Magnetic Center Alignment Results

09Oct2024

Presented by J. DiMarco

Alignment of MQXFA magnets during Cryo Assembly (CA) production

- Relies on Single Stretched Wire (SSW) system with magnets powered at 10A AC (7.8125 Hz freq)
- Repeated at various steps of production to check, and if necessary, adjust, magnet alignment of the CA

SSW provides measurements of

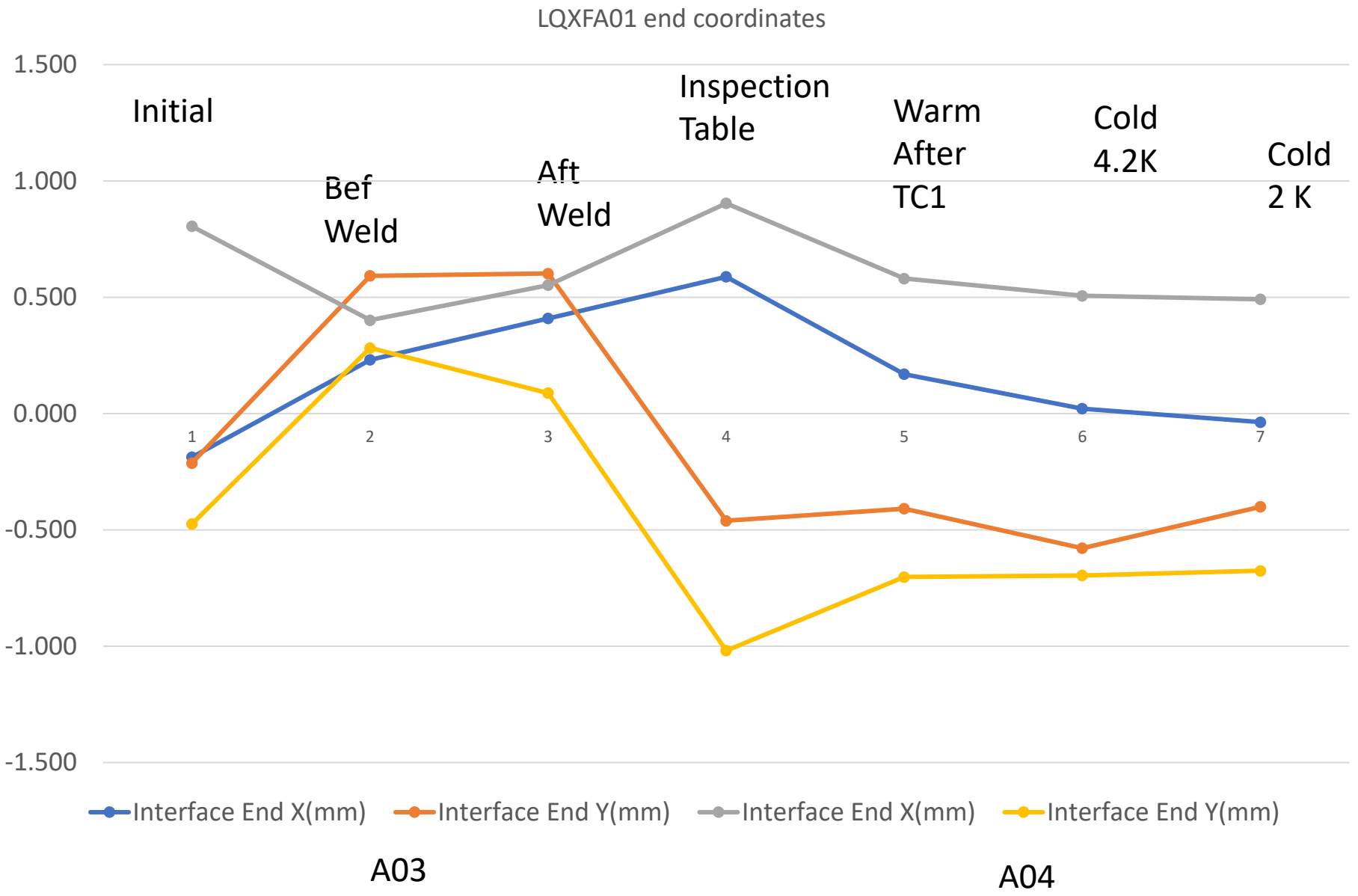
- X/Y centers
- Z-center location
- Yaw, Pitch, Roll angles
- Integrated magnet strength

SSW system in use during fabrication

For each CA, measurements are made at various fabrication steps. Below is a typical example for CA03 – multiple measurements may be made depending on need for adjustments or to confirm results

LQXFA03													
		Magnet positions relative to average center line											
		SSW-A											
		MQXFA11					MQXFA10						
		LE		Interface End		Roll	LE		Interface End		Roll	Z-distance A11-A10	deltaAngle(mrad
meas date	meas descrip.	X(mm)	Y(mm)	X(mm)	Y(mm)	(mrad)	X(mm)	Y(mm)	X(mm)	Y(mm)	(mrad)		
19-Apr-23	initial meas, no shell	-0.021	0.024	0.021	-0.024	-0.73	0.052	-0.228	-0.520	0.228	-0.26	4.7942	0.46
25-Aug-23	tacked, before weld	0.021	-0.062	-0.021	0.062	-6.30	0.421	-0.085	-0.421	0.085	-4.70	4.7934	1.59
27-Oct-23	after weld	-0.178	0.408	0.178	-0.408	-1.64	0.689	-0.695	-0.689	0.695	0.34	4.7932	1.97
31-Oct-23	after weld	-0.224	0.411	0.224	-0.411		0.685	-0.738	-0.685	0.738			
8-Jan-24	after end cap weld	-0.201	0.217	0.201	-0.217	8.24	0.683	-0.760	-0.683	0.760	10.02		1.78
4-Apr-24	on saddles	-0.104	0.320	0.104	-0.320		0.674	-0.572	-0.674	0.572			
5-Apr-24	on saddles, tacked	-0.119	0.324	0.119	-0.324		0.668	-0.612	-0.668	0.612			

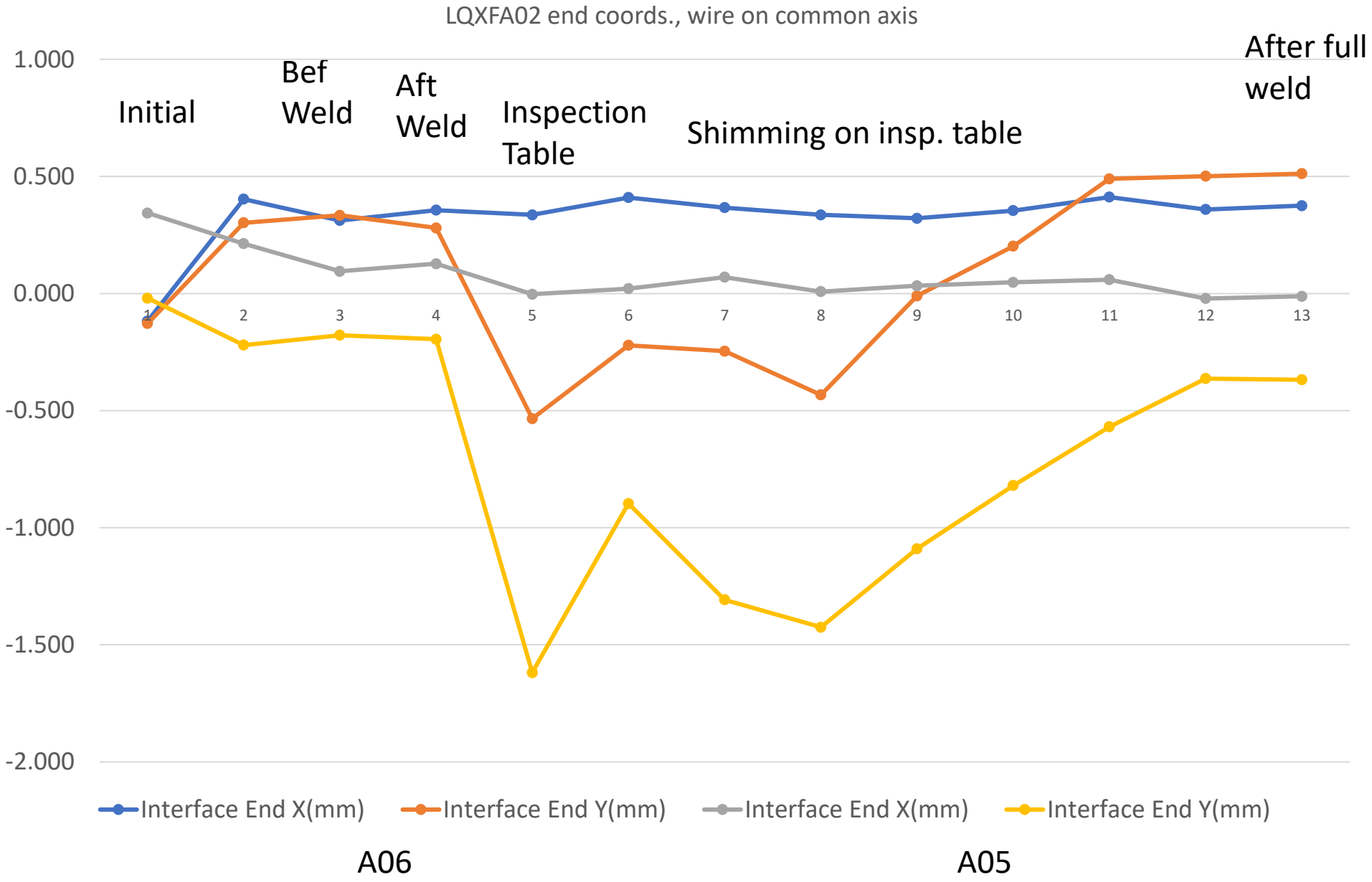
LQXFA01



Wire on 2-magnet average axis (common axis).

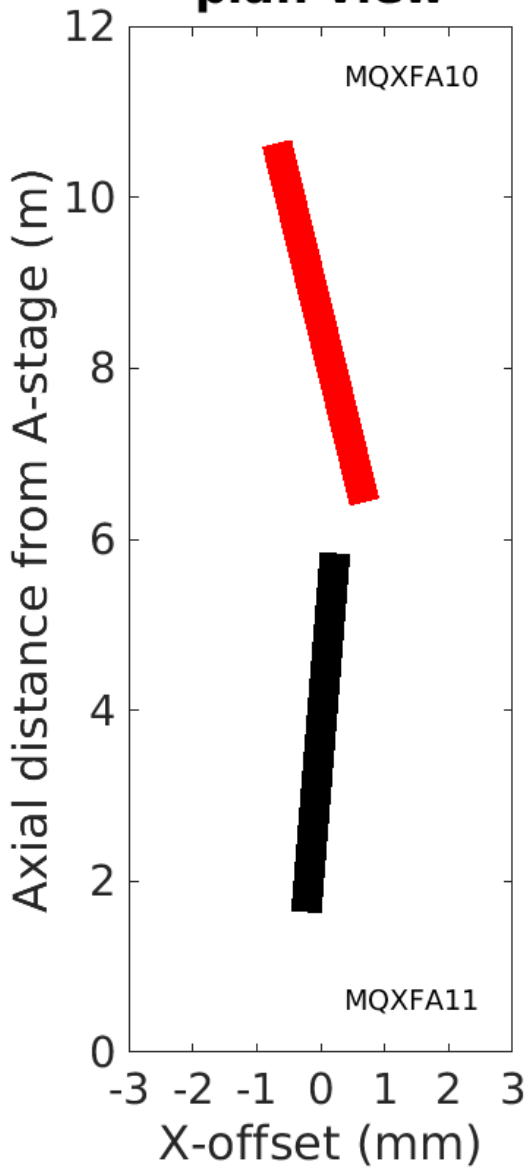
Reproducibility of end measurements generally on the ~0.1 mm level

LQXFA02


LQXFA02 end coords., wire on common axis
1.000
0.500
0.000
-0.500
-1.000
-1.500
-2.000
Initial
Bef Weld
Aft Weld
Inspection Table
Shimming on insp. table
After full weld
1
2
3
4
5
6
7
8
9
10
11
12
13
Interface End X(mm)
Interface End Y(mm)
Interface End X(mm)
Interface End Y(mm)
A06
A05

Alignment Relative to MQXFA11/MQXFA10 Average Center Line
27Oct2023 - after welding

Horizontal Offsets
plan view

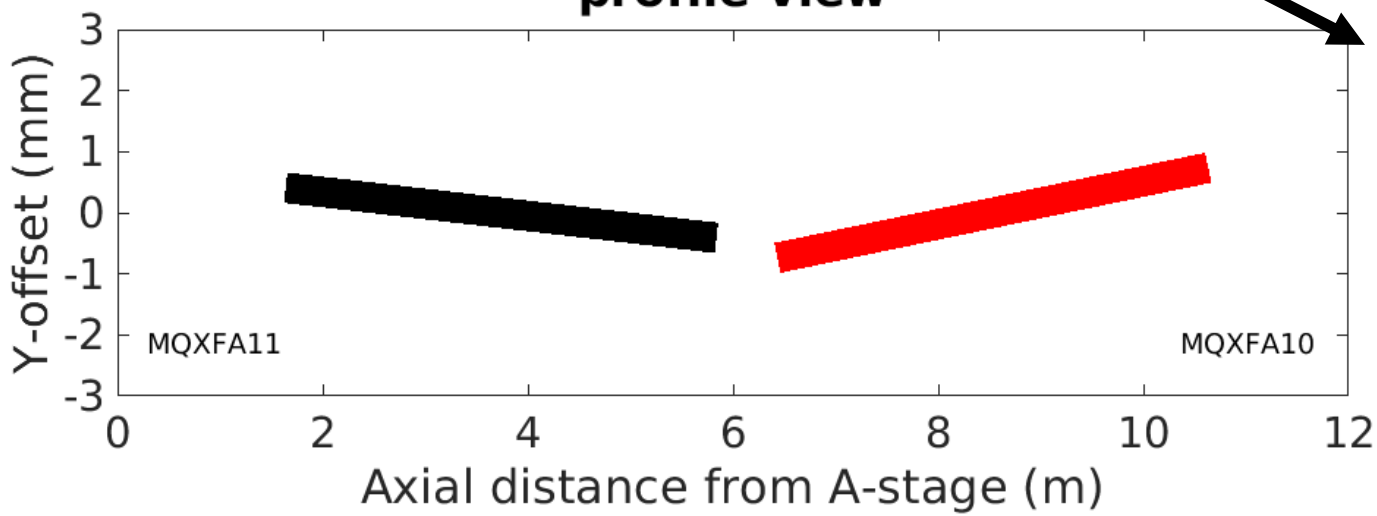


MQXFA11 Lead End: X= -0.224, Y= 0.411 mm
MQXFA11 Interface End: X= 0.224, Y= -0.411 mm
MQXFA10 Interface End: X= 0.685, Y= -0.738 mm
MQXFA10 Lead End: X= -0.685, Y= 0.738 mm

A11 roll angle = -1.64 mrad
A10 roll angle = 0.34 mrad
Delta angle = 1.97 mrad
Ave Angle = -0.65 mrad

A11 Z-dist A-stage to magnetic center = 3.7388 m
A10 Z-dist A-stage to magnetic center = 8.5320 m
Z-dist A11 to A10 = 4.7932 m (Lw=12.4866 m)

Vertical Offsets
profile view



Normal separation of magnet Z-centers ~4.792 m

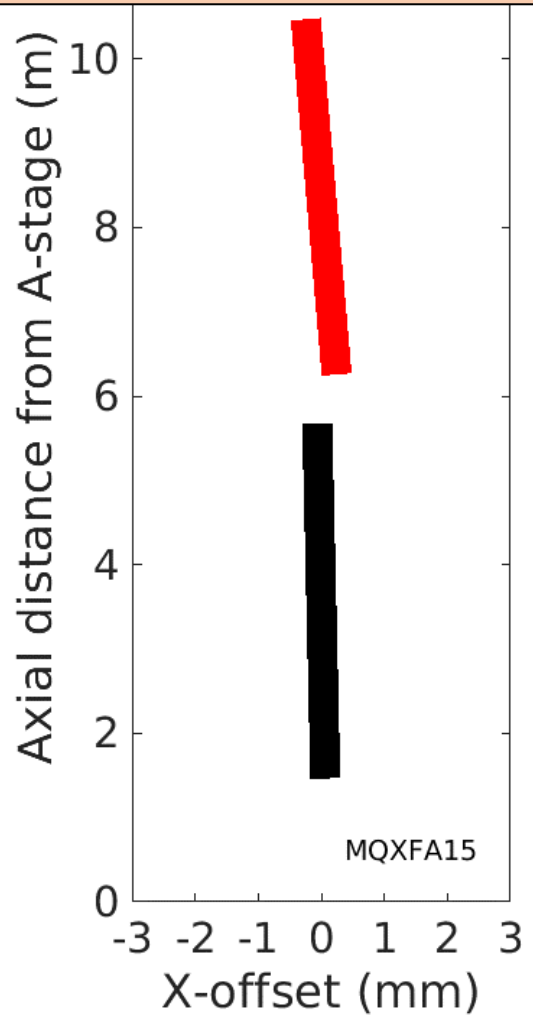
SSW_R_20231031_130136_AC_PitchYaw, SSW_R_20231027_163328_AC_PitchYaw

Alignment Relative to MQXFA15/MQXFA07b Average Center Line
10Jul2024 - Initial Meas.

CM05

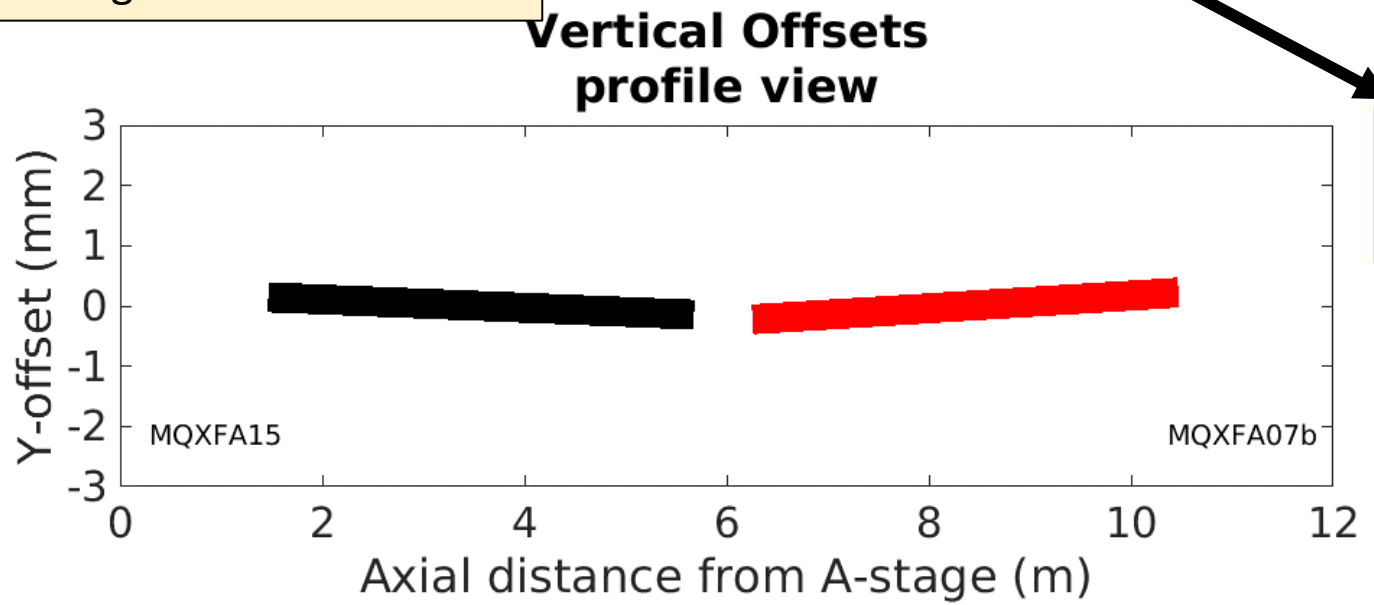
In the initial alignment of CM05, the Z-center separation looked too close (on the edge of allowed range)

MQXFA15 Lead End: X= 0.064, Y= 0.145 mm
MQXFA15 Interface End: X= -0.064, Y= -0.145 mm
MQXFA07b Interface End: X= 0.244, Y= -0.223 mm
MQXFA07b Lead End: X= -0.244, Y= 0.223 mm



A15 roll angle = -0.27 mrad
A07b roll angle = 0.55mrad
Delta angle = 0.82 mrad
Ave angle = 0.14 mrad

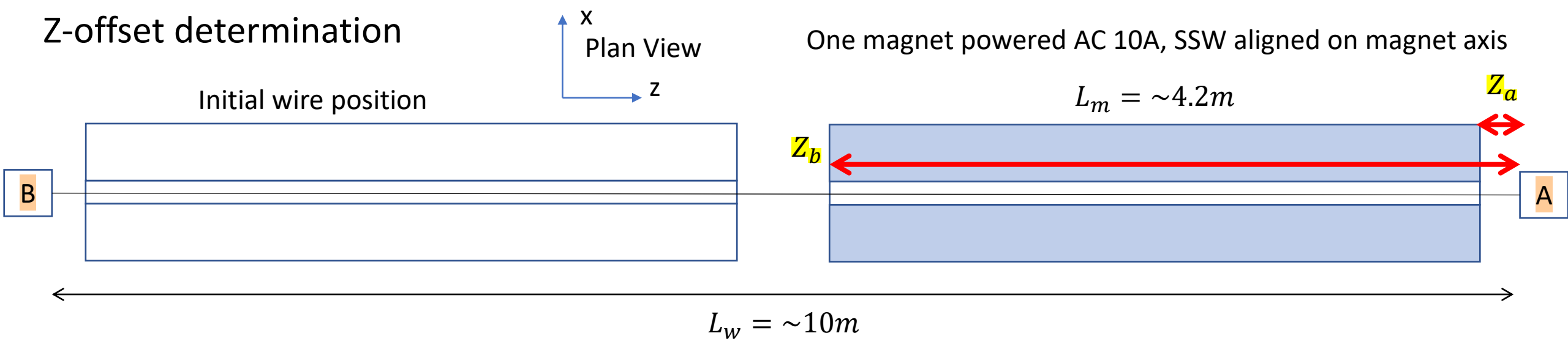
A15 Z-dist A-stage to magnetic center = 3.5665 m
A07b Z-dist B-stage to magnetic center = 3.5644 m
Z-dist A15 to A07b = 4.7843 m (Lw=11.9147 m)



Low by about 9 mm

SSW_R_20240710_172727_AC_PitchYaw, SSW_R_20240710_174549_AC_PitchYaw

Z-offset determination



Including any stage offsets from magnet axis, x_a, x_b, the position of the wire in the magnet for stage position x, y is :

$$x_m = x - \frac{x_b - x_a}{z_b - z_a}(z - z_a) - x_a$$

$$y_m = y - \frac{y_b - y}{z_b - z_a}(z - z_a) - y_a$$

Flux induced for wire motion is

$$\varphi_{CN\pm} = \int_{z=z_a}^{z_b} \int_{x=0}^{x=\pm D\left(1-\frac{2z}{L_w}\right)} g * (b_2 x_m - a_2 y_m)\, dx$$

Where g is the magnet gradient and b_2/a_2 are the normalized normal and skew quadrupole coefficients in the SSW frame (i.e. they allow for tilt of the SSW system wrt magnet)

Z-offset determination (continued)

$$\varphi_{CN\pm} = gL_m * \left(b_2 \frac{D_2}{2} * \left(1 - \frac{2(z_b+z_a)}{L_w} + \frac{4}{3} * \frac{z_a^2+z_b^2+z_a z_b}{L_w^2} \right) \mp additional\ terms \right)$$

If average +/- flux from counter-directional motions

$$\varphi_{CN\_Ave} = \frac{\varphi_{CN+} + \varphi_{CN-}}{2} = gL_m * \left(b_2 \frac{D_2}{2} * \left(1 - \frac{2(z_b + z_a)}{L_w} + \frac{4}{3} * \frac{z_a^2 + z_b^2 + z_a z_b}{L_w^2} \right) \right)$$

Geometry dependent terms

Also know that $z_a + L_m = z_b$

Where L_m is known from warm rotating coil measurements

Combine these to solve for $z_a + L_m/2$ which gives distance from the A-stage to the magnet center

$$z_C \equiv \left(z_a + \frac{L_m}{2} \right) = \frac{L_w}{2} \mp \frac{1}{2 * \sqrt{3}} \sqrt{\frac{6\varphi_{CN\_Ave}}{gL_m D^2} L_w^2 - L_m^2}$$

Estimating resolution and error

$$z_C \equiv \left(z_a + \frac{L_m}{2}\right) = \frac{L_w}{2} \mp \frac{1}{2 * \sqrt{3}} \sqrt{\frac{6\varphi_{CN\_Ave}}{gL_m D^2} L_w^2 - L_m^2}$$

$L_w = 10m$

$g = 0.089 \frac{T}{m} @ 10A, roomTemp$

$D = 0.06m$

$L_m = 4.2\ m$

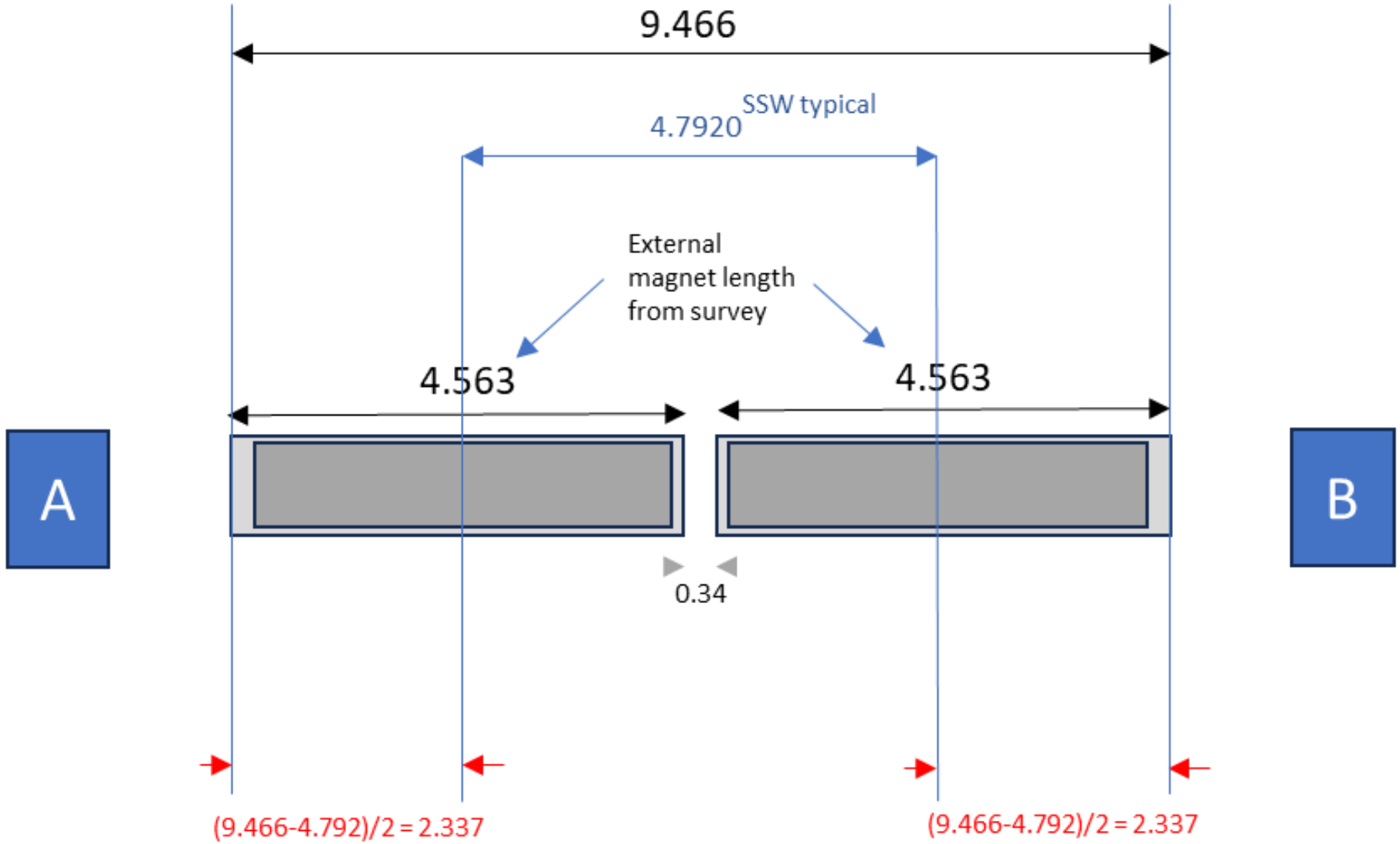
$\varphi_{CN\_Ave} = 1.95\text{x}10^{-4}$ Vs

$$\varphi_{CO\_Ave} = \frac{\varphi_{CO+} + \varphi_{CO-}}{2} = \frac{gL_m D^2}{2}$$

- φ_{CN_Ave} is measured by SSW during warm measurements to better than 5e-8Vs. An error in CN-flux of 2e-7Vs causes an error in z_C of 1.5mm. This implies that the fundamental resolution will be better than 0.5mm.

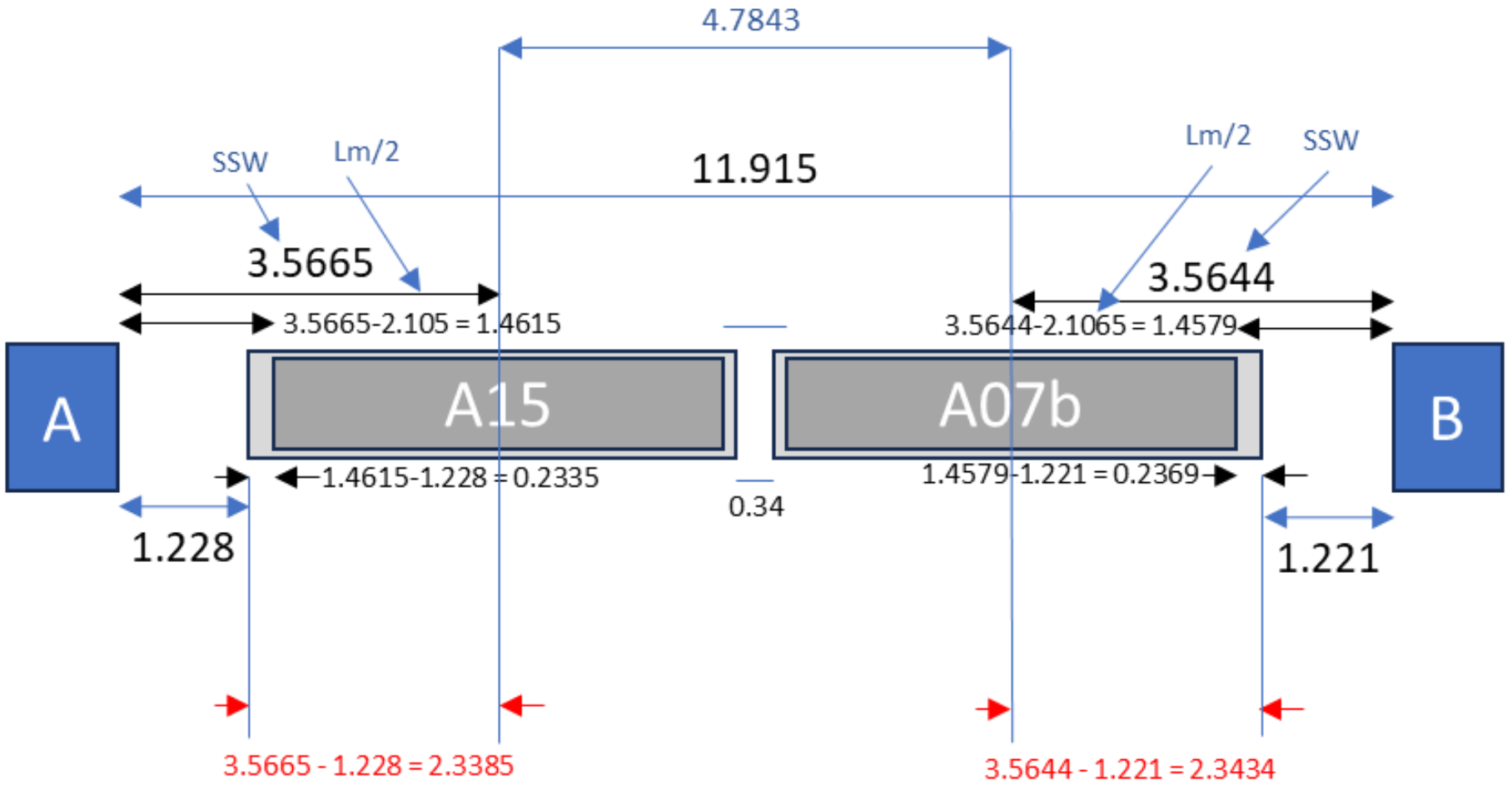
- L_w is measured with laser tracker to better than 100um so is not a significant contribution to measuring Z_c (0.1mm).
- $L_m g D^2 = \sim 1.35 * 10^{-3}\ Vs$ is measured by φ_{CO_ave} during SSW measurements (=average of +/- flux for co-directional stage motions) to a few units (~5e-4 ➔ 5e-7 Vs), which causes error in z_C around 0.5mm.
- L_m is calculated from the warm measurements with rotating coil at LBL/BNL to within ~2mm. This should be the largest error source. If Lm is off by 10mm, the error in Z_c will be 1.5mm, so expect the Lm error to contribute < 0.5mm

Nominally, assuming magnetic lengths are similarly centered in mechanical lengths



For CM05, A15 is 1.5 mm closer to center, and A07b is 6.4 mm closer to center than the nominal 2.337 m

Mechanics were set as normal, but coils were not centered as usual within yokes – especially for A07b



LBNL found a shift toward the return end in MQXFA07b consistent with SSW measurement. Coil center was set to be in the structure center, but there were differences btw lead and return end in each coil causing an offset. Will be monitored more closely in future.

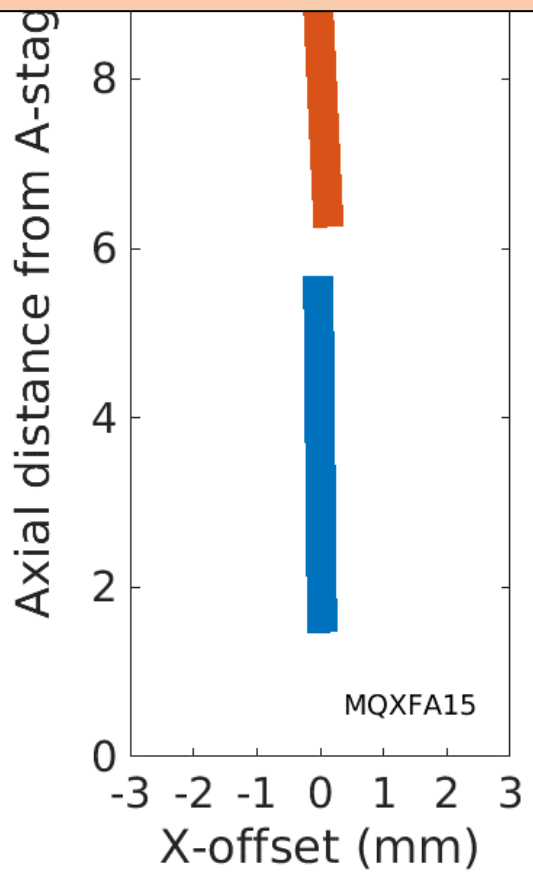
Alignment Relative to MQXFA15/MQXFA07b Average Center Line
7Aug2024 - Initial Meas. - after Zcen repositioning

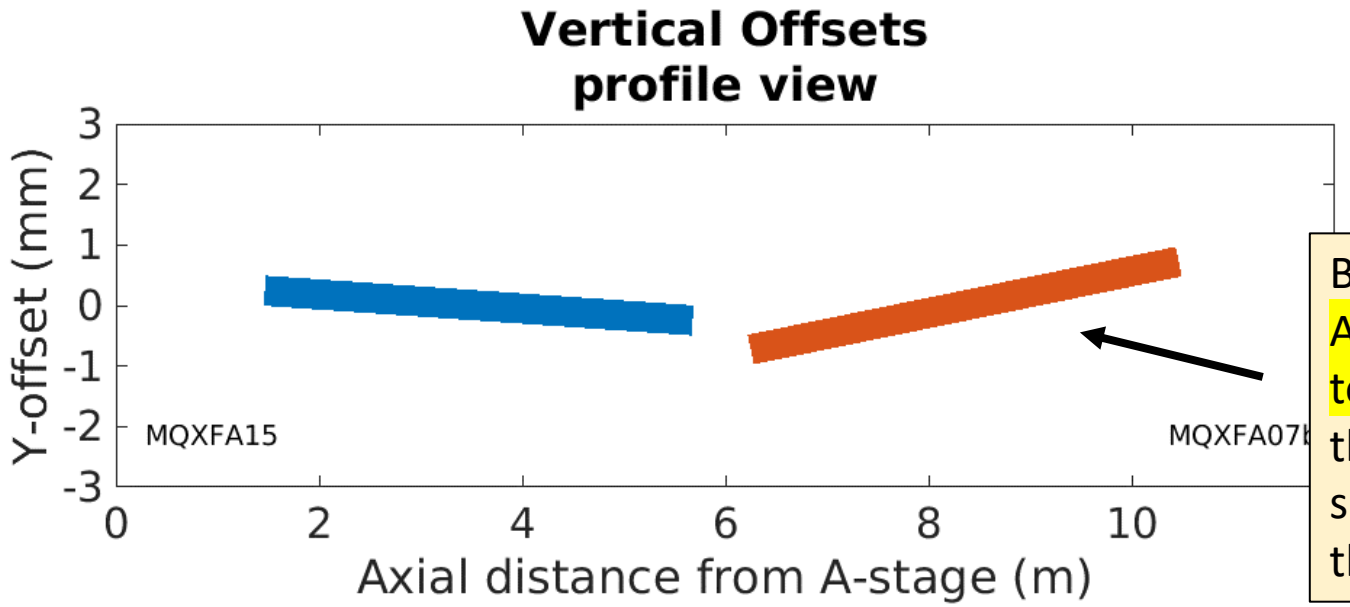
After adjustment of magnet supports in tooling, able to change separation by ~5 mm to be closer to normal and well within allowed range

MQXFA15 Lead End: X= 0.031, Y= 0.245 mm
MQXFA15 Interface End: X= -0.031, Y= -0.245 mm
MQXFA07b Interface End: X= 0.132, Y= -0.727 mm
MQXFA07b Lead End: X= -0.132, Y= 0.727 mm

A15 roll angle = -0.41 mrad
A07b roll angle = -0.07 mrad
Delta angle = 0.33 mrad
Ave angle = -0.24 mrad

A15 Z-dist A-stage to magnetic center = 3.5664 m
A07b Z-dist B-stage to magnetic center = 3.5588 m
Z-dist A15 to A07b = 4.7895 m (Lw=11.9147 m)

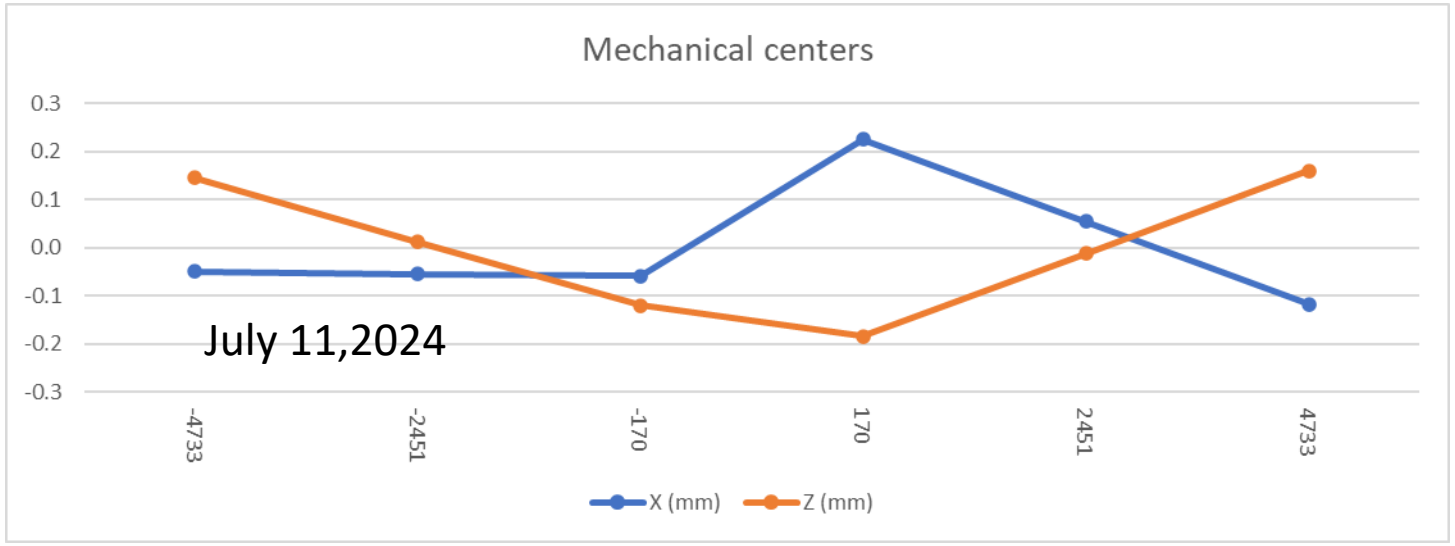


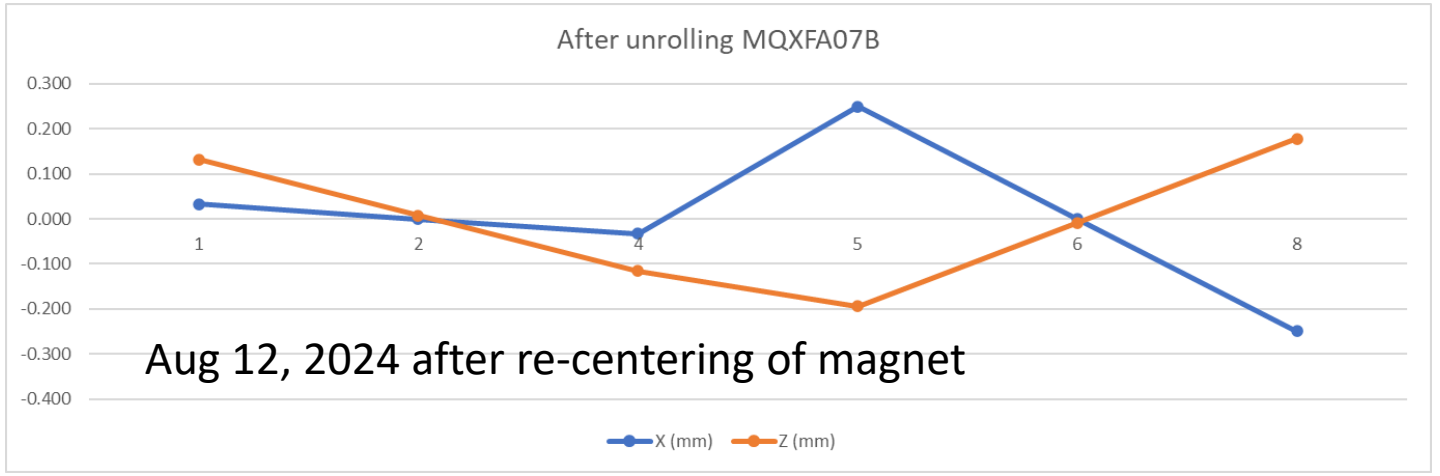


With final roll adjustment

But pitch of A07b seemed to change so that now slightly larger than 0.5 mm

SSW_R_20240807_153720_AC_PitchYaw, SSW_R_20240807_161914_AC_PitchYaw





Mechanical survey of fiducials indicates no significant change in position of magnet ends before and after axial adjustment

Alignment Relative to MQXFA07b/MQXFA15 Average Center Line
13Aug2024 - Meas. check after repositioning and survey - stages swapped

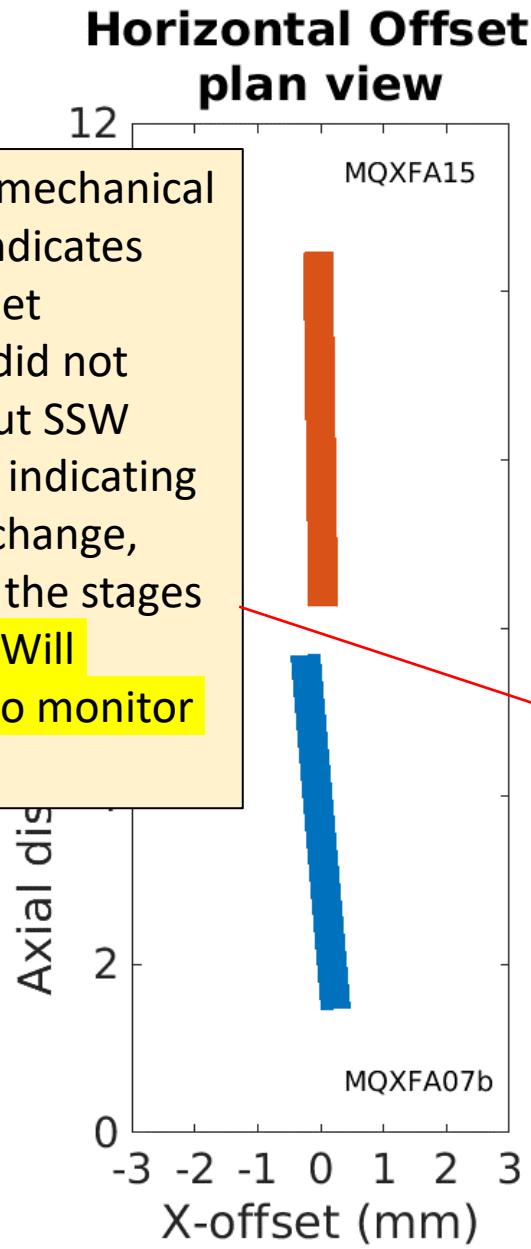
MQXFA07b Lead End: X= 0.241, Y= 0.752 mm
MQXFA07b Interface End: X= -0.241, Y= -0.752 mm
MQXFA15 Interface End: X= 0.040, Y= -0.101 mm
MQXFA15 Lead End: X= -0.040, Y= 0.101 mm

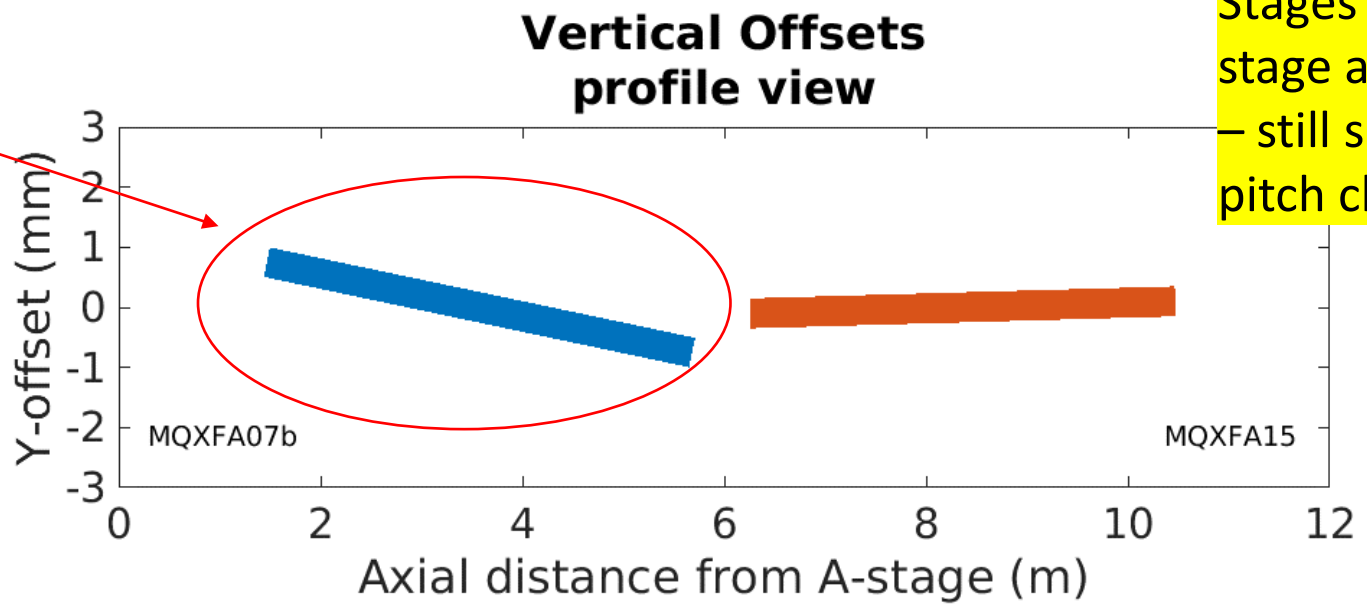
Survey of mechanical position indicates that magnet positions did not change, But SSW persists in indicating the pitch change, even with the stages swapped. Will continue to monitor this…

A15 roll angle = -0.41 mrad
A07b roll angle = -0.07 mrad
Delta angle = 0.33 mrad
Ave angle = -0.24 mrad

A15 Z-dist B-stage to magnetic center = 3.5525 m
A07b Z-dist A-stage to magnetic center = 3.5728 m
Z-dist A15 to A07b = 4.7894 m (Lw=11.9147 m)

Stages Swapped (A-stage at A07b leads) – still see A07b with pitch change

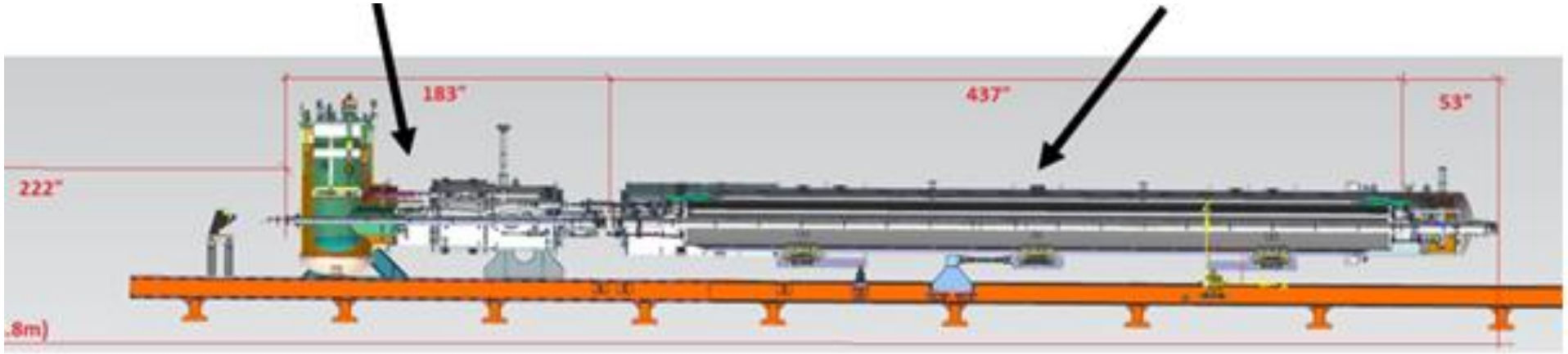




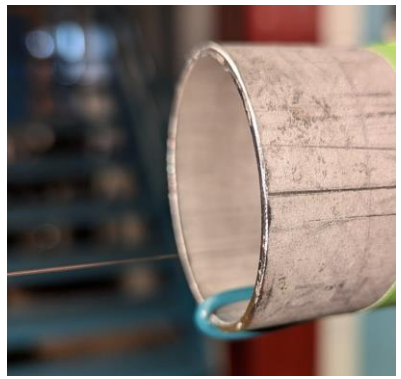
SSW_R_20240813_141531_AC_PitchYaw, SSW_R_20240813_140155_AC_PitchYaw

Feedcan adapter box (warm bore tube diameter ~44 mm)

Magnet assembly (warm bore tube diameter ~102 mm)

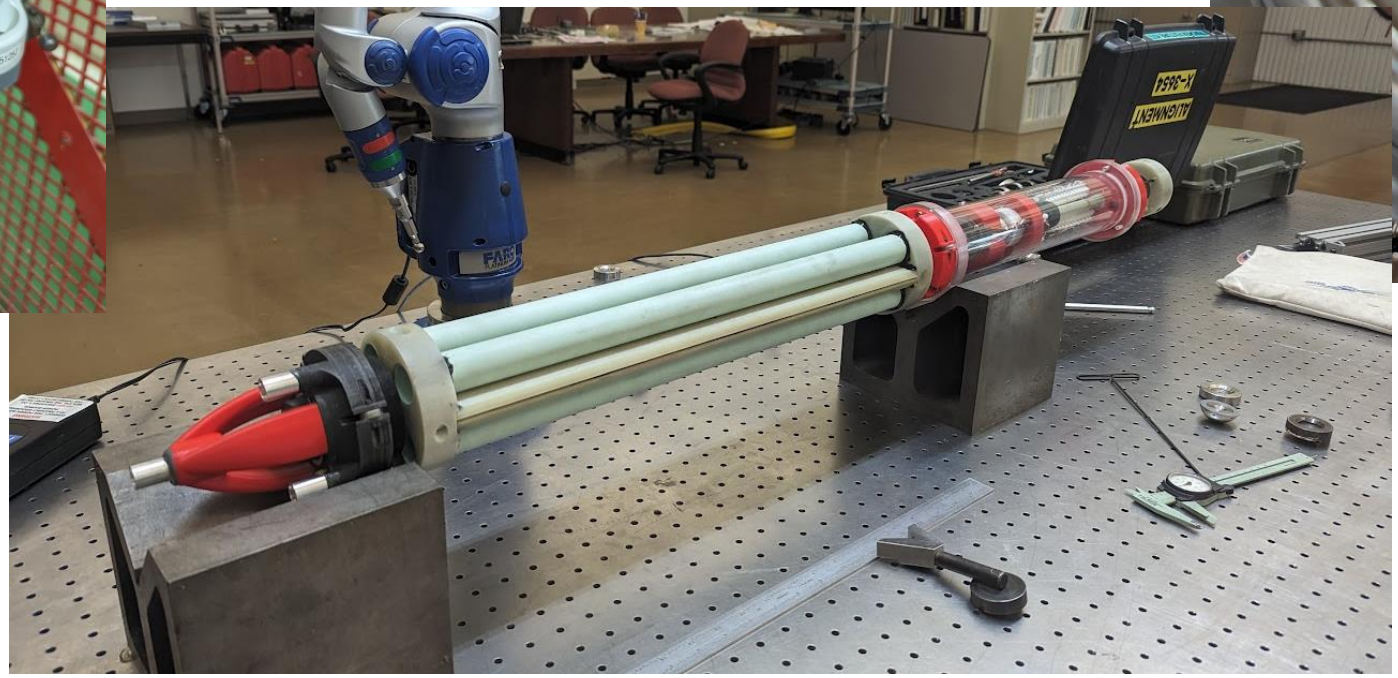


~18 m wire length



At 1.9K, SSW determination of magnet separation not presently accurate enough for cold measurements, at least partially because of more constrained wire motions at one end of the WBT

Ultimately, Z-center separation measured at 1.9 K with rotating coil outfitted with laser tracker targets



LQXFA01 Rotating Coil Summary at 16233A

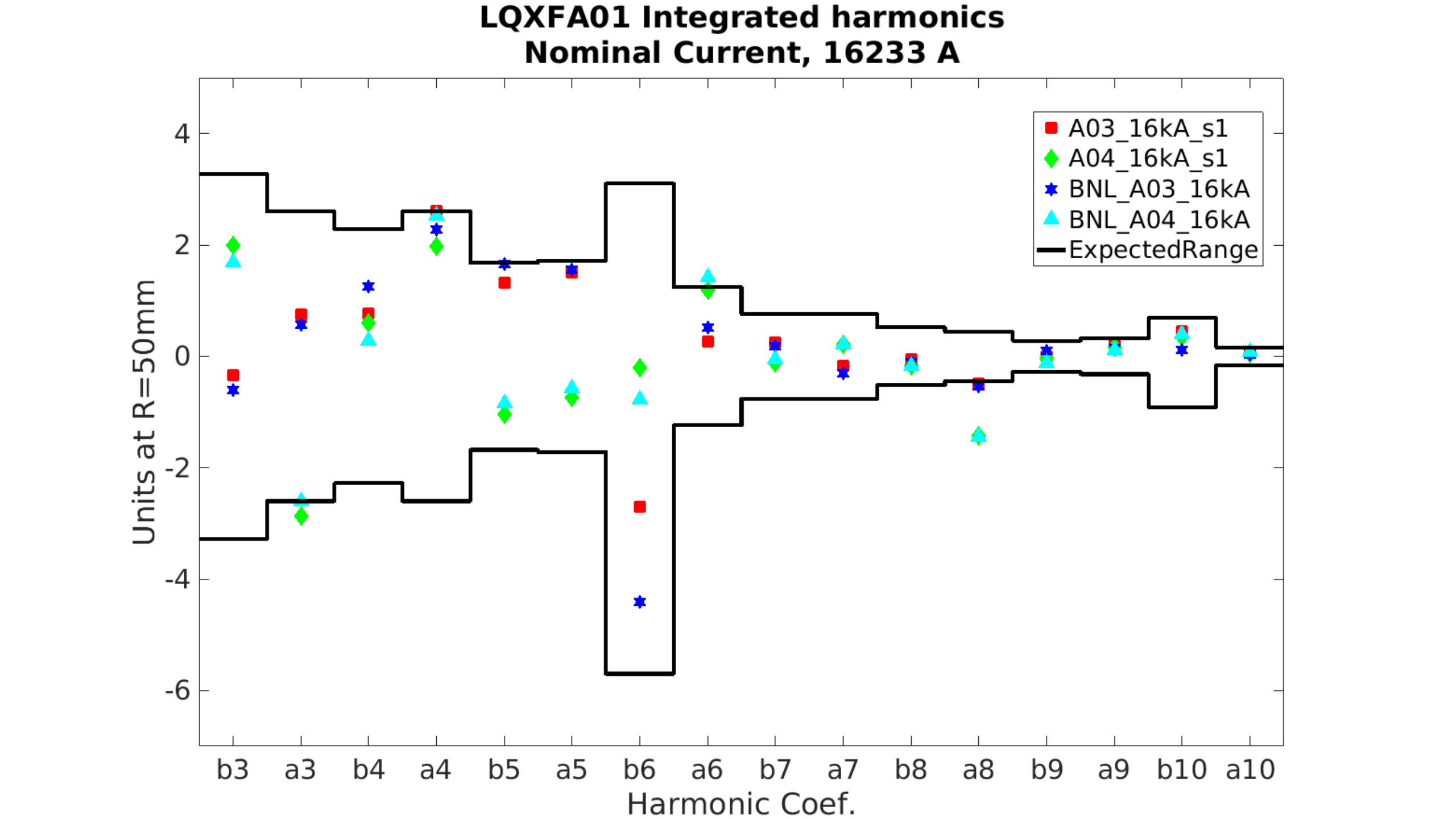
Cryo-Assembly Magnet:	A04	A03
Integral Gdl (T):	559.95	559.70
Magnetic length (m):	4.213	4.216
Body field TF (T/m/kA):	8.187	8.178
Magnet center separation (m):	4.7721	

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

Summary

- SSW measurements are used extensively in fabrication and cold test to determine alignment parameters and integral strength
- Change in alignment when CM was placed on inspection table was observed and corrected starting with CM02
- Separation variance in CM05 was found and adjusted to be within normal range
- Final axial magnet separation at 1.9K determined with rotating coil. Warm to cold axial shift observed was ~17 mm.

Additional Slides


LQXFA01 Integrated harmonics
Nominal Current, 16233 A
A03_16kA_s1
A04_16kA_s1
BNL_A03_16kA
BNL_A04_16kA
ExpectedRange
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.