MQXFAP1b Alignment and Field Quality

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Magnetic Measurements during Assembly

MQXFAP1b Magnet geometry and fabrication:

- Shorter magnetic length (4 m)
- Three previously used first-generation coils
- One new coil made with shorter length but incorporating many new features
  - See coil P06 review information at https://indico.fnal.gov/event/19381/
  - Mid-plane/pole shim for b6 correction still not implemented

Magnetic measurement system and plan

- Measurements performed for coil pack and after complete assembly
  - MQXFAP2: drive system was not complete for coil pack measurement, and splice box was not completed for "final" measurement
- New power supply (more stable, better controls, capability to switch polarity)
- Field harmonics as a function of longitudinal position
  - Including a detailed scan of the ends
- Magnetic axis vs. longitudinal position relative to external fiducials
- Relative change in the field orientation vs. longitudinal position
  - Including a scan step allowing to overlap the positions of the two probes mounted on the PCB

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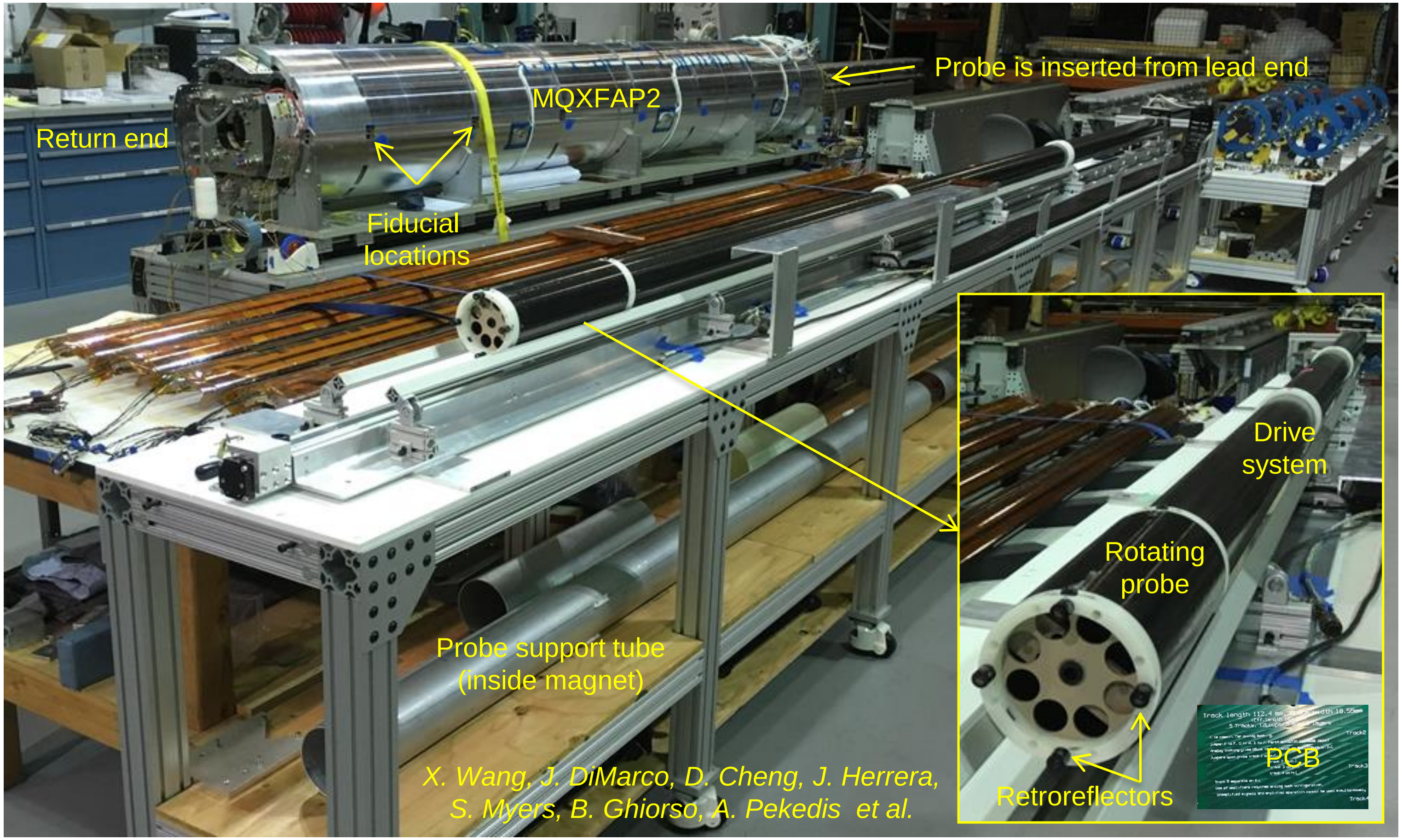
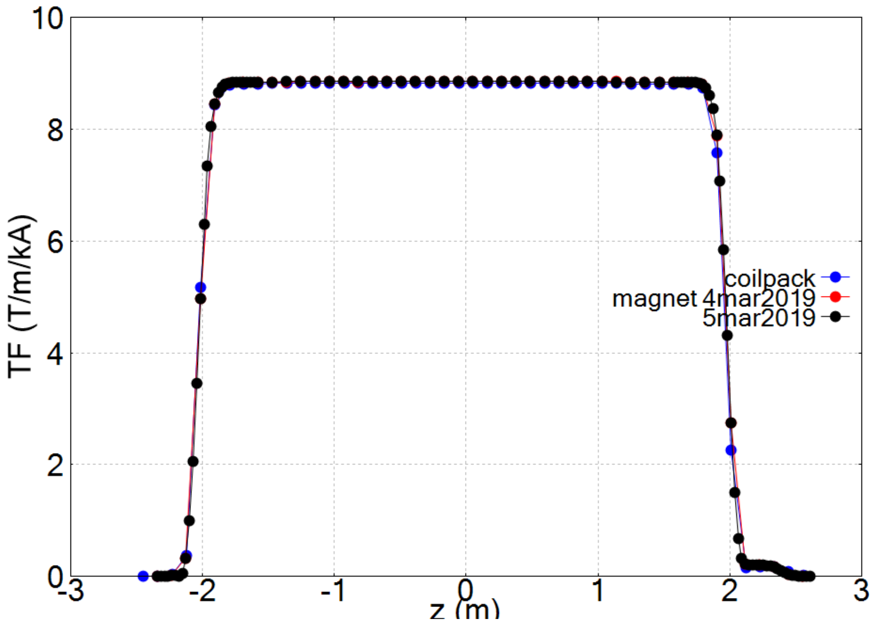
Magnetic Measurement System at LBNL

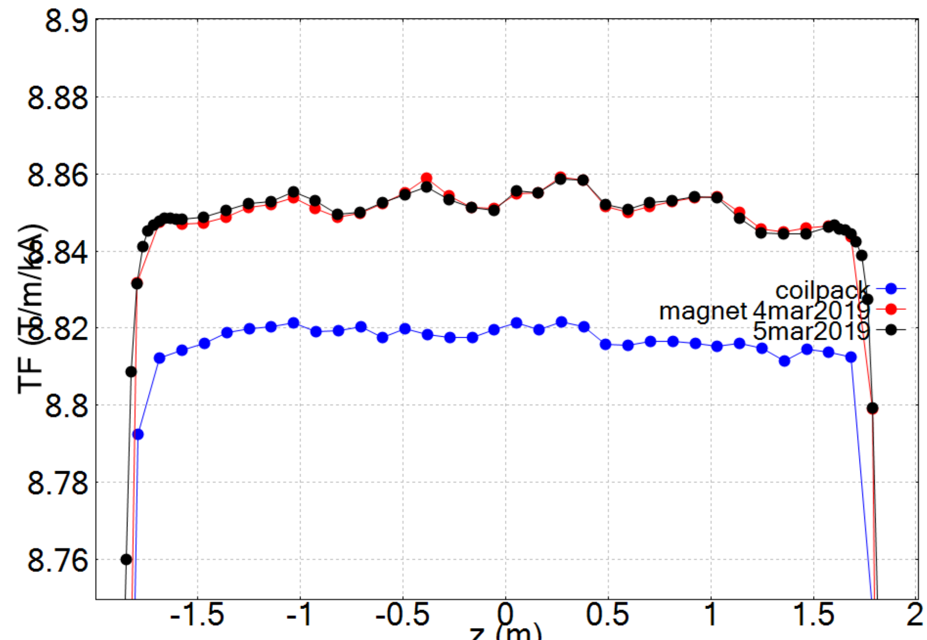


Rotating probe includes two identical PCBs from FNAL with 108.74 mm effective length and 59.5 mm radius

Longitudinal scan: Transfer Function

- TF increases by 0.4% from coil pack to final assembly
  - Effect of loading (iron pads are already present in coil pack measurement)
- Scan length is sufficient to cover both ends – however this is a shorter magnet, may need some improvement for full length magnet





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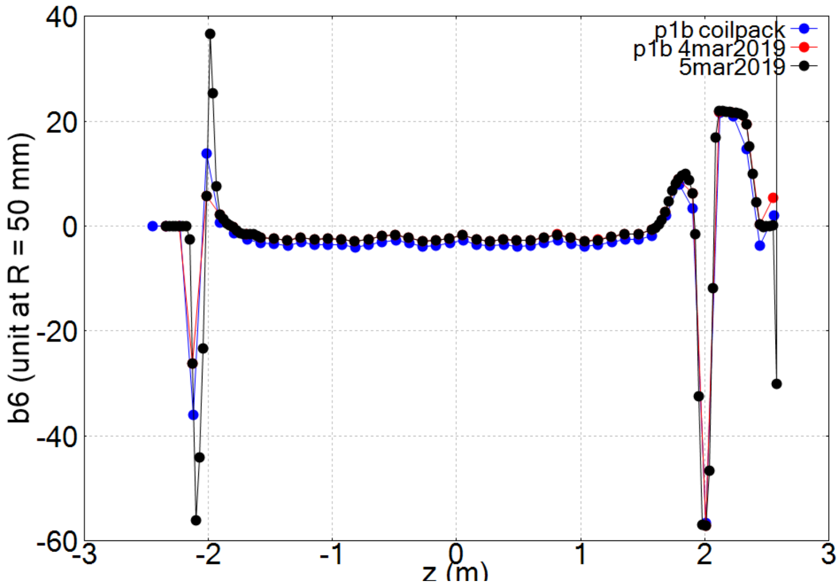
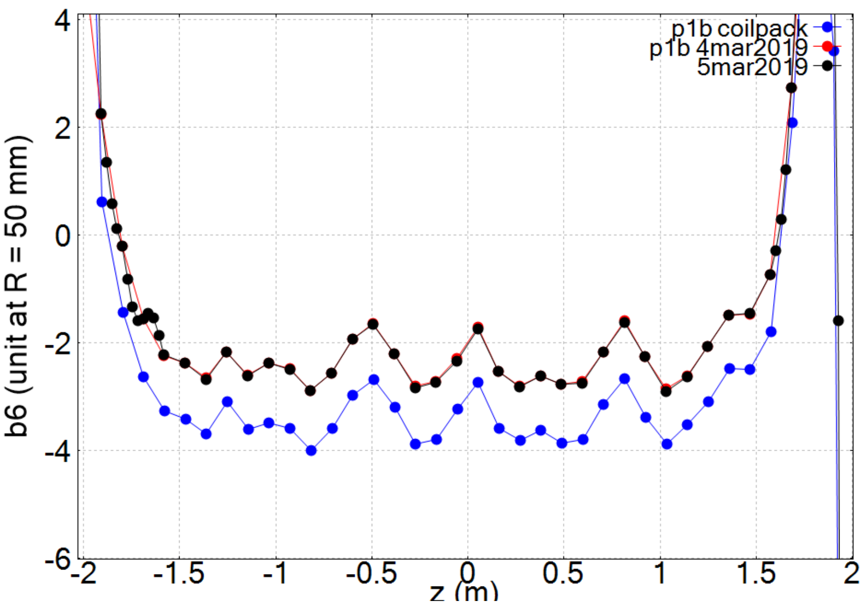
Longitudinal Scan: b6

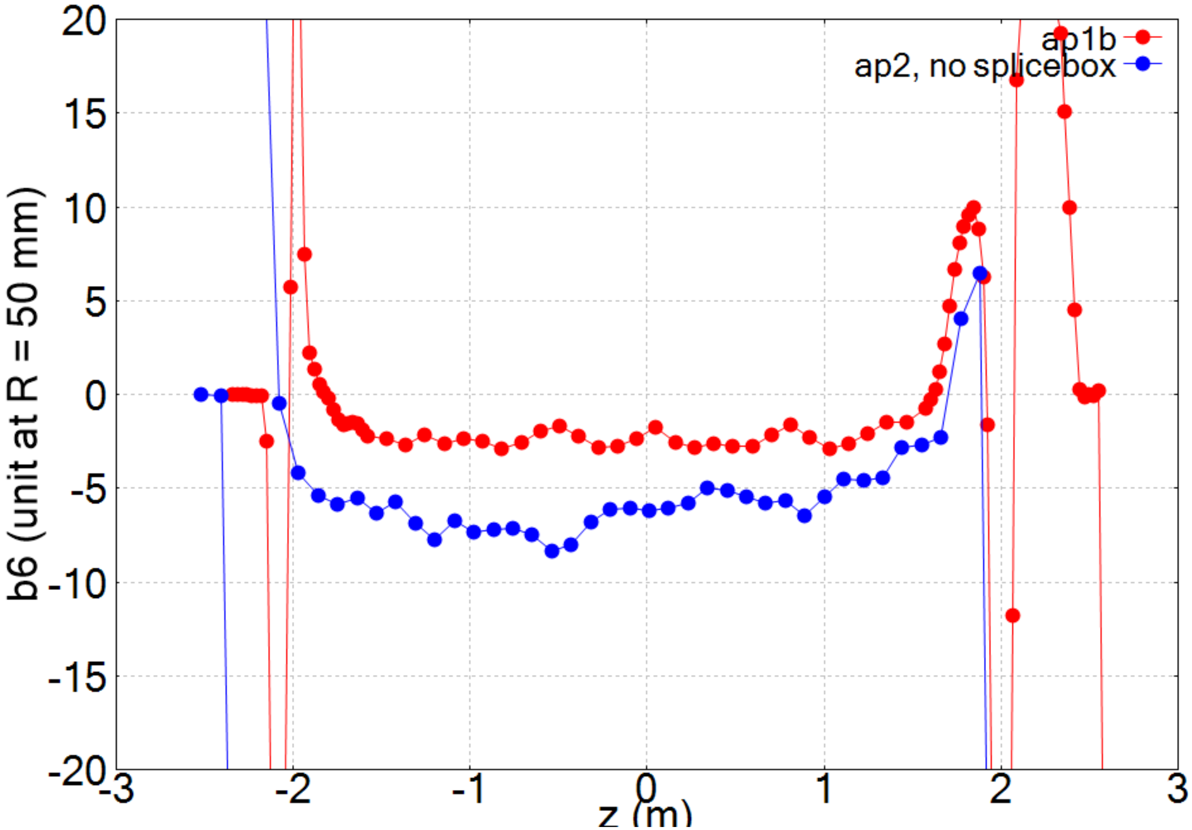
- b6 is around -2 units in the straight section (about 5 units smaller than AP2)
- Also much more stable along the length (about +/- 1 unit)
- Change of about 1 unit (-3 to -2) from coil pack to final.
- Fine (1/4) scan of magnet ends allows to accurately capture the peaks
- Useful to compare with models and for longitudinal reference
- Will be repeated in vertical test





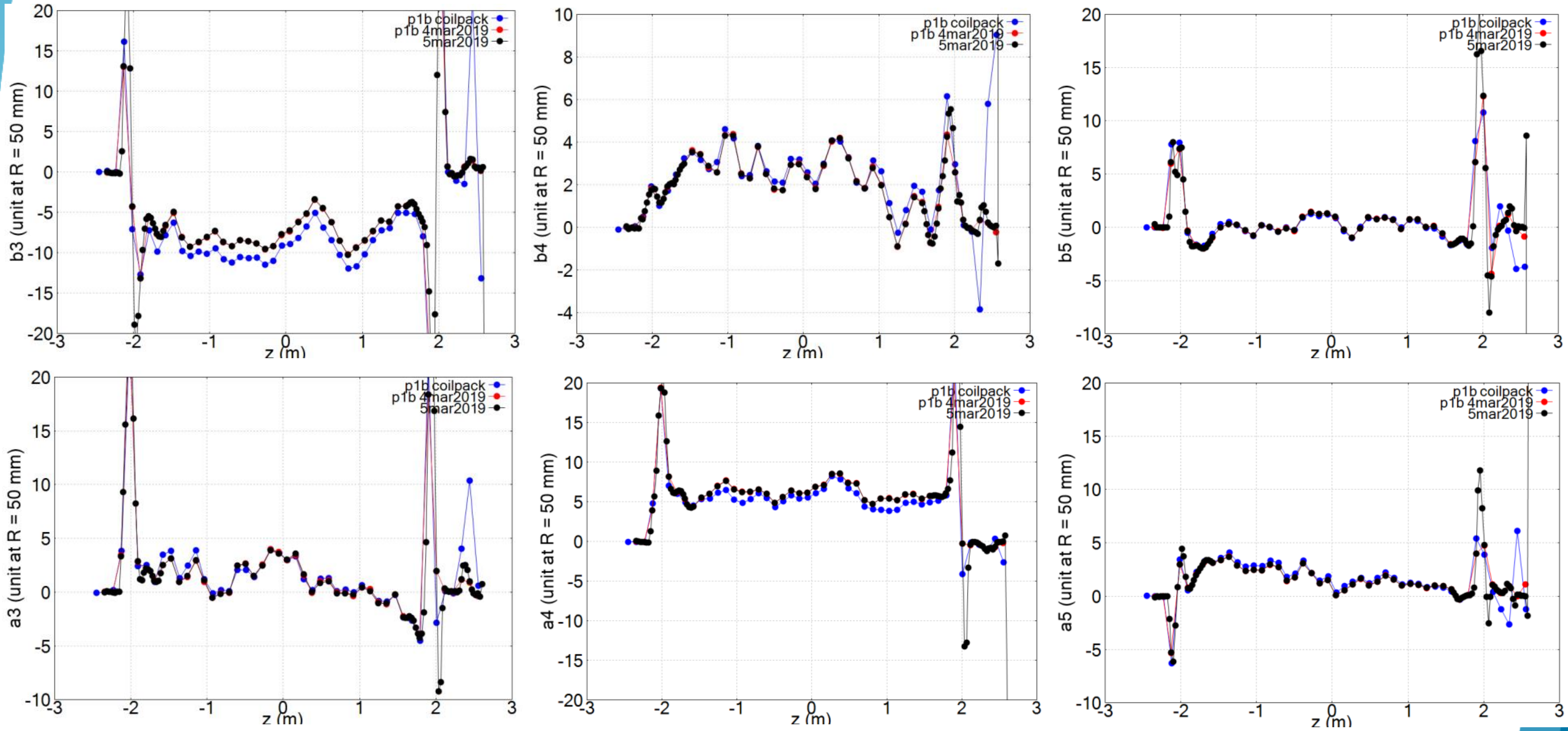
Comparison of MQXFAP1b and MQXFAP2

- b6 is smaller and more stable along the length

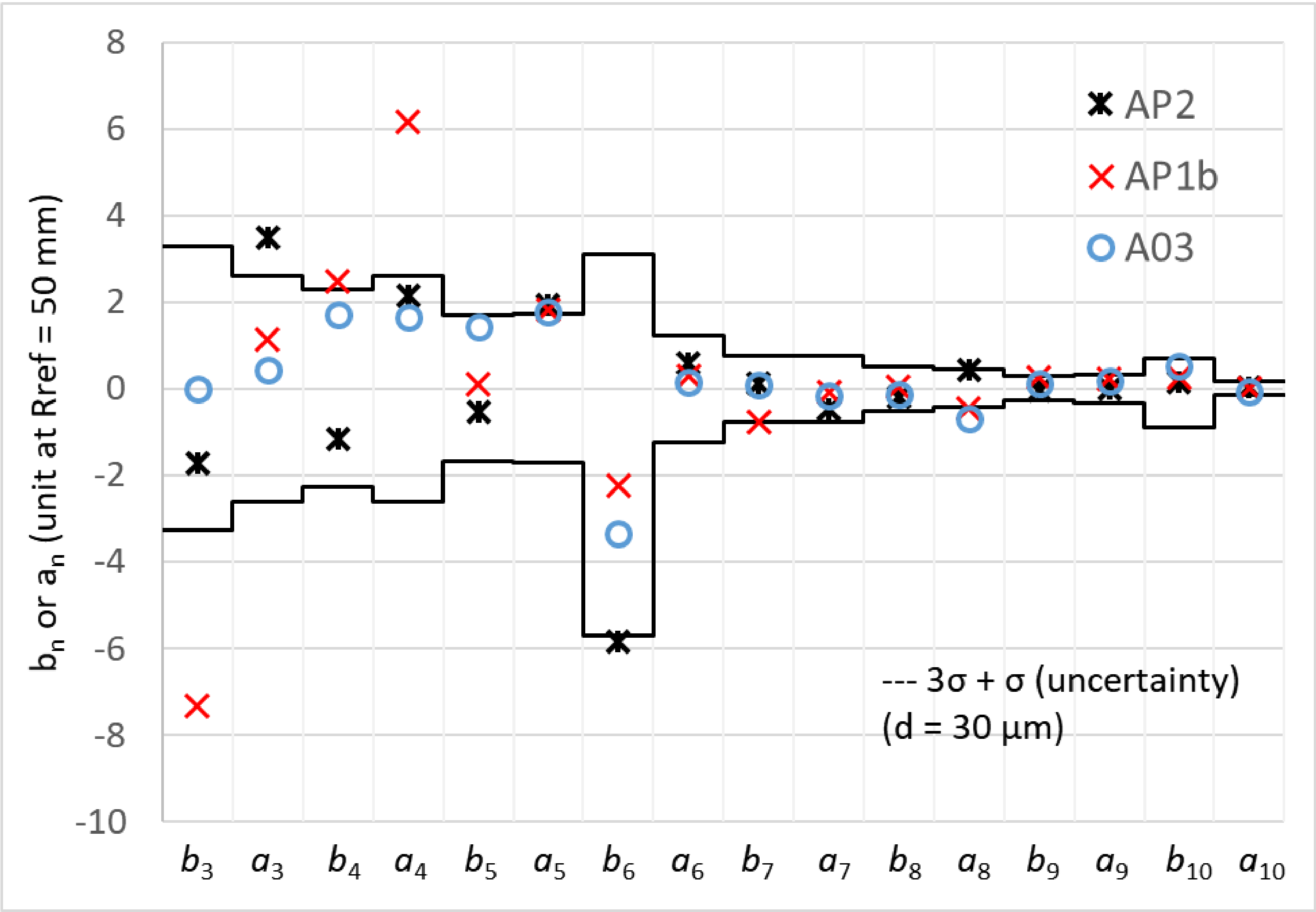


Longitudinal scan – other harmonics

- Change of 2 units of b3 from coil pack to final. All other harmonics do not change significantly
- Comparatively large a5



Comparison of harmonics after assembly



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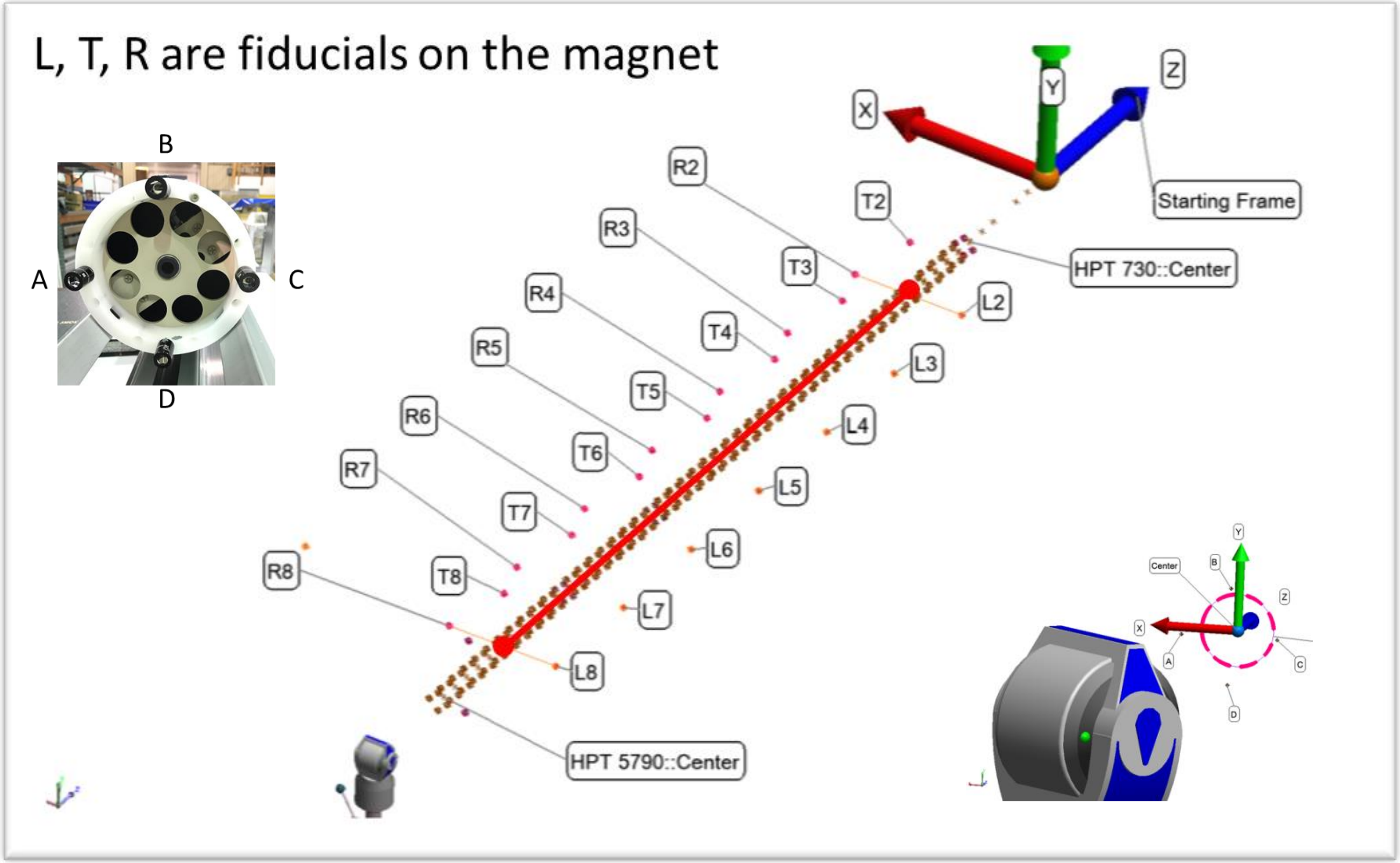
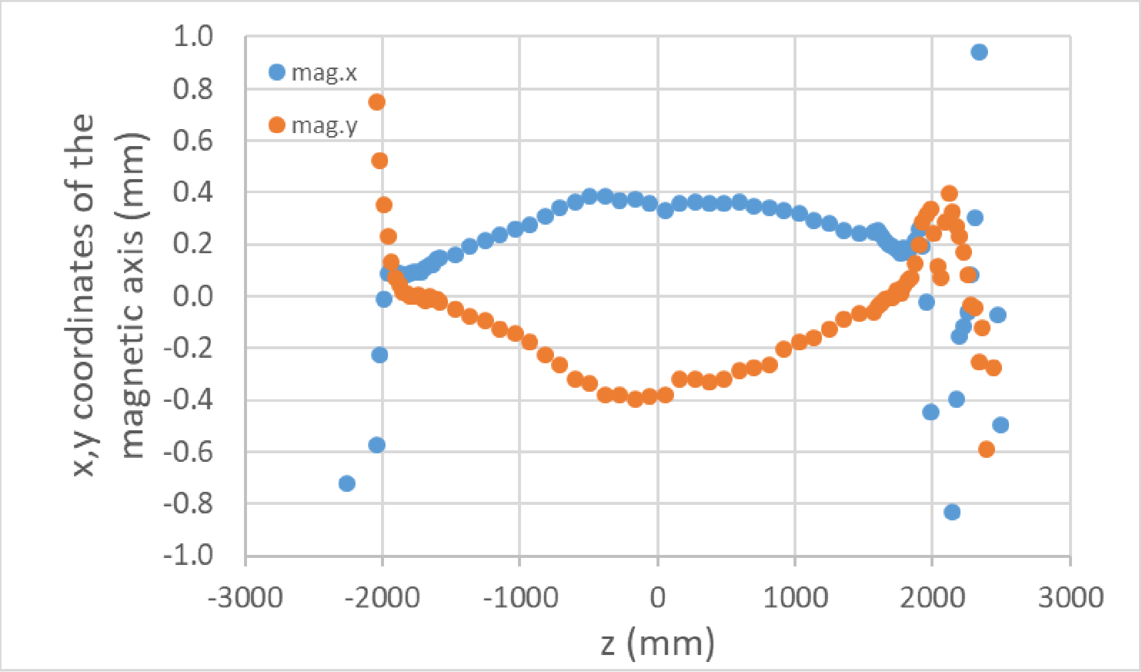
Reference axis and probe position survey



Survey performed by Chris Hernikl, Hongyan Zhu, Dan Ellis, and Federico Carrara (Survey & Alignment Group, Engineering Division)

Magnetic Axis

Magnetic center relative to reference axis



- The magnetic axis will be defined as the best fit, independently for x and y
- Variations of magnetic center relative to best fit are within +/- 0.2 mm (straight section)
- Requirement is +/- 0.5 mm
- Additional benefit from integration length (0.5 m)

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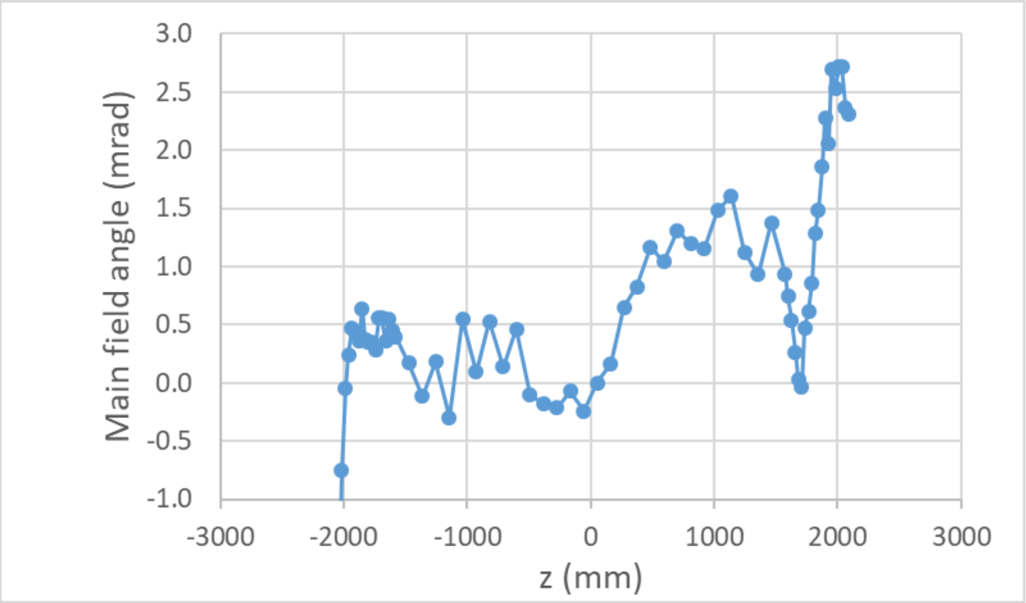
Magnetic Field Angle

Magnetic field angle along the magnet length



- Magnet angle can be adjusted for best fit
- Variations of magnetic field angle relative to best fit are within +/- 1 mrad
- Requirement is +/- 2 mrad
- Ends are excluded
- Additional benefit from integration length (0.5 m)

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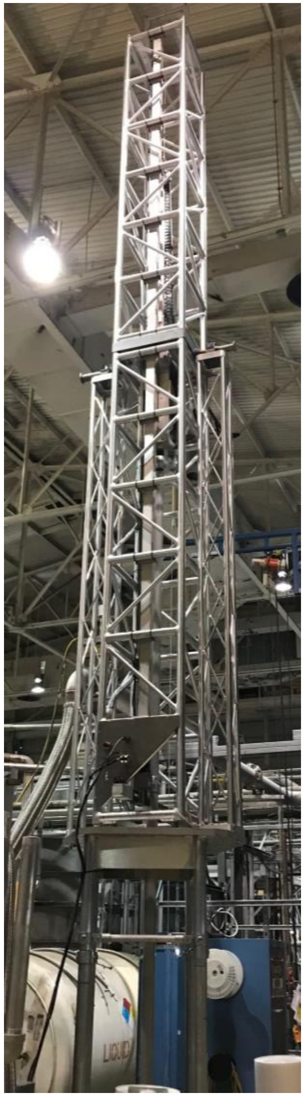
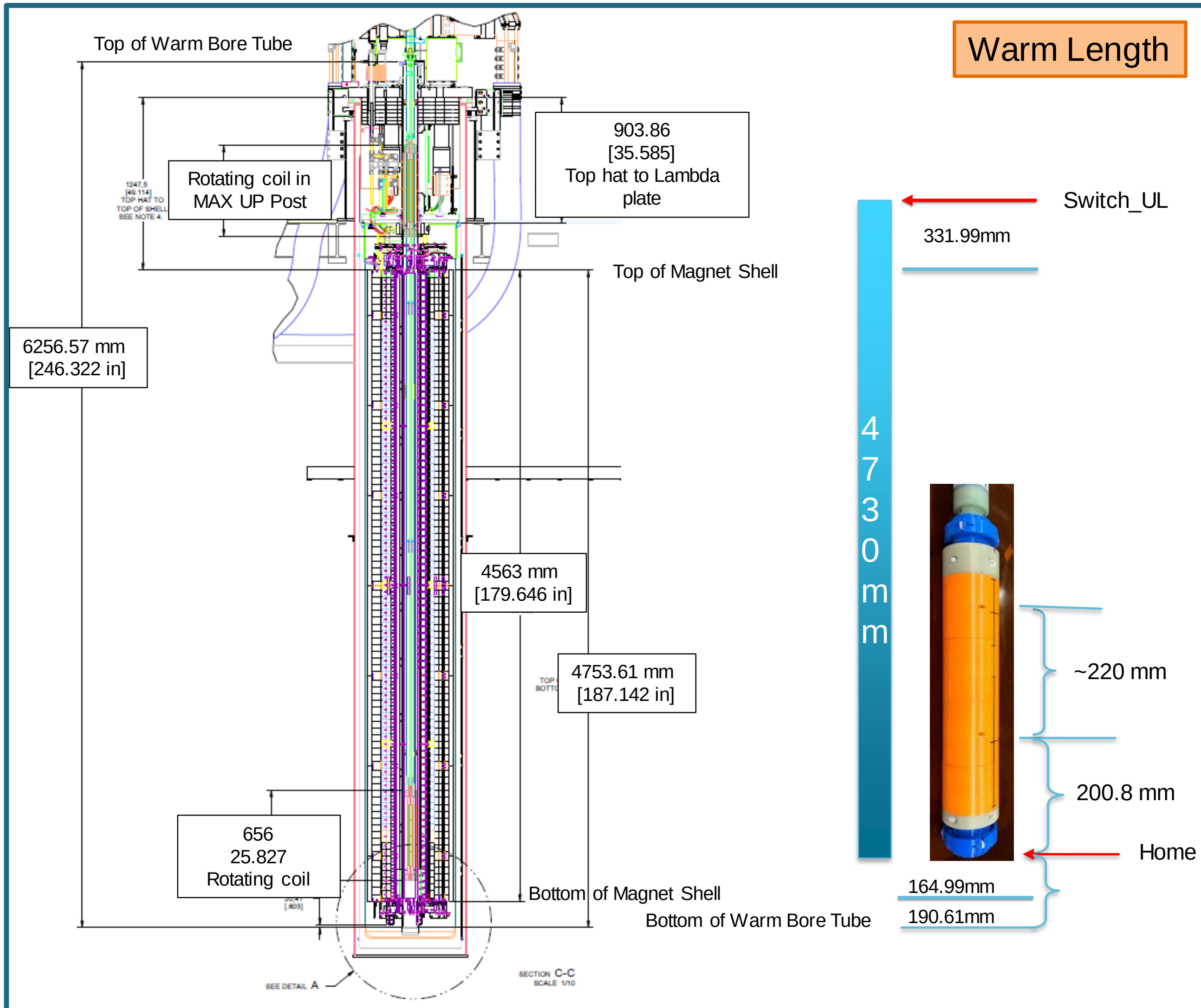
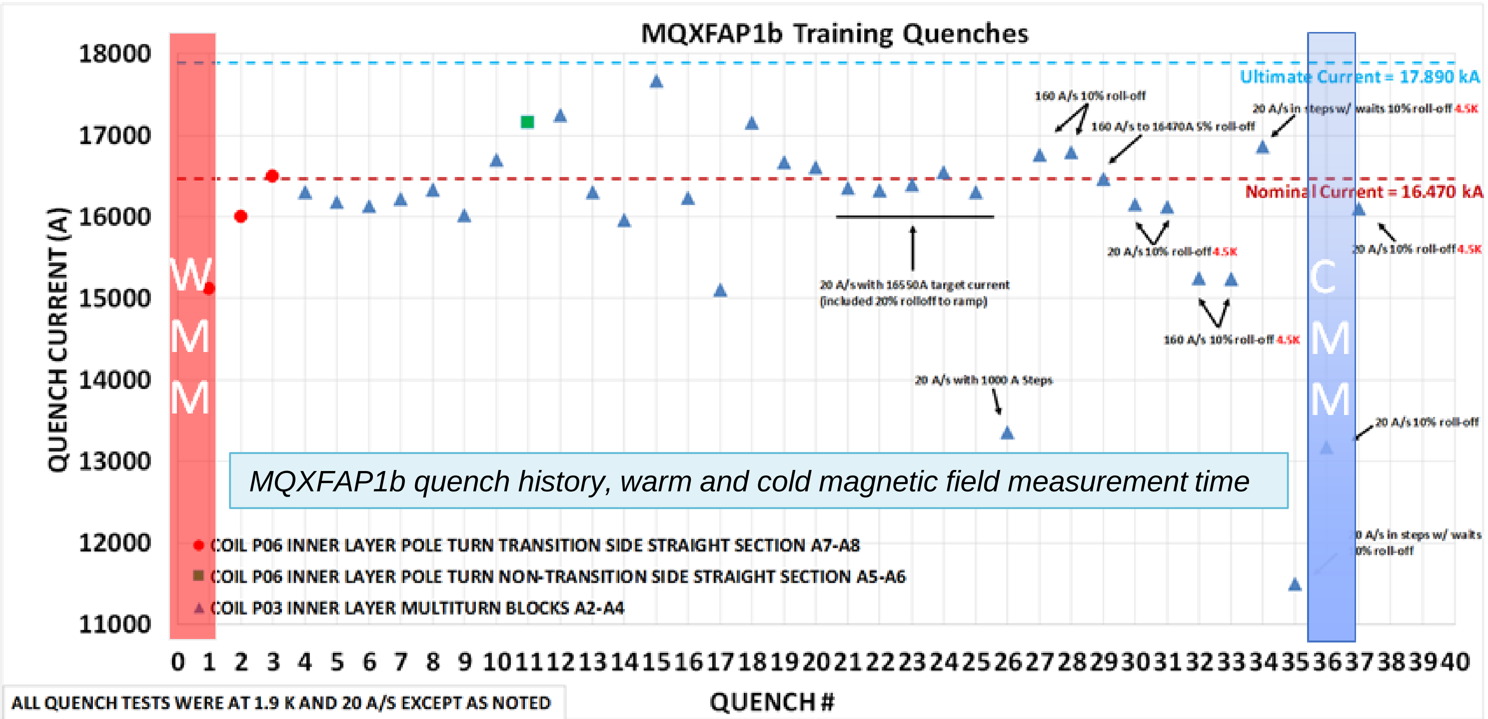
Magnetic Measurements System at BNL



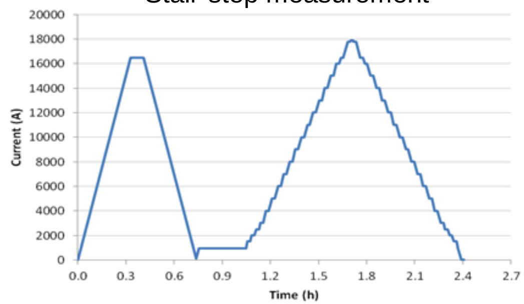


Magnetic Measurements during Vertical Test



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

Stair-step measurement



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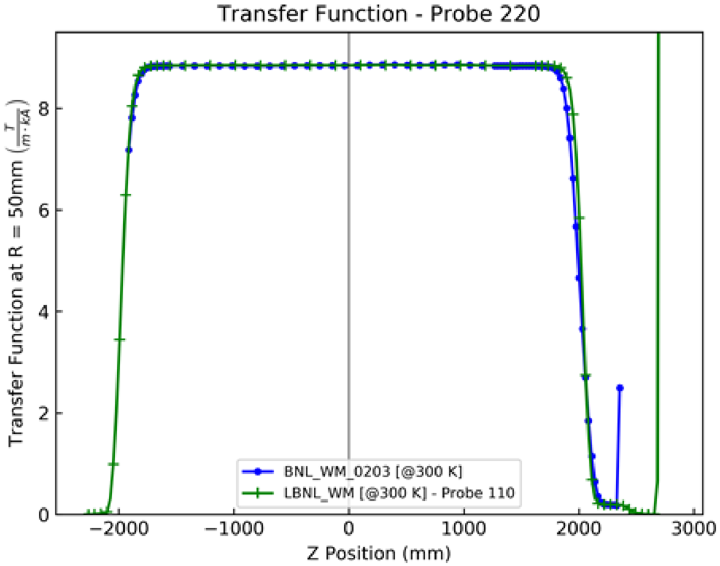
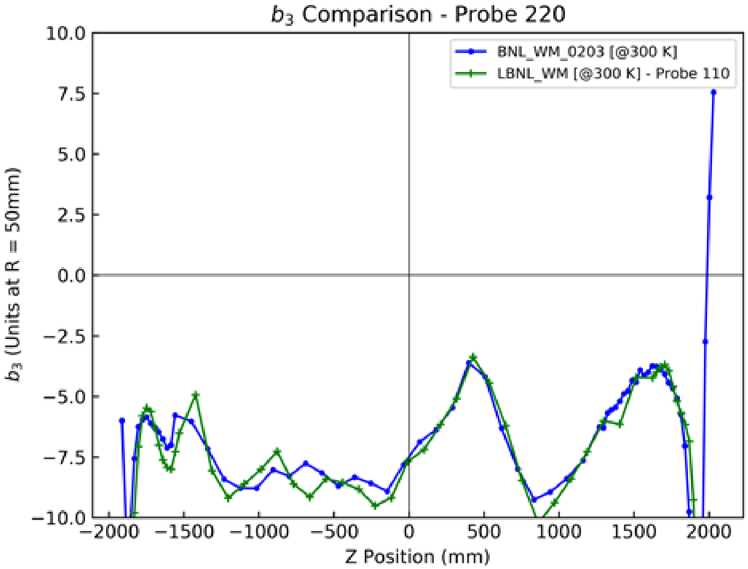
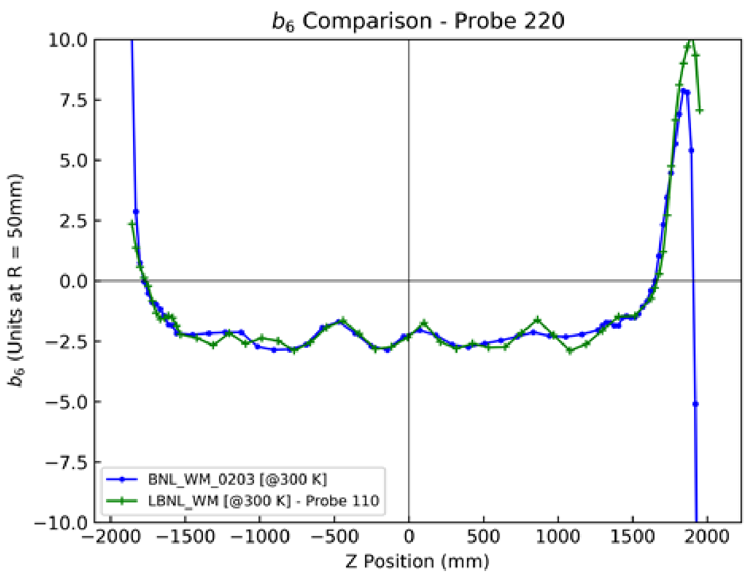
Warm Measurements during Vertical Test





- Comparison between warm measurements during assembly at LBNL and prior to vertical test at BNL are generally in good agreement
- No indications of changes during shipping, small differences are mainly due to different probe length
- New identical 440 mm probes from FNAL are under fabrication for future tests



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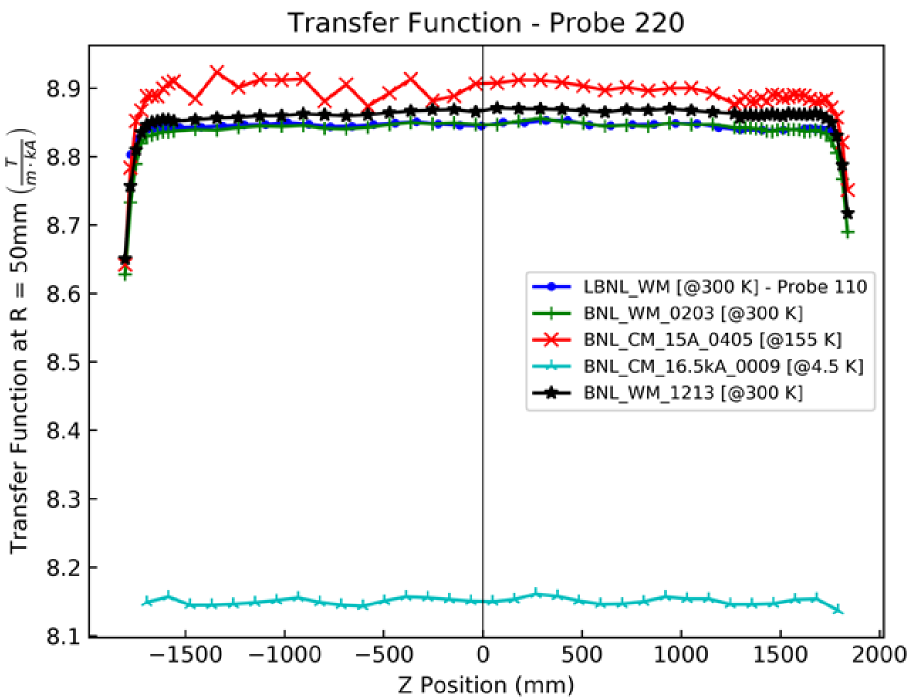
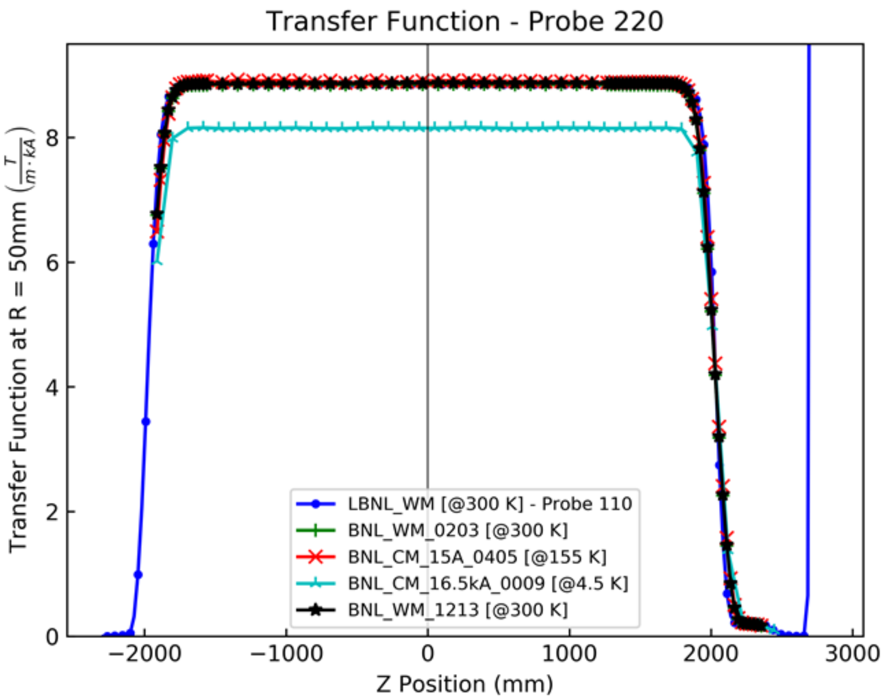
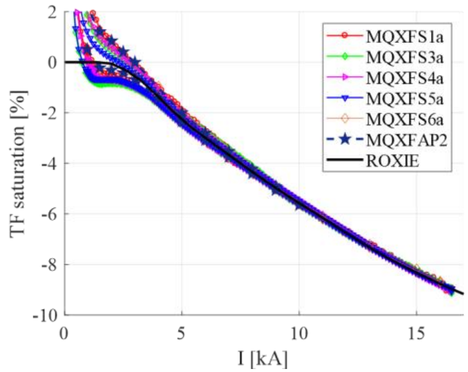
Cold Measurements during Vertical Test

Transfer function



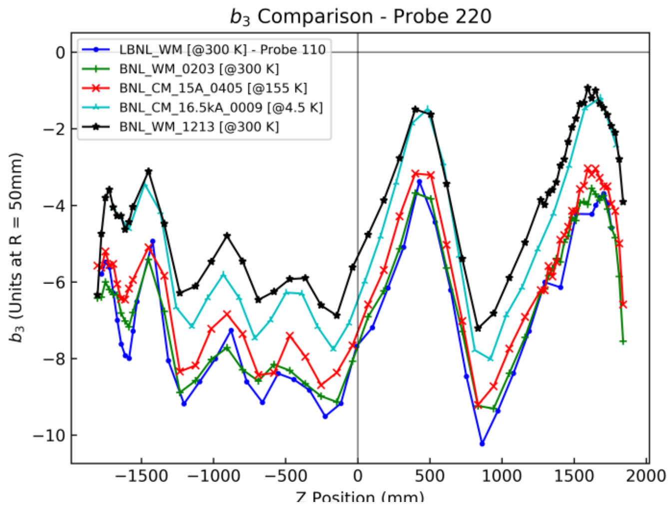


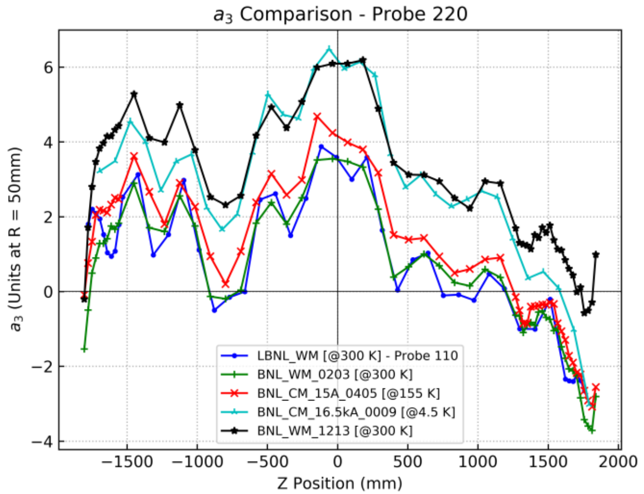
- Decrease on the transfer function from injection to nominal by ~ 9 % due to iron saturation, consistent with calculations and results from other model magnets and prototypes

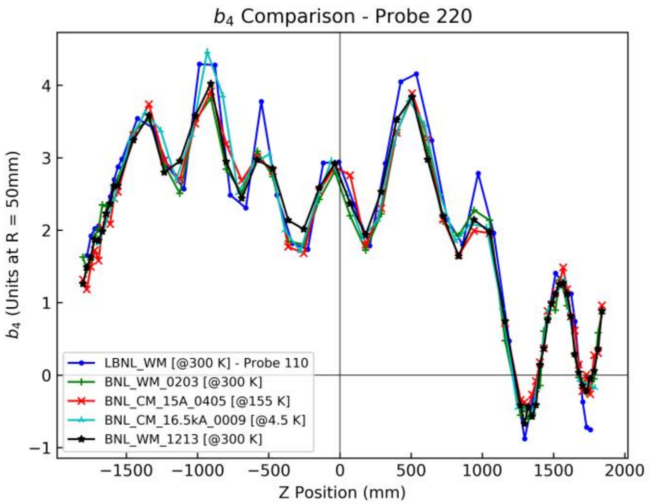


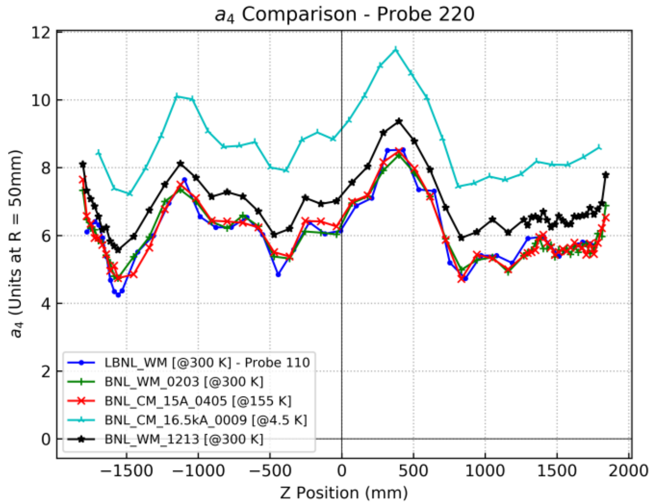
Cold Measurements during Vertical Test

Similar longitudinal variations at different temperature/current, with some offset (0-2 units)









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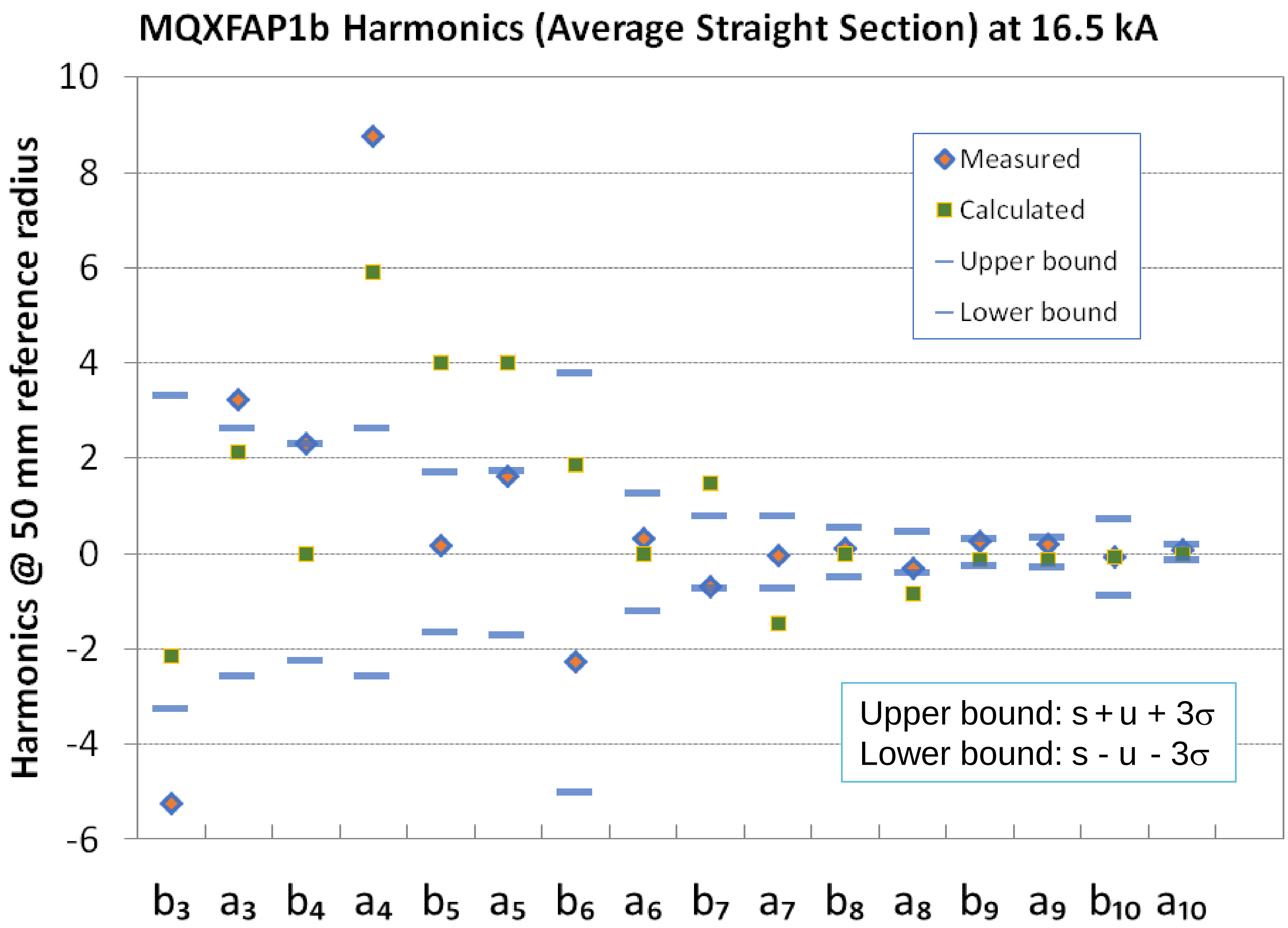
Cold Measurements during Vertical Test

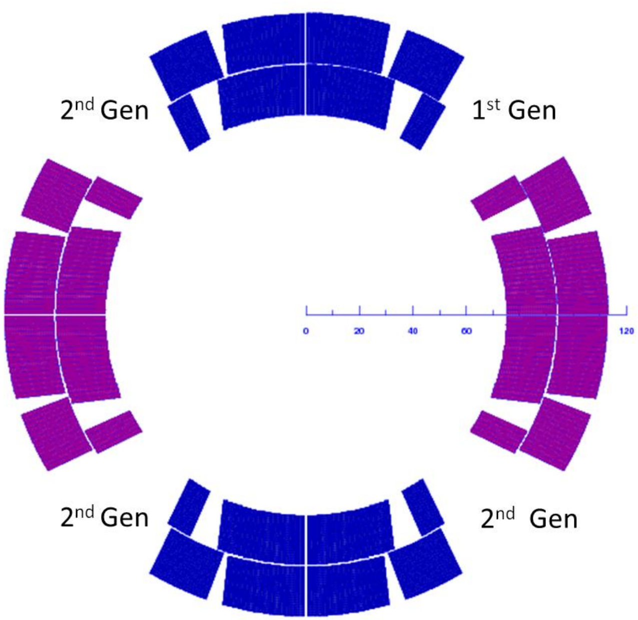


MQXFAP1b Calculated Harmonics

MQXFAP1 and MQXFAP1b included both 1st and 2nd generation coils

- One coil first generation (Quadrant 1 for the computations)
- Three coils second generation

Calculated field errors at nominal current (16.47 kA):



MAIN FIELD (T) .... -6.632254
MAGNET STRENGTH (T/(m^(n-1)) .... -132.6451

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	7.69590	b 2:	10000.00000	b 3:	-2.14583
b 4:	-0.02032	b 5:	4.00066	b 6:	1.87555
b 7:	1.48641	b 8:	-0.00057	b 9:	-0.13966
b10:	-0.06795	b11:	0.05543	b12:	-0.00000
b13:	-0.00739	b14:	-0.86125	b15:	0.01071
b16:	0.00000	b17:	-0.00879	b18:	-0.27134
b19:	-0.00537	b20:	0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	7.64431	a 2:	0.03835	a 3:	2.14023
a 4:	5.91075	a 5:	4.00123	a 6:	0.00005
a 7:	-1.48643	a 8:	-0.85097	a 9:	-0.13965
a10:	0.00000	a11:	-0.05543	a12:	-0.04562
a13:	-0.00739	a14:	-0.00000	a15:	-0.01071
a16:	-0.01477	a17:	-0.00879	a18:	-0.00000
a19:	0.00537	a20:	0.00535	a	

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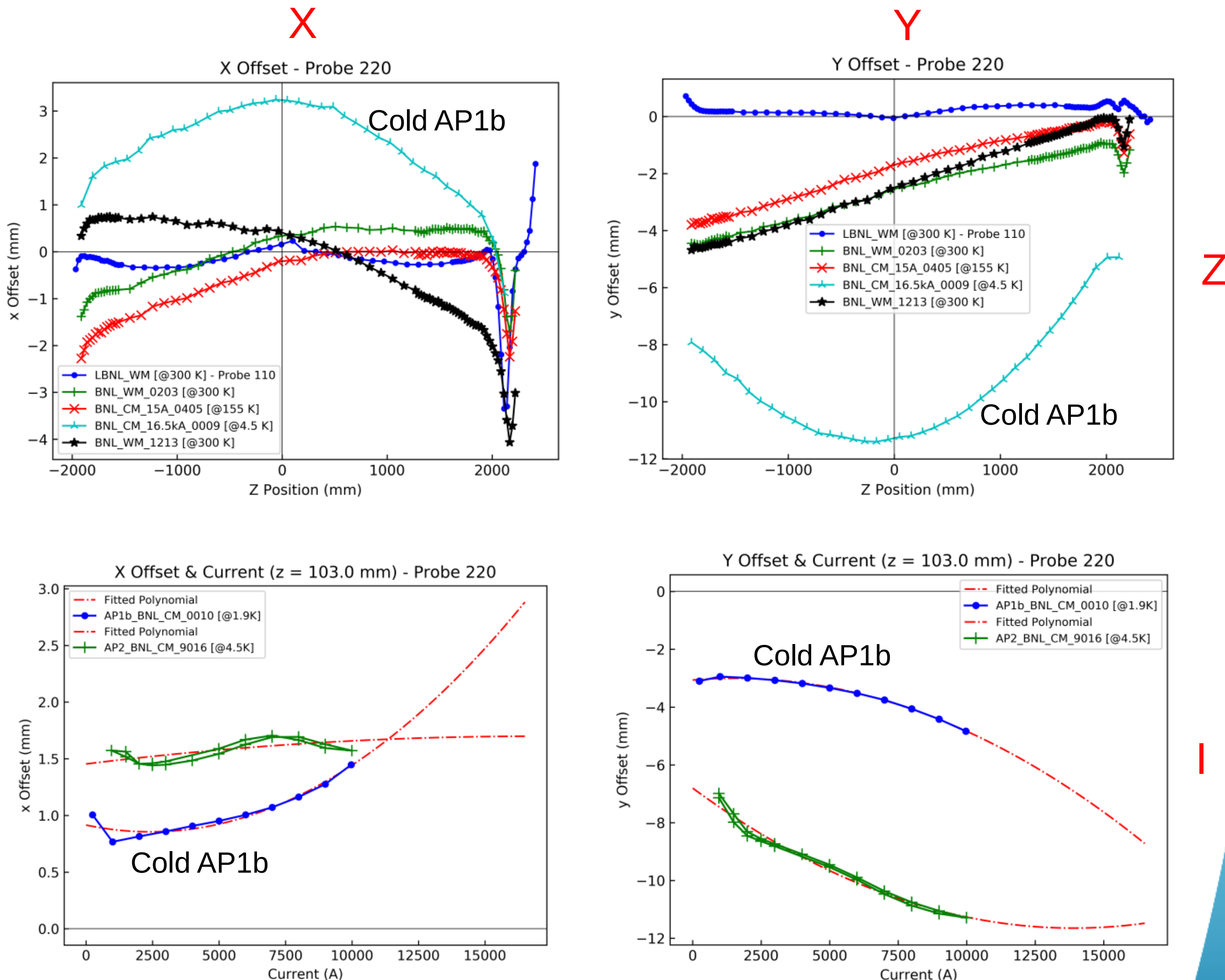
Cold Measurements during Vertical Test

- Relative shift of magnetic vs probe axis up to ~12 mm was observed
- Calculated - assuming measured dipole stems from probe offset in pure quad field
- Significant changes in value and pattern from warm to cold measurements
- About a factor of two change from low to high current
- Addressed with additional alignment features for the warm bore between AP2 and AP1b



Additional slides

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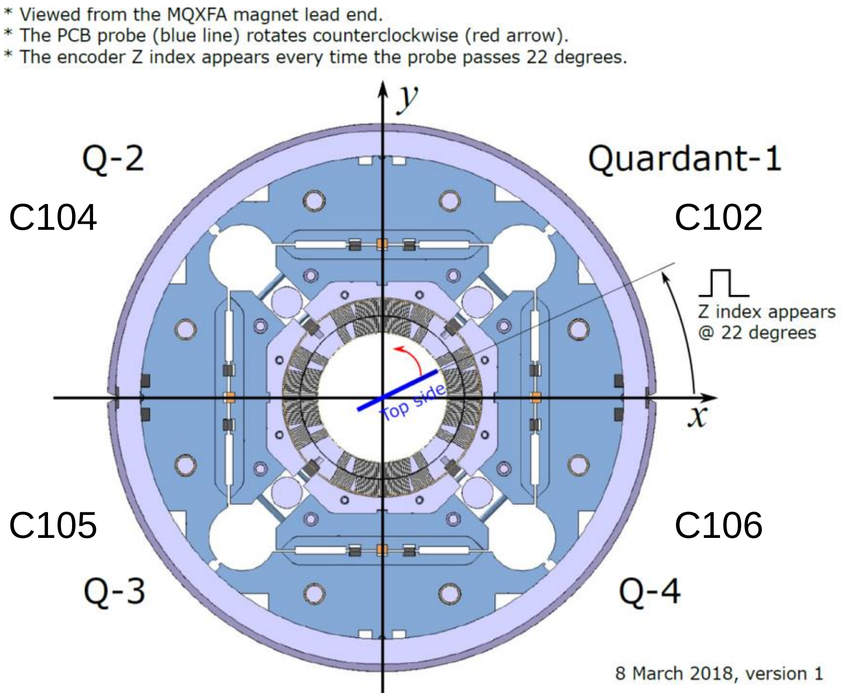
Field Quality Reference Table

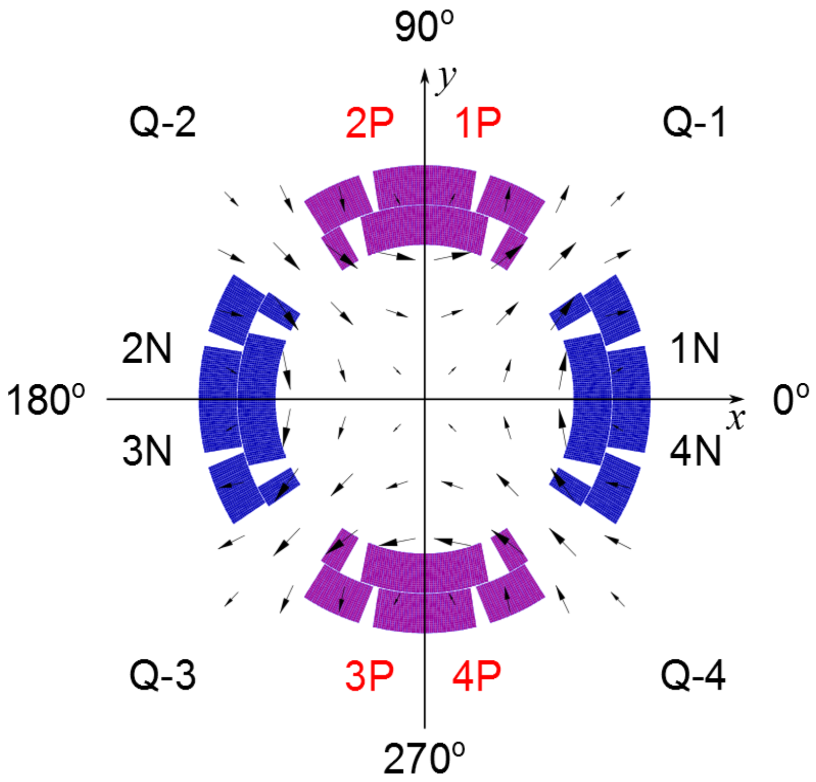
	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm																
	Straight part										Ends		Integral			
	Systematic						Uncertainty		Random				Q1/Q3		Q2a/b	
Normal	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	CS	NCS	Injection	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				

Reference Frame for Magnetic Measurements

- Longitudinal axis points from the return to the lead end
- z = 0 is defined as the magnetic center based on the integrated quadrupole strength
- Consider defining z=0 based on a specific geometric location/drawing
- Also need to introduce in the quadrant/coil diagram a geometric feature (e.g. main leads) to clarify angular reference



Quadrupole reference frame and powering



- Positive or negative quadrupole depending on powering
- Positive or negative depending on rotation (switches every 90 degrees)
- Positive or negative quadrupole depending on direction of travel
- Two magnets will be oriented opposite to each other in the cold mass

Next steps:

- Confirm quadrupole sign for given powering orientation at LBNL and BNL
- Some issue at LBNL comparing AP2 with AP1b:opposite quadrupole sign for nominally same powering
- But, AP2 measurement was performed with no splice box (coils connected manually)

MQXFAP1b Calculated Harmonics

MQXFAP1 and MQXFAP1b included both 1st and 2nd generation coils

- One coil first generation in Quadrant 3
- Three coils second generation

Calculated field errors at nominal current (16.47 kA):

```
MAIN FIELD (T) ....................................      6.632618
MAGNET STRENGTH (T/(m^(n-1)) .......................     132.6524

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:     -6.75314  b 2:  10000.00000  b 3:      2.02360
b 4:     -0.01077  b 5:     -3.98969  b 6:      1.87735
b 7:     -1.48728  b 8:     -0.00018  b 9:      0.13979
b10:     -0.06790  b11:     -0.05544  b12:      0.00000
b13:      0.00739  b14:     -0.86126  b15:     -0.01071
b16:      0.00000  b17:      0.00879  b18:     -0.27134
b19:      0.00537  b20:     -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:     -6.75314  a 2:     -0.00000  a 3:     -2.02360
a 4:      5.90296  a 5:     -3.98969  a 6:     -0.00000
a 7:      1.48728  a 8:     -0.85104  a 9:      0.13979
a10:     -0.00000  a11:      0.05544  a12:     -0.04562
a13:      0.00739  a14:      0.00000  a15:      0.01071
a16:     -0.01477  a17:      0.00879  a18:      0.00000
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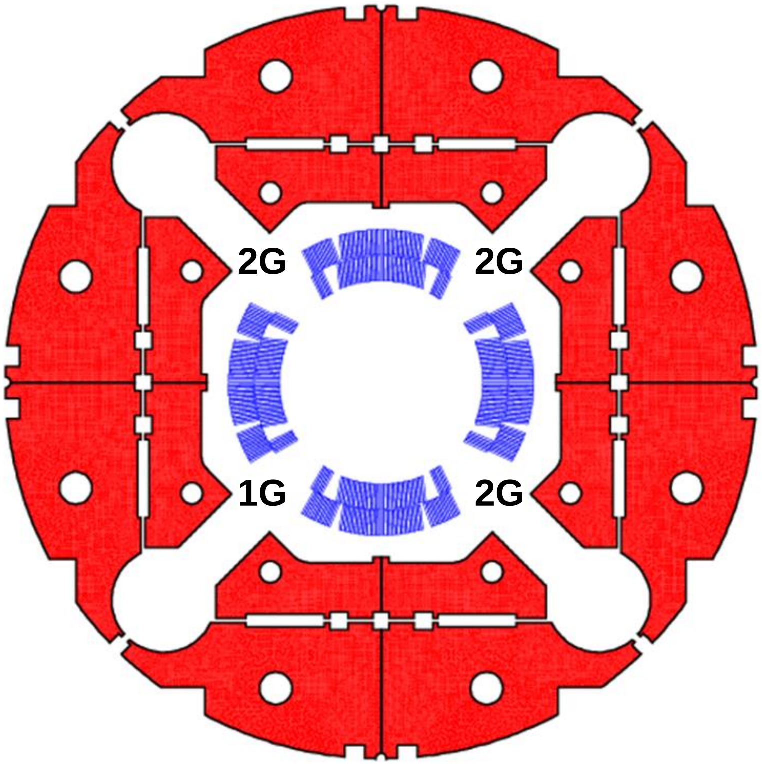

Cold Measurements during Vertical Test