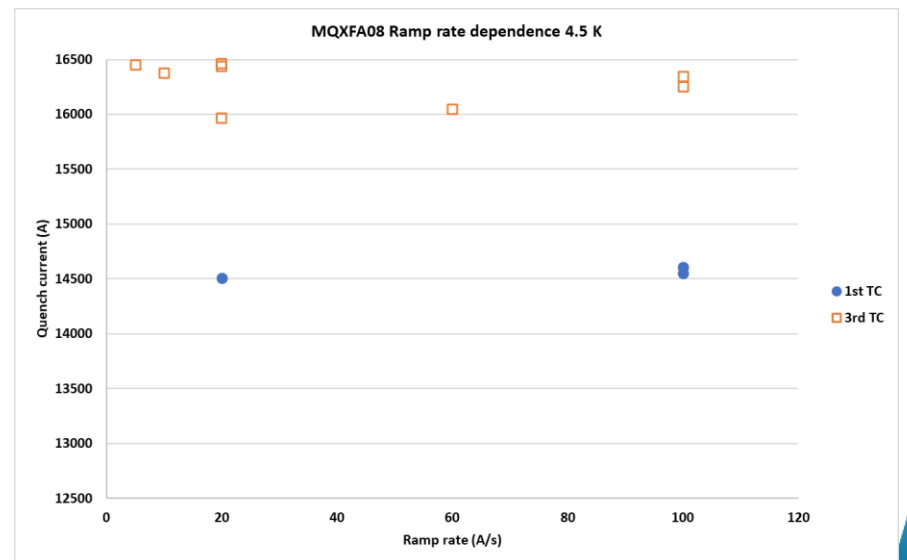
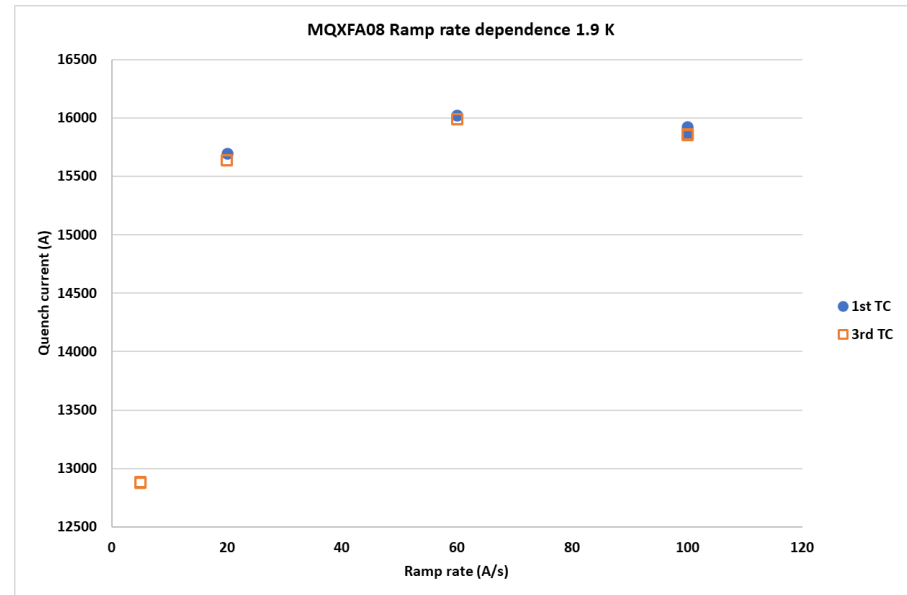
Temperature dependence

- Reverse temperature dependence of the quench current.
- Quench current at 4.5 K, during the first test cycle, was limited by the splice resistance.

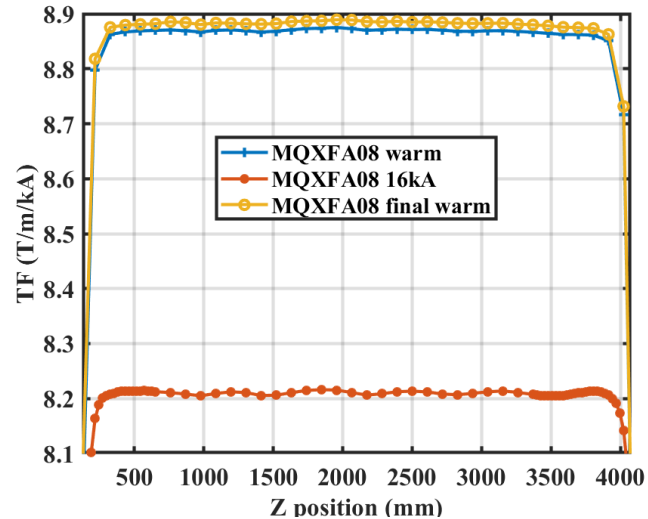
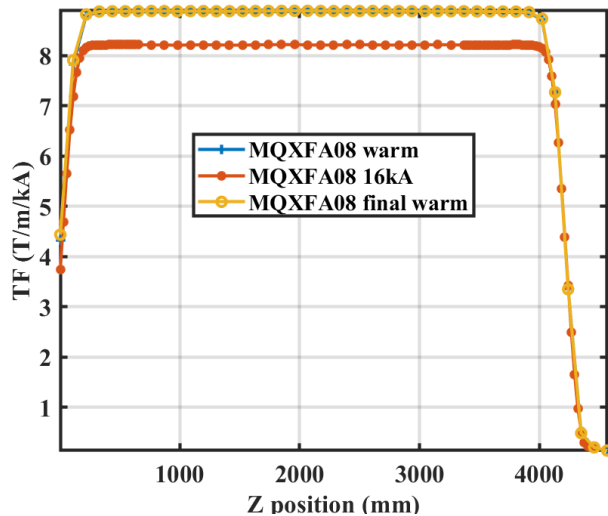


Ramp rate dependence

- At 1.9 K, reverse ramp rate dependence. Highest quench current at 60 A/s.
- At 4.5 K, no dependence on the ramp rate.
- Quench current at 4.5 K, during the first test cycle, was limited by the splice resistance.



Transfer Function



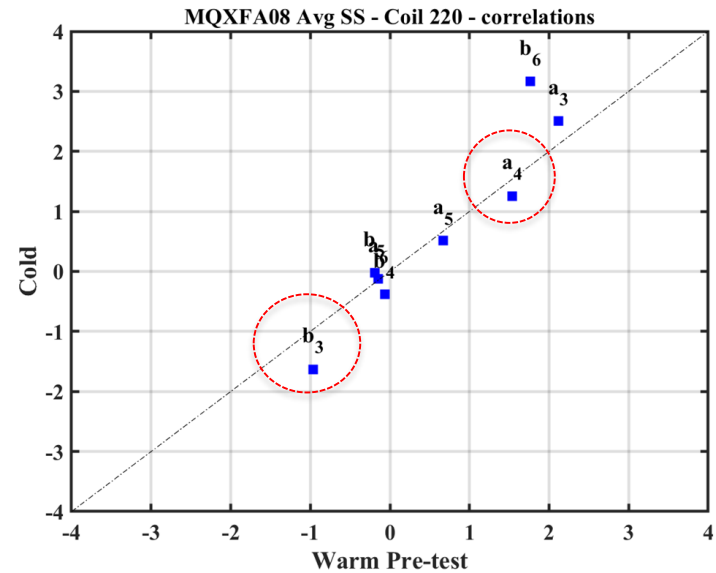
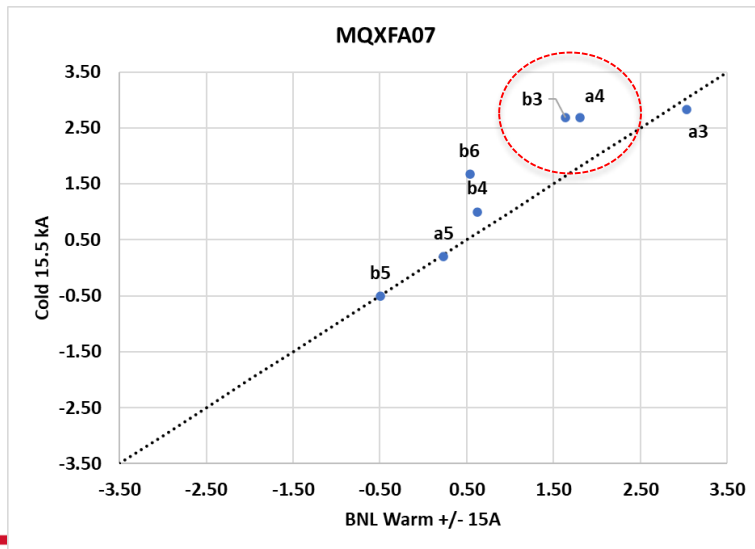
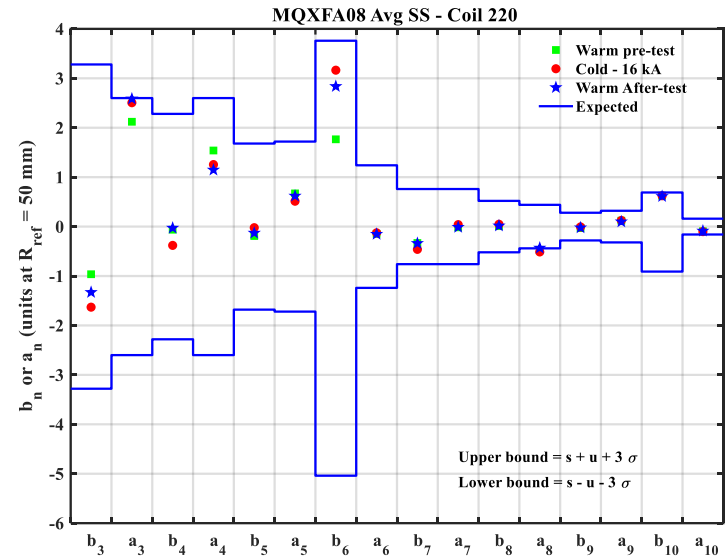
B2 - SS avg (T/m/kA)	MQXFA03	MQXFA04	MQXFA05	MQXFA06*	MQXFA07	MQXFA08
Warm pre-test	8.837	8.831	8.862	8.839	8.867	8.868
Cold at Inom	8.166	8.175	8.205	8.189	8.230	8.210
Warm after test	8.846	8.853	8.873	8.873	8.882	8.883
change before and after cold test (units)	11	25	13	19	17	16

- In terms of coil deformations during cold test, the behavior is consistent with previous magnets.

*rot coil changed during the test. The new coil reads ~0.2% higher. For MQXFA06, measured change is 39 unit (corresponding to 19 unit after accounting for coil change).

Field Quality in the straight section

- Change in the non-allowed harmonics similar to that observed in MQXF A07.



MQXFA08 - Summary

- After initially reaching 16.53 kA, MQXFA08 had a current loss of ~900 A.
- All limiting quenches were in coil 213 (Q3) inner layer multiturn (A3-A4) in the lead end.
- Reverse temperature and ramp-rate dependences.
- Changes in the non-allowed harmonics.
- The behavior points to the same limiting mechanism in MQXFA07 (“Analysis of MQXFA07 Test Non-Conformity” **US-HiLumi-Doc-4293 EDMS 2777612**): self-field instability enhanced by conductor damage.

MQXFA05 Endurance test

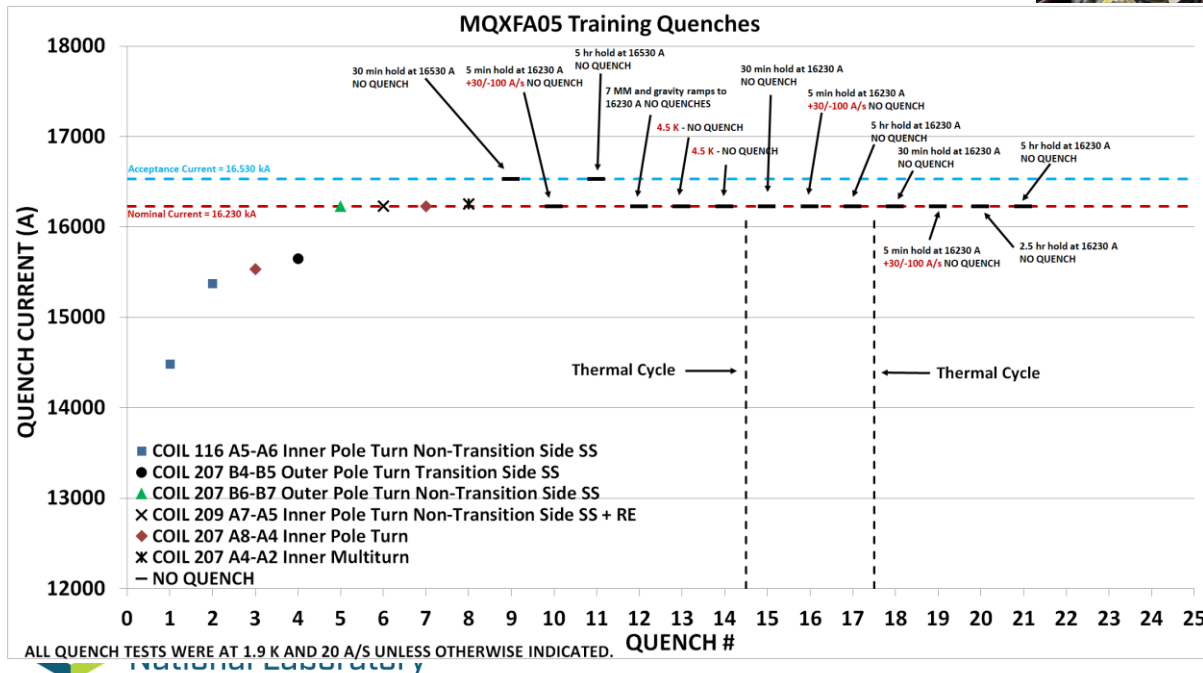


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MQXFA05

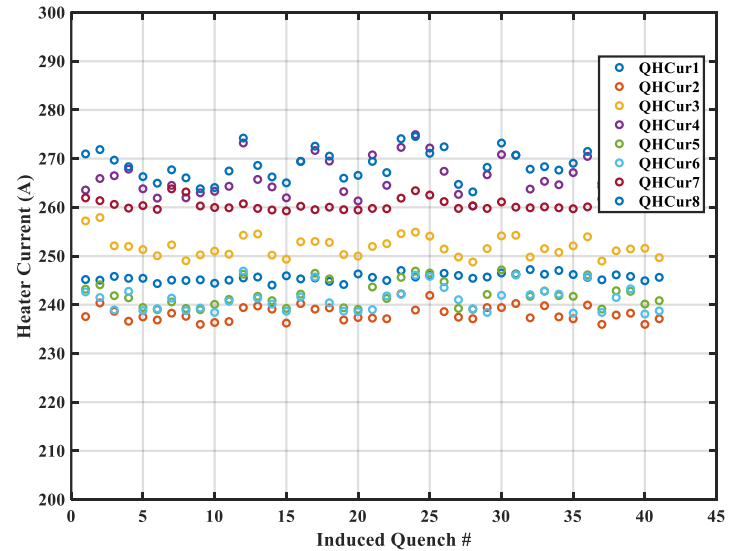
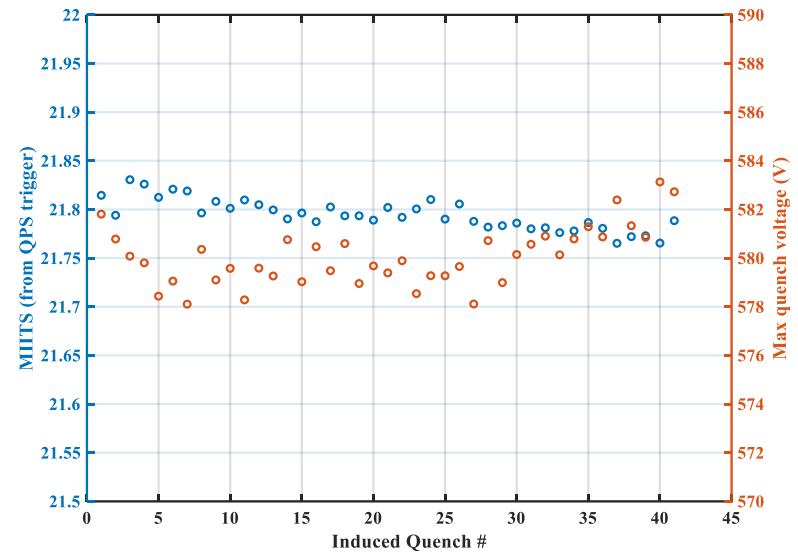
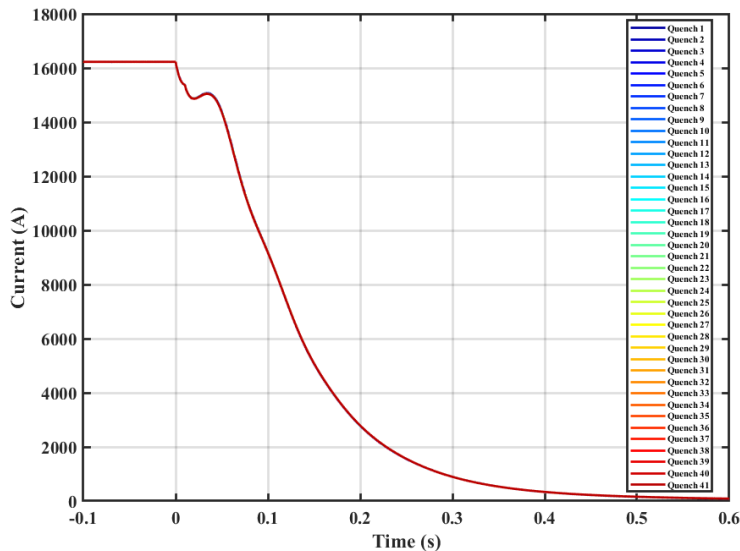


- Initial test:
 - 8 quenches at 1.9 before reaching nominal + 300A = 16530A.
 - Training memory demonstrated after 2 thermal cycles. No Quenches.
- Endurance test:
 - An additional 42 quenches from nominal.
 - Two additional thermal cycle.
 - Verify the magnet meets the acceptance criteria at the end of the test.



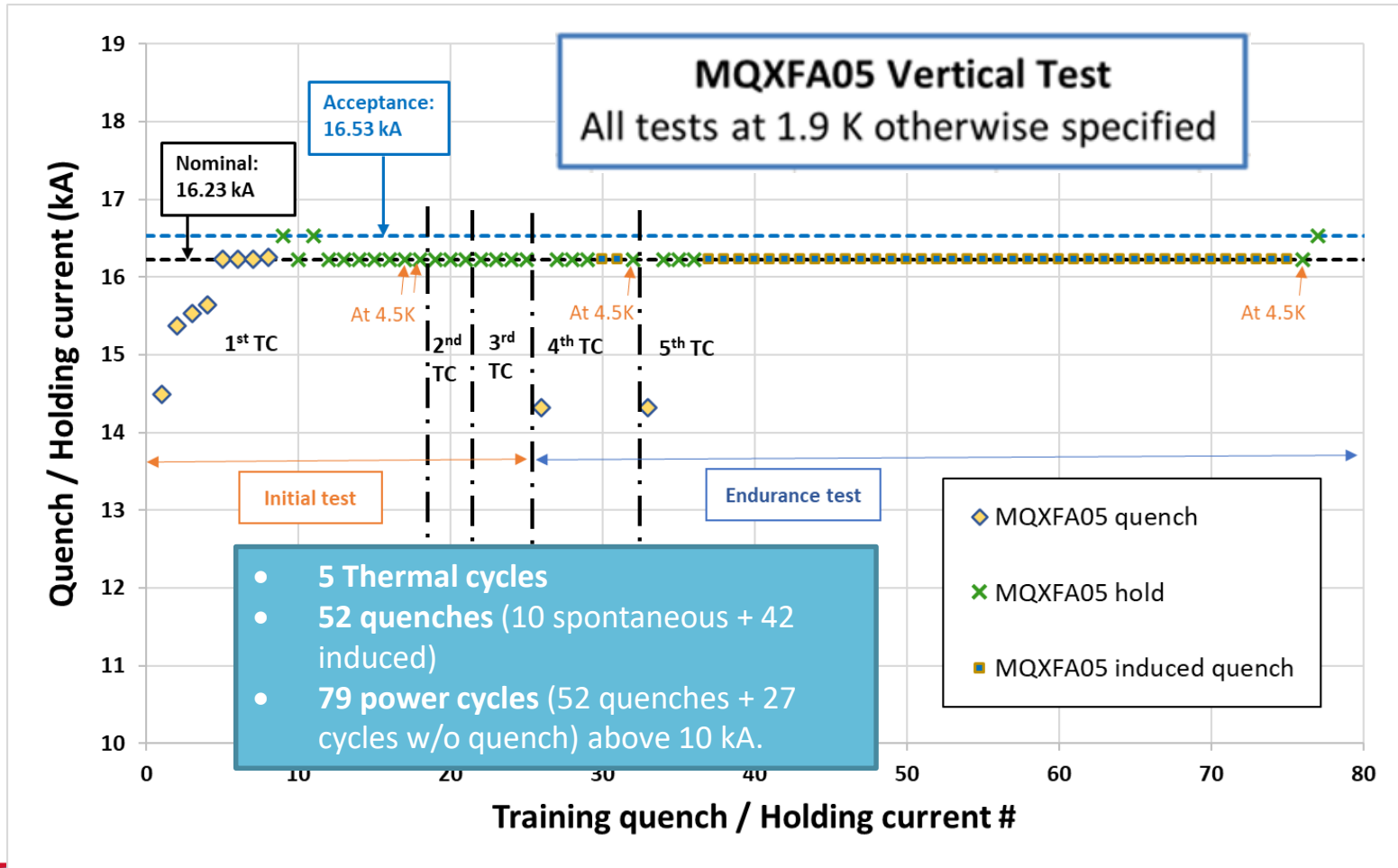
MQXFA05 Endurance Test

- Induced quenches:
 - HF+LF Heater voltage: 600 V
 - CLIQ parameters: 500 V, 40 mF
 - Dump resistance: 37.5 m Ω with 10ms delay
- 41 induced quenches from nominal (16.23 kA).
- Quench integral: 21.8 MIITS.
- All QPS signals nominal.



MQXFA05 - Summary

- Total of **5 TC** and **52** high-current quenches (10 spontaneous, 42 induced at nominal current via quench heaters).
- At the end of the 5th TC, the magnet reached Nominal current at 4.5K and achieved again Acceptance current (16.53kA).



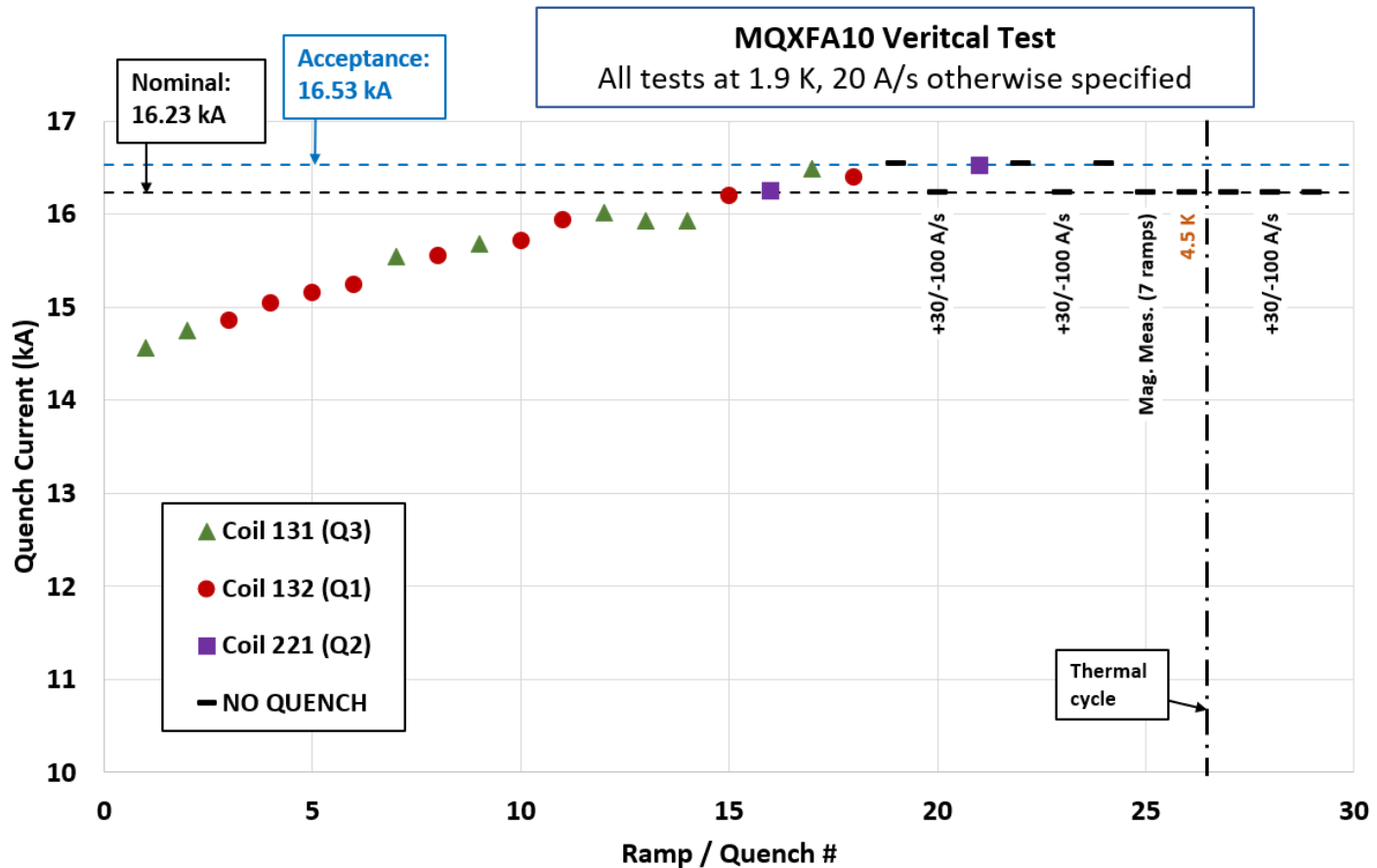
MQXFA10



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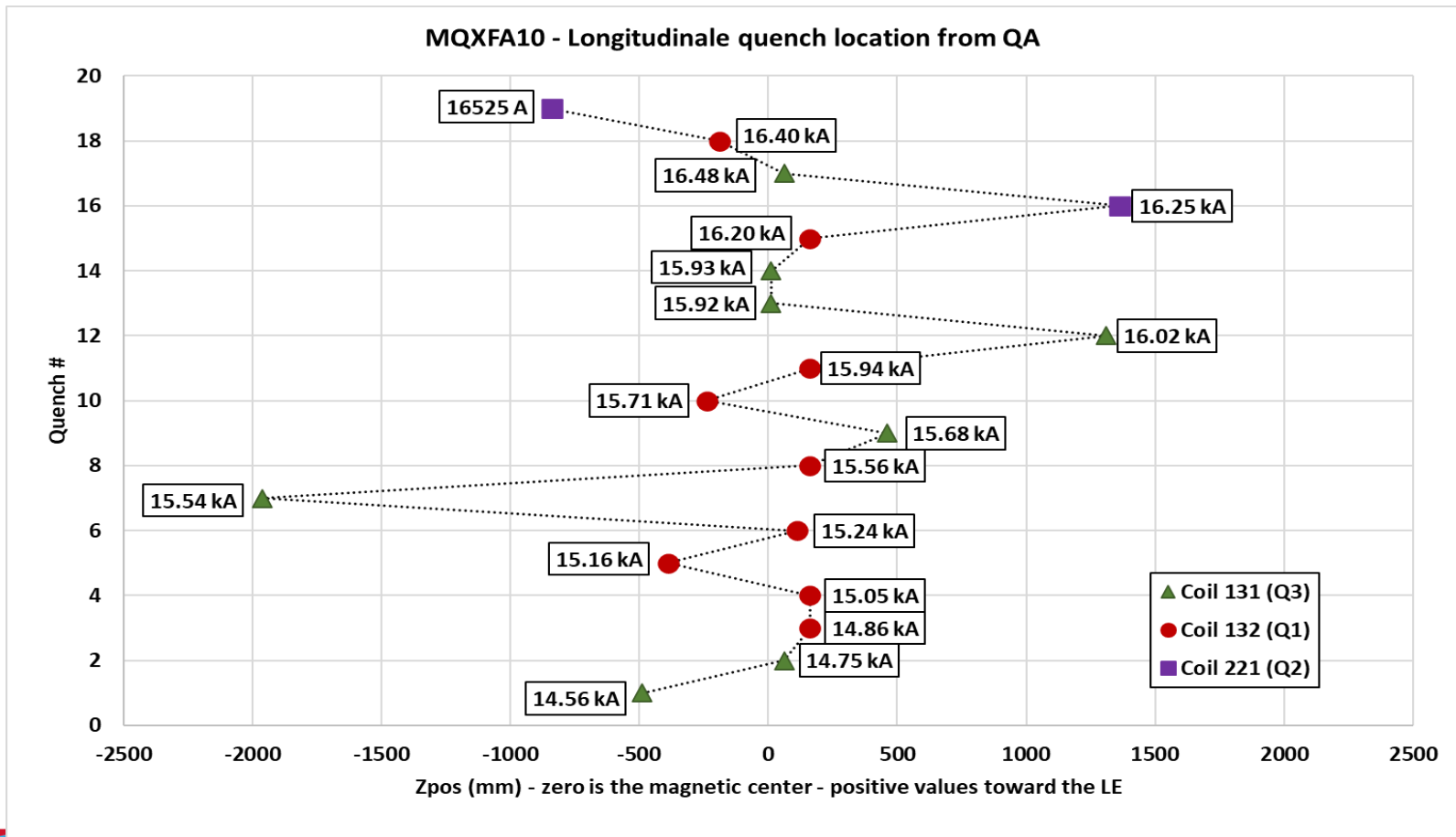
MQXFA10

- First magnet tested after the lessons learned from A07/08.
- Achieved nominal + 300A after 19 quenches.
- 11 ramps without quench (2 to nominal + 300 A).
- No quenches after the thermal cycle.

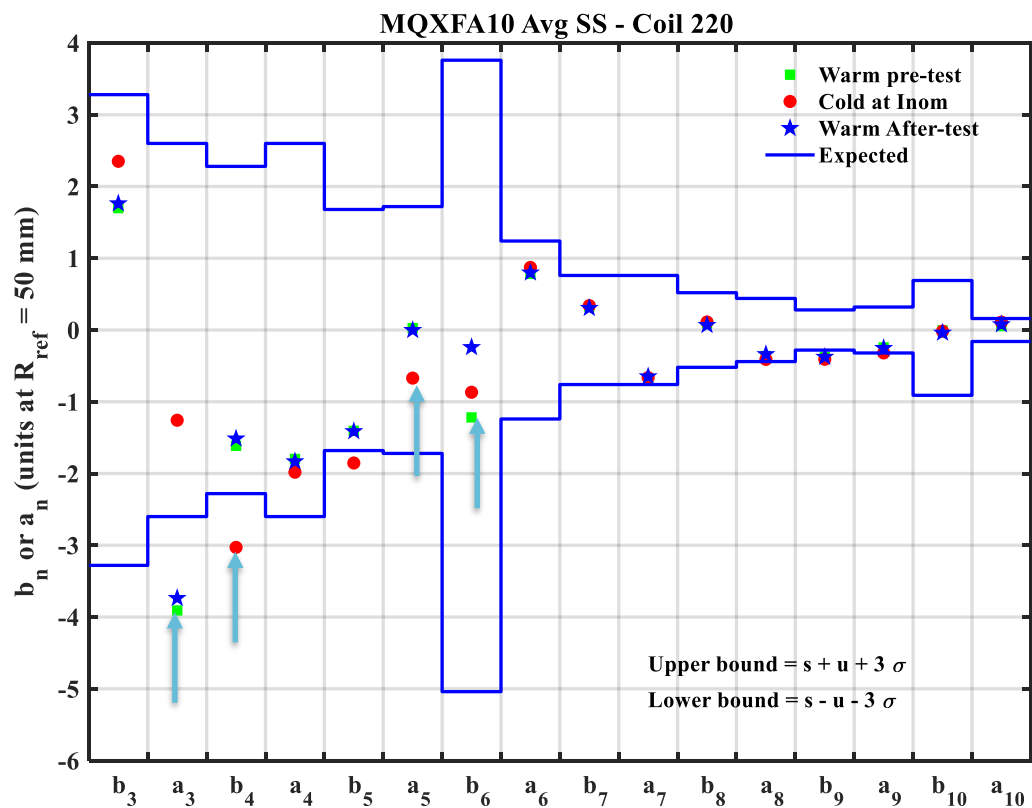


MQXFA10 – Quench locations

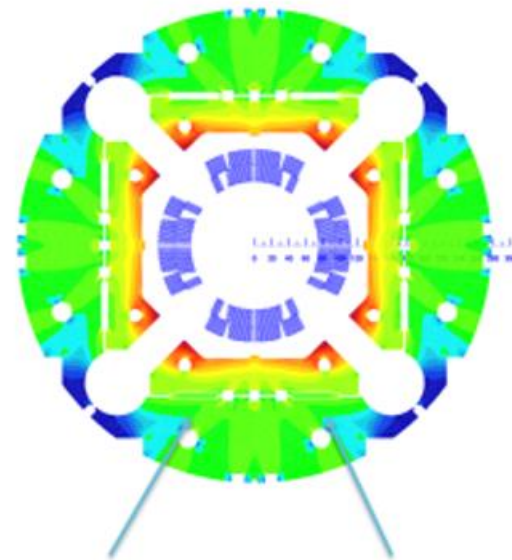
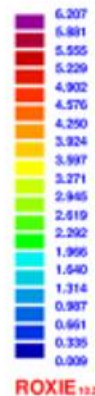
- Longitudinal quench locations from quench antenna array.
- 15 out of 19 quenches were around the magnet center.



MQXFA10 – Field Quality in the straight section



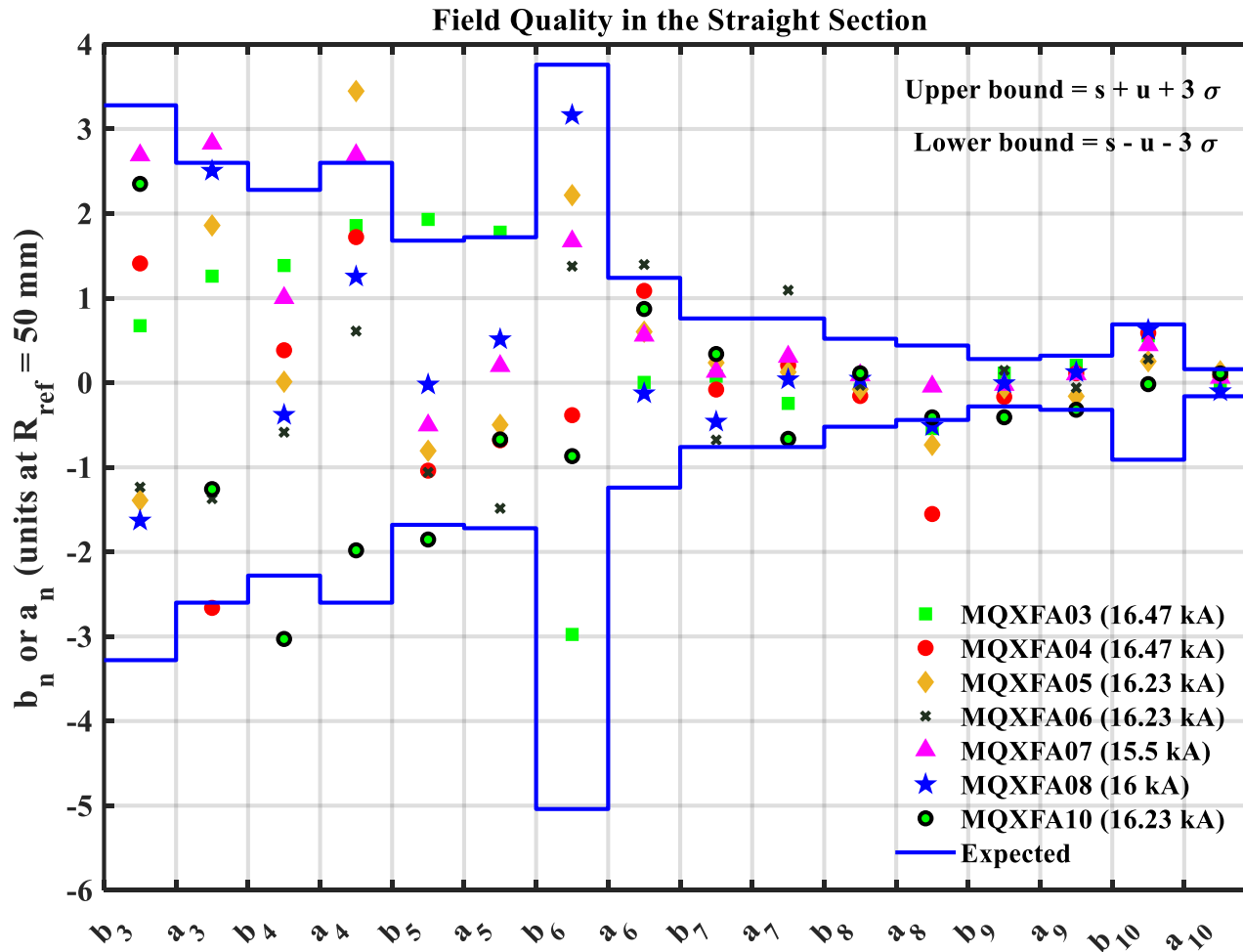
(a) flux density (T)



Magnetic shims location

- Main field error corrected for: a3.
- Measured: +2.7 units correction.

FQ summary– A03/4/5/6/7/8/10



MQXFA – Gradient Summary

At 16.230 kA	Unit	MQXFA04 (#)	MQXFA05 (#)	MQXFA06 (#)	MQXFA10	Design/Target
Central Gradient (*)	T/m	132.68 (+)	133.16	132.90	133.18	132.6
Integrated Gradient	T	559.37 (+)	561.48	560.32	562.72	557 [± 3]
Magnetic length	m	4.211	4.211	4.210	4.213	4.2 [± 0.005]

At 15.500 kA	Unit	MQXFA07 (at 15.5 kA)	MQXFA08 (at 16 kA)
Central Gradient (*)	T/m	127.56	131.23
Integrated Gradient	T	537.67	553.81
Magnetic length	m	4.210	4.211

(*) Average along the magnet straight section.

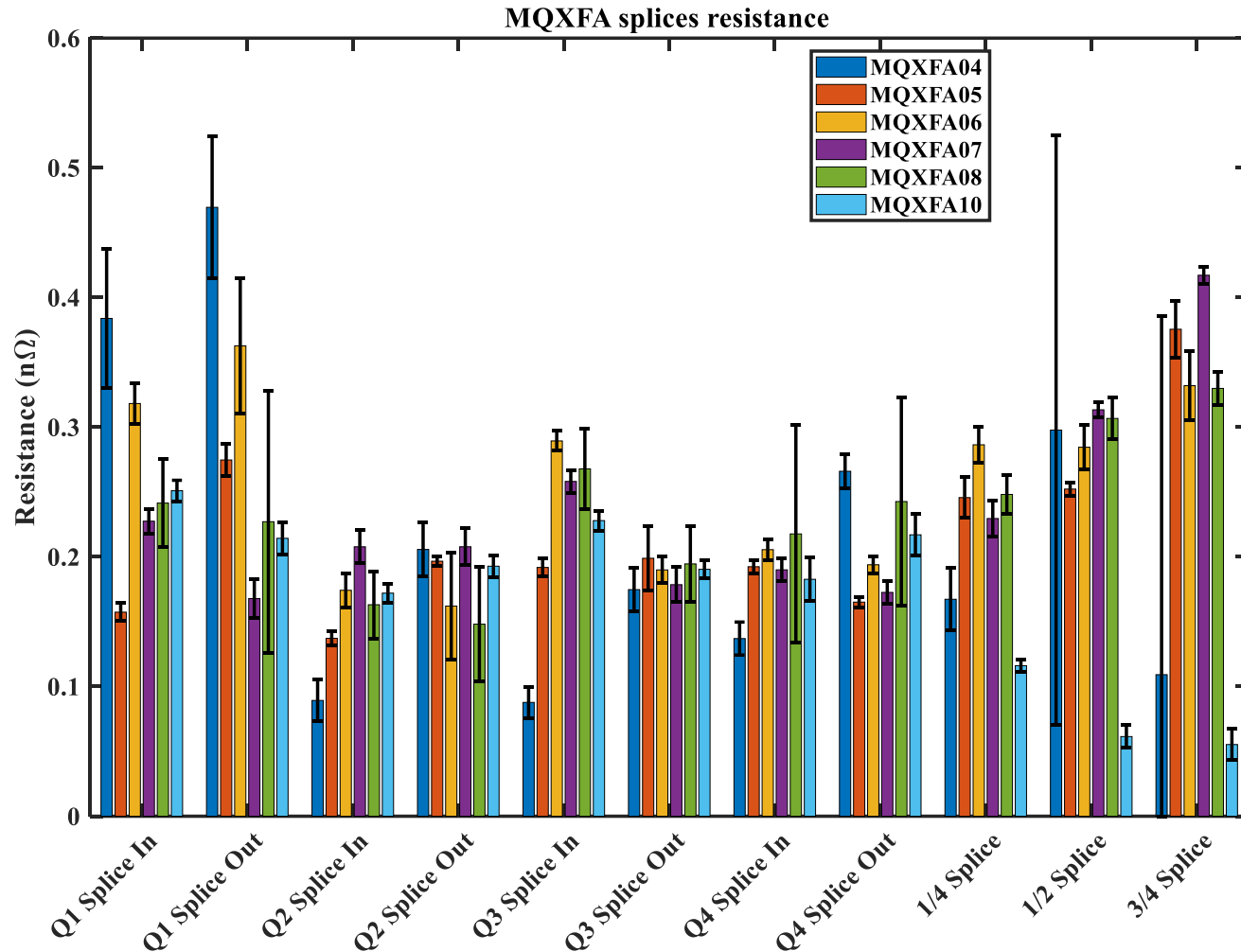
(+) Linear scaling from measurements at 16.47 kA

(#) MQXFA04 has 1 coil with b6 correction; MQXFA05-06 have 4 coils with b6 correction

- Expected gradient increase from A04 to A05/A06 due to 3 additional coils with b6 correction: 12 units (about +0.16 T/m i.e. from 132.68 T/m to 132.84; or about 0.66 T from 559.37 T to 560.03 T)
- Acceptance criteria for IG: magnets with same x-sec within 3T, magnets with different x-sec within 6T
- Acceptance criteria for ML: difference between any pair of magnets < 10 mm

MQXFA – Splice measurements

- All magnet splices < 0.5 nΩ.



MQXFA10 – Summary

- Magnet training:
 - 19 quenches at 1.9 K before reaching nominal + 300A = 16530A.
 - Quenches occurred in 3 out of 4 coils.
 - 15 out 19 quenches were around the magnet center.
- After training finished, 14 ramps with no quenches.
 - 11 ramps in the first test cycle (2 to nominal + 300A).
 - 3 ramps to nominal without quench after the thermal cycle.
- Magnetic field measurements: field errors within bound except for b4 and b5.
- All cold and warm hipots were successful.

Conclusion

7 MQXFA quadrupoles tested:

- 5 magnets met acceptance requirements.
- Limiting mechanism in MQXFA07/8 identified.
- Successful endurance test of MQXFA05.

THANK YOU

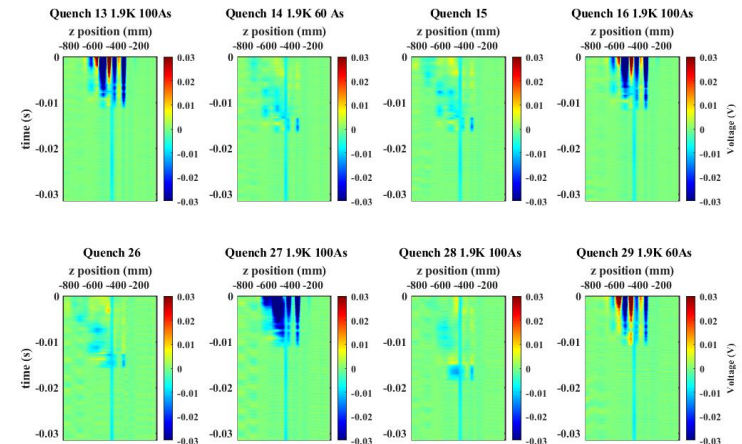
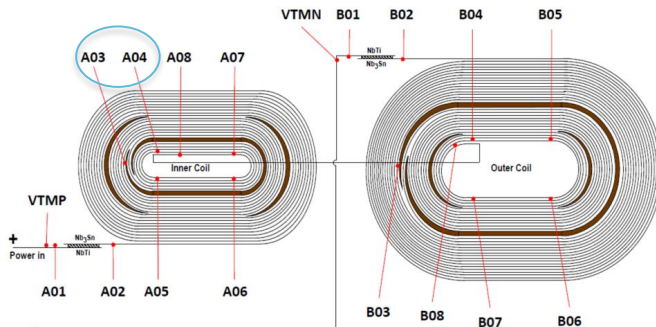
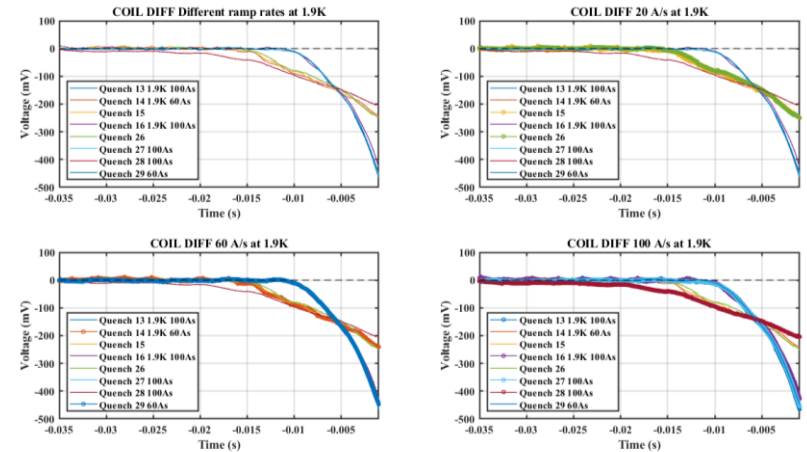


BACK UP SLIDES



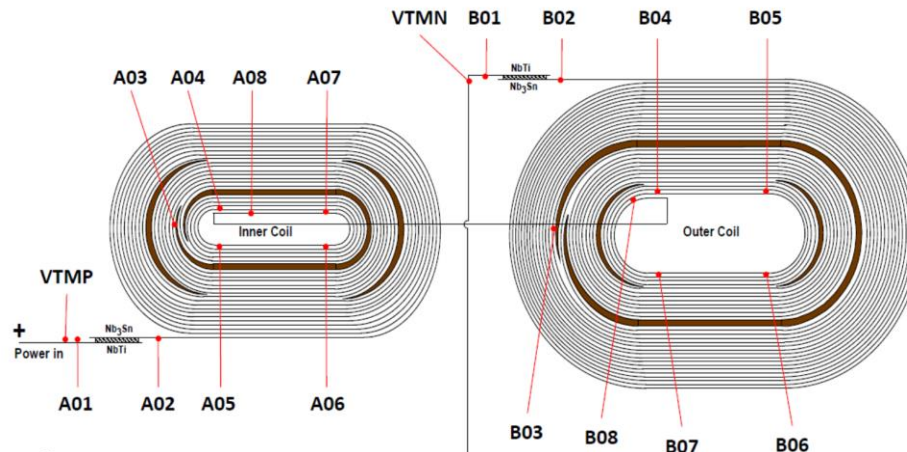
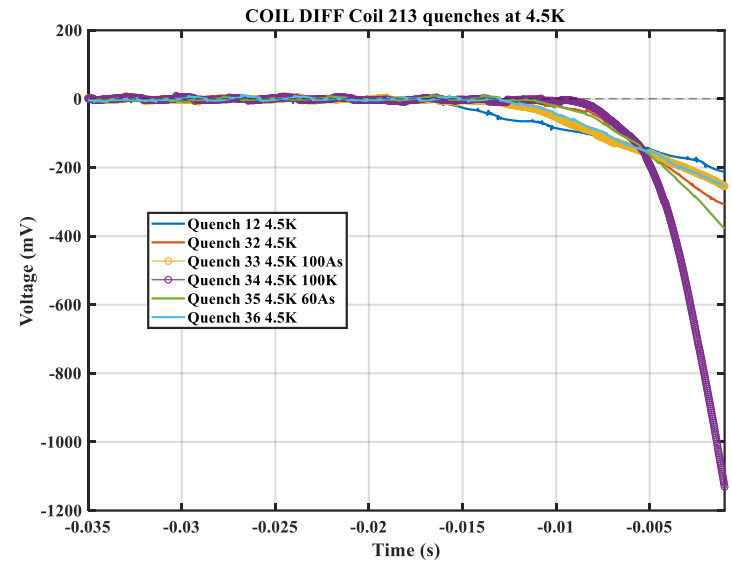
MQXFA08 1.9K quenches

- All occurred in A3-A4.
- Ramps at 20 A/s: quench start 16 ms pre-trigger.
- Ramps > 20 A/s, two behavior:
- Some quenches are identical to the 20A/s.
- Others show faster voltage growth with quench starting in multiple VT segments (A3-A4 and A4-A5).
- VT observation consistent with that of the quench antenna.



MQXFA08 4.5K quenches

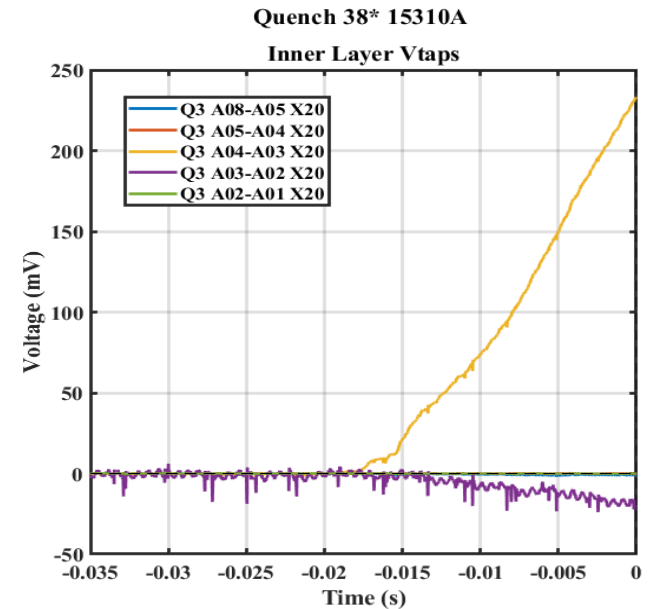
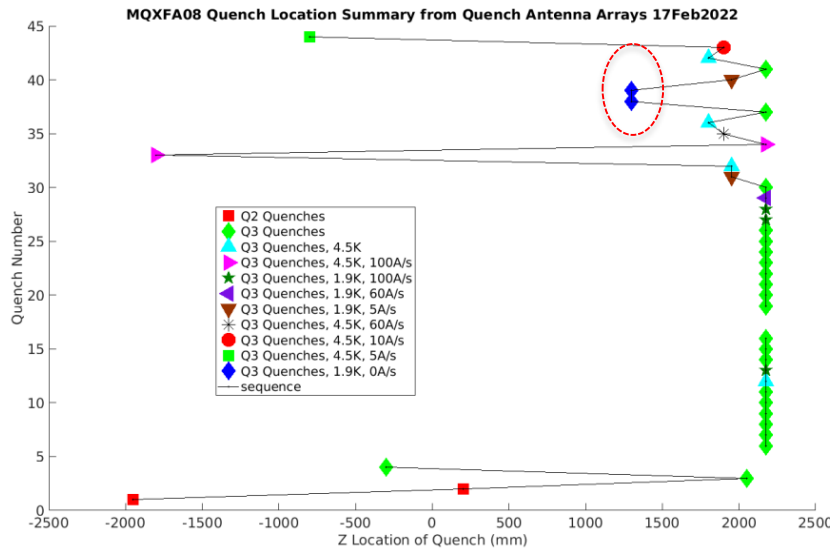
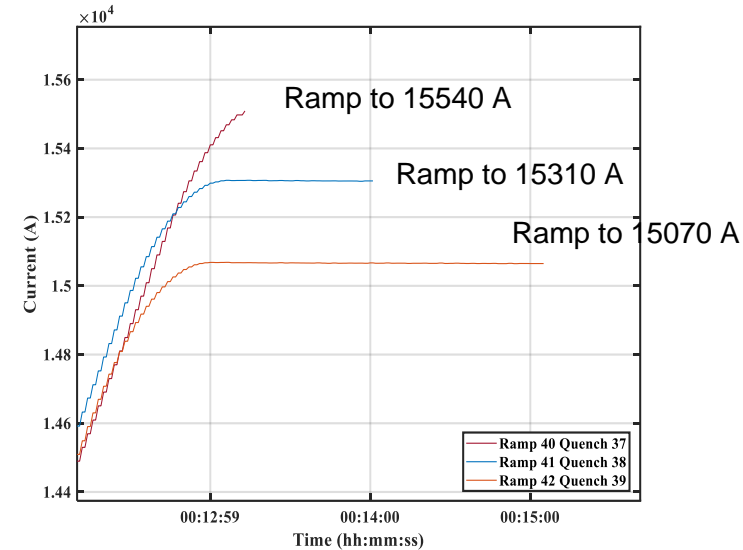
- Quench location changes:
 - A5-A8
 - 6 out of 8 were in the outer layer:
 - B4-B7 (4x)
 - B7-B8
 - B2-B4



MQXFA08 Holding quenches

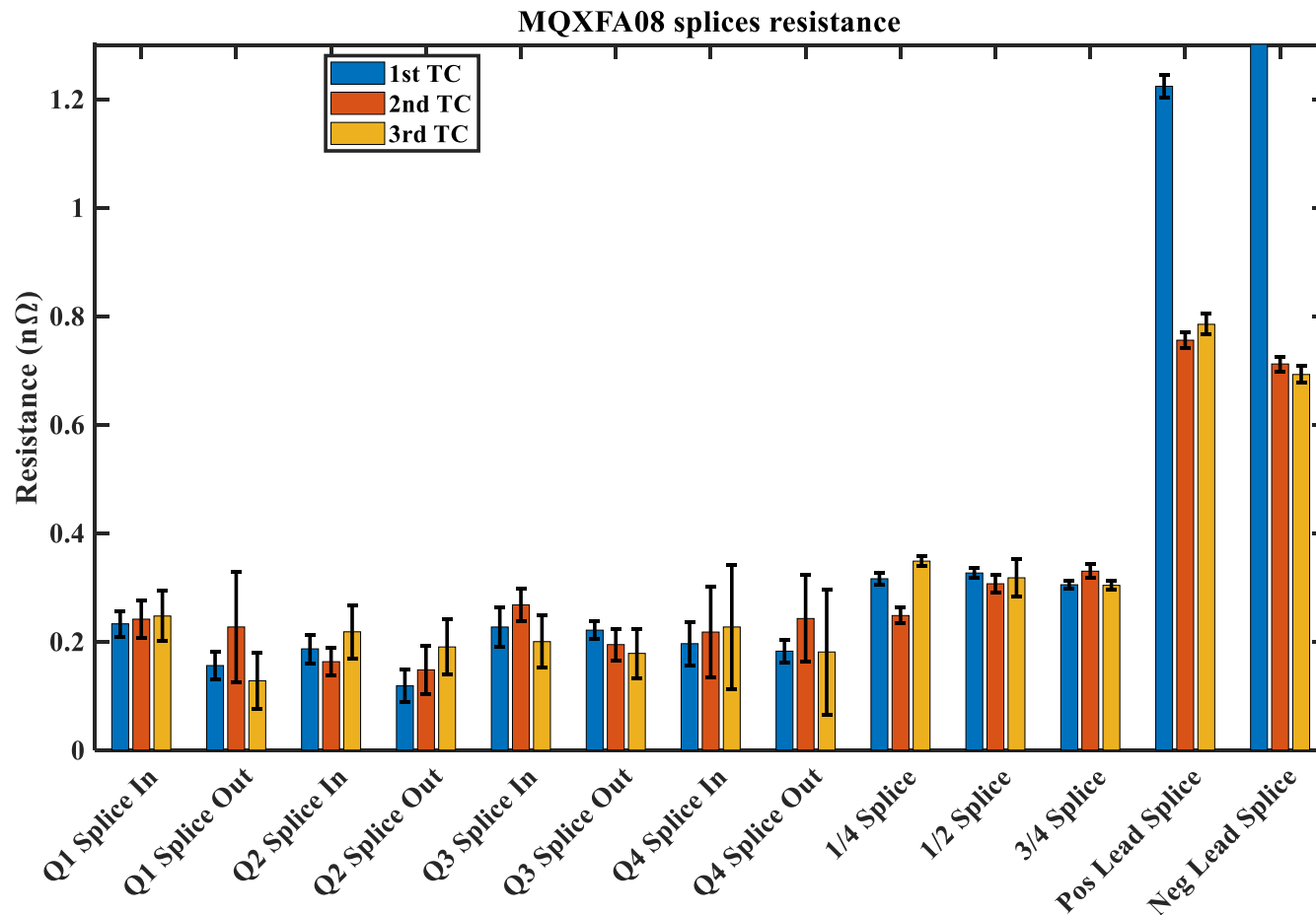
Ramp to 15540 A: quench at 15511 A.
 Ramp to 15310 A: quench after 40 s.
 Ramp to 15070 A: quench after 125 s.

- The quench occurs in A3-A4.
- Different longitudinal location.

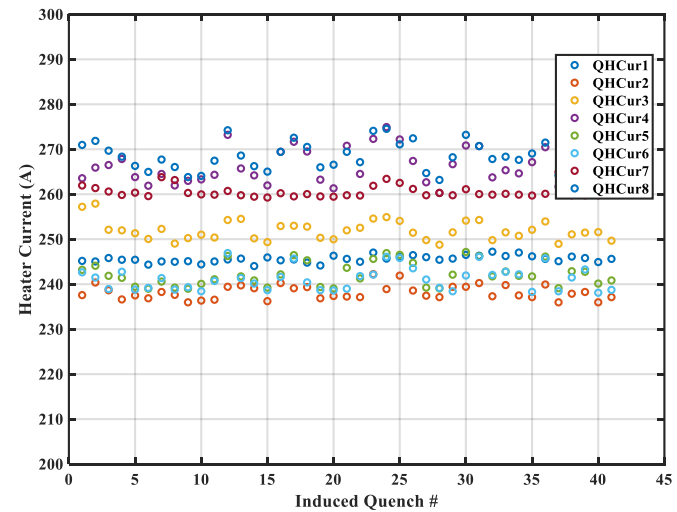
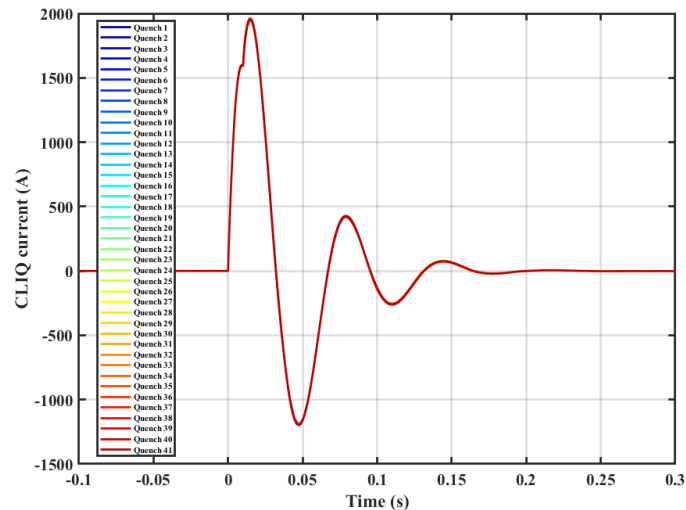
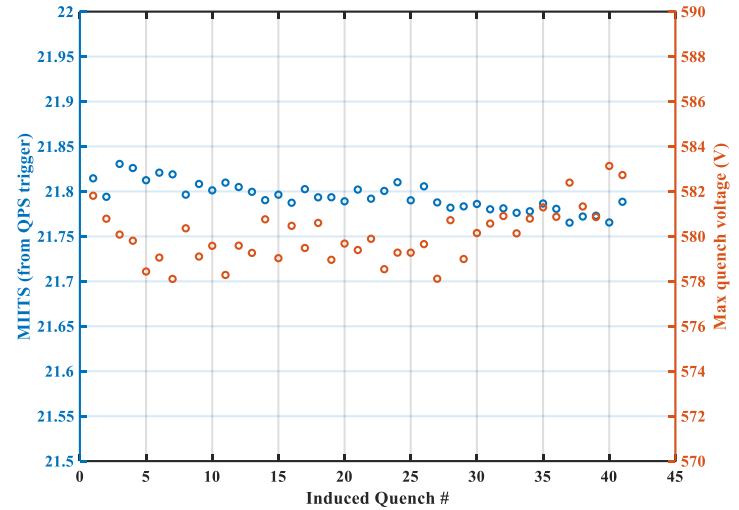
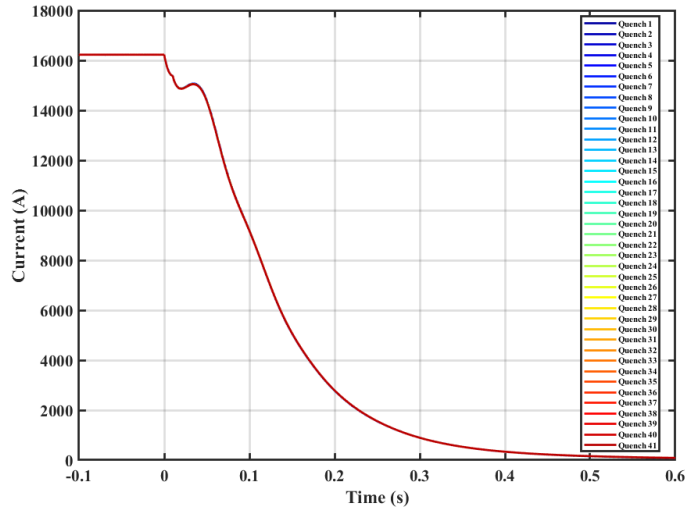


Splice resistance – MQXFA08

- During the first TC, the negative lead splice (to test fixture) was $42\text{n}\Omega$.

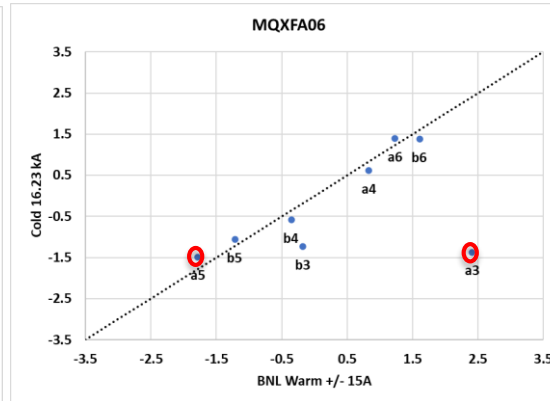
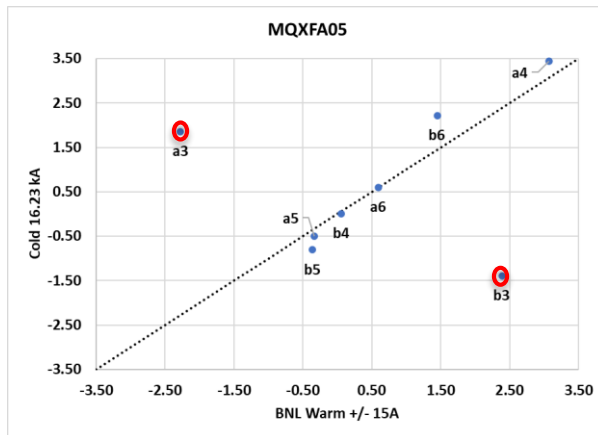
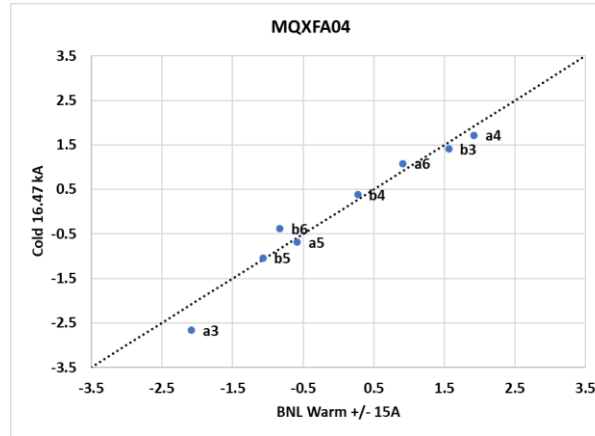
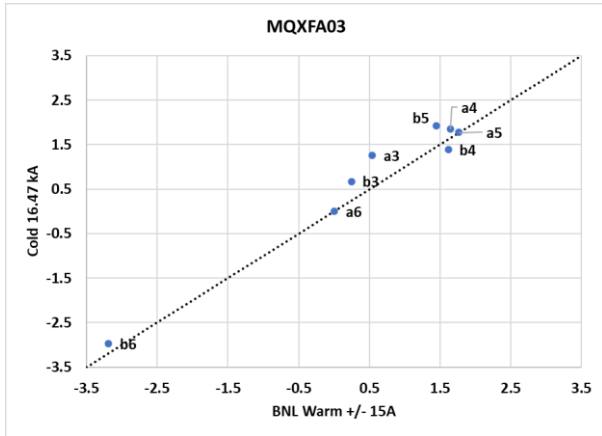


MQXFA05 Endurance Test



MAGNETIC FIELD MEASUREMENTS

Warm/Cold Correlation A03/4/5/6



○ - harmonics affected by coil shims

Summary table – Integrated field quality

Integ (unit)	MQXFA03	MQXFA04	MQXFA05	MQXFA06	MQXFA07	MQXFA08	MQXFA10
b3	-0.598	1.687	-1.219	-1.870	2.09	-1.77	2.48
b4	1.258	0.292	0.293	-0.198	1.31	-0.30	-3.04
b5	1.646	-0.845	-0.745	-1.071	-0.24	-0.09	-1.77
b6	-4.412	-0.773	1.962	1.058	1.06	2.06	-1.06
b7	0.180	-0.064	0.315	-0.663	0.14	-0.37	0.29
b8	-0.104	-0.171	-0.076	-0.031	0.05	0.02	0.06
b9	0.099	-0.117	-0.071	0.130	0.02	-0.01	-0.36
b10	0.123	0.398	0.145	0.149	0.32	0.33	-0.23
b11	-0.088	-0.065	0.057	-0.094	-0.04	-0.10	-0.12
b12	0.171	-0.781	-0.003	0.049	0.04	0.04	0.03
b13	-0.109	2.508	0.109	0.006	-0.05	0.18	0.10
b14	-1.747	-2.804	-1.017	-0.883	-0.82	-1.16	-1.11
b15	2.878	-5.536	-0.645	-0.068	0.10	-0.35	-0.46

MQXFA03/4:16.47 kA.

MQXFA05/6/10: 16.23 kA

MQXFA07: 15.5 kA (at 4.5 K)

MQXFA08: 16 kA (at 4.5 K)

Summary table – Integrated field quality

Integ (unit)	MQXFA03	MQXFA04	MQXFA05	MQXFA06	MQXFA07	MQXFA08	MQXFA10
a3	0.564	-2.601	1.650	-0.993	3.17	3.18	0.09
a4	2.275	2.527	2.750	0.336	3.43	1.94	-2.23
a5	1.554	-0.581	-0.494	-1.617	0.41	0.50	-0.40
a6	0.517	1.417	1.009	1.648	0.73	0.23	1.16
a7	-0.304	0.220	0.050	1.051	0.30	0.02	-0.62
a8	-0.537	-1.453	-0.724	-0.476	-0.03	-0.48	-0.40
a9	0.141	0.123	-0.136	-0.065	0.13	0.11	-0.19
a10	0.026	0.075	0.139	0.105	0.04	-0.07	0.08
a11	-0.091	0.290	0.141	0.170	-0.02	-0.21	-0.10
a12	0.241	-0.656	-0.083	-0.087	0.01	-0.12	0.03
a13	-0.759	-0.603	-0.044	0.034	0.01	0.02	-0.07
a14	1.569	5.029	0.406	-0.167	-0.21	0.29	0.27
a15	-1.831	-7.326	-0.906	0.388	0.45	-0.98	-0.73

MQXFA03/4:16.47 kA.

MQXFA05/6/10: 16.23 kA

MQXFA07: 15.5 kA (at 4.5 K)

MQXFA08: 16 kA (at 4.5 K)