LQXFA/B01 Magnetic Measurements

26Sep2023

Presented by J. DiMarco

Measurements at 1.9K/4.5K for LQXFA/B01 (MQXFA03 and MQXFA04 magnets)

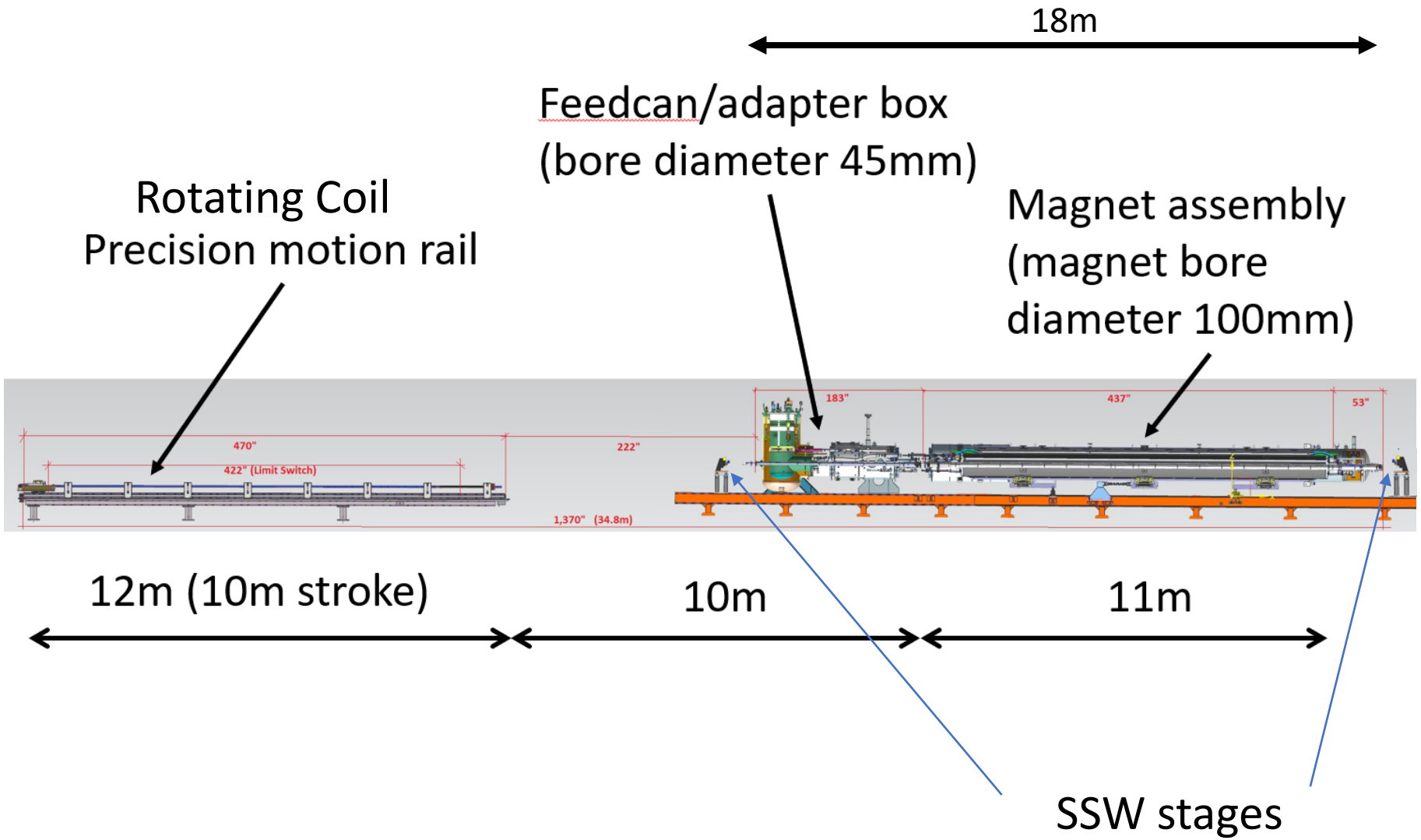
- 4.2 K rotating coil Zscan at 6 kA
- 1.9 K rotating coil Zscan at 16.23 kA
- SSW DC strength measurements at 16.23 kA, 1.9 K
- SSW alignment measurements at 10A AC, 1.9 K

First set of full-length zscans at high currents were met with several simultaneous issues:

- Cryo heat excursions which could trip the system at random times (max. about 1.5 hours, typically about 40 min.)
- Occasional problems with motion rail
- Laser tracker losing sight/unable to read targets
- Probe shaft coupling slippage

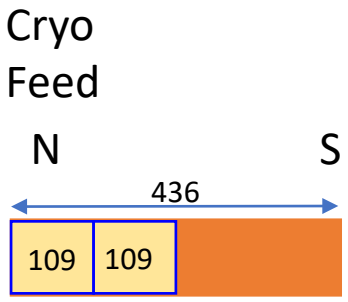
These all were causing scans to stop – the latter three were mitigated, and eventually we held nominal current and were able to take a couple of Zscans and get the full field integral.

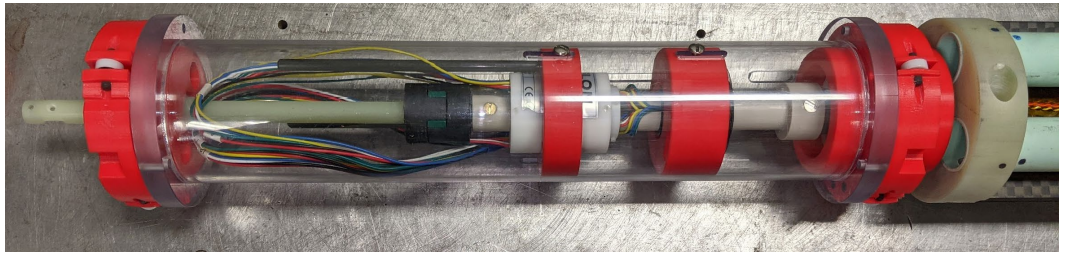
Magnetic measurements at horizontal test bench



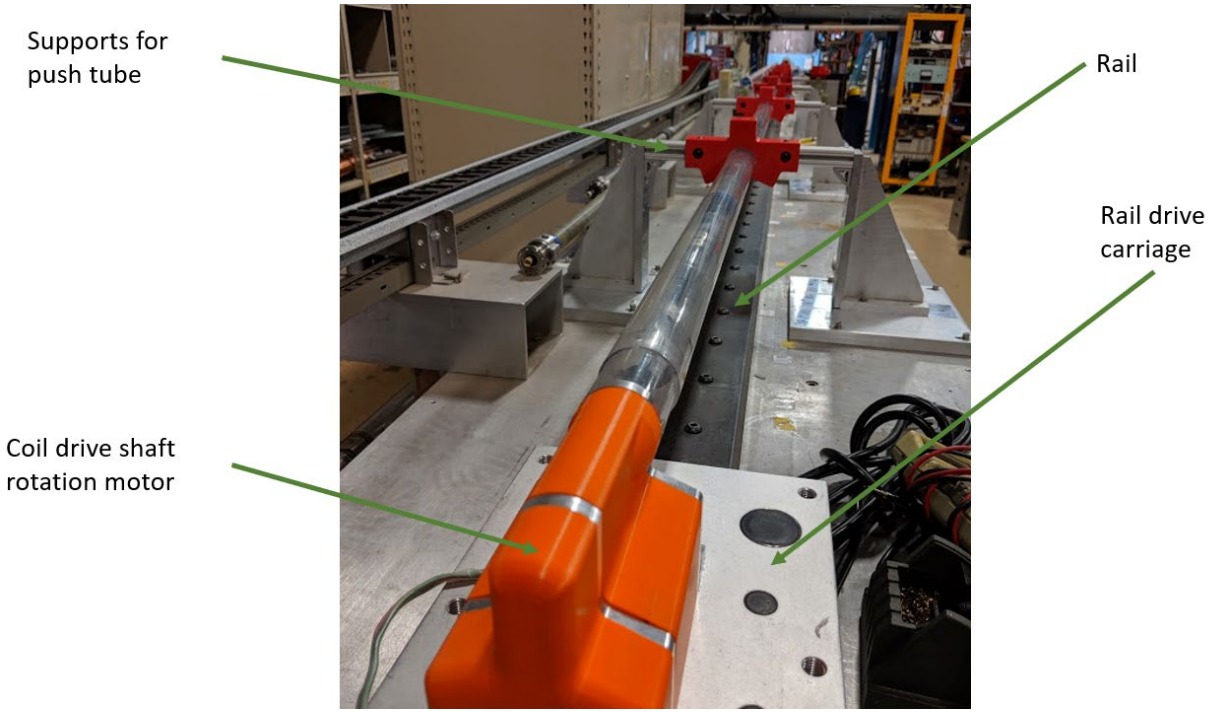
Rotating coil ‘FERRET’ probe

Probe has 436mm-long winding and two ‘back-to-back’ 109mm-long windings.

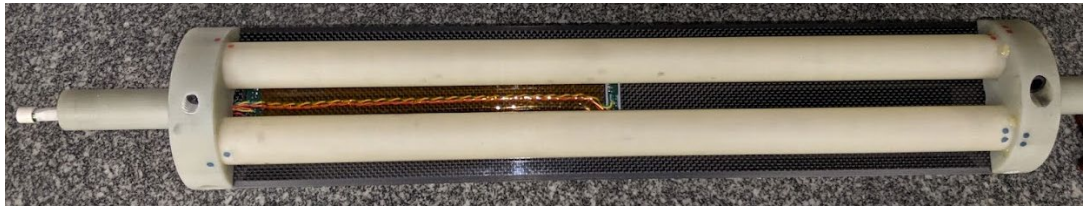




Local encoder and slipring



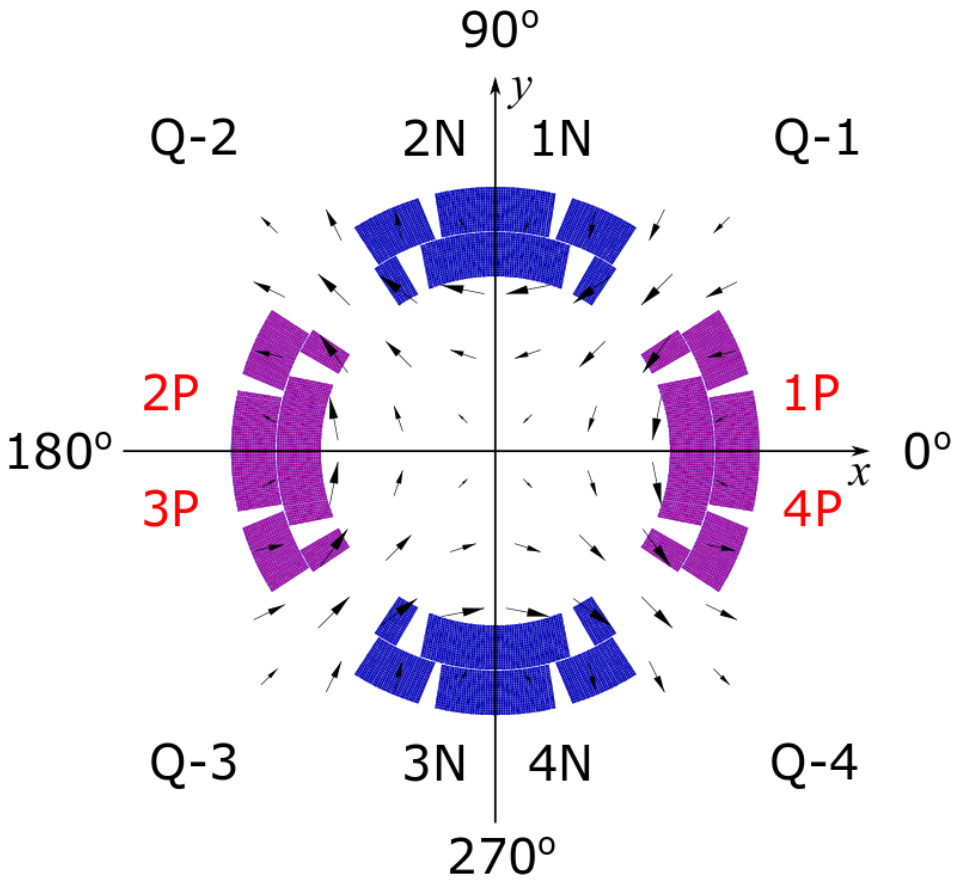
22m-long, 6mm diameter carbon fiber rotating drive shaft and polycarbonate push-tube



PCB probes stiffened with carbon fiber or G10

Laser tracker targets visible from non-drive end

The harmonics are reported for a negative normal quadrupole



- A negative normal quadrupole viewed from the magnet lead end. Positive current (“P”) flows towards the reader (along the positive z axis)

This reporting is the same for each of the two MQXFA magnets of the Cryo Assembly

Reference radius 50mm

Courtesy Xiaorong Wang

SSW system used for alignment/strength measurements (shown here during fabrication)

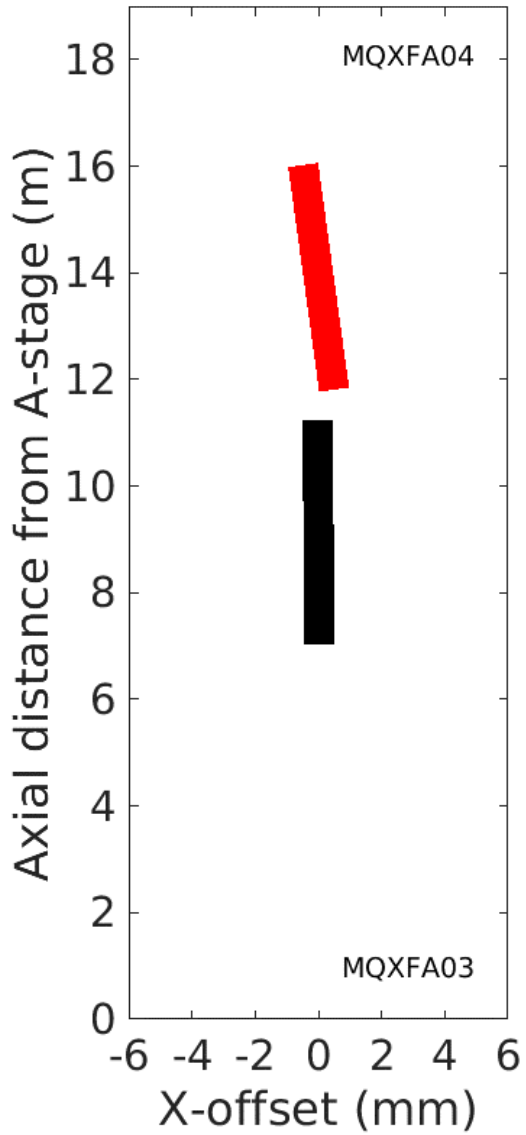
MQXFA03/MQXFA04 Alignment
After move to average axis
23Aug2023 - cold TC2, 2K

~0.2mm over
0.5mm acpt. criteria

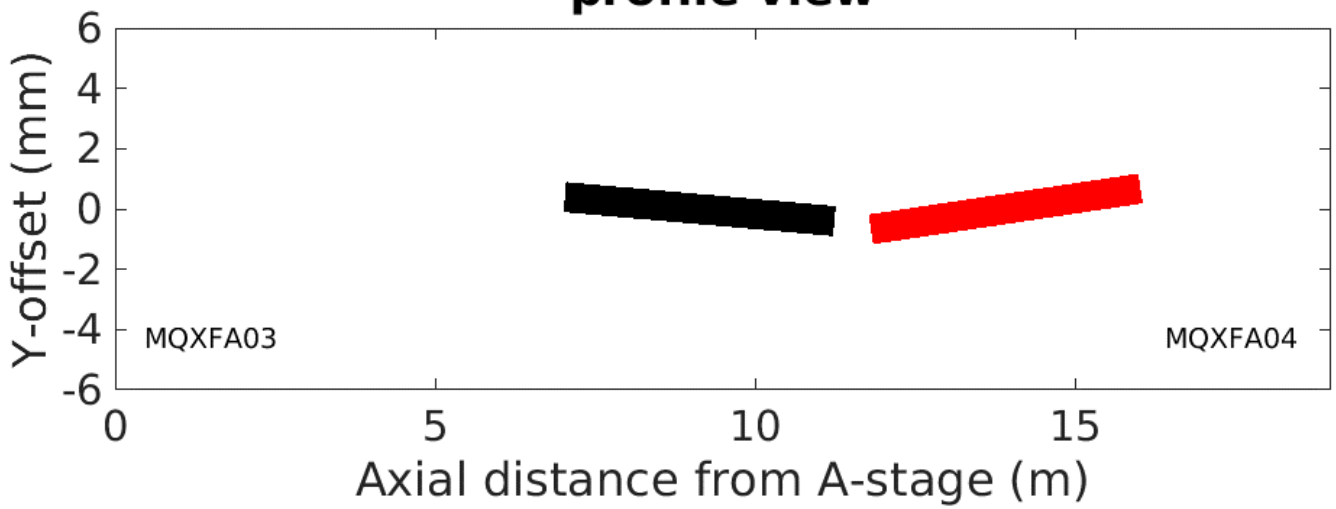
MQXFA03 Lead End: X= 0.042, Y= 0.394 mm
MQXFA03 Interface End: X= -0.030, Y= -0.402 mm
MQXFA04 Interface End: X= 0.498, Y= -0.676 mm
MQXFA04 Lead End: X= -0.482, Y= 0.681 mm

MQXFA03 roll angle = 4.59 mrad
MQXFA04 roll angle = 2.26 mrad
Delta angle = 2.32 mrad
Ave angle = 3.42 mrad

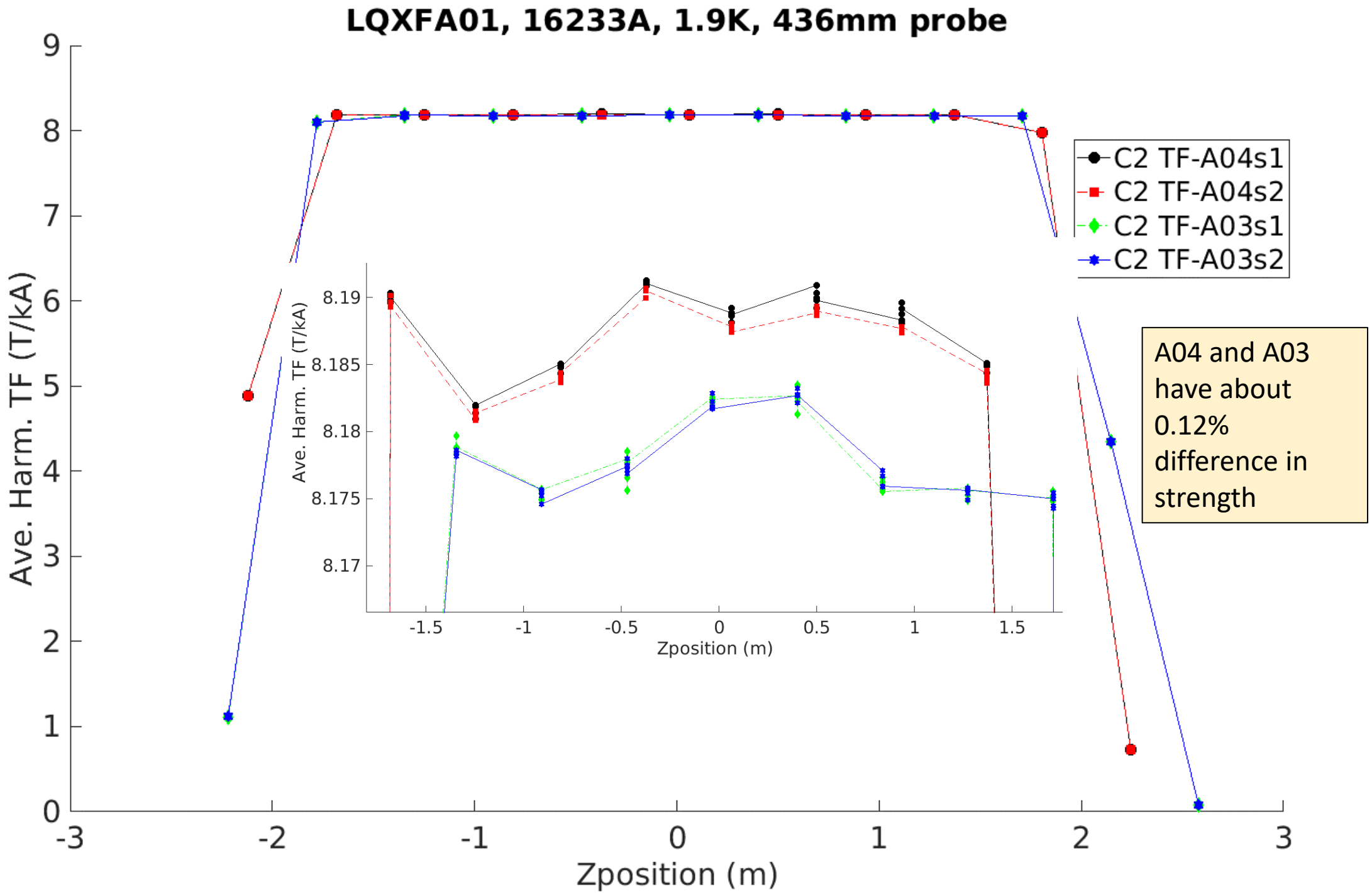
Horizontal Offsets
plan view



Vertical Offsets
profile view



SSW_R_20230823_181305_AC_PitchYaw, SSW_R_20230823_180625_AC_PitchYaw


LQXFA01, 16233A, 1.9K, 436mm probe
Ave. Harm. TF (T/kA)
Zposition (m)
C2 TF-A04s1
C2 TF-A04s2
C2 TF-A03s1
C2 TF-A03s2
A04 and A03 have about 0.12% difference in strength

To minimize the effect of the variations in positioning, take average body field and length of body field for calculations

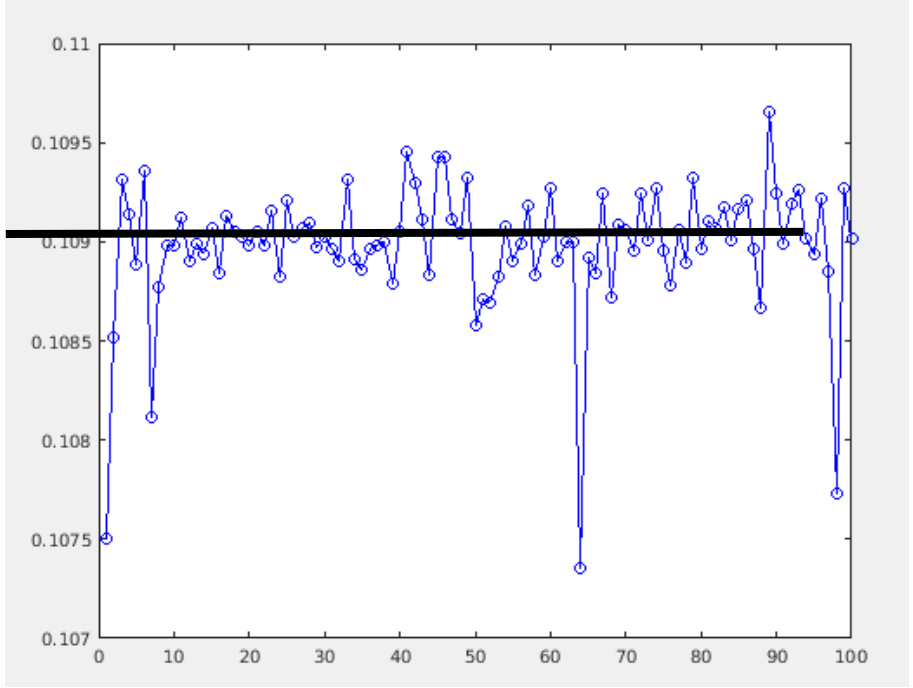
$$\int gdl = \int LE + \int NLE + g_{body\_ave} * L_{body}$$

Define Z-center as the point at which the integral starting from one end of the magnet accumulates half the value of $\int gdl$

(Also simply summed consecutive positions assuming that they were all in steps of the probe length – no significant difference)

Actual distance measured by Laser Tracker

109mm step



Usually rail motion is within +/- 0.25 mm measured by LT, but worst case ~1.5mm

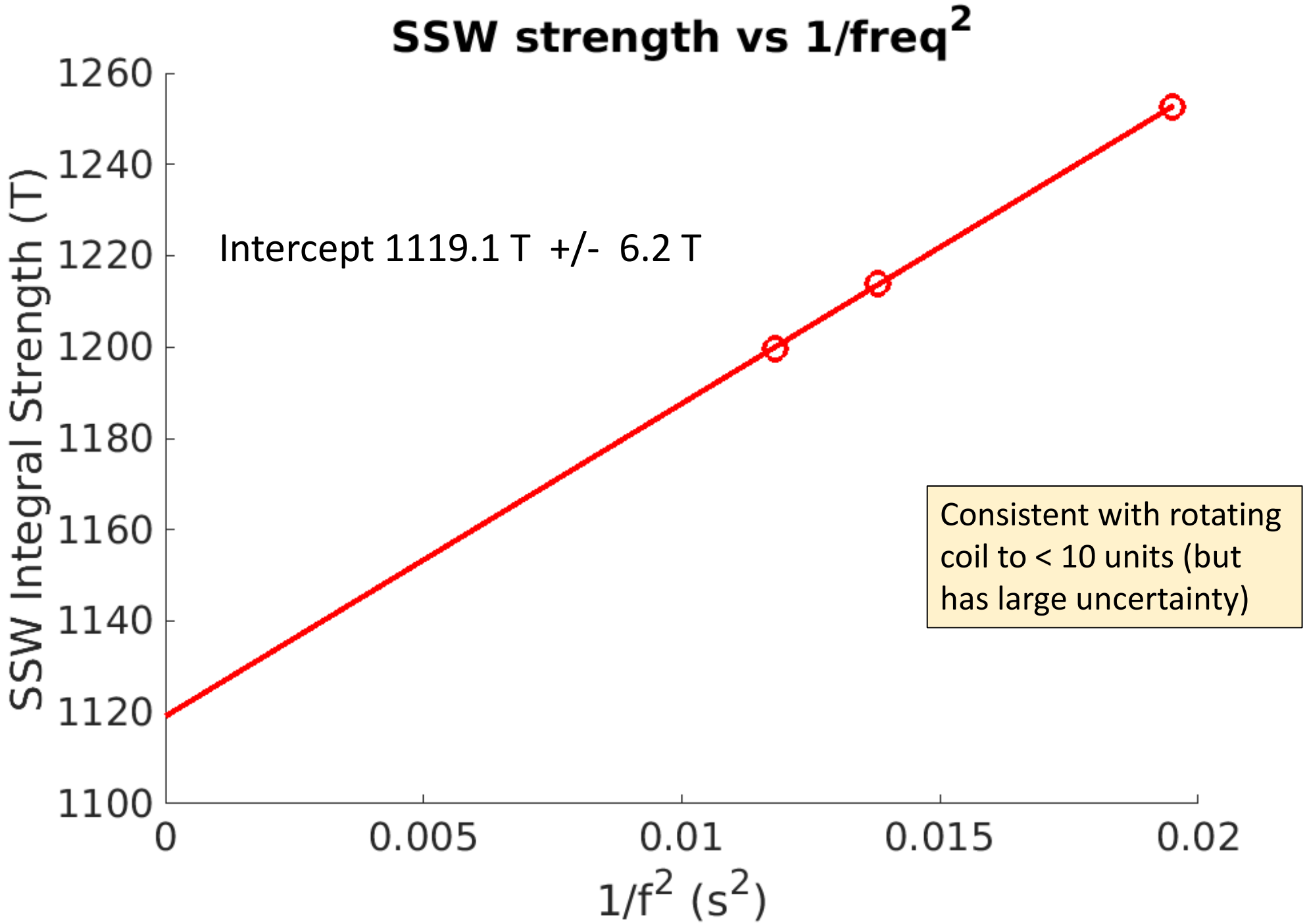
LQXFA01 Rotating Coil Strength Summary at 16233A

Cryo-Assembly Magnet:	A04	A03
Integral Gdl (T):	559.95	559.70
Magnetic length (m):	4.213	4.216
Body field TF (T/m/kA):	8.187	8.178
Magnet center separation (m):	4.7721	

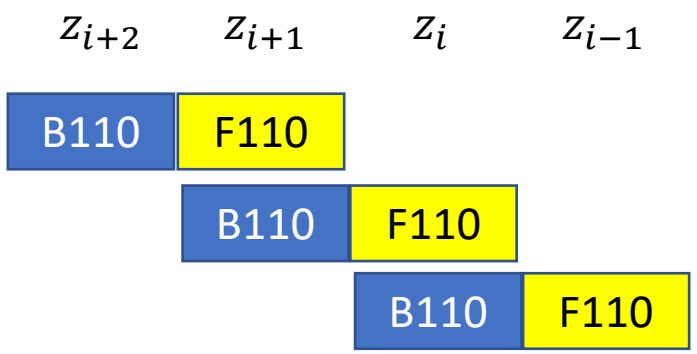
Sum = 1119.65 T

(Magnet separation measured by SSW during fabrication was 4.7892 m, expected shrinkage ~ 15mm, (observe ~17))

Integral strength requirement ~1114 T


SSW strength vs 1/freq^2
SSW Integral Strength (T)
1260
1240
1220
1200
1180
1160
1140
1120
1100
0
0.005
0.01
0.015
0.02
1/f^2 (s^2)
Intercept 1119.1 T +/- 6.2 T
Consistent with rotating coil to < 10 units (but has large uncertainty)

Local Field Angle Variation measured with dual 109 mm – length probes



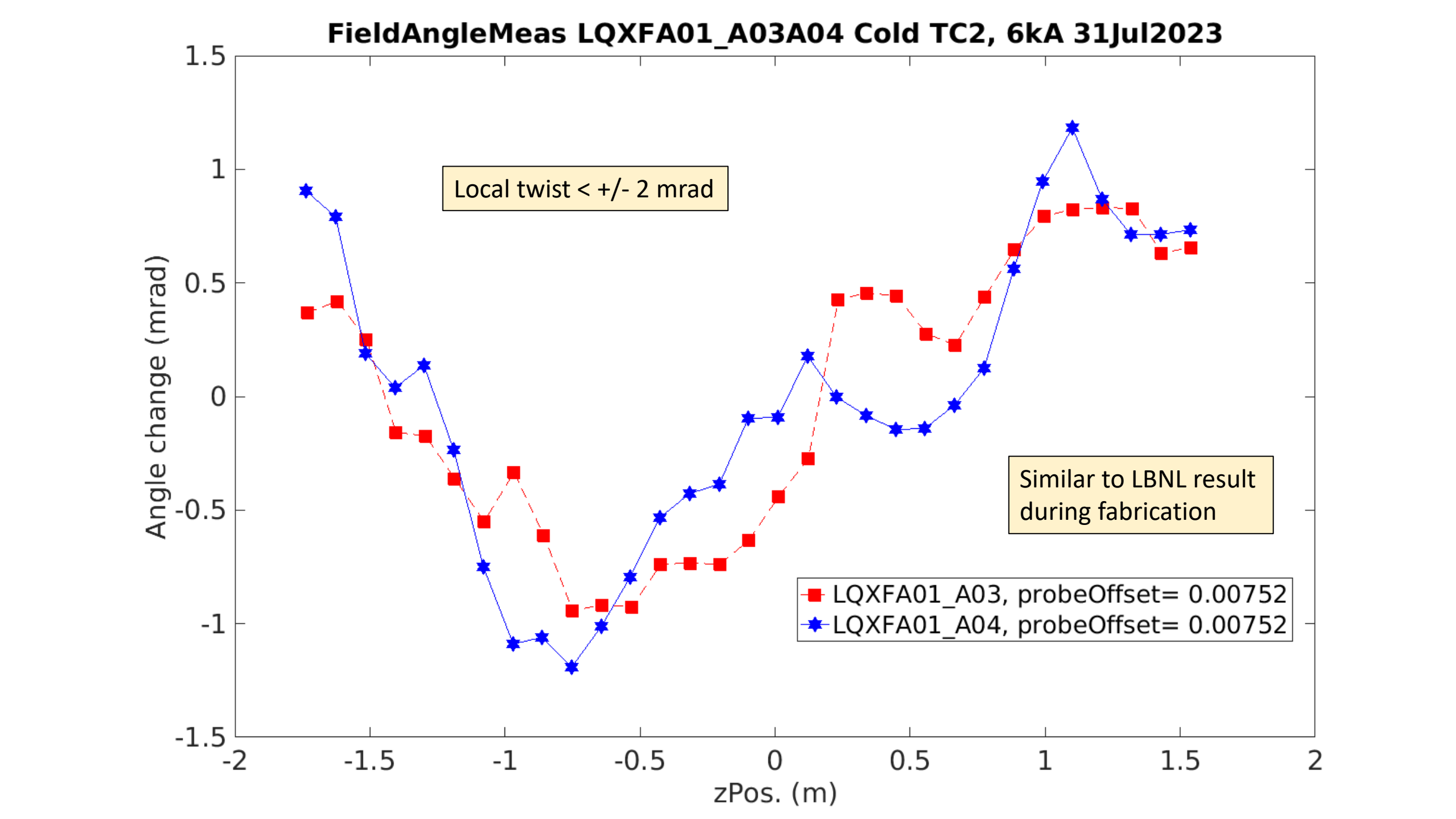
For each Z position, the trailing probe provides a relative orientation of the measurement of the lead probe

Cumulative sum gives total local variation:

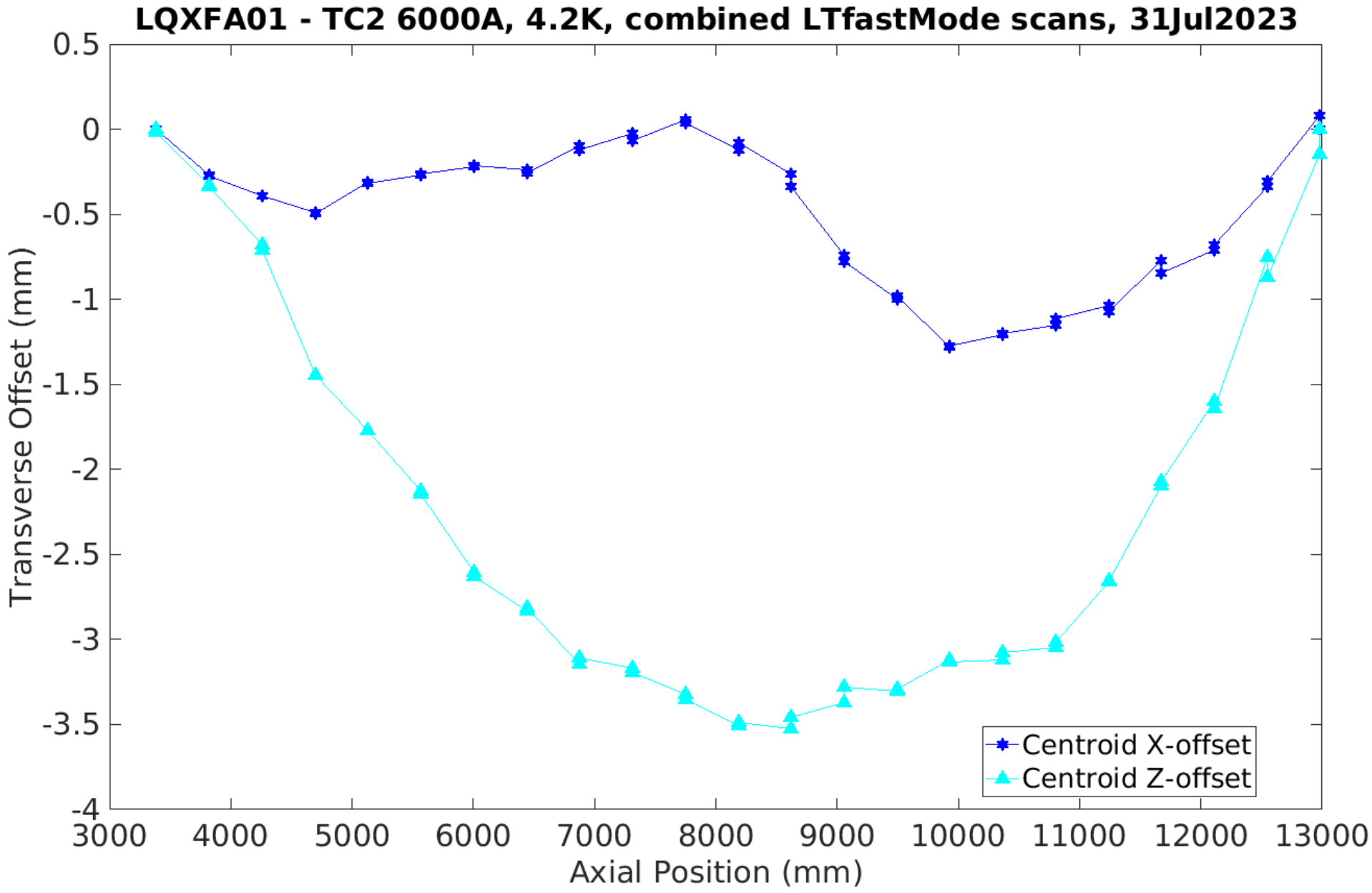
$$\Delta\theta(n) = \theta_{magNonLin}(z_n) + n * \beta_{magLin} * \Delta z$$

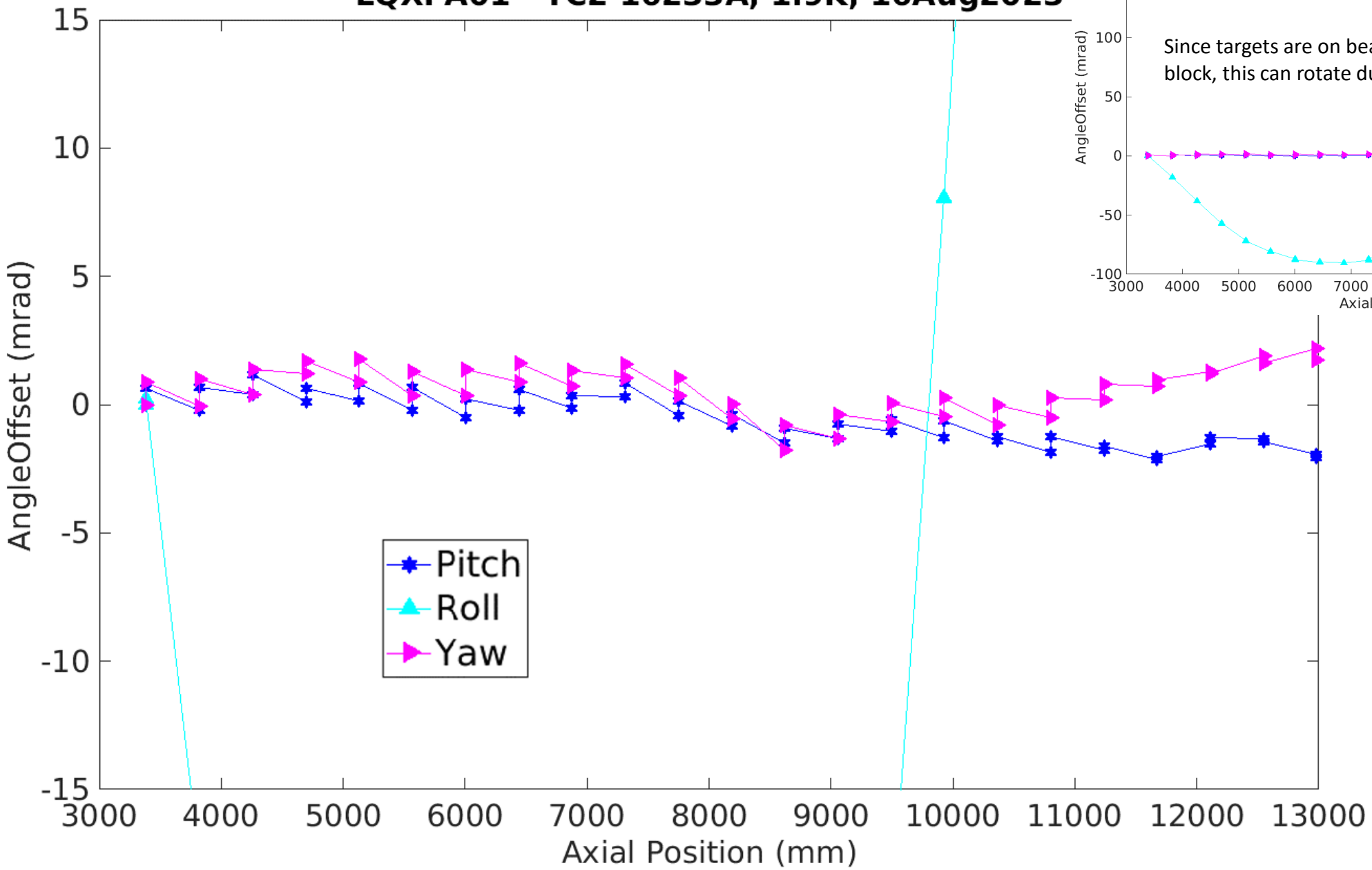
Local non-linear angle variation

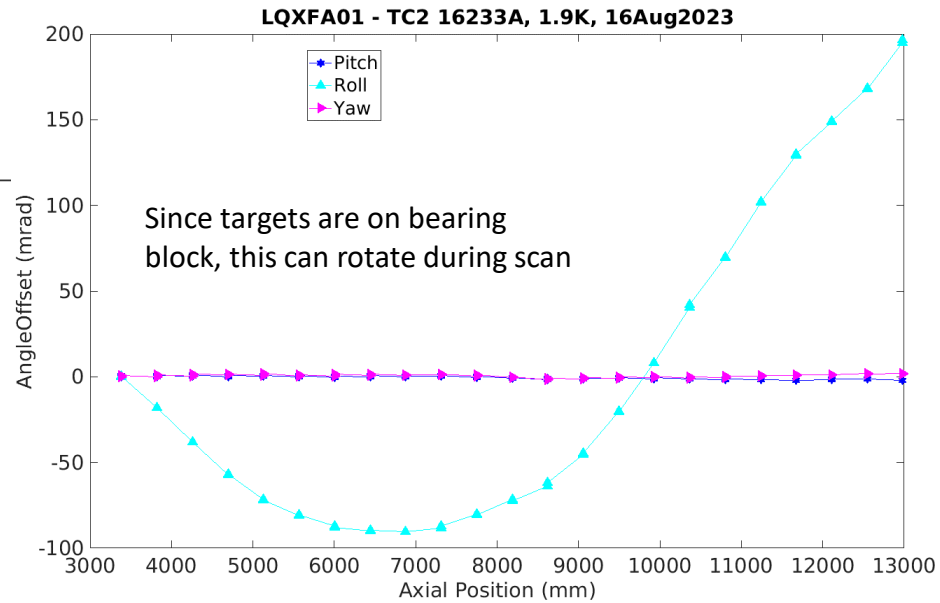
local effect of overall twist (note that need to remove angle offset between the probes to see this)


FieldAngleMeas LQXFA01_A03A04 Cold TC2, 6kA 31Jul2023
Local twist < +/- 2 mrad
Similar to LBNL result during fabrication
LQXFA01_A03, probeOffset= 0.00752
LQXFA01_A04, probeOffset= 0.00752
Angle change (mrad)
zPos. (m)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

Laser tracker measures probe position variation during Z-scan (as does the RC probe itself from feed-down)



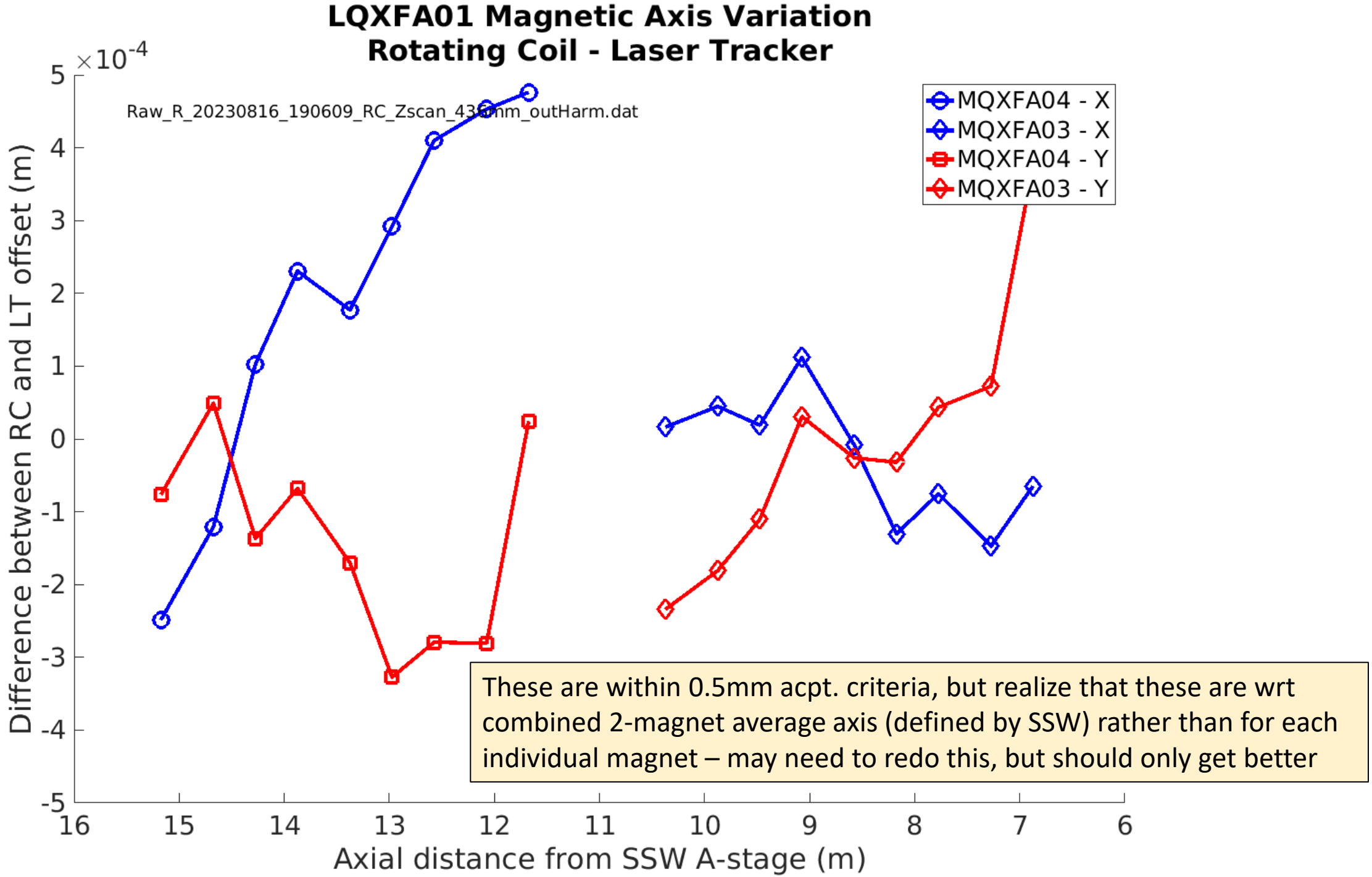


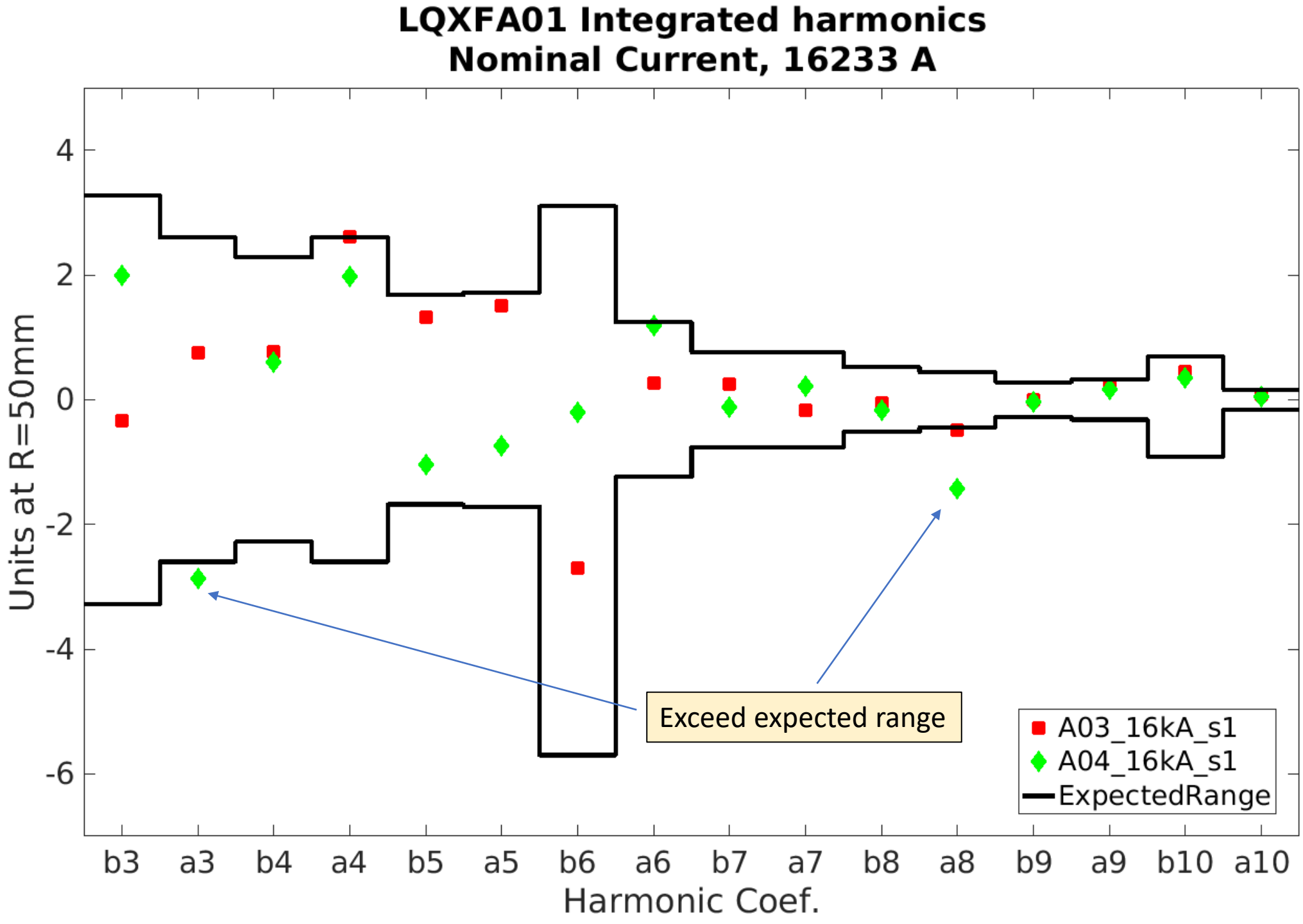


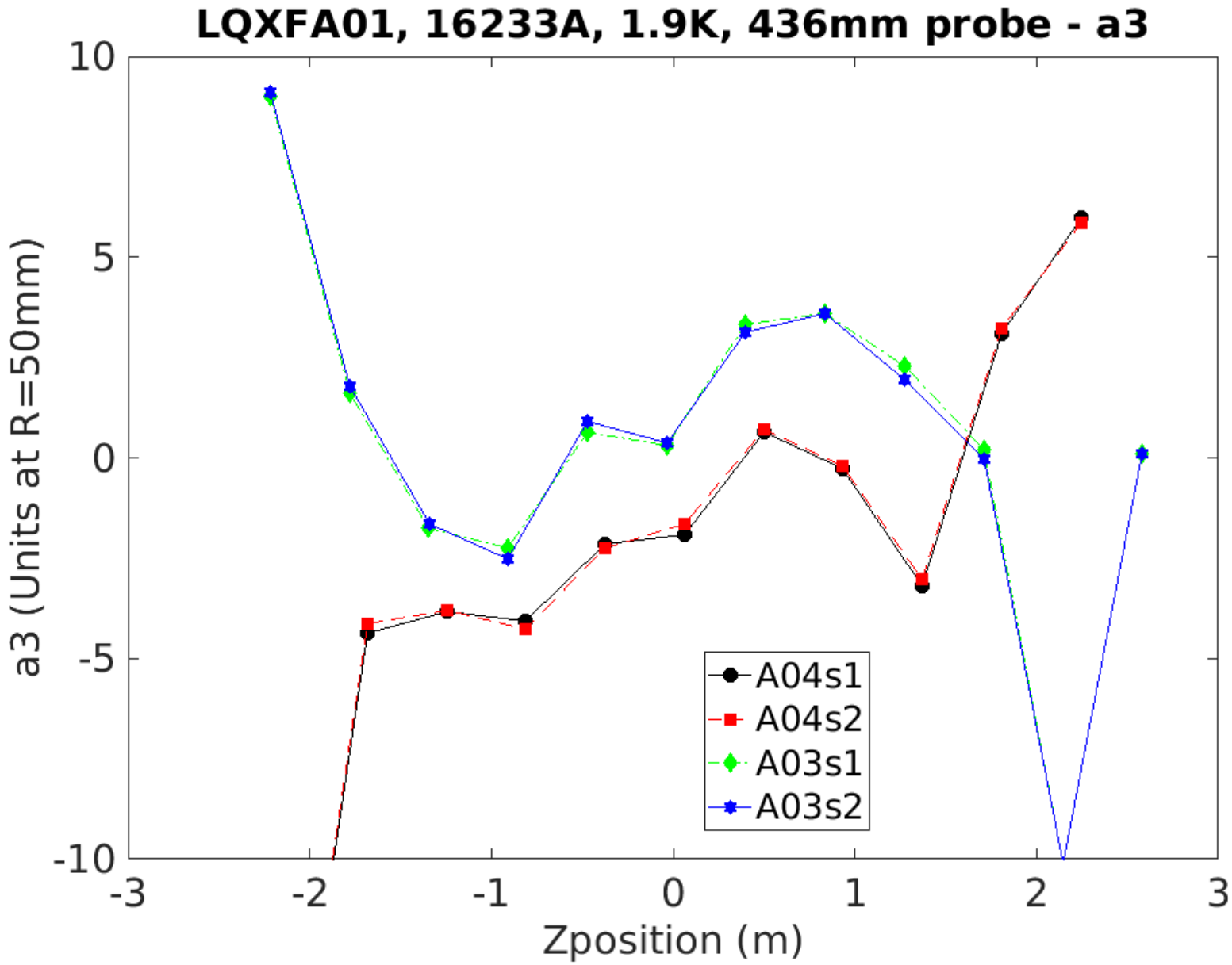
Since targets are on bearing block, this can rotate during scan

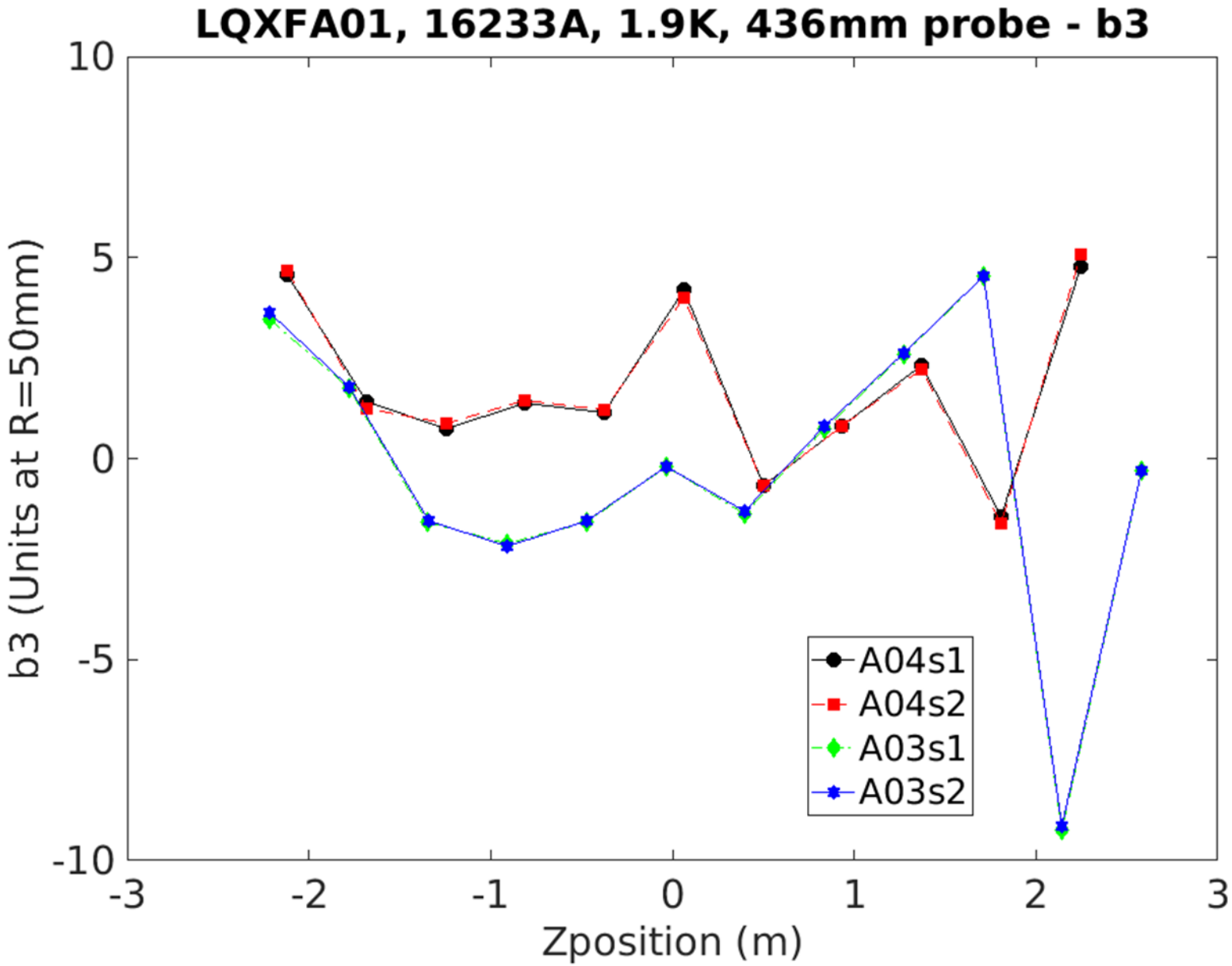
Probe pitch/yaw of 1-2 mrad at LT targets ➔ offset ~ 1mm at the probe (~0.7m away)

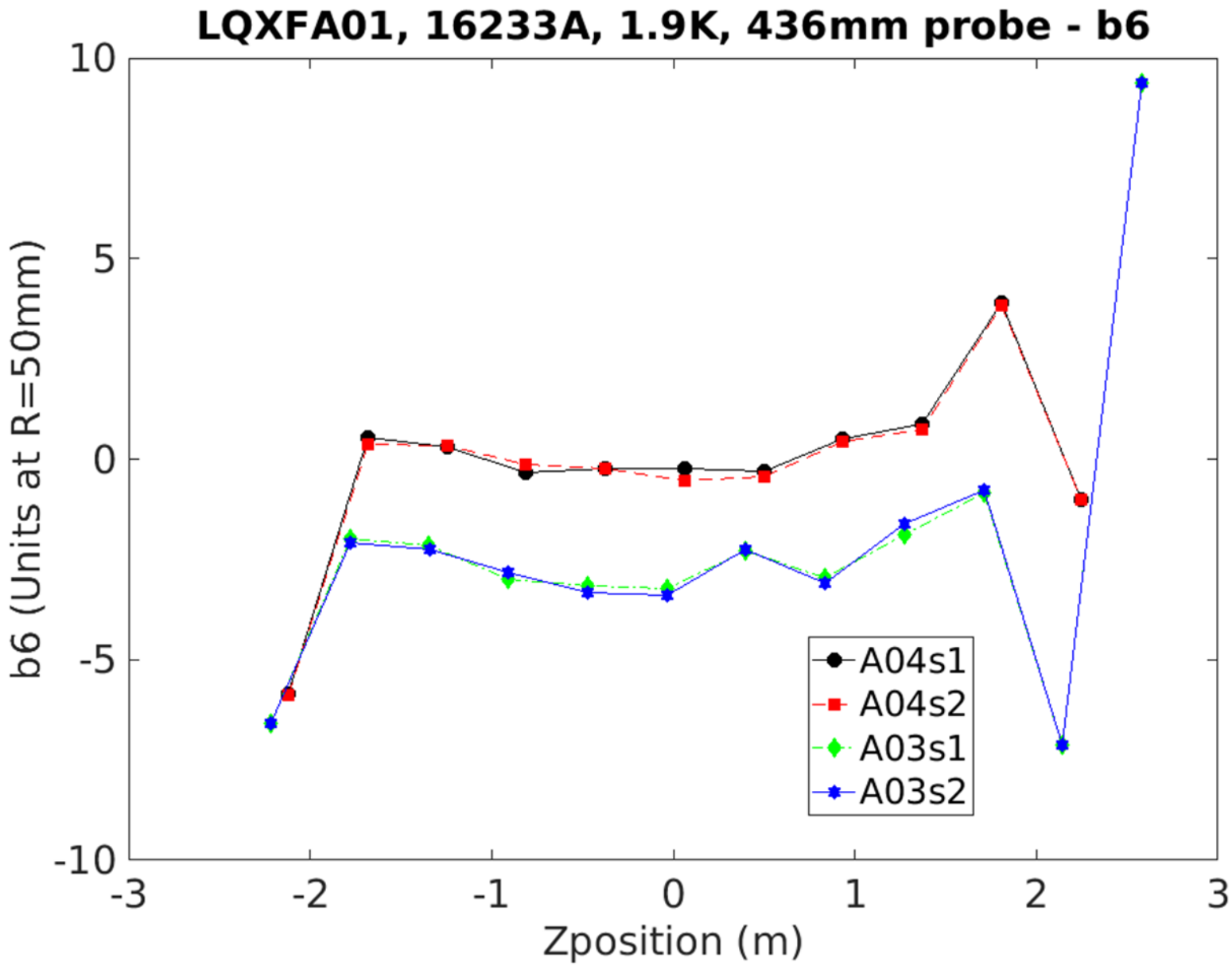
Correct for this using Helmert transform at each position

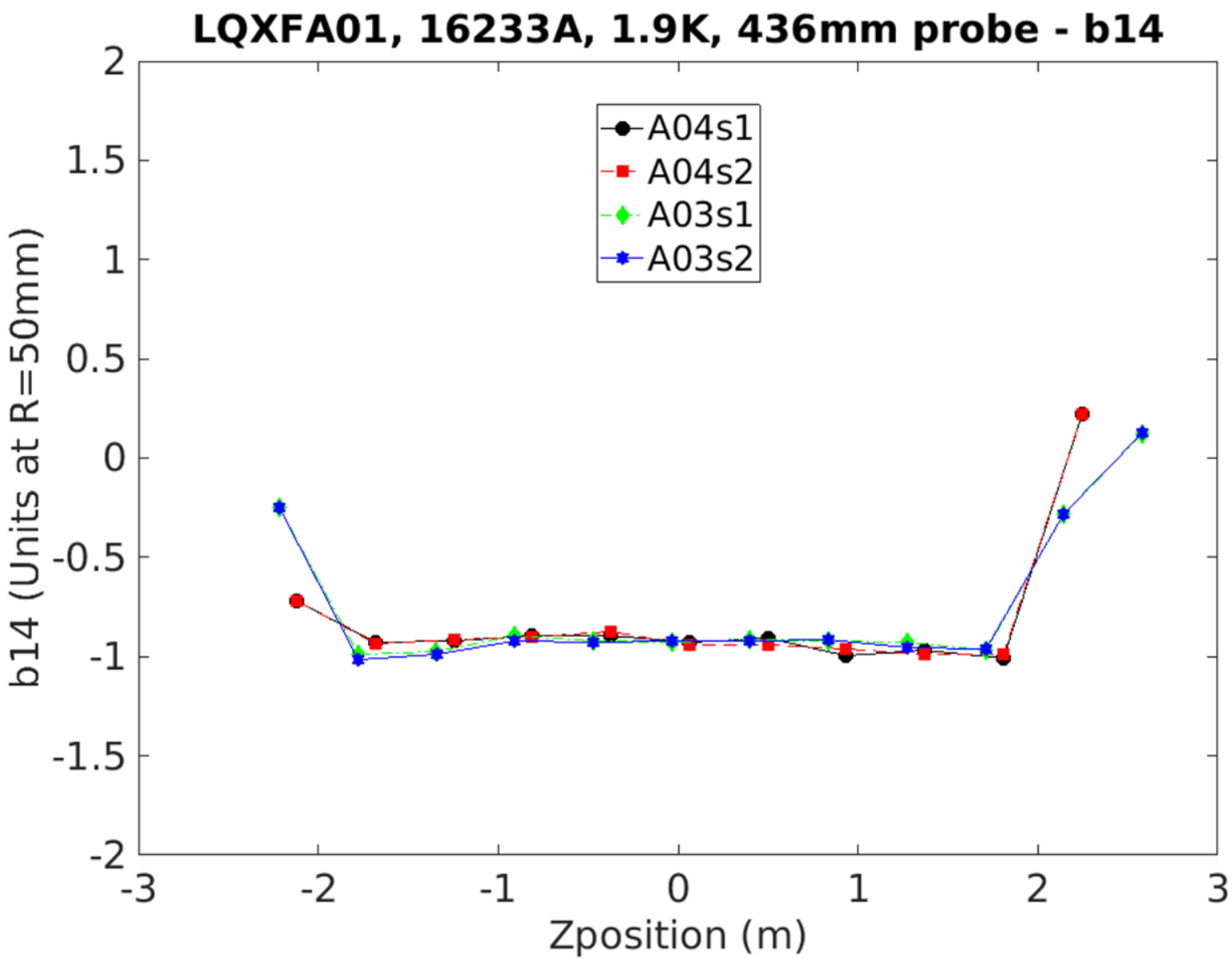

LQXFA01 Magnetic Axis Variation
Rotating Coil - Laser Tracker
×10^-4
Raw_R_20230816_190609_RC_Zscan_436mm_outHarm.dat
MQXFA04 - X
MQXFA03 - X
MQXFA04 - Y
MQXFA03 - Y
Difference between RC and LT offset (m)
Axial distance from SSW A-stage (m)
5
4
3
2
1
0
-1
-2
-3
-4
-5
16
15
14
13
12
11
10
9
8
7
6
These are within 0.5mm acpt. criteria, but realize that these are wrt combined 2-magnet average axis (defined by SSW) rather than for each individual magnet – may need to redo this, but should only get better


LQXFA01 Integrated harmonics
Nominal Current, 16233 A
Units at R=50mm
4
2
0
-2
-4
-6
b3
a3
b4
a4
b5
a5
b6
a6
b7
a7
b8
a8
b9
a9
b10
a10
Harmonic Coef.
Exceed expected range
A03_16kA_s1
A04_16kA_s1
ExpectedRange


LQXFA01, 16233A, 1.9K, 436mm probe - a3
a3 (Units at R=50mm)
Zposition (m)
10
5
0
-5
-10
-3
-2
-1
0
1
2
3
A04s1
A04s2
A03s1
A03s2


LQXFA01, 16233A, 1.9K, 436mm probe - b3
b3 (Units at R=50mm)
Zposition (m)
10
5
0
-5
-10
-3
-2
-1
0
1
2
3
A04s1
A04s2
A03s1
A03s2


LQXFA01, 16233A, 1.9K, 436mm probe - b6
b6 (Units at R=50mm)
Zposition (m)
10
5
0
-5
-10
-3
-2
-1
0
1
2
3
A04s1
A04s2
A03s1
A03s2


LQXFA01, 16233A, 1.9K, 436mm probe - b14
A04s1
A04s2
A03s1
A03s2
b14 (Units at R=50mm)
Zposition (m)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-3
-2
-1
0
1
2
3

Summary

- Magnetic measurements on the first LQXFA cold mass assembly were able to determine all quantities of interest, with precision adequate to characterize the magnet.
- The magnetic parameters meet acceptance criteria except for 0.2 mm alignment offset at the ends of magnet A04 with respect to the average axis of the two magnets.
- The a3 (marginally) and a8 harmonics of magnet A04 also exceed expected range.
- Total integrated gradient is 1119.6 T at nominal current.