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High Field Magnetic Field Measurement of MQXFA Magnets – for High Luminosity Upgrade at CERN – US DOE AUP Program

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U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY

IMMW21
International Magnetic Measurement Workshop
24th – 28th June 2019
ESRF
The European Synchrotron

Acknowledgment

- Collaborators at BNL, LBNL, FNAL, CERN, including G. Ambrosio, K. Amm, M. Anerella, D. W. Cheng, G. Chlachidze, **J. DiMarco**, S. Feher, P. Ferracin, S. Izquierdo Bermudez, **A. Jain**, P. Joshi, M. Marchevsky, J. Muratore, H. Pan, S. Prestemon, G. Sabbi, J. Schmalzle, E. Todesco, P. Wanderer, X. Wang, M. Yu and many others.
- This work was supported in part by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, through the U.S. LHC Accelerator Research Program, and in part by the High Luminosity LHC project at CERN.

Outline

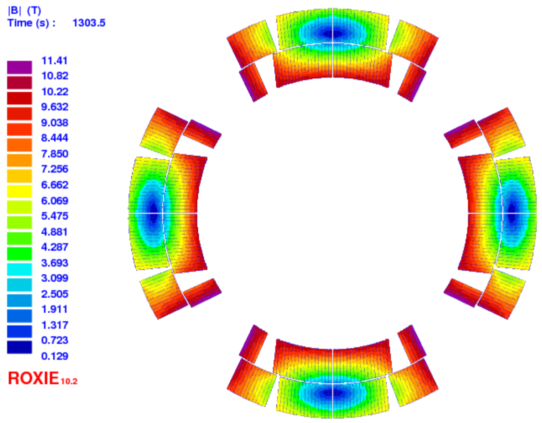
- Introduction
- Preparation for high field magnetic measurement of MQXFA Quads
- AP2 measurement results
- AP1b (one of the 4 coils has been replaced due to heater insulation issue)
- Summary

MQXFA Magnets and Magnetic Field Measurement for both Prototype and Production

- Magnetic field measurement for MQXFAP magnet
  - Monitor quality of the magnet production process
  - Ensure magnetic fields meets functional requirements and acceptance criteria.

Current [kA]	Symbol	Gradient [T/m]	Remarks
0.1	I.res	0.9	Reset level for pre-cycle
0.96	I.inj	8.5	Injection level
6.0	I.lim	48.8	Current limit (pre-training)
16.48	I.nom	132.6	Nominal level
17.89	I.ult	143.2	Ultimate level

- AUP MQXFA magnet parameter



Parameters	value
T_{op}	1.9 [K]
Reference radius	50 [mm]
Coil magnetic length	4.2 [m]
Total length with end plates	5 m (norm)
Conductor	Nb_3Sn

MQXFAP magnet

Magnetic Measurement Probe and Calibration

HT-Basic MM readout

Calibration Quad

LabVIEW based vertical transport

PCB Rotating Coil

Rotary NSK motor drive

DMMs for signals

Courtesy P. Joshi

NSK Rotary motor

Probe 220 Probe 110

- Long probe is 220mm, short is 110mm, on single board
- 5 'Tracks', 12 loops/track, 2 layers (➔ 24 turns/track)
- Width is 18.55mm/track.
- Board length 425mm, width 95mm, thickness 4.57mm

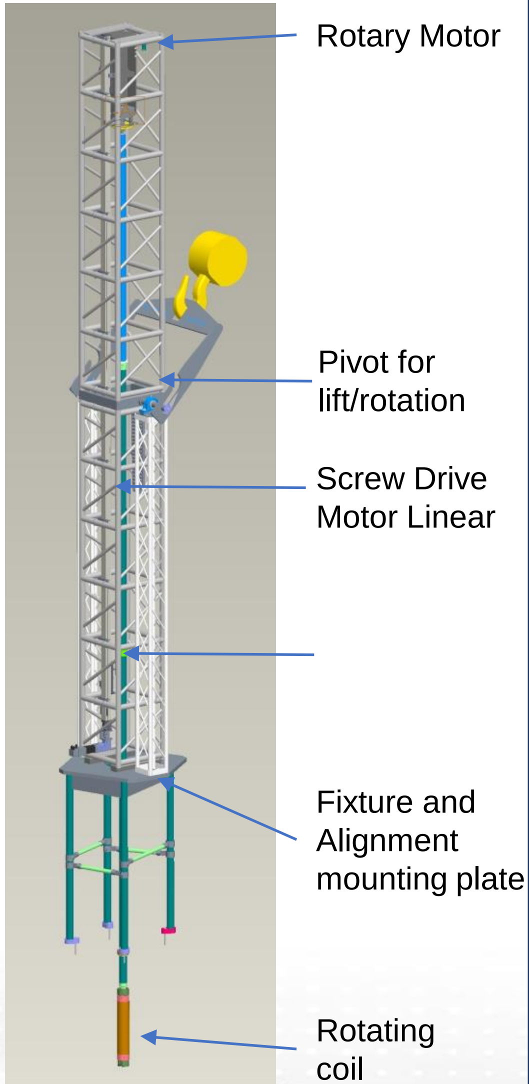
<u>Designed By J. DiMarco, Fermi Lab</u>
<u>Has been used in short magnet measurement</u>

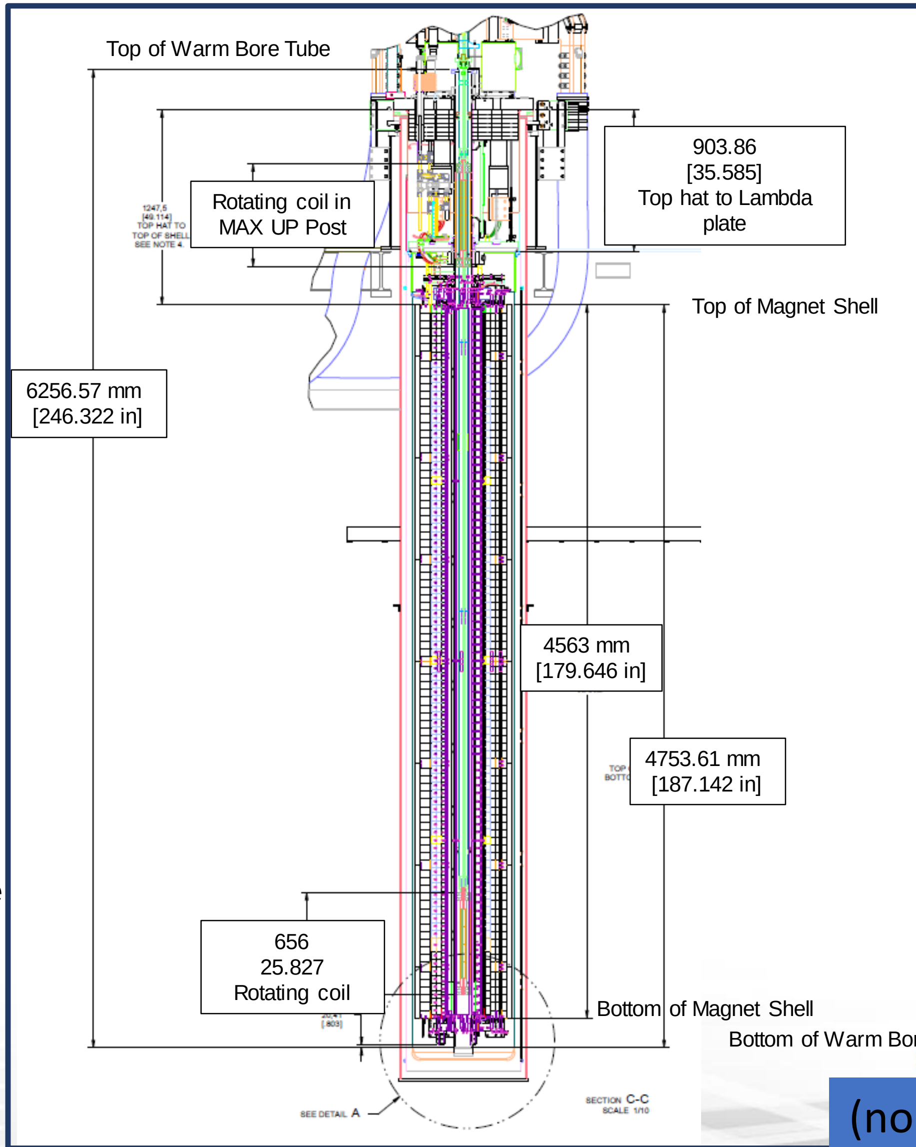
In PCB analog bucked configuration, there are 3 signals per circuit: UnBucked (UB), Dipole Bucked (DB) and Dipole-Quad Bucked (DQB).

#	Signals	R
1	UB_220	63.2 Ω
2	DB_220	120.6 Ω
3	DQB_220	235.0 Ω
4	UB_110	34.7 Ω
5	DB_110	65.0 Ω
6	DQB_110	125.4 Ω

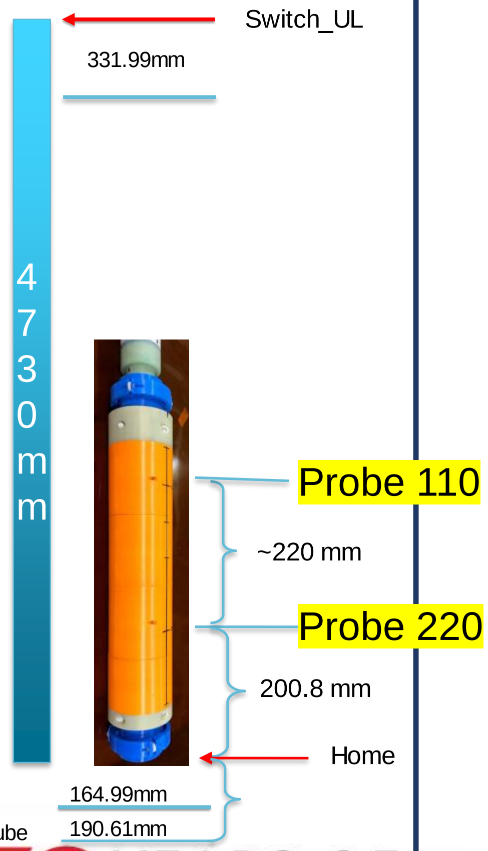
Bare wires on the mating connector

Vertical Transport System for ZSCAN along Magnet Axis



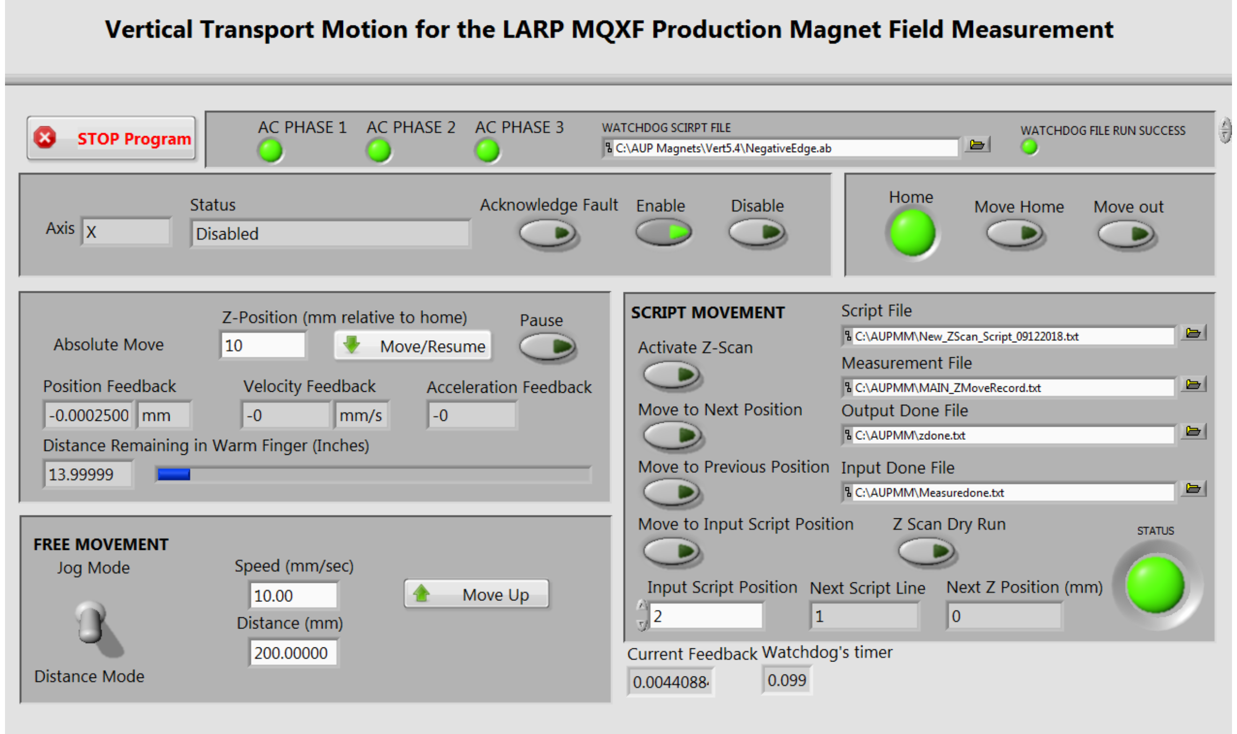


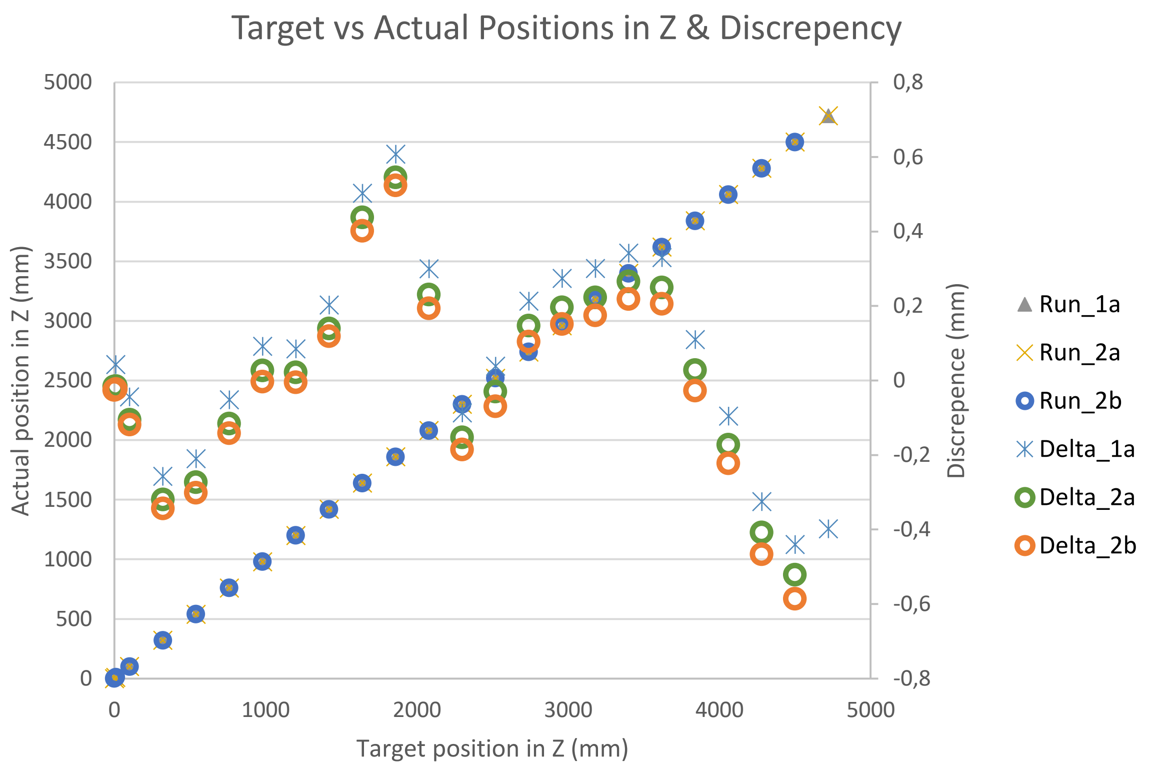
Warm Length



(no return end data due to cryostat limit)

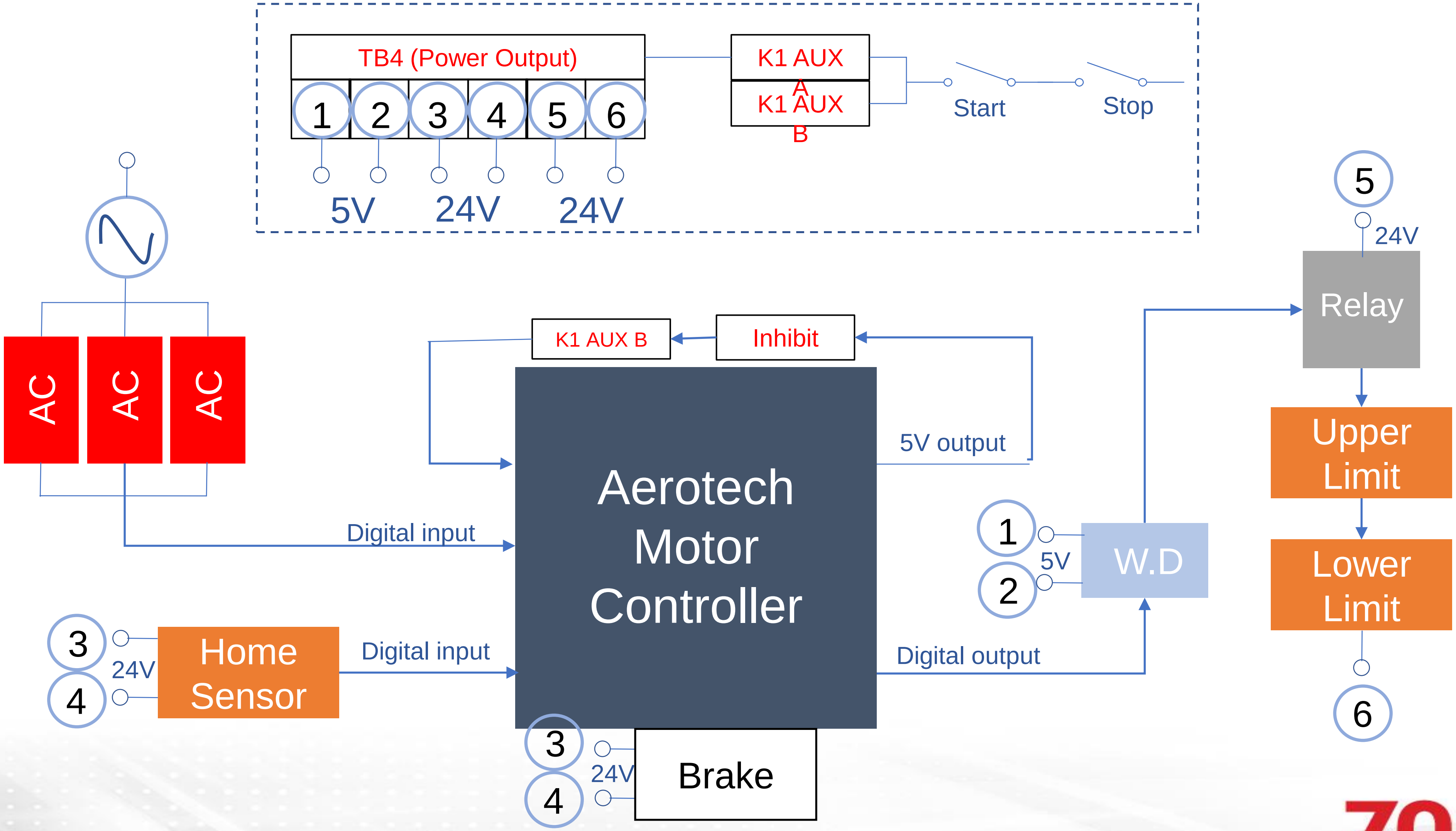
Vertical Transport Linear Motion Control and Emergency System



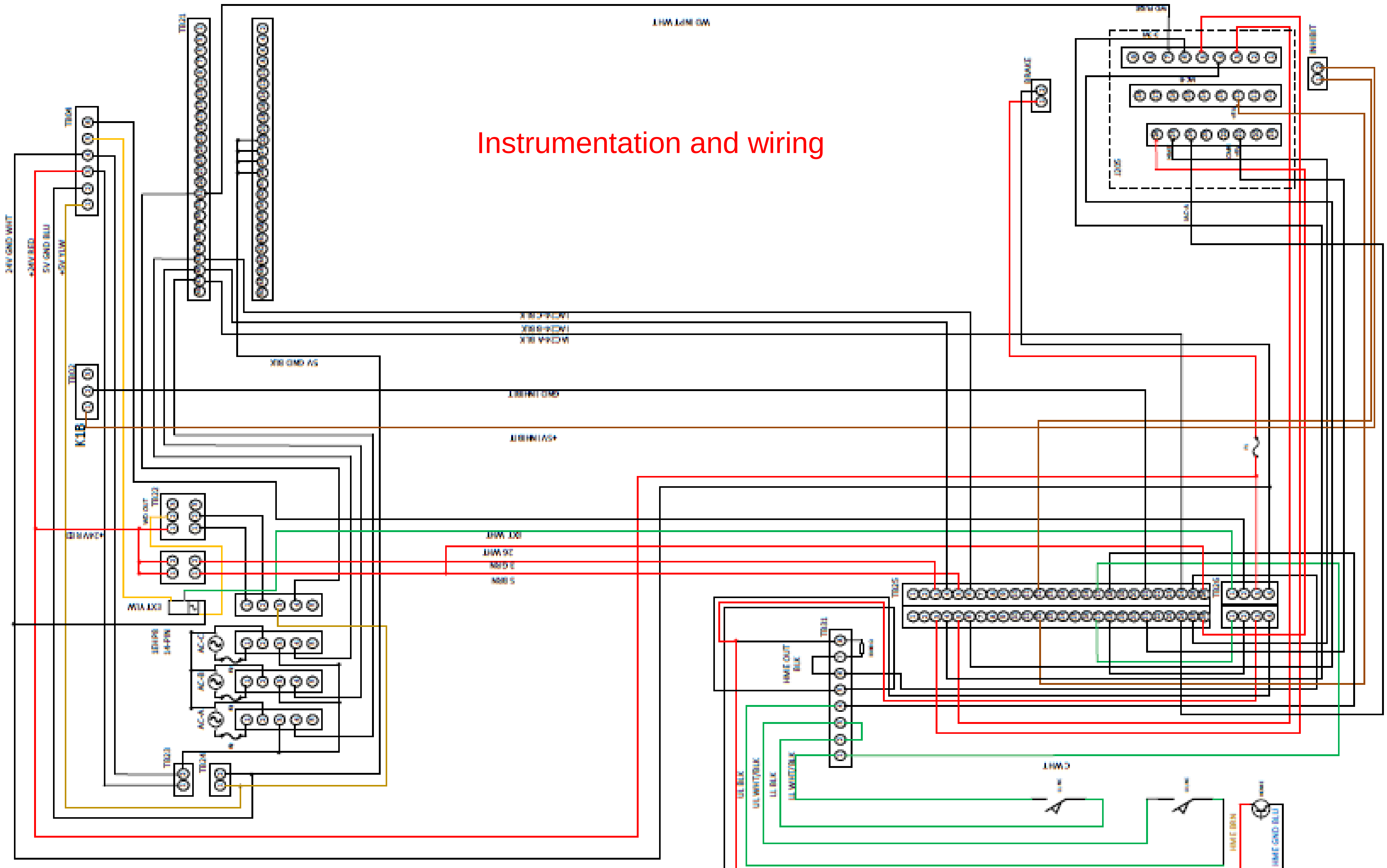


- Developed LabVIEW based vertical transport motion system
- Survey along the Z-axis - completed, three runs, Run_1a, 2a/2b.
- Measured discrepancy is less than ±0.6 mm, good repeatability.

Hardware and software programming for motion control and logic control

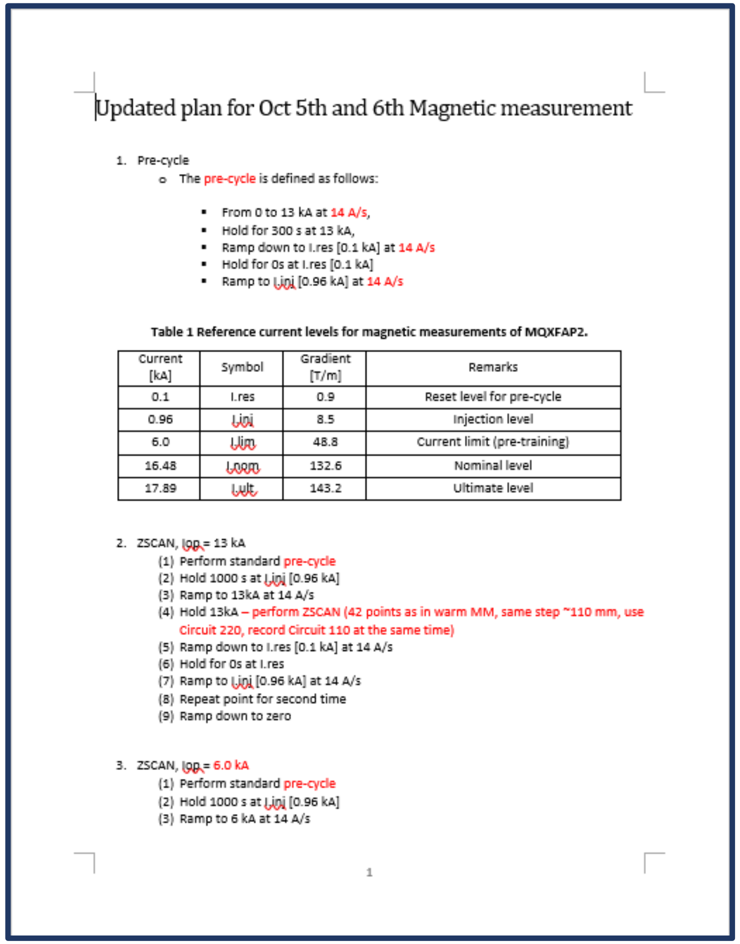


Instrumentation and wiring



Preparation for Magnetic Field Measurement - Plan

- **Warm MM prior to quench tests +/-15 A (averaged)**
- Most quenches are in or close to magnet ends. All coils participated in training quenches.
- Magnet reached 15 kA in 9 quenches, and showed detraining after quench 11.
- **Cold MM after quench 13**,
  - ZSCAN
    - Start with pre-cycle
    - 960A (injection), 6kA, 10 kA
  - ISCAN
    - •Stair-step, (DC Loop), up to 10 kA (pre-cycle)
      - •Did try 13 kA, but quenched at 4.2 K, magnet back to quench training
- Further tests and analyses are in progress.



Updated plan for Oct 5th and 6th Magnetic measurement

1. Pre-cycle
   - The pre-cycle is defined as follows:
     - From 0 to 13 kA at 14 A/s,
     - Hold for 300 s at 13 kA,
     - Ramp down to I.res [0.1 kA] at 14 A/s
     - Hold for 0s at I.res [0.1 kA]
     - Ramp to I.inj [0.96 kA] at 14 A/s

Table 1 Reference current levels for magnetic measurements of MQXFAP2.

Current [kA]	Symbol	Gradient [T/m]	Remarks
0.1	I.res	0.9	Reset level for pre-cycle
0.96	I.inj	8.5	Injection level
6.0	I.lim	48.8	Current limit (pre-training)
16.48	I.nom	132.6	Nominal level
17.89	I.ult	143.2	Ultimate level

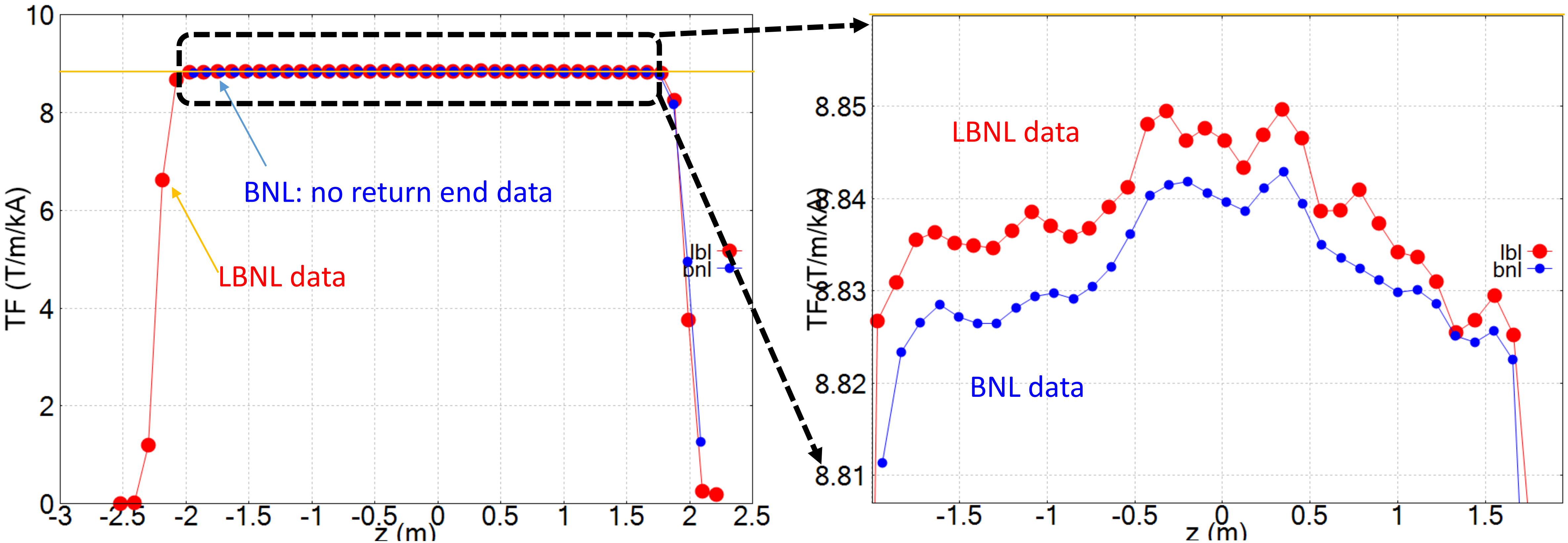
2. ZSCAN, Iop = 13 kA
   (1) Perform standard pre-cycle
   (2) Hold 1000 s at I.inj [0.96 kA]
   (3) Ramp to 13kA at 14 A/s
   (4) Hold 13kA – perform ZSCAN (42 points as in warm MM, same step ~110 mm, use Circuit 220, record Circuit 110 at the same time)
   (5) Ramp down to I.res [0.1 kA] at 14 A/s
   (6) Hold for 0s at I.res
   (7) Ramp to I.inj [0.96 kA] at 14 A/s
   (8) Repeat point for second time
   (9) Ramp down to zero

3. ZSCAN, Iop = 6.0 kA
   (1) Perform standard pre-cycle
   (2) Hold 1000 s at I.inj [0.96 kA]
   (3) Ramp to 6 kA at 14 A/s

1

Updated MM Plan
Drafted by H. Song, et al, 2018/10

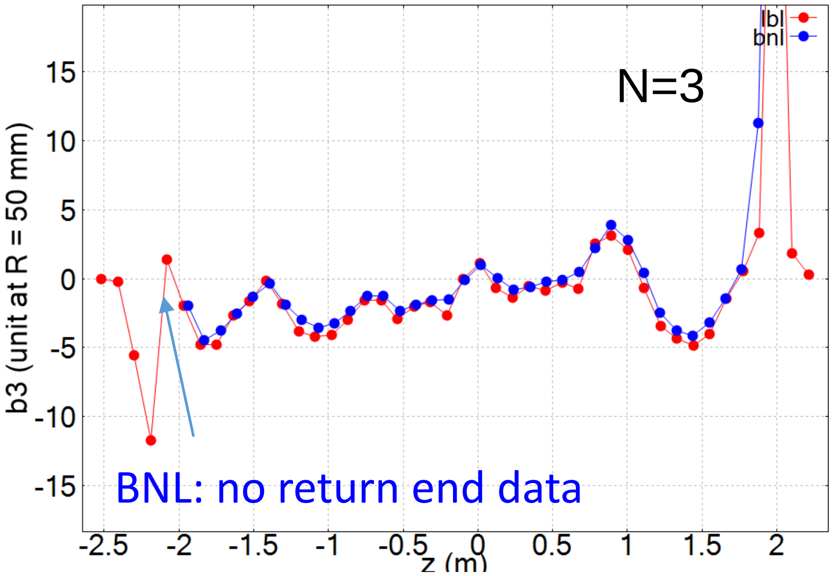
Warm Measurement of MQXFAP2, Averaged +/-15 A - BNL Probe 220 (10/15) vs LBNL Probe 110 Data (6/15)

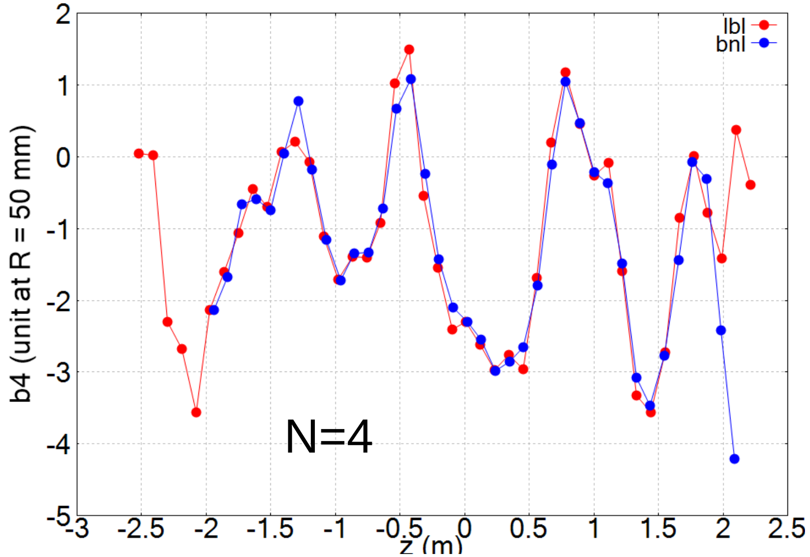


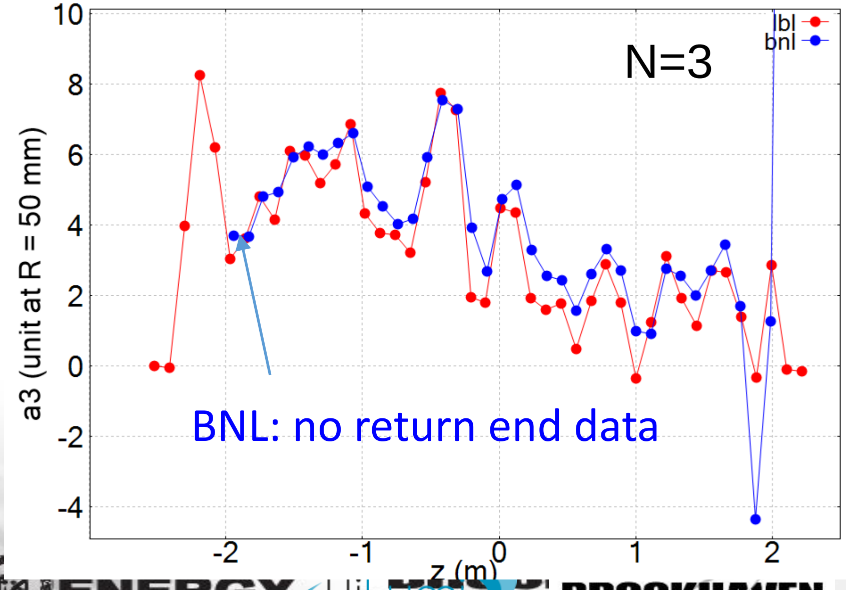
- Low current T.F. = 8.86 T/m/kA (Design)
- Reasonable agreement in T.F. between measured and design

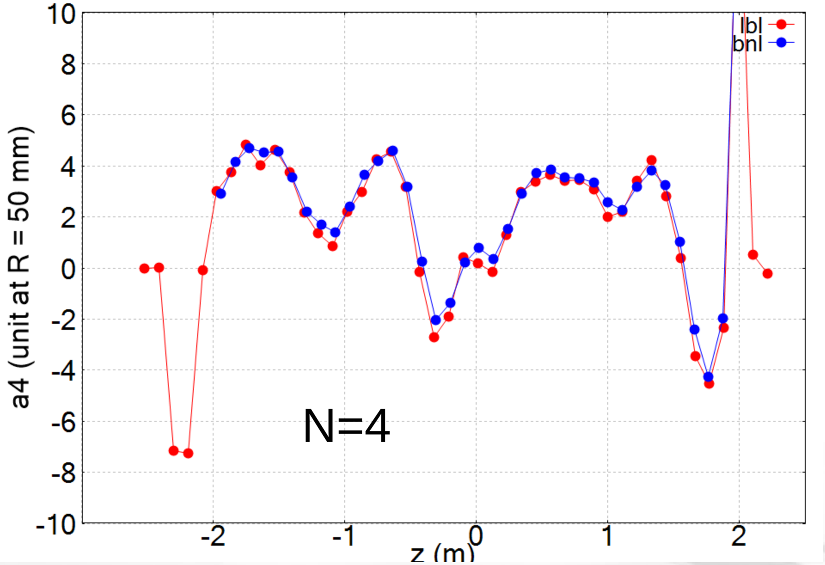
Courtesy of X. Wang

More Comparison in Multipole Coefficients between LBNL (Probe 110) and BNL (Probe 220) Warm Measurement



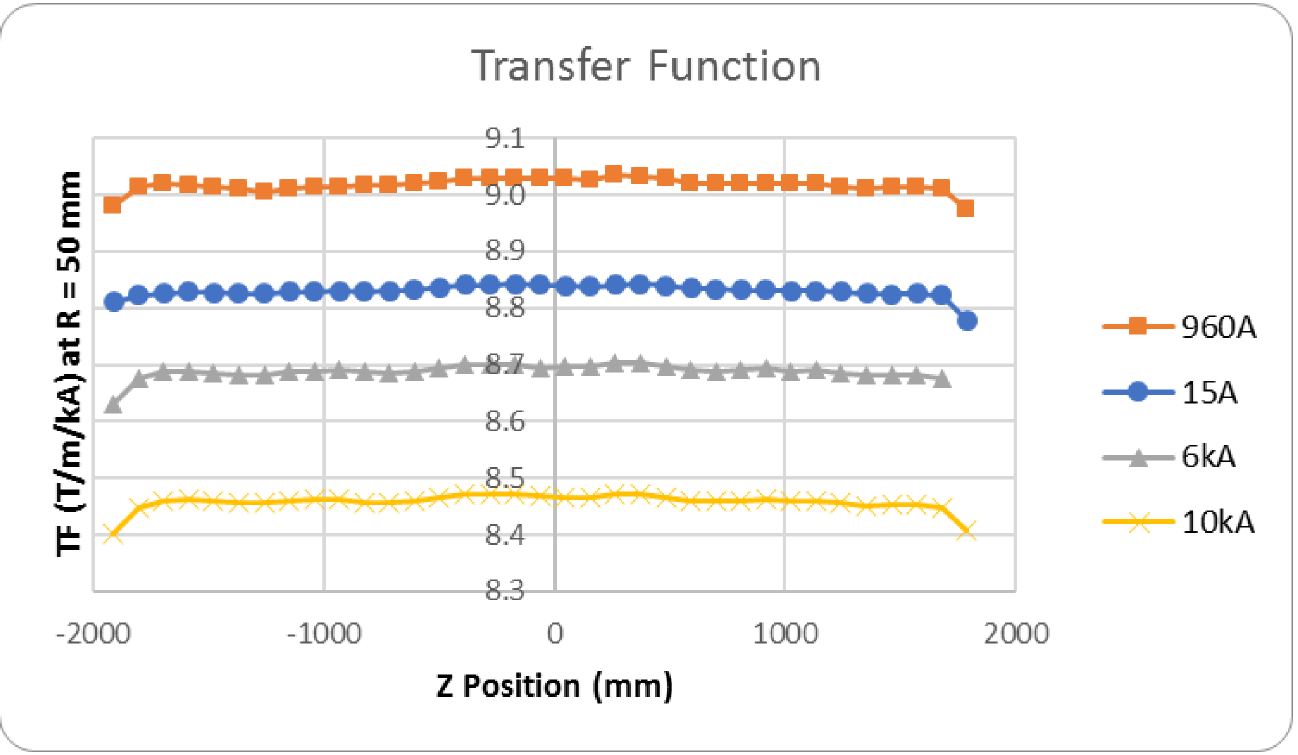


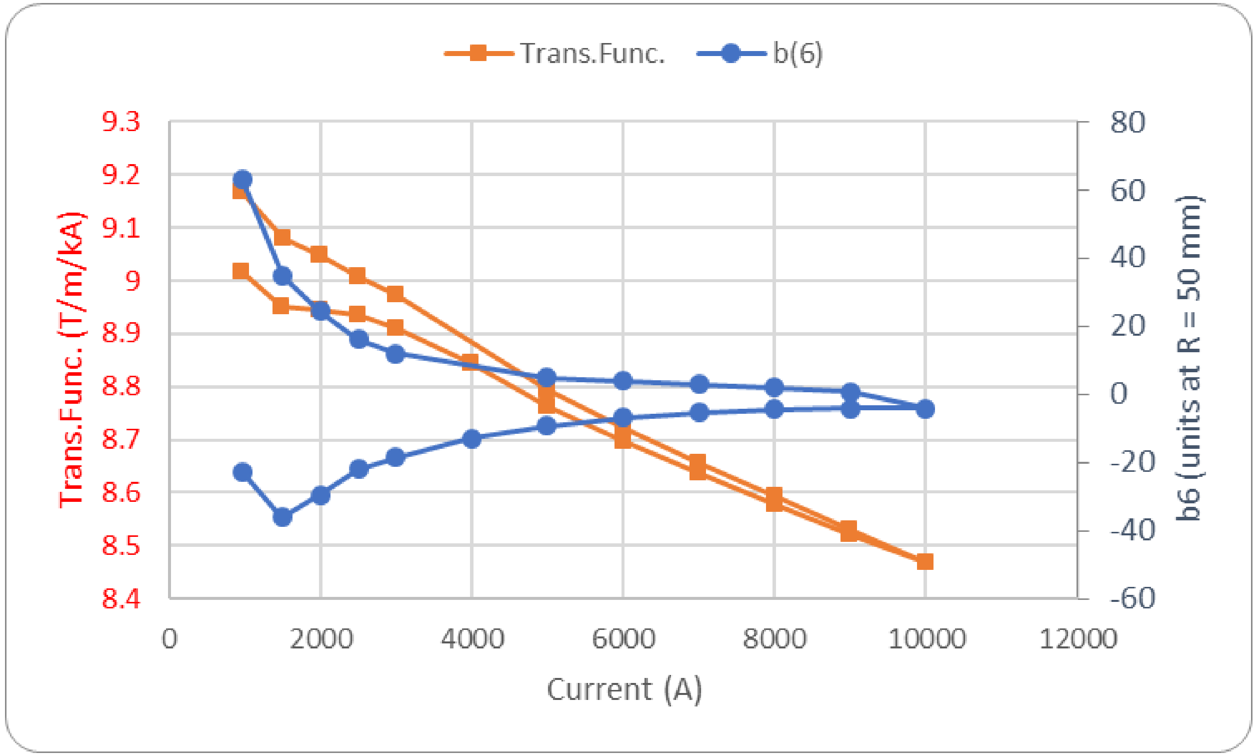




- Good Agreement between BNL and LBNL Warm MM Results
- The Vertical MM System are Ready for Cold MM
- Probe 110 seems to have better accuracy
- More data on Probe 220 and 110 in cold MM

Preliminary Cold vs Warm Measurement, **Transfer Function** (Probe 220 Data)





ZSCAN,

- 42 Z positions,
- Centered by Magnet Center and Probe 220 Center
- Slight decrease at higher current → iron saturation

ISCAN (Stair-step, DC Loop)

- 24 currents,
- Ramped from I_{inj} 960A, up to 10 kA, (missed 3kA)
- Hysteresis → persistent current

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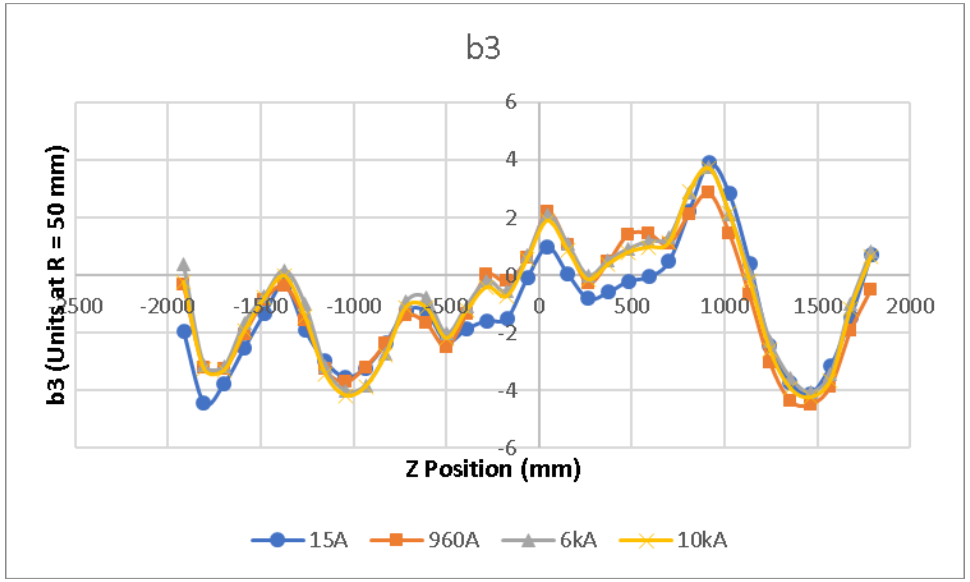
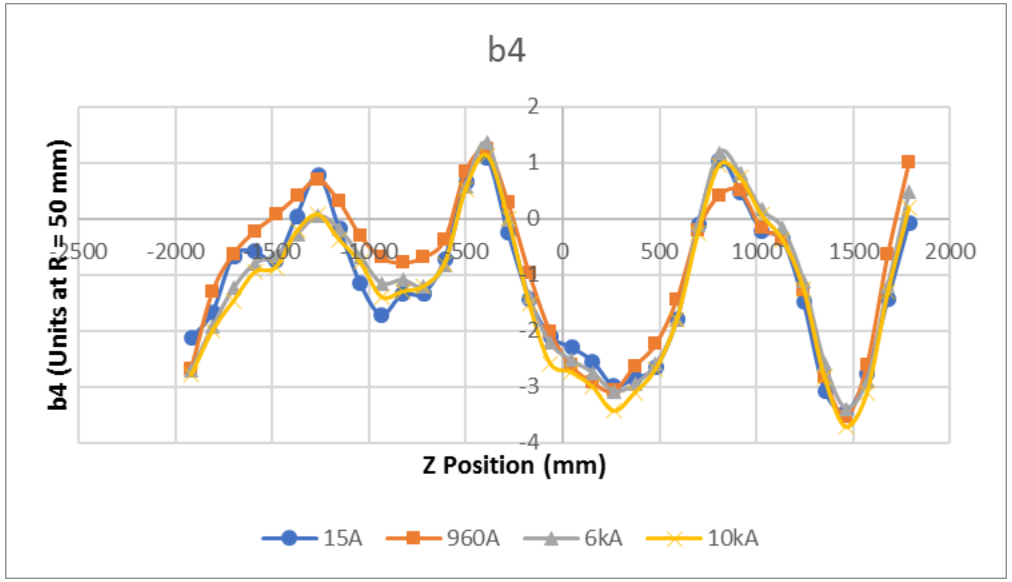
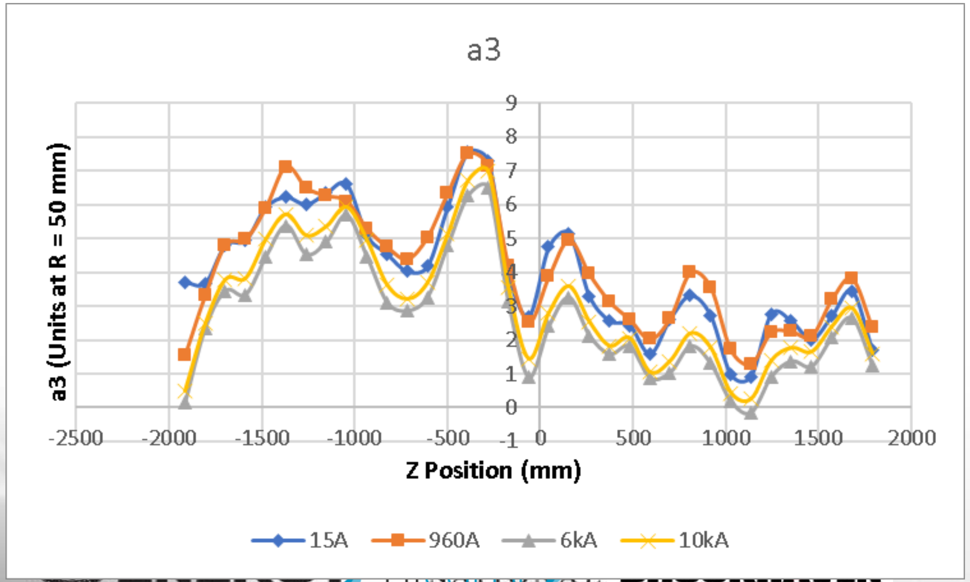
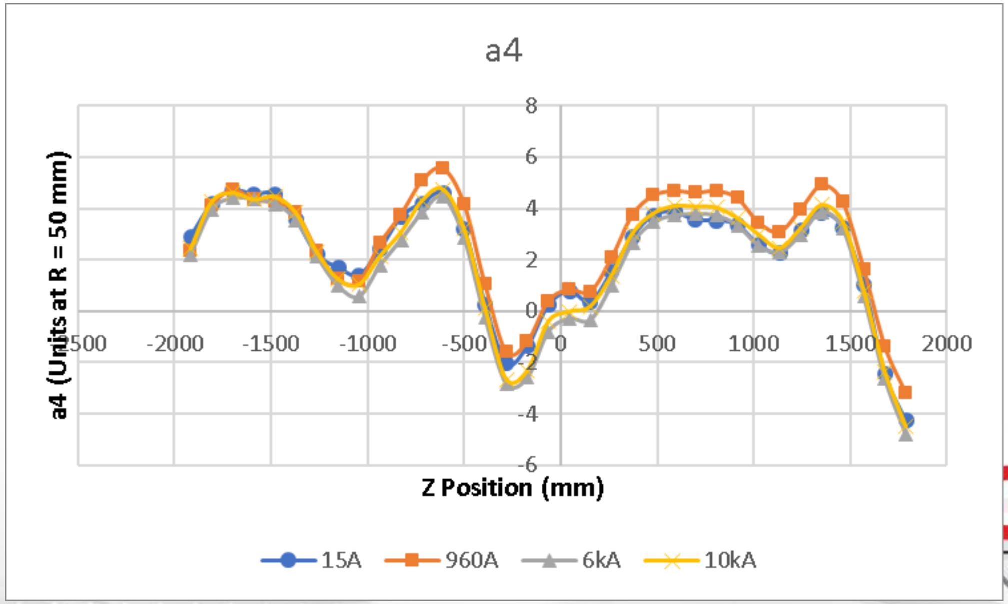
Cold vs Warm Magnetic Measurement: **Harmonics** (Probe 220 Data)



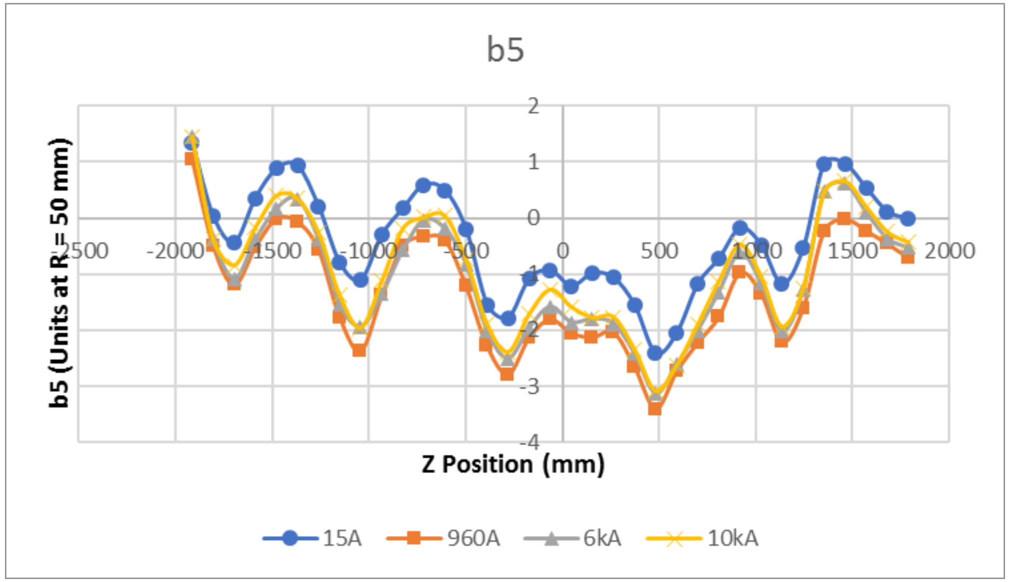


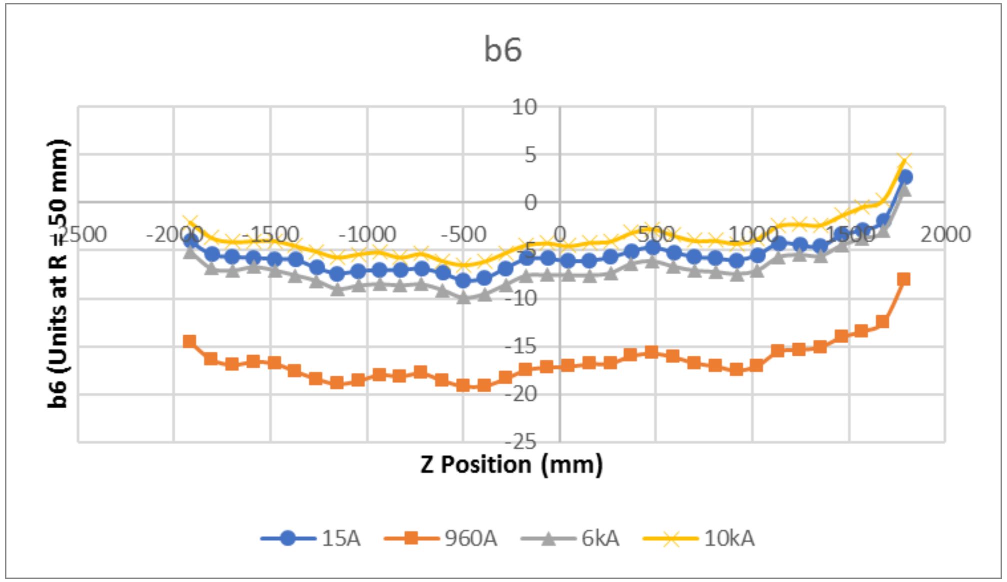


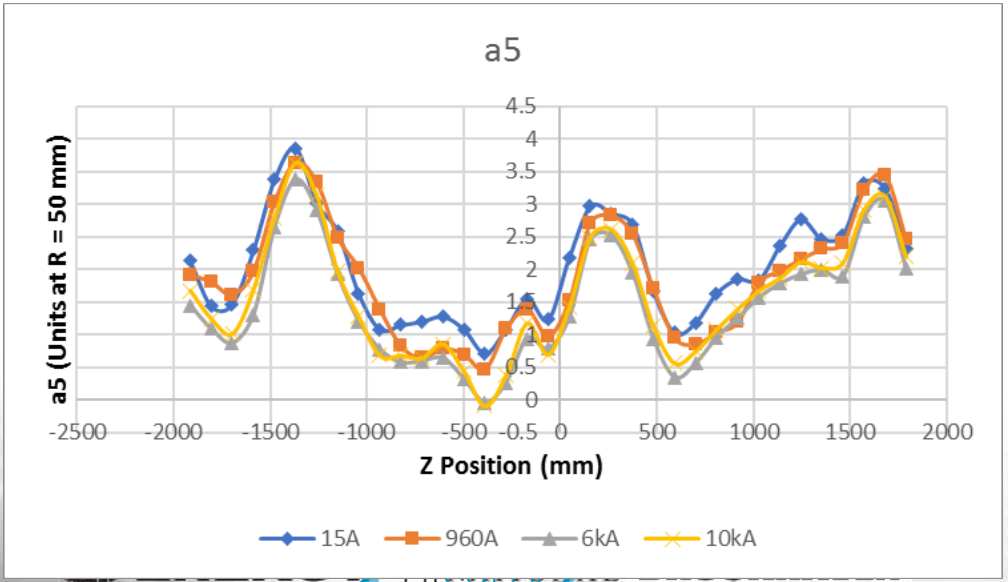


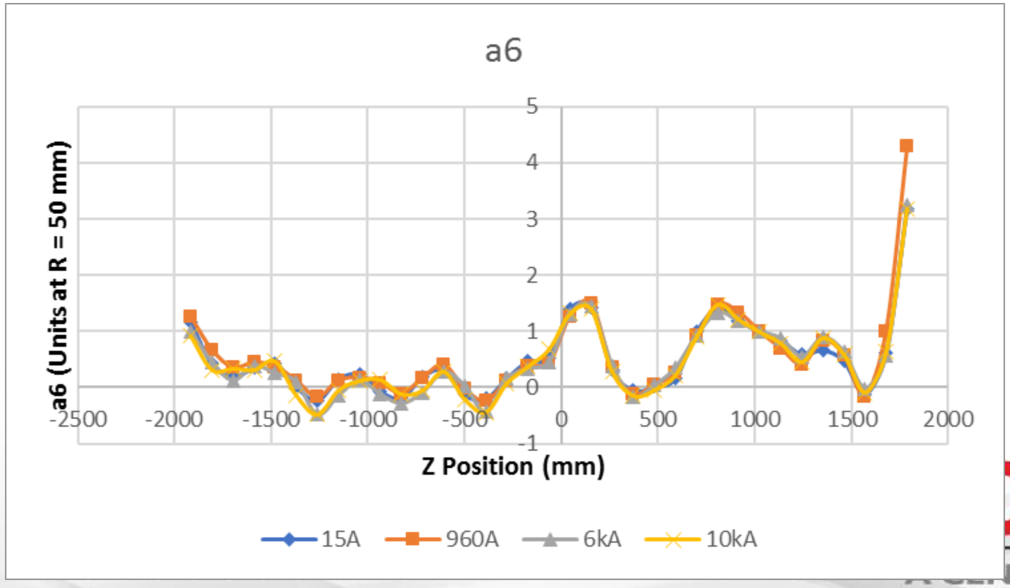
- Reasonable agreement between Warm MM at15 A, and Cold MM at 960A, 6kA, 10 kA

Cold vs Warm Magnetic Measurement: **Harmonics** (Probe 220 Data)



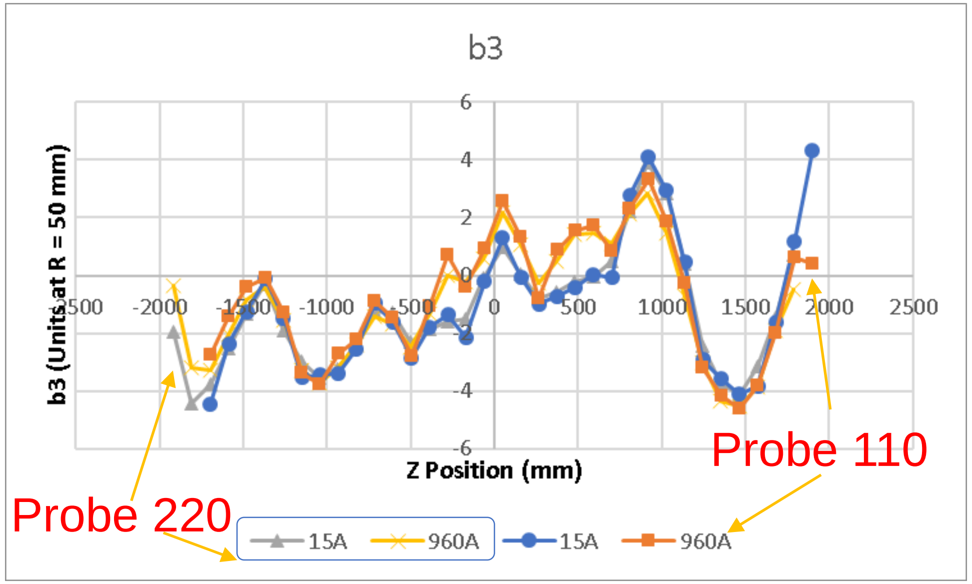


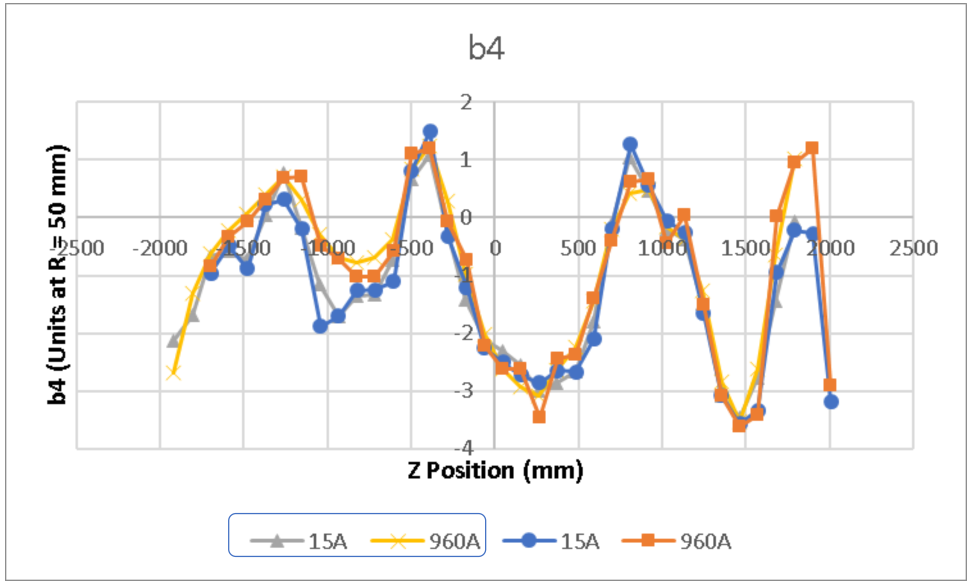


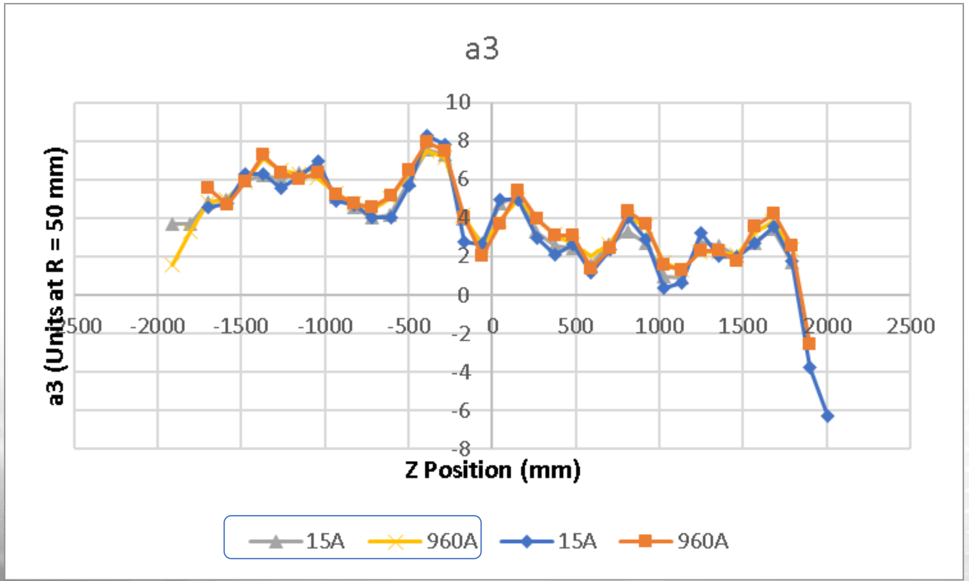


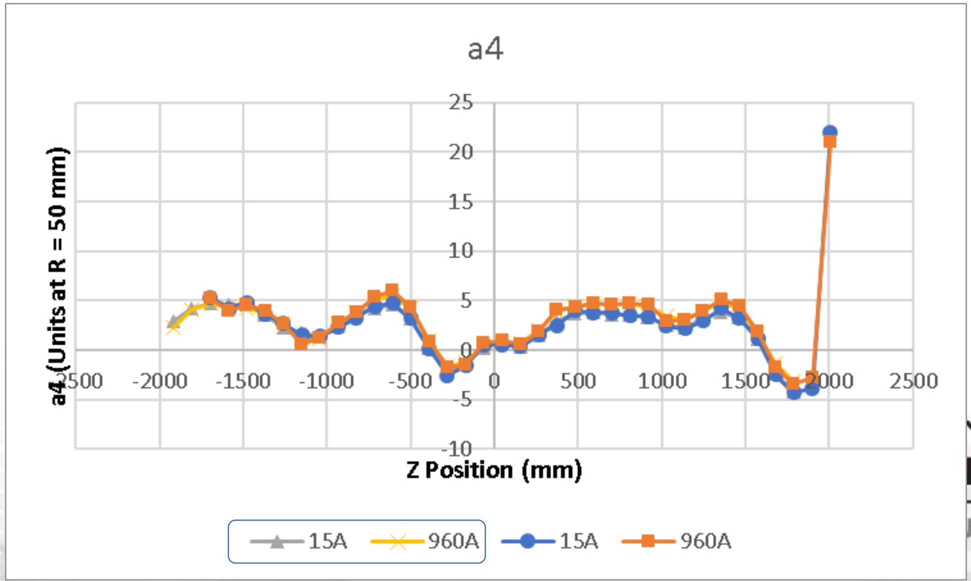
- Reasonable agreement between Warm MM at15 A, and Cold MM at 960A, 6kA, 10 kA
- Slight difference in b6 due to iron saturation

Cold vs Warm Magnetic Measurement: **Harmonics** (Probe 220 vs Probe 110) – 220 mm apart









- Probe 220 is ~220 mm higher than Probe 110
- Good agreement between Probe 220 and 110 data.

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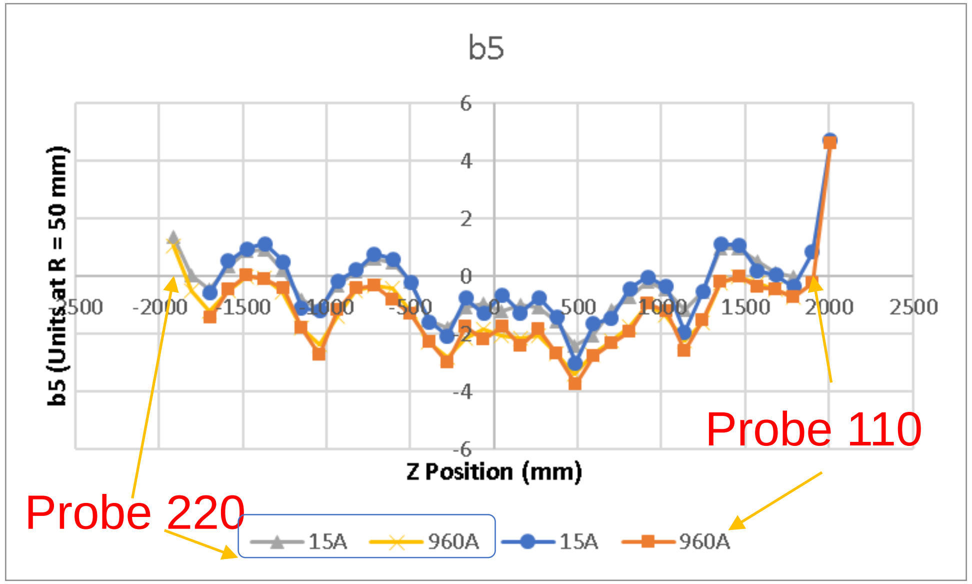
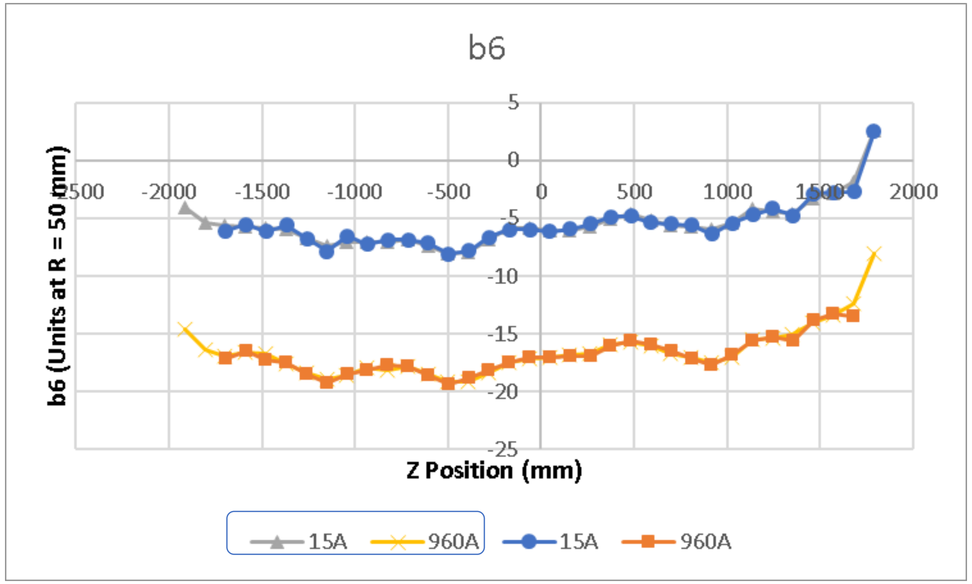
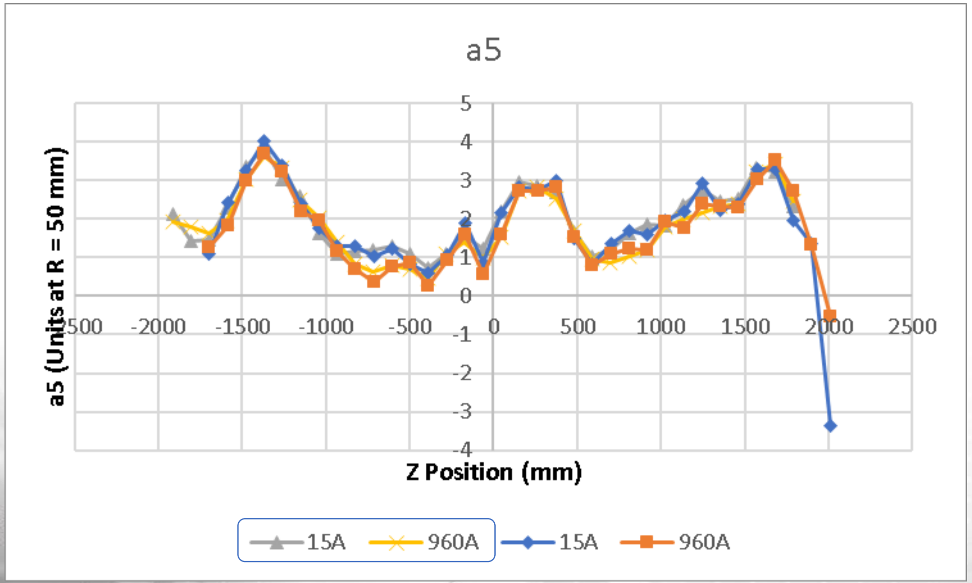
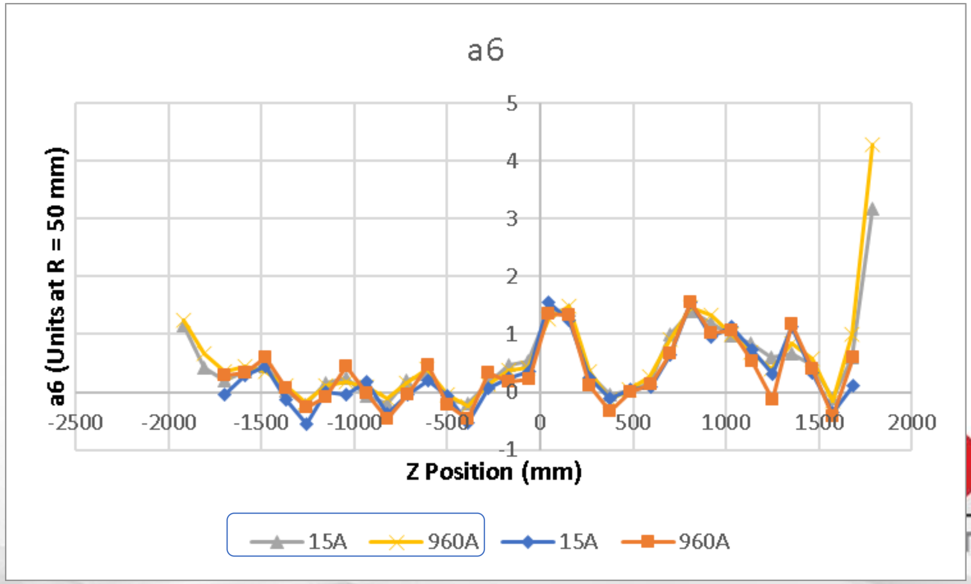
Cold vs Warm Magnetic Measurement: **Harmonics** (Probe 220 vs Probe 110) – 220 mm apart







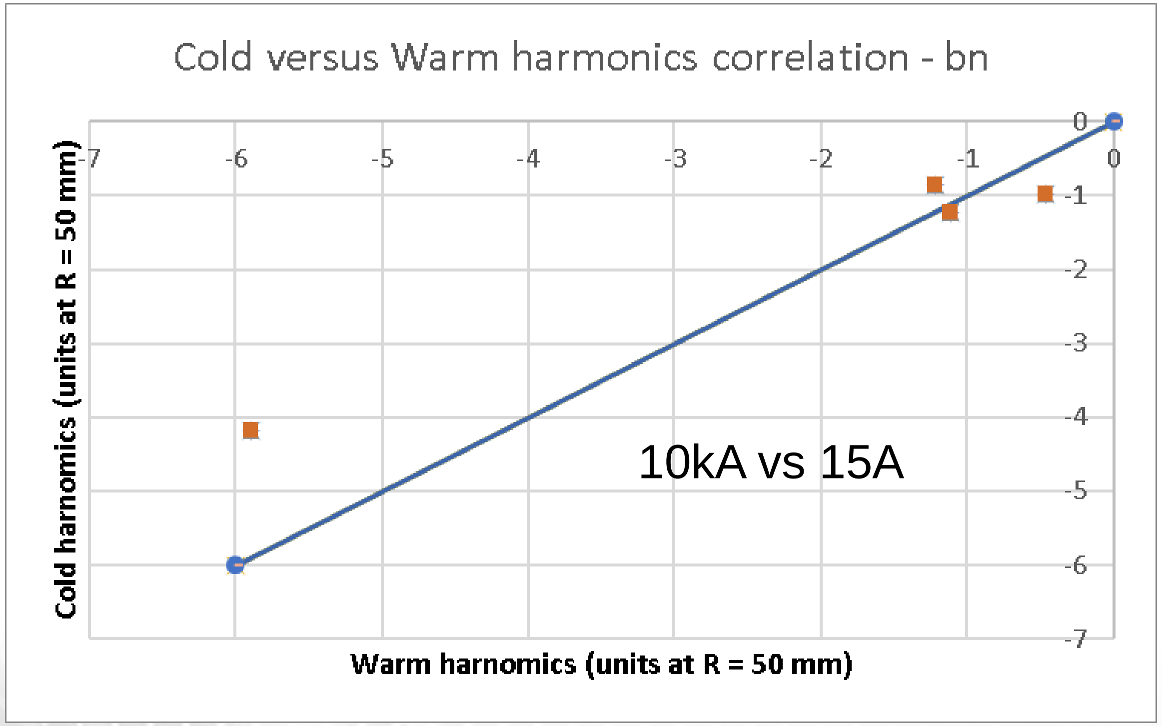


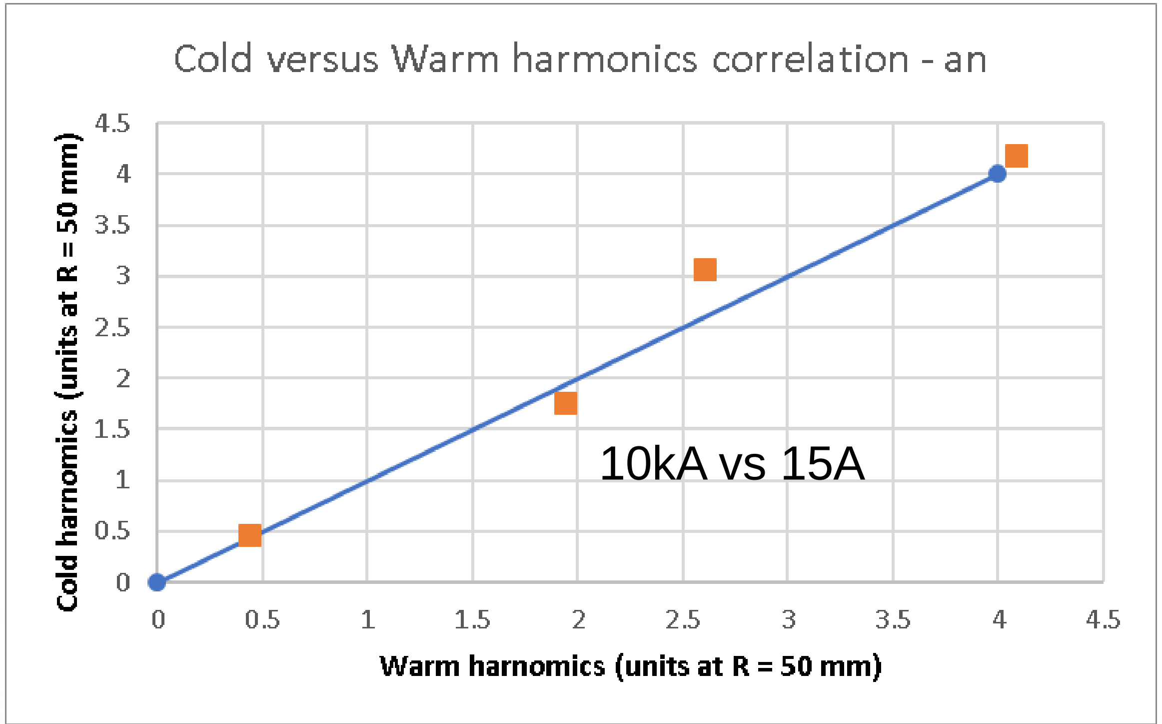
- Allowed b6
- Good agreement between Probe 220 and 110 data.

Straight-Section Averaged Field and r.m.s. - Probe 220
Cold and Warm Harmonics Correlation

	b3		b4		b5		b6	
Current	mean	rms	mean	rms	mean	rms	Mean	Rms
15A	-1.23	1.96	-1.12	1.25	-0.46	0.95	**-5.90**	1.12
960A	-0.92	2.02	-0.91	1.30	-1.38	1.02	-17.03	1.28
6kA	-0.67	2.07	-1.11	1.28	-1.12	1.06	-7.37	1.28
10kA	-0.87	2.09	-1.25	1.33	-0.99	1.06	-4.18	1.26

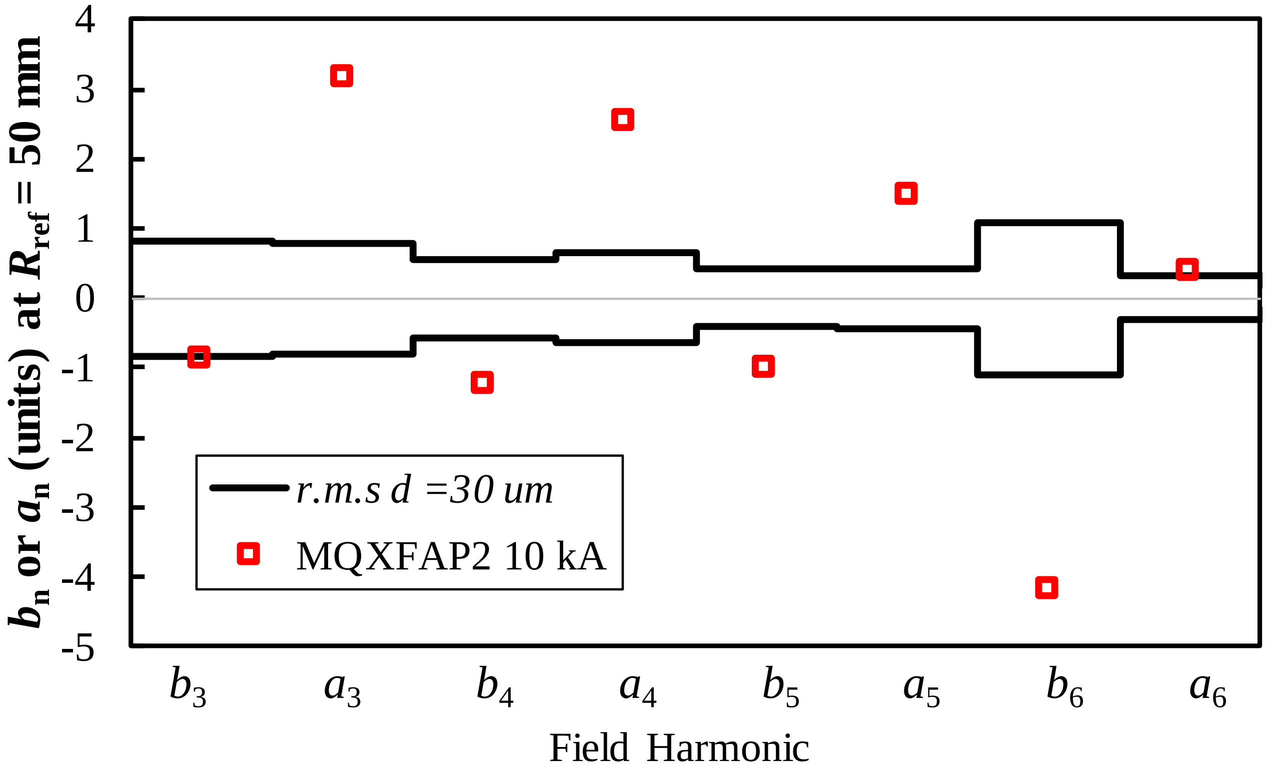
	a3		a4		a5		a6	
Current	mean	rms	mean	rms	mean	rms	mean	rms
15A	4.10	1.77	2.61	1.69	1.94	0.78	0.45	0.49
960A	4.19	1.77	3.07	1.83	1.75	0.82	0.47	0.49
6kA	2.79	1.82	2.24	1.96	1.35	0.83	0.40	0.52
10kA	3.17	1.85	2.54	1.95	1.48	0.85	0.40	0.52





Averaged harmonics in straight section (-1915<z<1642mm)(values)

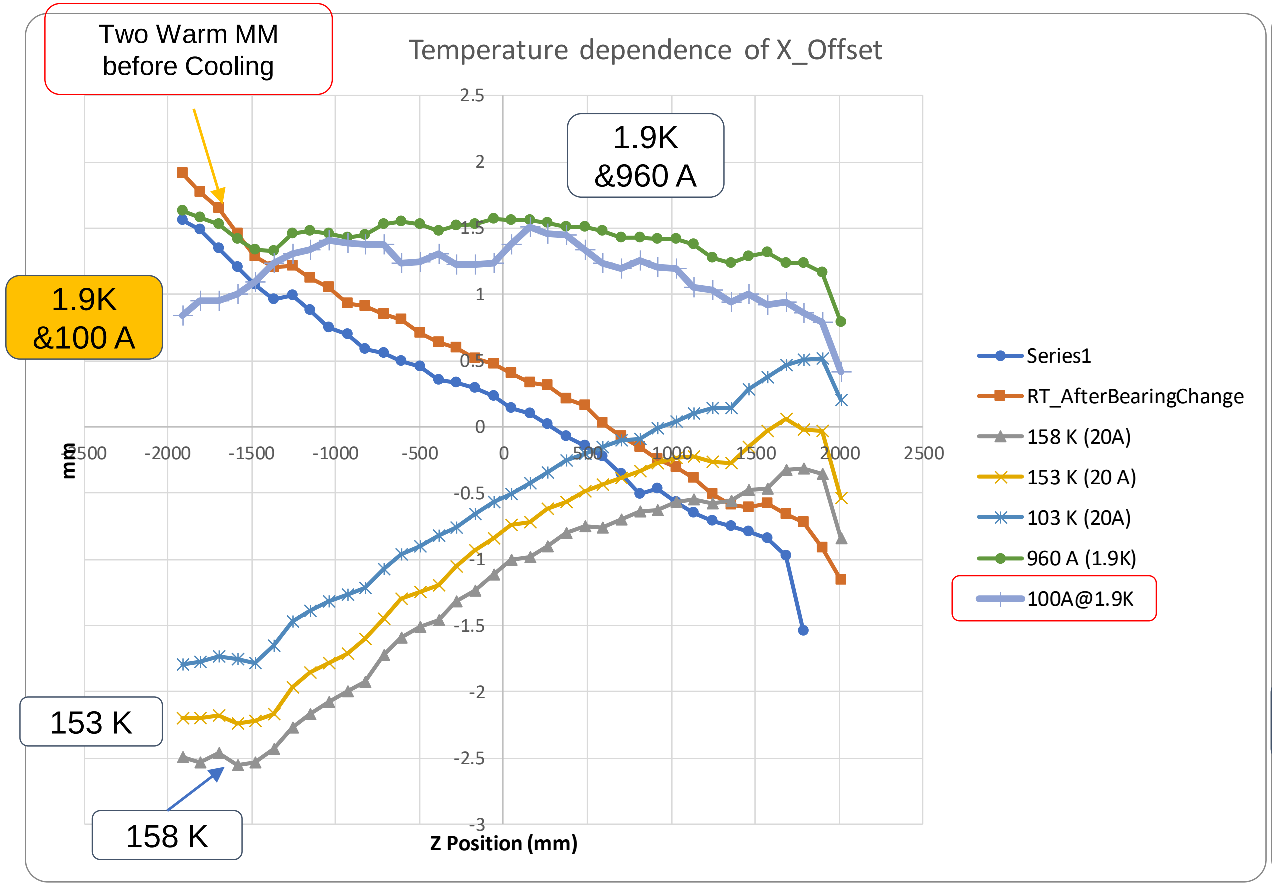
Measured harmonics vs requirement

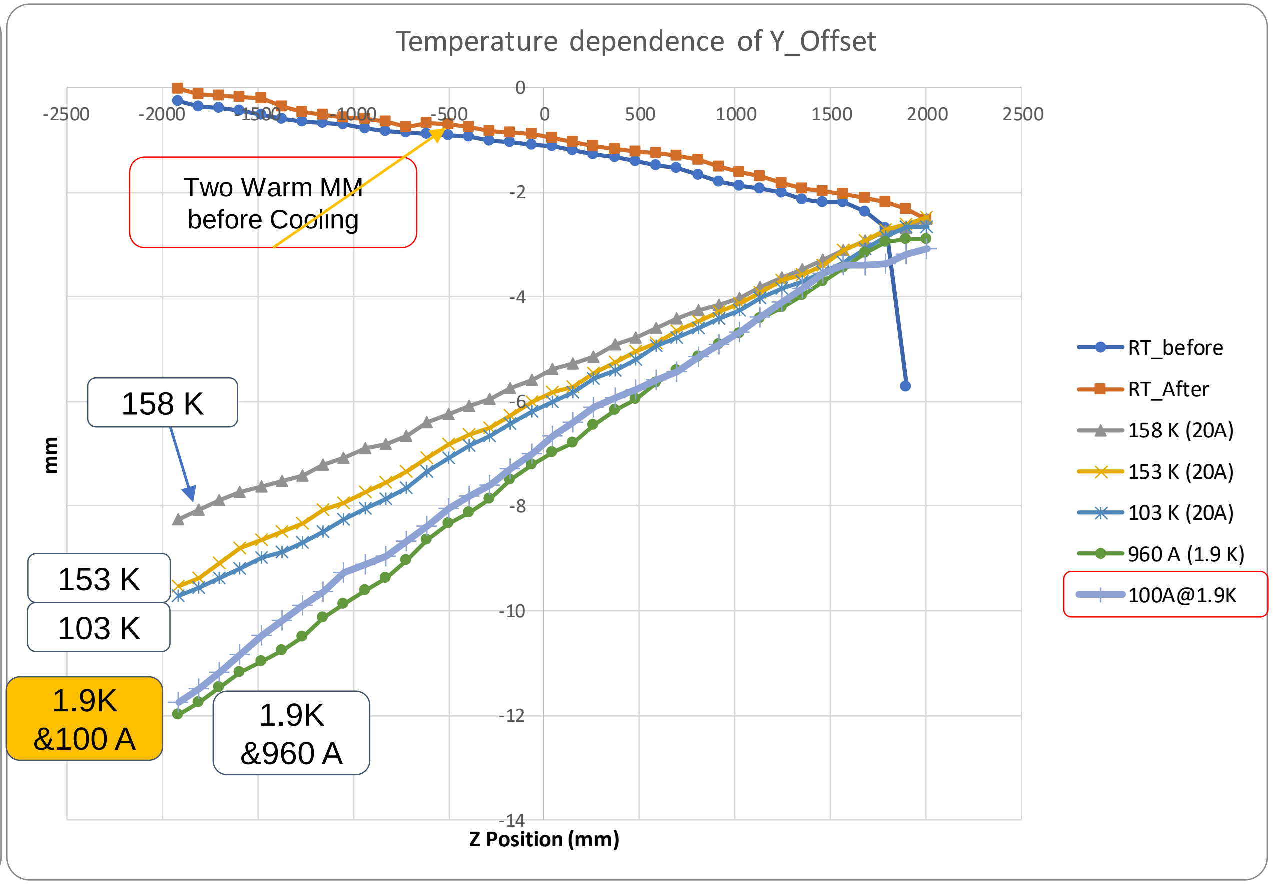


Normal harmonics at high field of 10 kA compared to expected field quality requirements (as determined from achievable 30 μm fabrication tolerances).

A decision has been recently made and shall be implemented for the future magnets through a change of 0.125 mm shims in the pole and in the midplane.

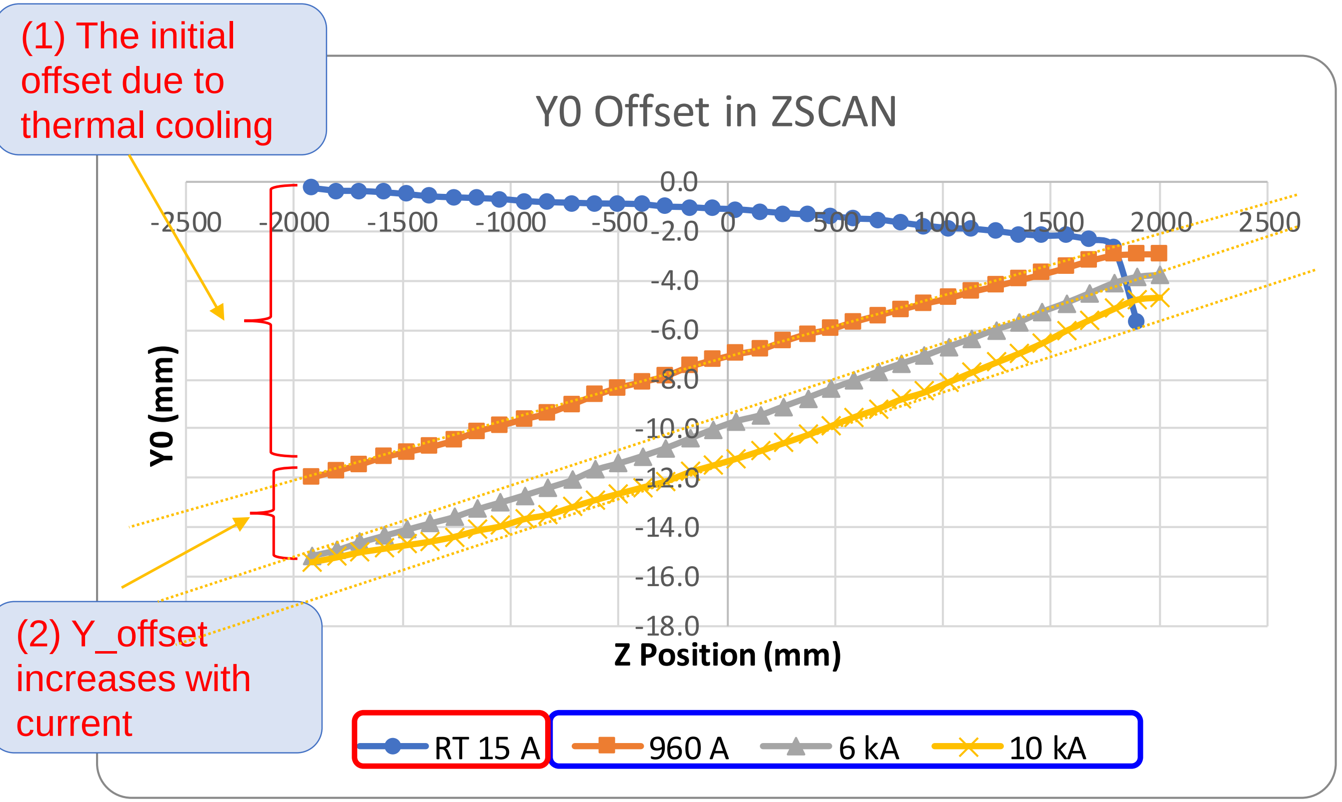
MQXFAP2 Center offsets – dipole centering

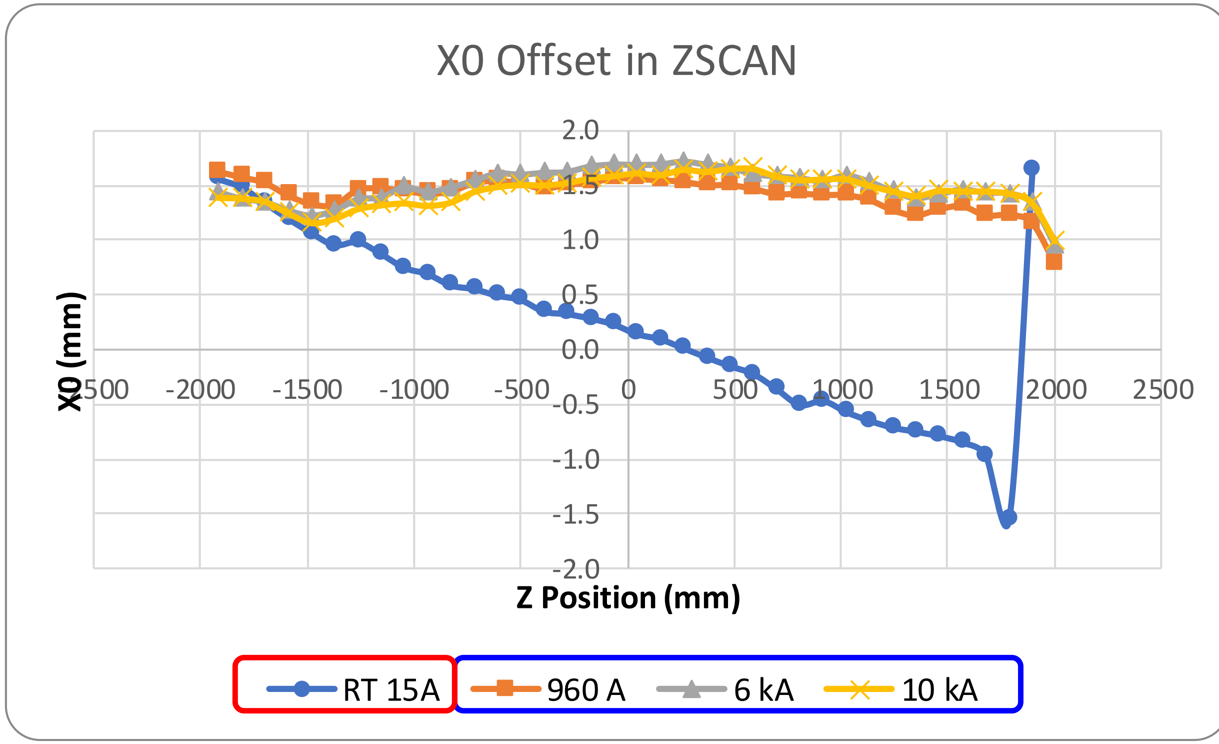




- Y_offset (up to -12 mm) is more significant than X_offset (1-2 mm) only during thermal cooling.
- Small currents (15A - 100A) does not change Y_offset much – thermal shrinkage is primary cause.

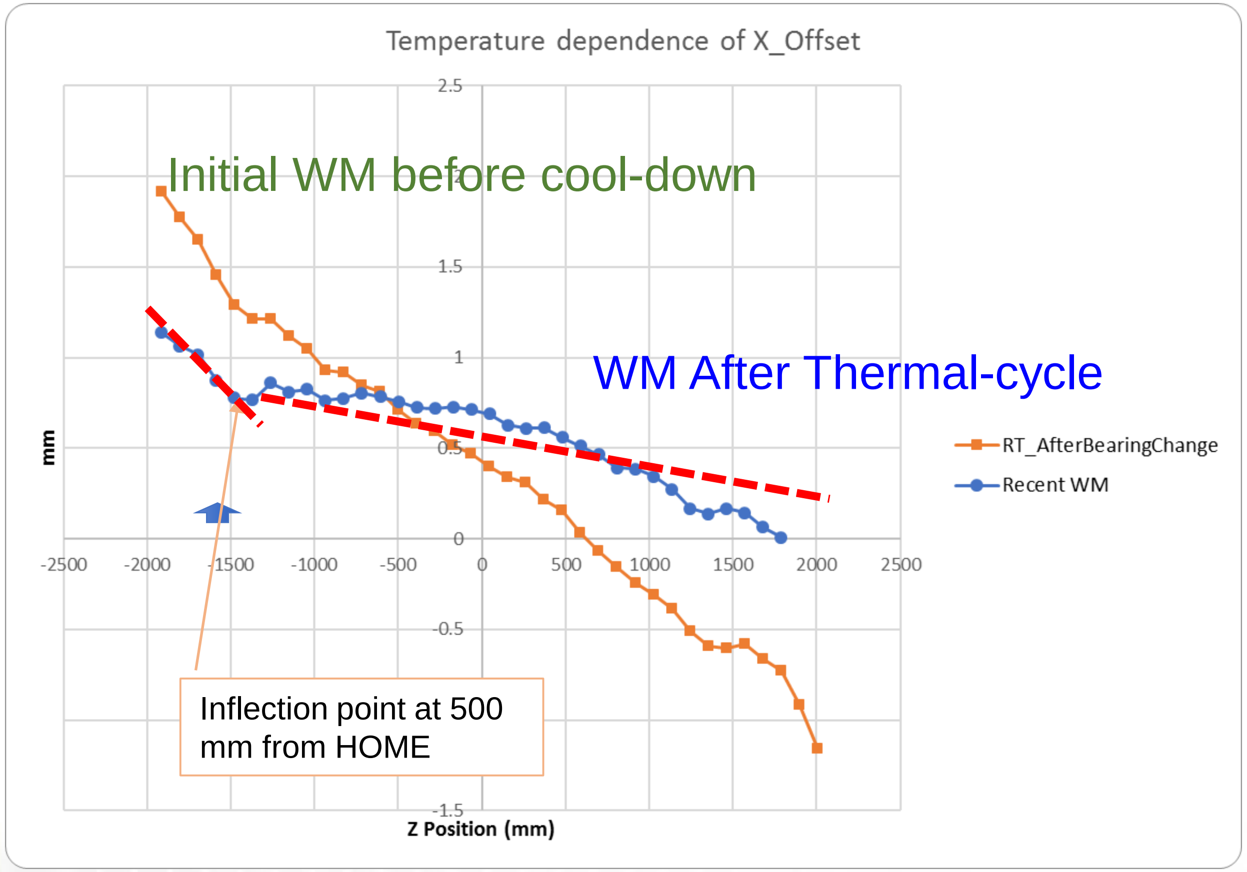
Found Offset (~15mm) between Magnet Center and Probe Center

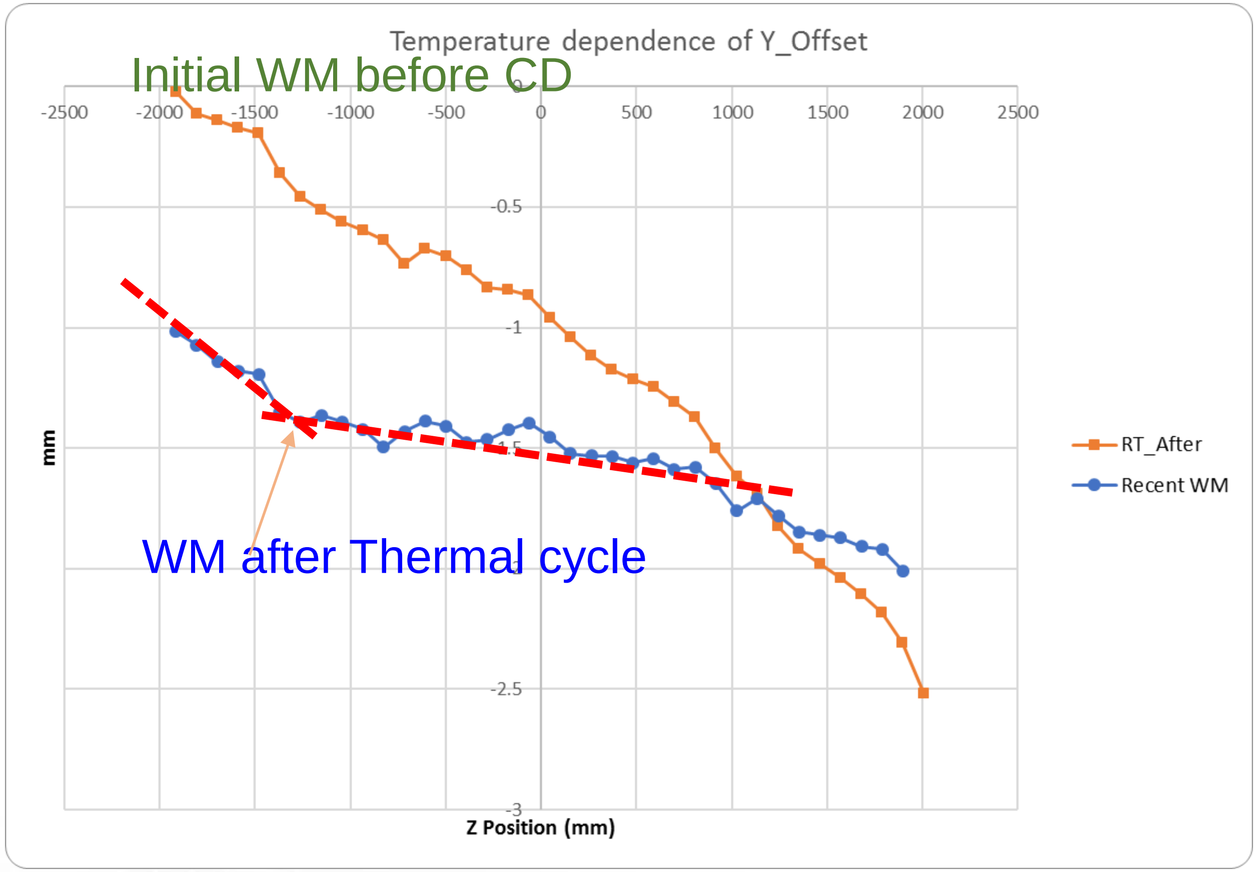




- ZSCAN at 960 A, the inflection in X_offset is more observable than Y_offset
- At higher current of 6 kA, the Y_offset(Z) line becomes nonlinear at around Z = 1750 mm from HOME
- At 10 kA, the Y_offset(Z) becomes more curved, and the inflection point is Z = 1750 mm from HOME

Warm MM before and after the cool-down
- Measured Center Offsets (X and Y) – Probe 220

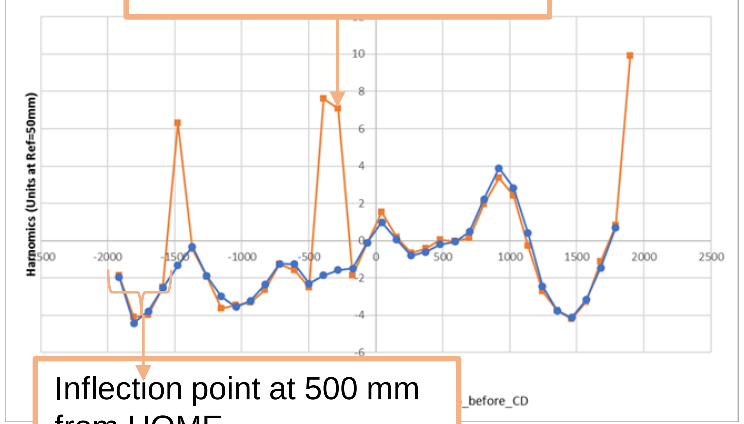




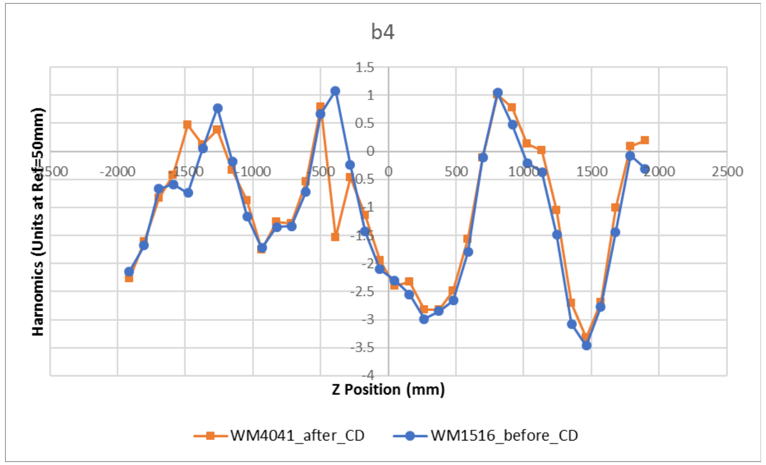
First observed by M. Anerella, P. Wanderer, H. Song

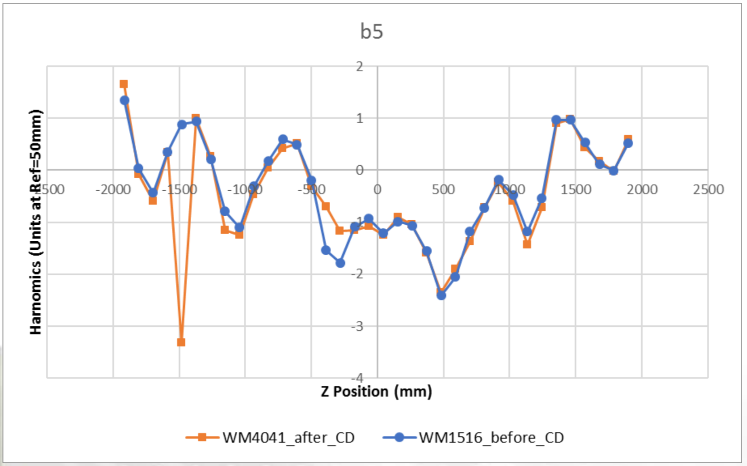
Harmonics bn Analysis (two WM comparison before and after the cooling

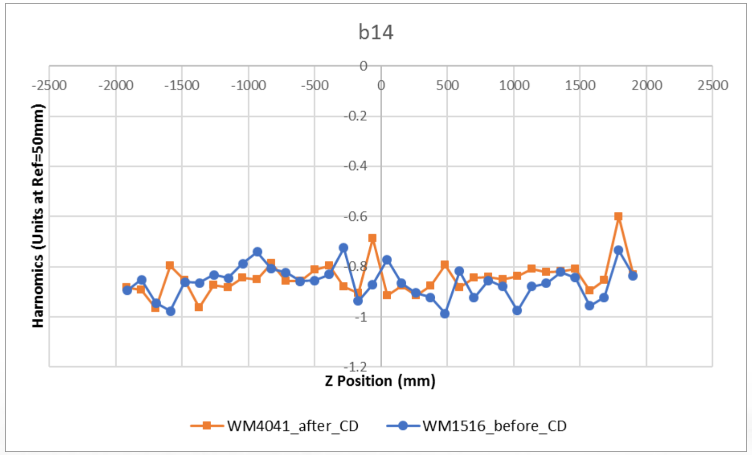
Inflection point at 1750 mm from HOME

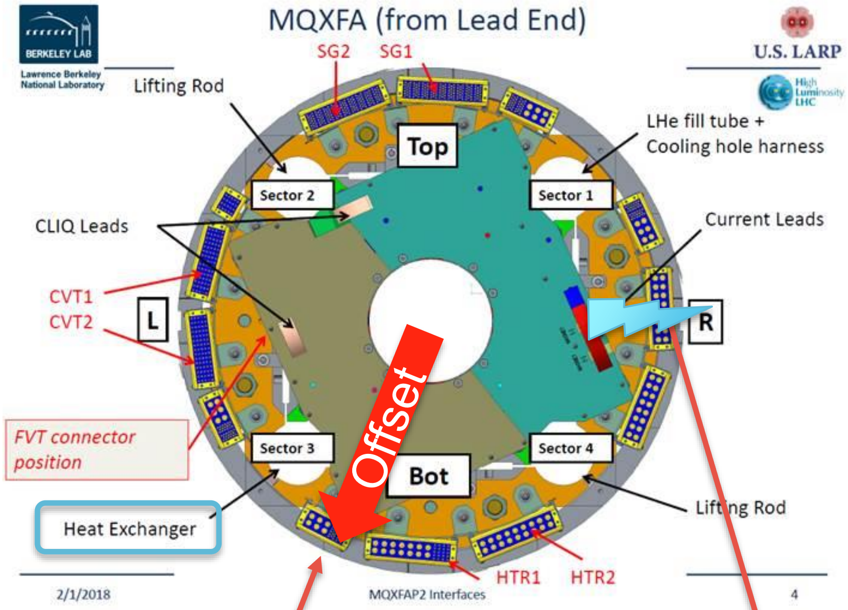


Inflection point at 500 mm from HOME



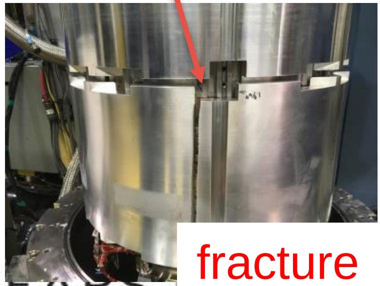






Courtesy D. Cheng

The offset vector is pointing at 7 o'clock



fracture

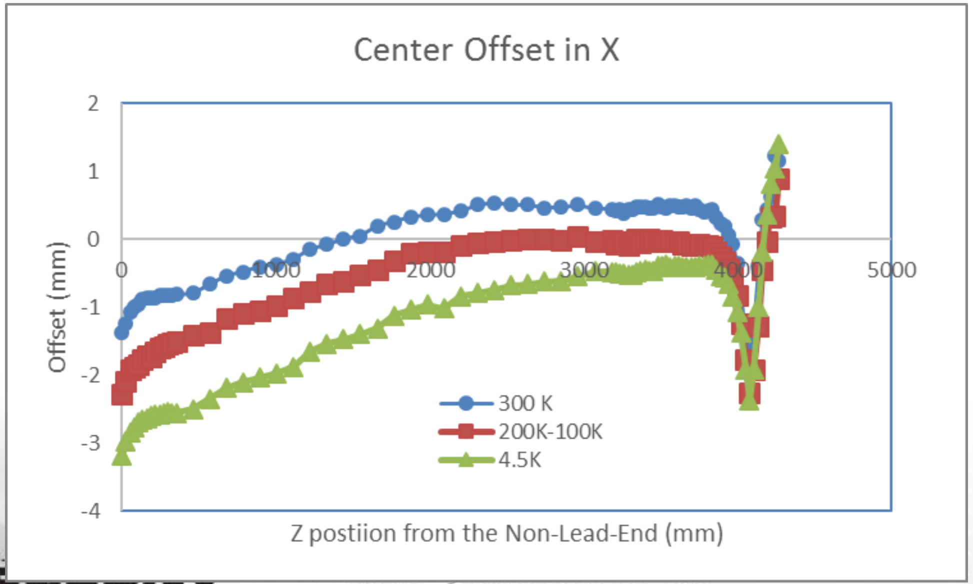
MQXF 1b magnet

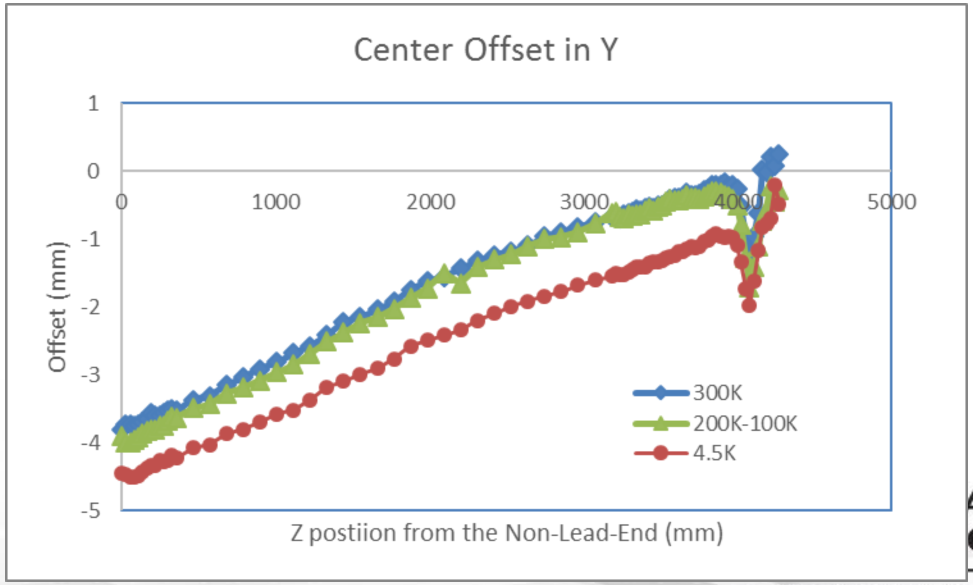
April 20
Saturday
Morning

Getting ready
For Magnetic Field
Measurement

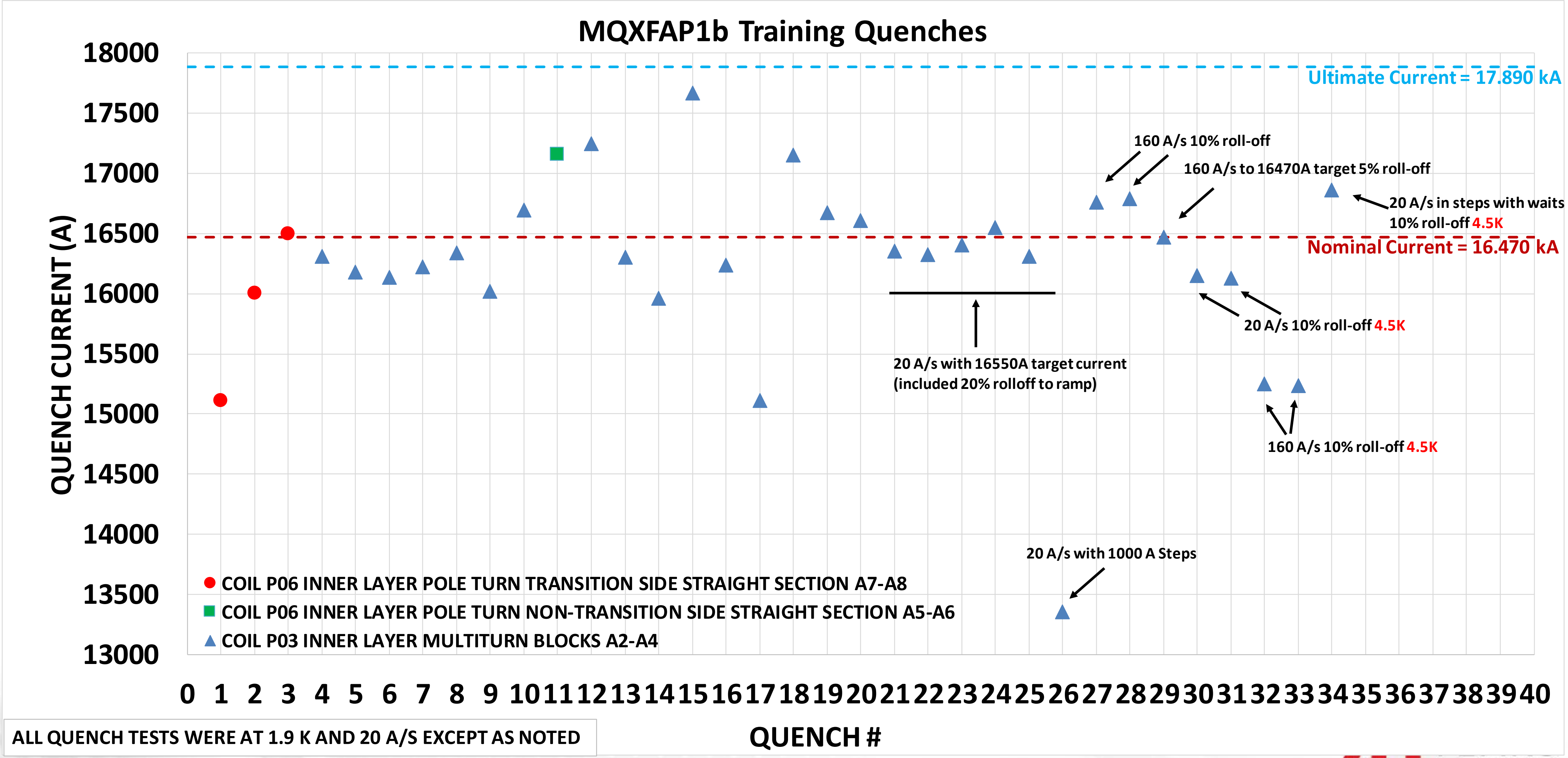
Magnetic Field Measurement

- Three sets of measurement have been completed
  - Room temperature, +/- 15A, April 20,
  - T_lead = 200K, T_non-lead = 100 K, April 21
    - Observed by P Joshi – the wrap wire for Aluminum crack detection – broken
    - Emergency call on Sunday, Asked to check the magnetic field center offsets
    - Strain gauges data was analyzed in parallel
  - T = 4.2 K , April 22 – no large offsets measured – unlikely any crack.





On-going Quench Training on MQXF AP1b



Measurement - ongoing

First ZSCAN at 16500 A achieved yesterday!
More measurements to come….

index	zpos	current	ramprate	wait	
1	1915.71	100	14	60	measure
2	1915.71	105	14	60	measure
3	1915.71	110	14	60	measure
4	1915.71	979	14	1000	measure
5	1915.71	1520	14	60	measure
6	1915.71	2022	14	60	measure
7	1915.71	2524	14	60	measure
8	1915.71	3026	14	60	measure
9	1915.71	4029	14	60	measure
10	1915.71	5033	14	60	measure
11	1915.71	6036	14	60	measure
12	1915.71	7040	14	60	measure
13	1915.71	8043	14	60	measure
14					
15					
16	1915.71	9047	14	60	measure
17	1915.71	8043	14	60	measure
18	1915.71	7040	14	60	measure
19	1915.71	6036	14	60	measure
20	1915.71	5033	14	60	measure
21	1915.71	4029	14	60	measure
22	1915.71	3026	14	60	measure
23	1915.71	2524	14	60	measure
24	1915.71	2022	14	60	measure
25	1915.71	1520	14	60	measure
26	1915.71	979	14	60	measure
27	1915.71	0	14	60	EOF

ISCAN – DC Loops – Stair steps at Center

INDEX	ZPOS	CURRENT	RAMPRATE	WAITTime
1	0.000	15	1	10
2	27.185	15	1	10
3	54.370	15	1	10
4	81.555	15	1	10
5	108.740	15	1	10
6	135.925	15	1	10
7	163.110	15	1	10
8	190.295	15	1	10
9	217.480	15	1	10
10	244.665	15	1	10
11	271.850	15	1	10
12	299.035	15	1	10
13	326.220	15	1	10
14	353.405	15	1	10
15	462.145	15	1	10
16	570.885			
17	679.625			
18	788.365			
19	897.105			
20	1005.845			
21	1114.585			
22	1223.325	15	1	10
23	1332.065	15	1	10
24	1440.805	15	1	10
25	1549.545	15	1	10
26	1658.285	15	1	10
27	1767.025	15	1	10
28	1875.765	15	1	10
29	1984.505	15	1	10
30	2093.245	15	1	10
31	2201.985	15	1	10
32	2310.725	15	1	10
33	2419.465	15	1	10
34	2528.205	15	1	10
35	2636.945	15	1	10
36	2745.685	15	1	10
37	2854.425	15	1	10
38	2963.165	15	1	10
39	3071.905	15	1	10

ZSCAN
(1) Constant steps, 108 mm
(2) Finer steps at magnet ends.

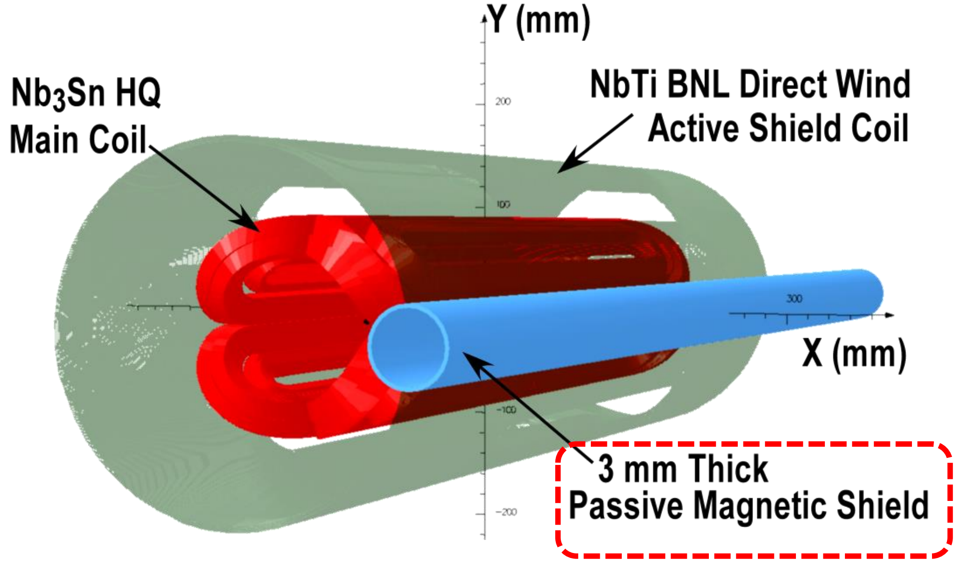
Summary

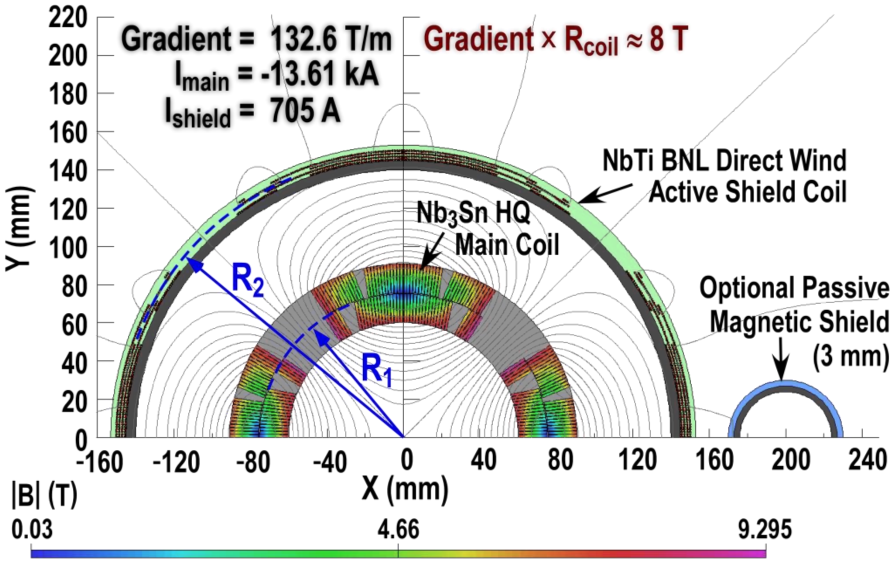
- High field Magnetic field measurement
  - Successfully upgraded existing magnetic field measurement system
  - Well positioned for future magnet testing of AUP MQXFAP magnets
  - Completed the MQXFAP2 magnet measurement last year
- Magnetic field measurement for diagnostics
  - Rotating coil – good diagnostics tool for magnet condition check
- Magnetic field measurement on MQXF AP1b is on-going

Thank You for Your Attention!

Recently awarded SBIR project with HyperTech on MgB2 tube passive shielding for EIC

eRHIC IR Quadrupoles R&D programs





Coil Field |B| T

Here 9.3 T at coil but few gauss at e-beam!

- To develop superconducting critical state modeling for MgB2 tube optimization

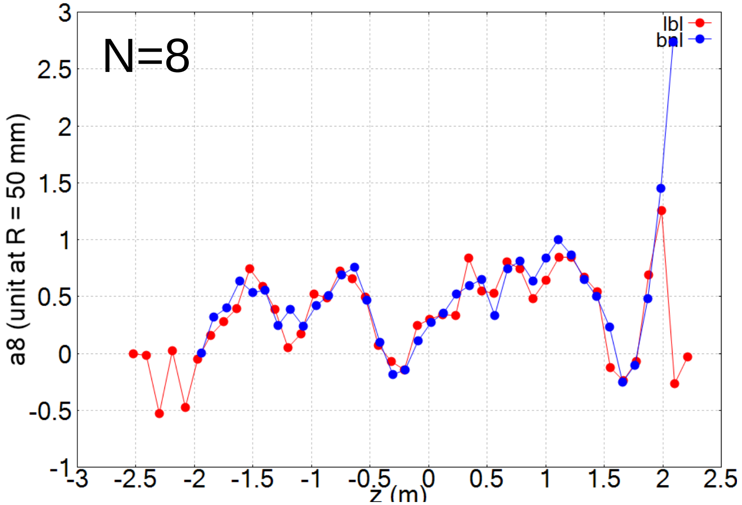
Magnetic Field Measurement in the Functional Specifications

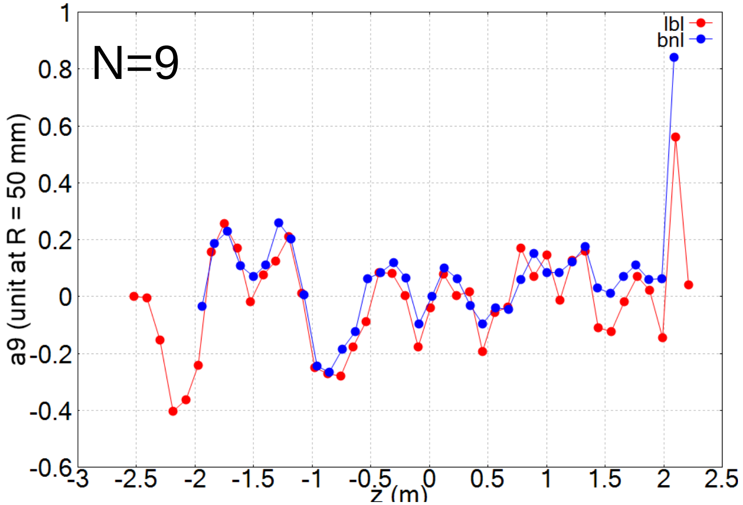
- R-T-03: The MQXFA magnet must be capable of operate at steady state providing a gradient of 143.2 T/m in superfluid helium at 1.9 K, when powered with current of 17.9 kA.
- R-T-04: The MQXFA magnetic length requirement is 4.2 m with a tolerance of ± 5 mm at 1.9 K.
- R-O-02: The MQXFA field harmonics must be optimized particularly at high field. Table 2 (next slide) provides expected values for field harmonics at a reference radius of 50 mm.

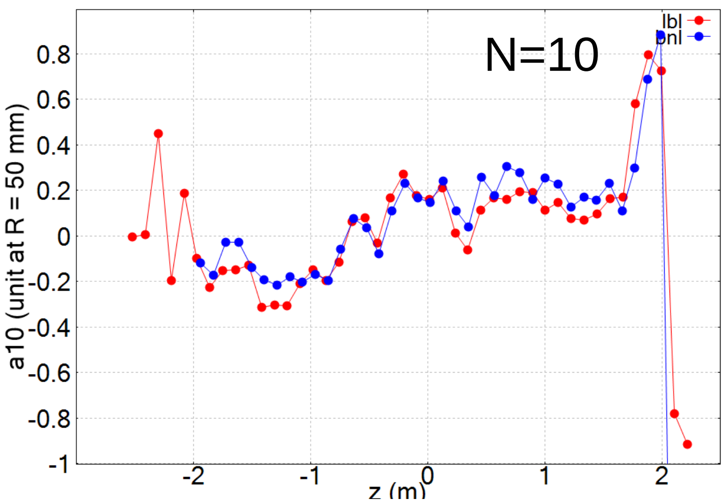
	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm															
	Straight part										Ends		Integral			
	Systematic						Uncertainty		Random				Q1/Q3		Q2a/b	
Normal	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	CS	NCS	Injection	High Field	Injection	High Field
2									10	10						
3	0.000	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420			0.000	0.000	0.000	0.000
6	-2.200	0.900	0.660	-20.000	-21.300	-0.640	1.100	1.100	1.100	1.100	8.943	-0.025	-16.692	0.323	-18.593	-0.075
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070			0.000	0.000	0.000	0.000
10	-0.110	0.000	0.000	4.000	3.890	-0.110	0.200	0.200	0.200	0.200	-0.189	-0.821	3.119	-0.175	3.437	-0.148
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009			0.000	0.000	0.000	0.000
14	-0.790	0.000	-0.080	1.000	0.210	-0.870	0.023	0.023	0.023	0.023	-0.545	-1.083	0.033	-0.856	0.106	-0.862
Skew																
2									10.000	10.000	-31.342		-2.985	-2.985	-1.753	-1.753
3	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430			0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310	2.209		0.210	0.210	0.124	0.124
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080			0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040	0.065		0.006	0.006	0.004	0.004
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010			0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	-0.222		-0.021	-0.021	-0.012	-0.012
	Magnetic length straight part				Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends		0.400	0.341				

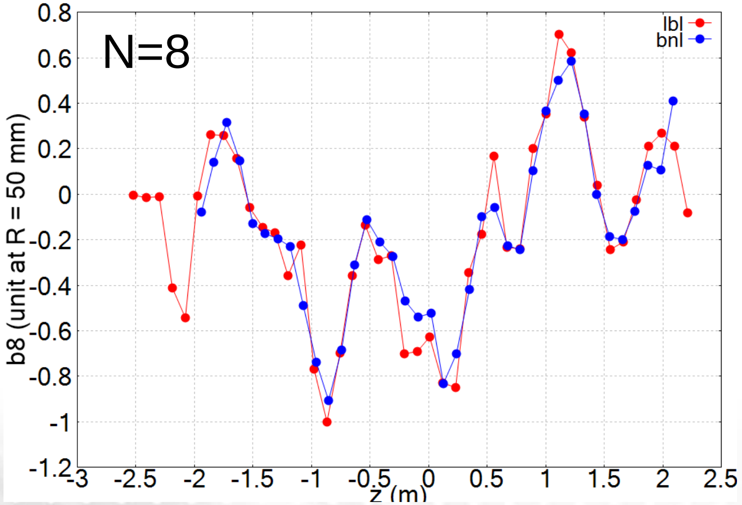
Field Quality Reference Table
in "Functional Requirements Specification" Document

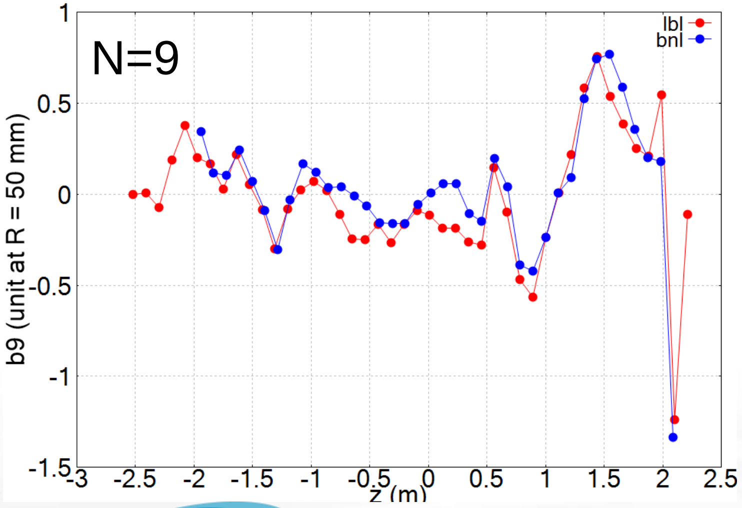
Warm Measurement of MQXFAP2, Averaged +/-15 A
- BNL (10/15) vs LBNL Data (6/15) – continued

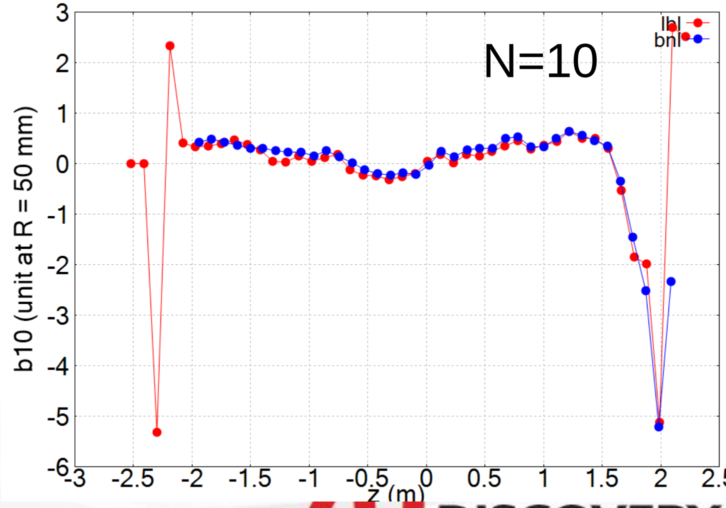












Warm Measurement of MQXFAP2, Averaged +/-15 A - BNL (10/15) vs LBNL Data (6/15) – continued