Overview of magnetic measurements for the Advanced Photon Source Upgrade*

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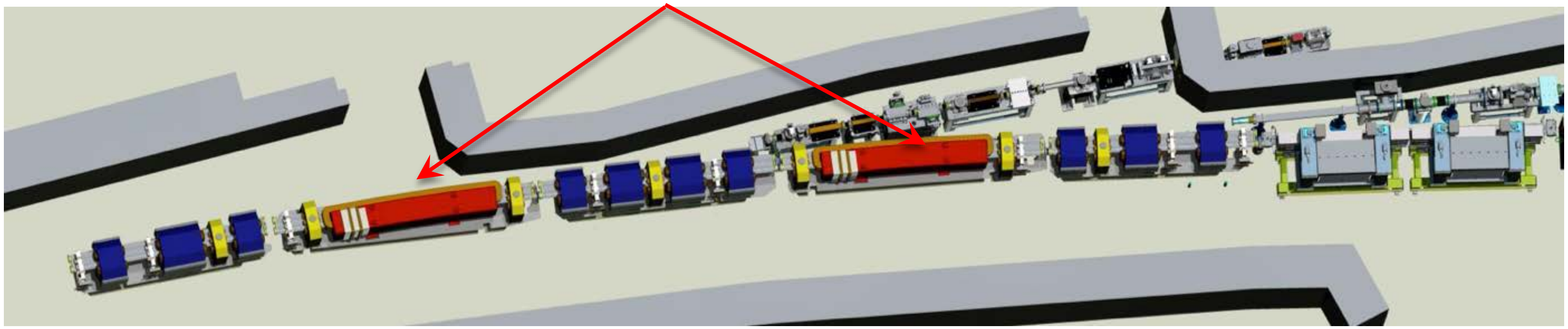
Introduction

- The Advanced Photon Source (APS) is a heavily used light source facility currently operating at the Argonne National Laboratory.
- It is planned to upgrade this facility to provide much brighter beams of X-rays (the APS-U project).
- As part of this upgrade, the entire storage ring will be replaced with a new storage ring based on a 42 pm Multi-bend Achromat (MBA) lattice.
- The new storage ring will contain a total of 1320 new magnets, which will have to be measured and aligned in an assembly of magnets.
- Some of the magnets are regular quadrupoles and sextupoles, and can be easily measured using well established measurement techniques.
- The APS-U will also contain magnets such as the transverse gradient dipoles (Q-bends) which are more challenging from a measurements perspective.
- Plans for measurements of the APS-U magnets are presented here.

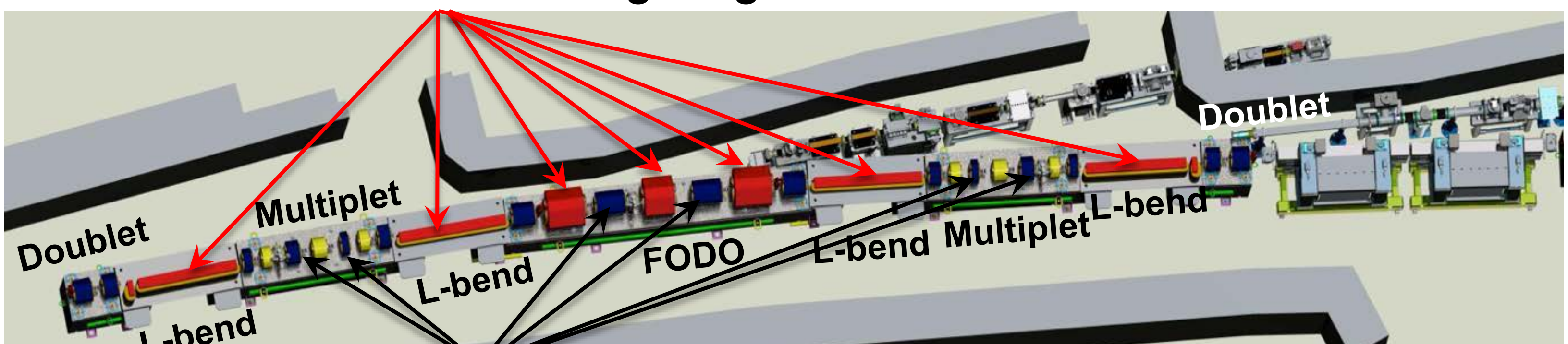
Advanced Photon Source Upgrade (APS-U)

2 bending magnets (Double Bend Achromat)



Present Lattice

7 "forward" bending magnets



Upgrade Lattice

6 "reverse" bending magnets

4 longitudinal gradient dipoles (L-bends; Dipole field only)
3 transverse gradient dipoles (**Q-bends**; dipole + quadrupole fields)
6 reverse bending magnets (**R-bends**; dipole + quadrupole fields)
13 bends total (Multi-bend Achromat)

Simple measurements with rotating coils

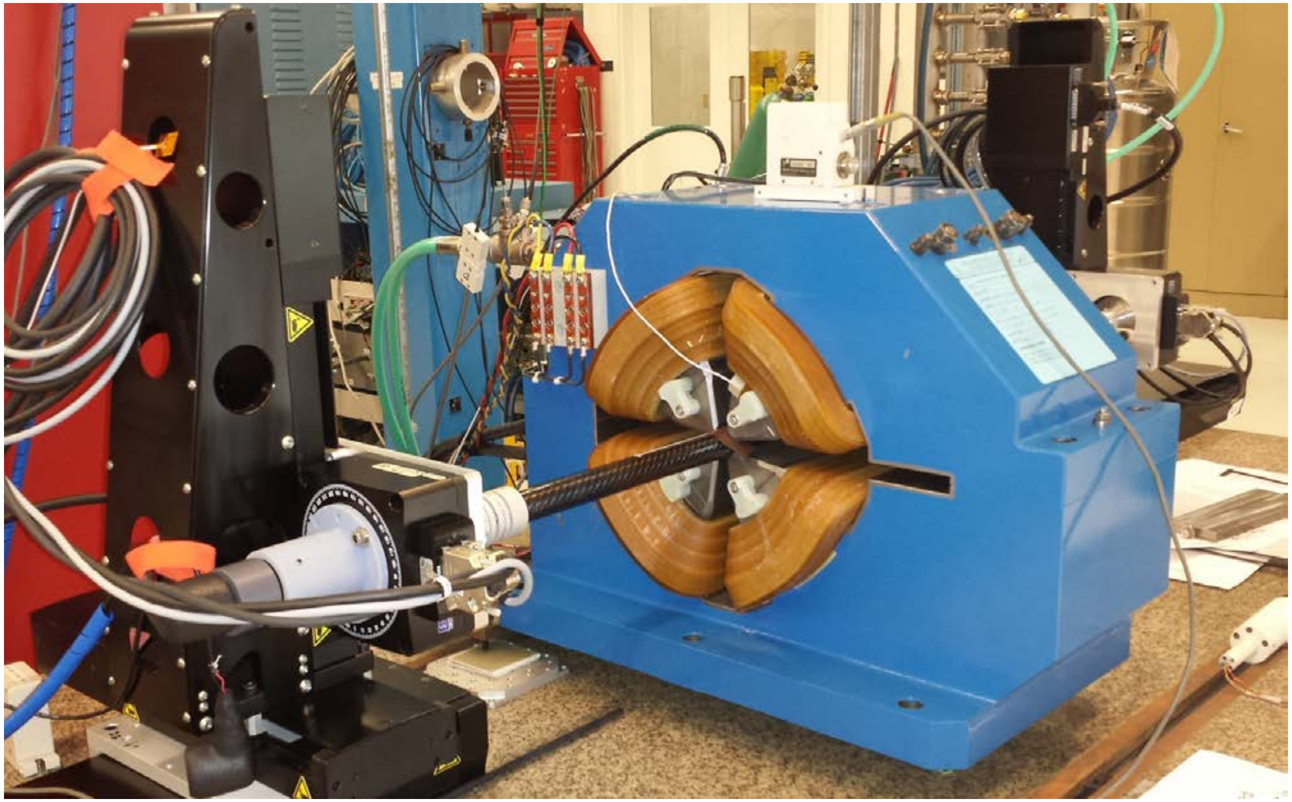
Magnet Type	Length (m)	Quantity	Bend Angle (mr)	Comments
Q1	0.250	80	--	Quadrupole
Q2, Q3, Q6	0.225	240	--	Quadrupoles
Q4*	0.244	80	-1.7069	Sagitta = 0.052 mm
Q5*	0.150	80	-1.1575	Sagitta = 0.022 mm
Q7	0.424	80	--	Quadrupole
Q8*†	0.646	80	-5.3586	Sagitta = 0.433 mm
S1, S3	0.229	160	--	Sextupoles
S2	0.260	80	--	Sextupole
Fast Correctors	0.160	160	--	Normal and skew dipole; skew quad
Total		1040	(~79% of all magnets)	

Two rotating coil lengths should cover all of these magnets.

* Sagitta is small and simple rotating coil measurements should suffice.

† It is not yet determined if Q8 can be measured as a simple quadrupole.

Rotating coil setup in a R&D quadrupole



Active length = 425 mm; 14-layer printed circuit board, built by Fermilab

Unbucked, D-bucked, DQ-bucked, and DQS-bucked signals

Typical noise in higher harmonics is < 10^{-5} of the main field (0.1 “units”)

Similar coils with different lengths will be built for other magnet types.

See the talk by Roger Dejus on Thu June 8, for measurement results in R&D magnets.

Simple measurements with Hall probes

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M1	2.225	80	28.5716	5-segment L-bend B_{max}/B_{min} ~ 4.6
M2	1.985	80	23.2944	5-segment L-bend B_{max}/B_{min} ~ 2
Total		160	(~12% of all magnets)	

- These magnets are built straight, but the beam is curved with a curvature changing with axial position, as the field changes.
- These magnets will be mapped on a rectangular grid at the magnet midplane.
- The Hall maps will be used to:
  – Ensure that the field integral on a nominal beam path is within tolerance (< ±0.1% magnet-to-magnet variation), and adjust the end shields if necessary.
  – Determine the optimal installation of the magnet to preserve the vertex point and minimize beam excursion from the magnet centerline.

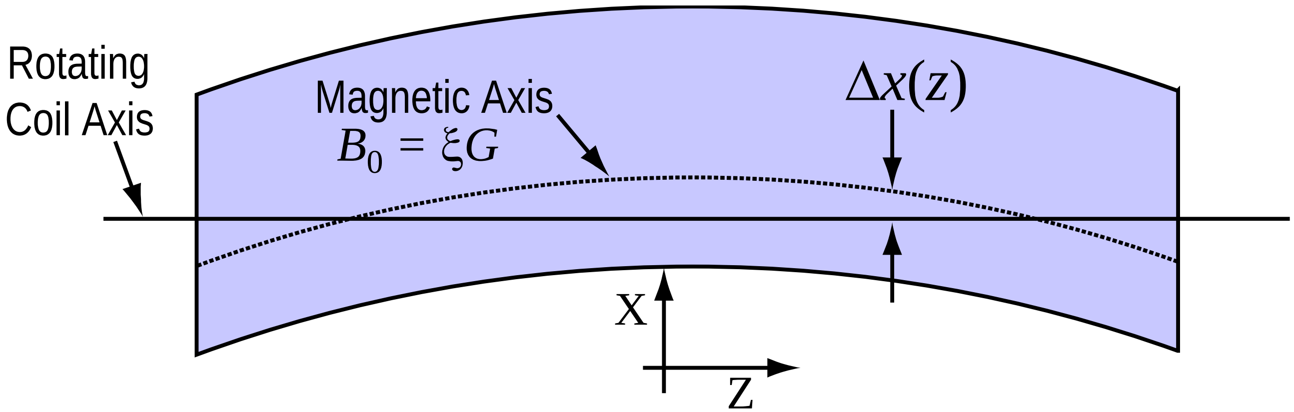
Most challenging magnet types

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M3	0.820	80	25.0793	Sagitta = 2.571 mm
M4	0.700	40	19.6350	Sagitta = 1.718 mm
Total*		120	(~9% of all magnets)	

* Note: *The Q8 magnets (Qty 80) with a sagitta of ~0.4 mm may also end up in this category*

- These magnets have strong dipole and quadrupole components.
- Magnet yokes are built straight, but are fitted with curved pole tips.
- Hall maps are inconvenient to measure (no access from the side).
- Also need to locate the “magnetic center” precisely enough for aligning to other magnets in the same FODO assembly to 0.030 mm.
- Need to devise new measurement methods that can be easily applied in a production environment (best to adapt well known techniques).
- A scheme has been developed to measure field quality using a straight rotating coil, and magnetic center using straight wires.

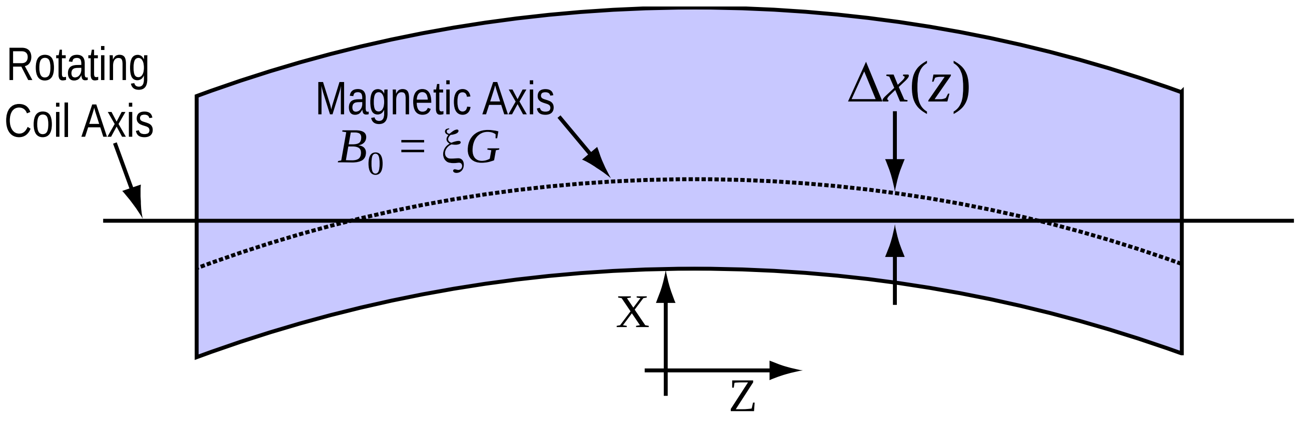
Q-bend measurements using a straight rotating coil



Hard Edge model; Dipole and quadrupole fields are assumed constant along the curved magnetic axis, and zero outside the magnet.

- Curved and straight path lengths are the same within ~20 ppm
- Quadrupole term is not affected by small offsets (< 1 mm), as long as the sextupole and other higher order terms are small.
- Integrated quadrupole field can be obtained with sufficient accuracy, limited mainly by the absolute calibration.
- Dipole and other harmonic terms are affected by offsets $\Delta x(z)$.

Q-bend measurements: The dipole term



Hard Edge model; Harmonics assumed constant along the curved magnetic axis, and zero outside the magnet.

Measured dipole field = $(B_0 L)' = \int_0^L \left[B_0 + G\Delta x(z)\right] dz$ [to first order in $\Delta x(z)$]

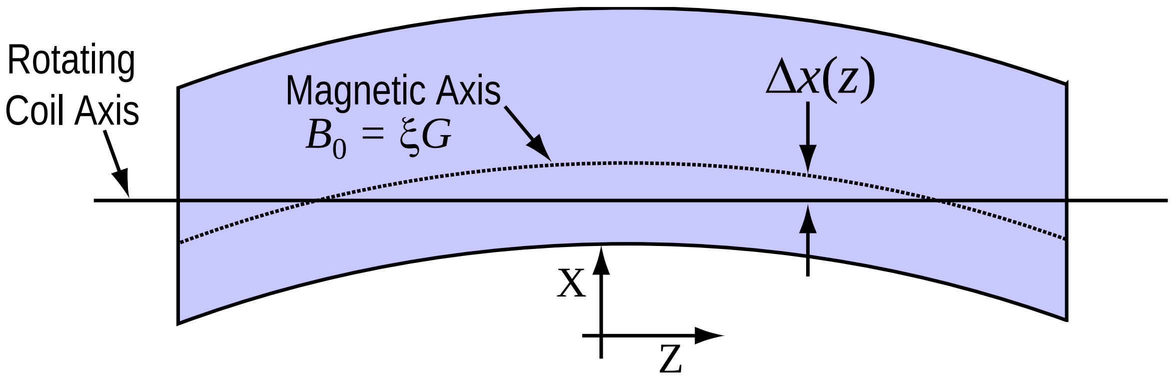
$$= (B_0 L) + (GL)\left(\overline{\Delta x}\right) \qquad \overline{\Delta x} = \frac{1}{L}\int_0^L \Delta x(z)\, dz$$

$$\frac{(B_0 L)'}{GL} = \frac{(B_0 L)}{GL} + \overline{\Delta x} = \xi + \overline{\Delta x}$$

If the data are centered (by post-processing) such that the dipole to quadrupole ratio is ξ as per design, then the average offset of rotating coil is zero. => Dipole term is not really measured, it is *enforced*.

(Nothing new here, it is standard practice for regular quadrupoles!)

Q-bend measurements: higher harmonics



Hard Edge model; Harmonics assumed constant along the curved magnetic axis, and zero outside the magnet.

Measured Normal (B_n) and Skew (A_n) Harmonics:

$$(B'_n + iA'_n)L = \int_0^L \sum_{k=n}^{\infty} (B_k + iA_k)L \left[\frac{k!}{n!(k-n)!}\right] \left(\frac{\Delta x(z)}{R_{ref}}\right)^{k-n} dz$$

(n = 0 is dipole)

$$\approx (B_n + iA_n)L + (n+1)(B_{n+1} + iA_{n+1})L \left(\frac{\overline{\Delta x}}{R_{ref}}\right)$$

[to first order in $\Delta x(z)$]

If the data are centered such that the dipole to quadrupole ratio is as per design, then the average offset, $\overline{\Delta x}$, is zero. Measured harmonics should be OK.

The curvature of pole tips may limit the radius of rotating coil that can be used.

Real Q-bend magnets: will a rotating coil work?

- The analysis assumes a hard edge model, with constant harmonics along the beam trajectory.
- In real life, the field falls off gradually at the ends, and there are strong end harmonics. These features may invalidate the simple data analysis presented so far.
- How to know if the proposed scheme will really work?
  - Detailed Opera-3D simulations of Q-bends exists (M. Jaski)
  - Use field harmonics from Opera-3D simulations to compute the *true integral* on the curved path, and also to compute the *measured integral* on a straight path.
  - Apply the analysis described earlier to the *measured integral* and see if the results are close to the *true integral*.
  - Results of simulations for a M4 magnet are presented here.

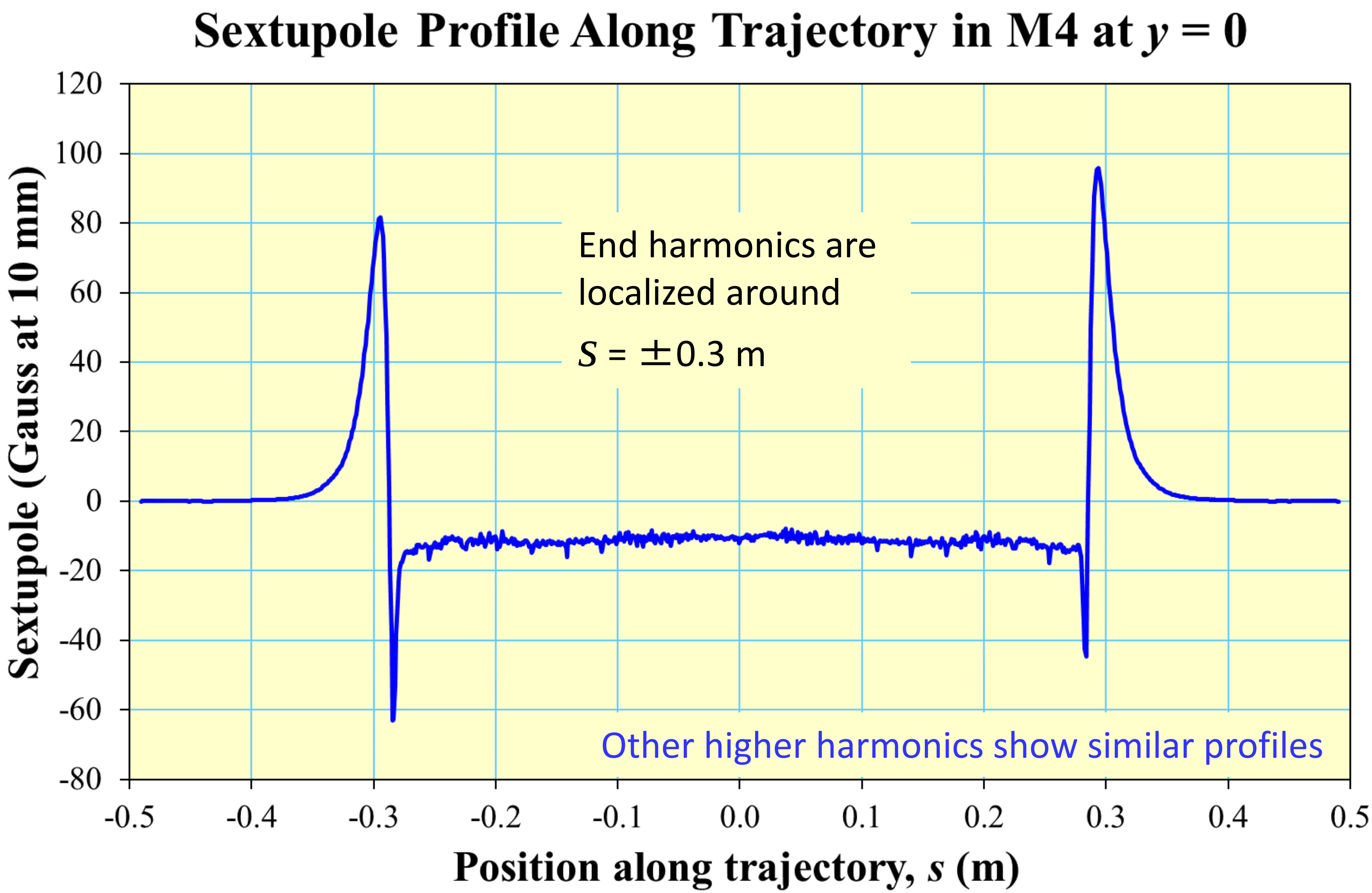
Simulation of rotating coil measurement in M4

Desired B0/G=	-12.7994 mm	Offset applied =	-0.1457 mm
X_Center_Final =	-12.580 mm	X_Ends_Final =	-12.580 mm
Offset Error =	0.0000 mm		

Computed integral after Offset:			True values on curve		Error	
n	T.m	Units	T.m	Units		
0	-3.930E-01	-10000	-3.928E-01	-10000	0.037%	
1	3.070E-01	7812.9	3.069E-01	7812.9	0.037%	
2	-4.006E-04	-10.2	-2.905E-04	-7.4	-2.8	units @ 10 mm
3	-5.045E-04	-12.8	-5.717E-04	-14.6	1.7	units @ 10 mm
4	9.749E-06	0.2	1.282E-06	0.0	0.2	units @ 10 mm
5	-2.701E-04	-6.9	-2.346E-04	-6.0	-0.9	units @ 10 mm
6	2.587E-05	0.7	-1.028E-05	-0.3	0.9	units @ 10 mm
7	-2.557E-05	-0.7	2.704E-05	0.7	-1.3	units @ 10 mm
8	4.660E-04	11.9	3.809E-04	9.7	2.2	units @ 10 mm
9	-4.760E-04	-12.1	-3.643E-04	-9.3	-2.8	units @ 10 mm
10	-7.056E-06	-0.2	-1.215E-04	-3.1	2.9	units @ 10 mm
11	1.843E-04	4.7	2.870E-04	7.3	-2.6	units @ 10 mm
12	2.186E-04	5.6	1.279E-04	3.3	2.3	units @ 10 mm
13	-5.800E-04	-14.8	-5.154E-04	-13.1	-1.6	units @ 10 mm
14	3.521E-04	9.0	3.542E-04	9.0	-0.1	units @ 10 mm
15	1.846E-04	4.7	1.008E-04	2.6	2.1	units @ 10 mm
16	-3.953E-04	-10.1	-2.806E-04	-7.1	-2.9	units @ 10 mm
17	1.780E-04	4.5	8.221E-05	2.1	2.4	units @ 10 mm

Using a simple straight line integral measurement gives errors of up to ~ 3 units.

Axial distribution of sextupole term in M4

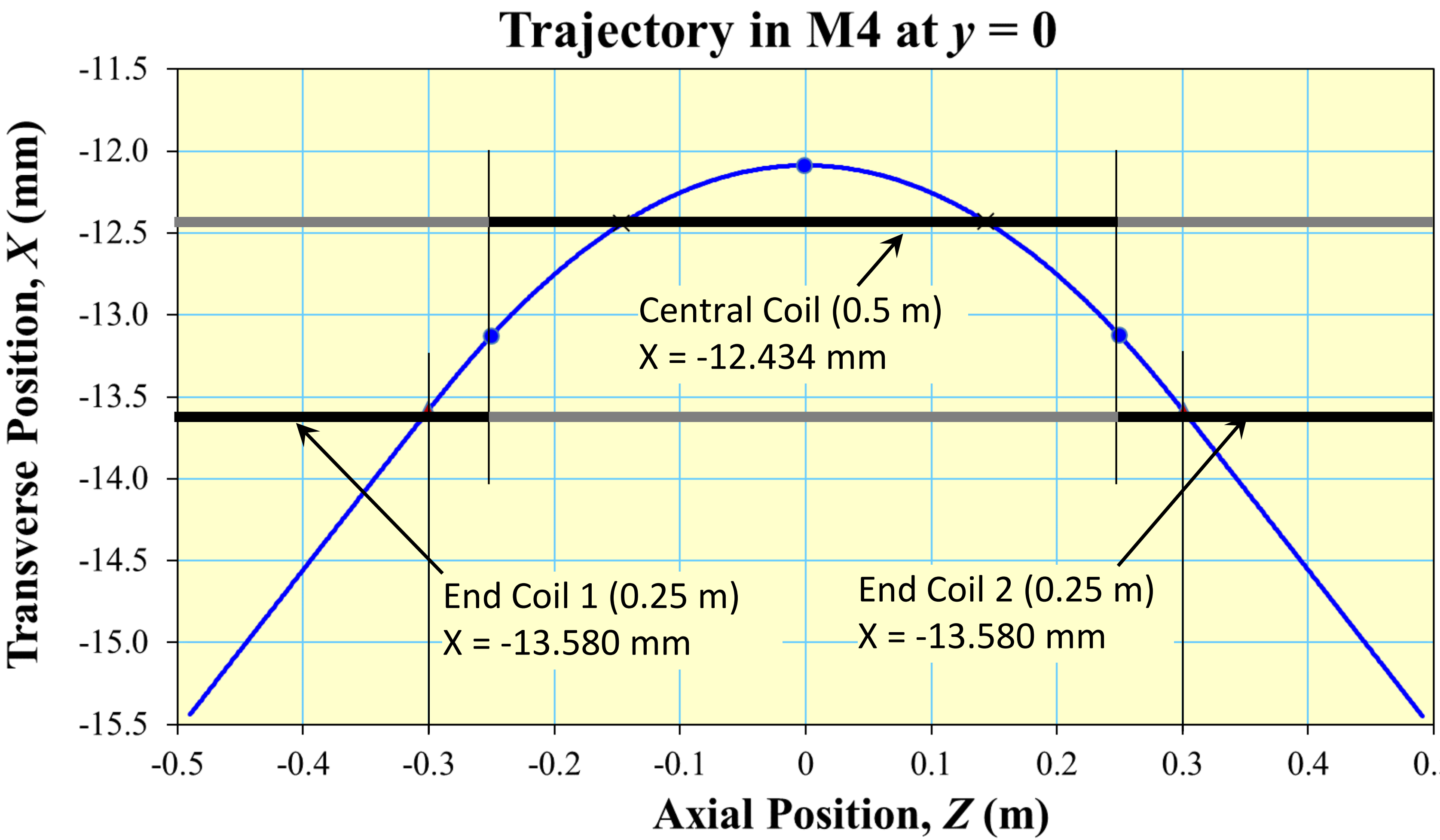


Based on data from *M. Jaski, APS*

How to improve the measurement accuracy?

- The simple averaging of offsets does not work because the field harmonics are not constant along the curve.
- There is a central region of ~0.5 m with nearly constant harmonics. The method should work if applied to integral over the central 0.5 m only.
- Since the end harmonics are highly localized, their contribution can be measured correctly if the rotating coil is placed at the trajectory position where the end harmonics have a peak.
  - **Measure central 0.5 m region at one transverse position**
  - **Measure the two ends at another transverse position, suitably offset from the first position.**

Selecting the ideal locations for measurement



Ends should be measured with an offset of -1.146 mm from the central coil (for this particular design of the M4 type Q-bend magnet)

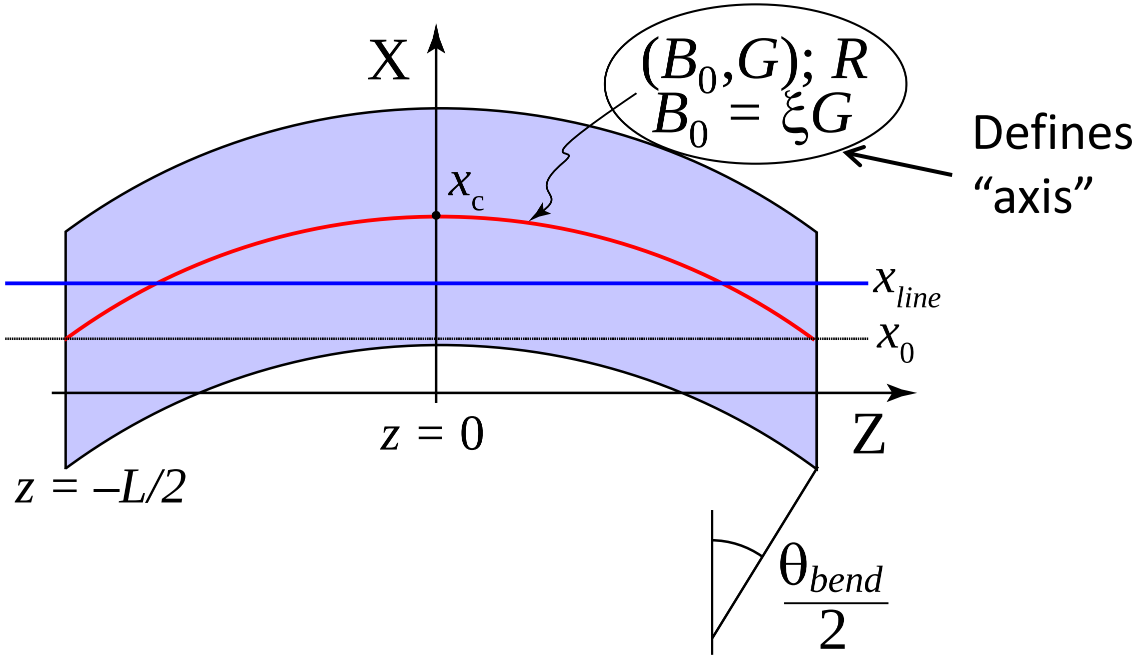
Simulation of 3-part rotating coil measurement in M4

Desired B0/G=	-12.7994 mm		Offset applied =	0.0316 mm
X_Center_Final =	-12.402 mm		X_Ends_Final =	-13.548 mm
Offset error =	0.0000 mm			

			True values on curve		Error	
n	T.m	Units	T.m	Units		
0	-3.929E-01	-10000	-3.928E-01	-10000	0.016%	
1	3.070E-01	7812.9	3.069E-01	7812.9	0.016%	
2	-2.998E-04	-7.6	-2.905E-04	-7.4	-0.2	units @ 10 mm
3	-5.662E-04	-14.4	-5.717E-04	-14.6	0.1	units @ 10 mm
4	-8.166E-06	-0.2	1.282E-06	0.0	-0.2	units @ 10 mm
5	-2.191E-04	-5.6	-2.346E-04	-6.0	0.4	units @ 10 mm
6	-2.949E-05	-0.8	-1.028E-05	-0.3	-0.5	units @ 10 mm
7	4.458E-05	1.1	2.704E-05	0.7	0.4	units @ 10 mm
8	3.699E-04	9.4	3.809E-04	9.7	-0.3	units @ 10 mm
9	-3.717E-04	-9.5	-3.643E-04	-9.3	-0.2	units @ 10 mm
10	-8.693E-05	-2.2	-1.215E-04	-3.1	0.9	units @ 10 mm
11	2.381E-04	6.1	2.870E-04	7.3	-1.2	units @ 10 mm
12	1.637E-04	4.2	1.279E-04	3.3	0.9	units @ 10 mm
13	-5.242E-04	-13.3	-5.154E-04	-13.1	-0.2	units @ 10 mm
14	3.436E-04	8.7	3.542E-04	9.0	-0.3	units @ 10 mm
15	1.234E-04	3.1	1.008E-04	2.6	0.6	units @ 10 mm
16	-3.169E-04	-8.1	-2.806E-04	-7.1	-0.9	units @ 10 mm
17	1.219E-04	3.1	8.221E-05	2.1	1.0	units @ 10 mm

The revised scheme gives errors typically < 1 unit, comparable to Opera-3D errors.

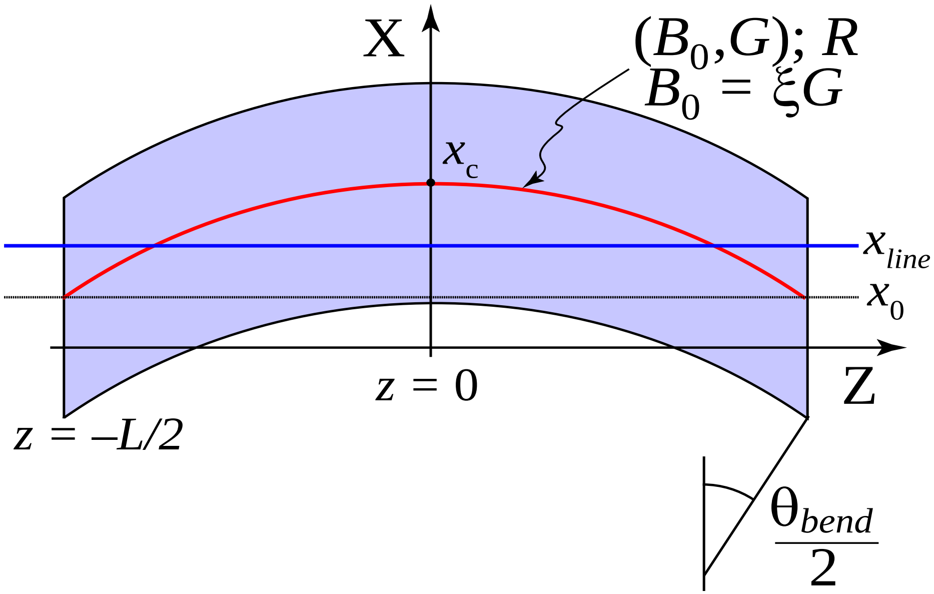
Wire based measurements of the axis of Q-bends

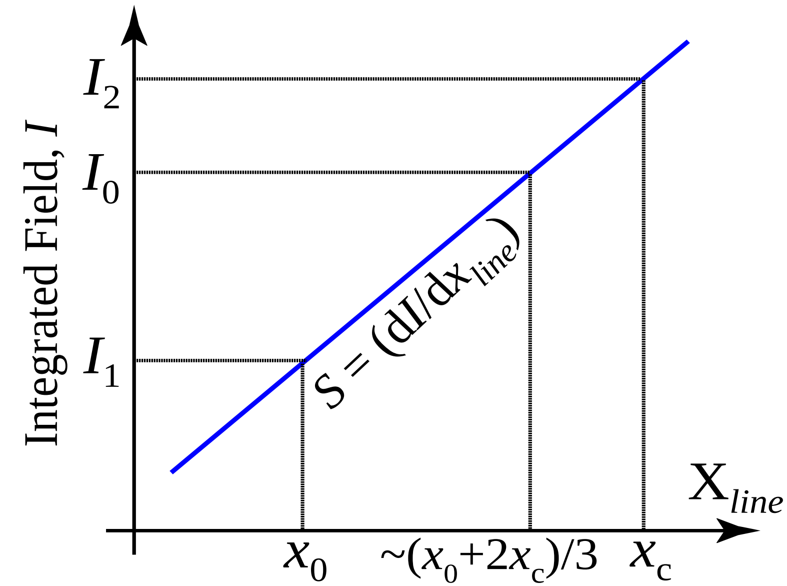


For the APS-U Q-bend magnets, 0.1 mm alignment error will consume about 20% of the total bending correction available.
$\Rightarrow$ Need to align much better than 0.1 mm in X.
Tolerance: 30 μm rms.

- Known Parameters: R, ξ, θ_{bend}
- Integration path is assumed parallel to tangent at x_c
  (Analysis of general case shows up to 20 mr misalignment is acceptable; < 5 mr should be easily achievable.)
- Goal is to locate the point x_c relative to magnet fiducials. This information can then be used to align the magnet.

Center of Q-bend based on Integral along a line





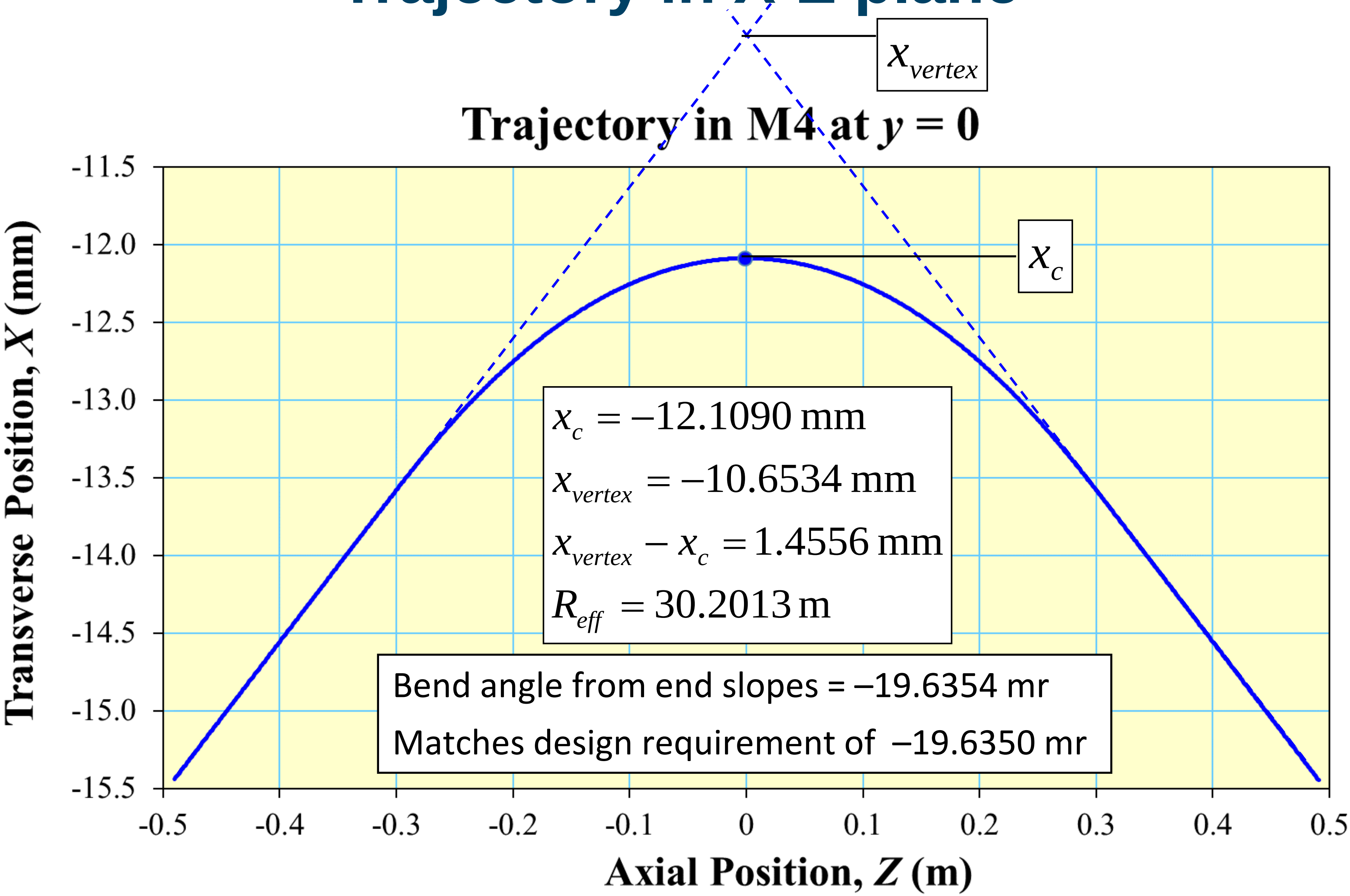
$$I_2 = S\left[\xi + R\left\{1-\frac{\theta_{bend}+\sin\theta_{bend}}{4\sin(\theta_{bend}/2)}\right\}\right] \approx S\left[\xi + \frac{R\theta_{bend}^2}{24}\right]$$

$$x_{vertex} = x_c + R\left[\frac{1-\cos(\theta_{bend}/2)}{\cos(\theta_{bend}/2)}\right]$$

Knowing Integrated field Vs. X , the “center” can be determined using other known constants.

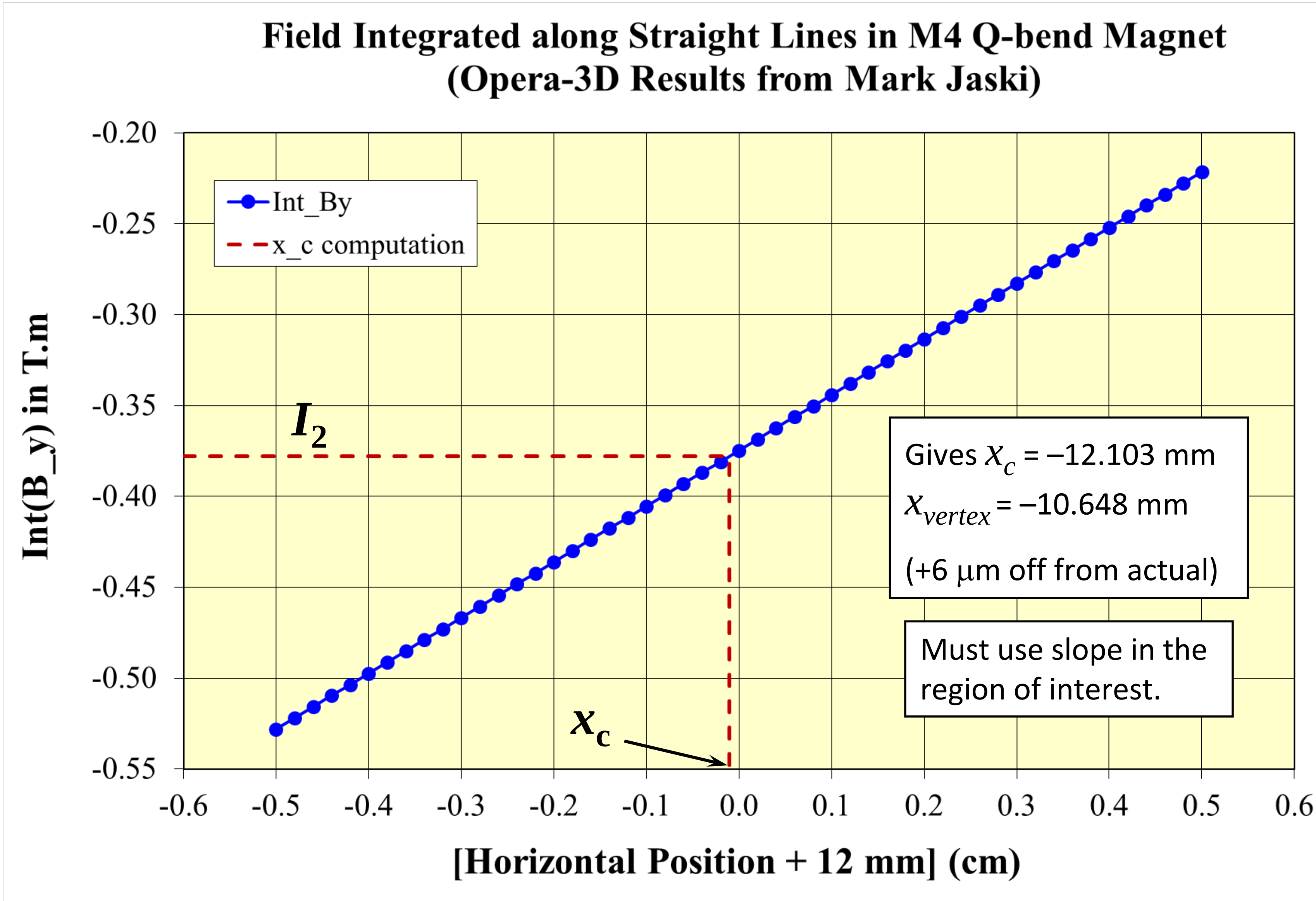
Absolute measurement is not needed: any wire based method should work.

Trajectory in X-Z plane

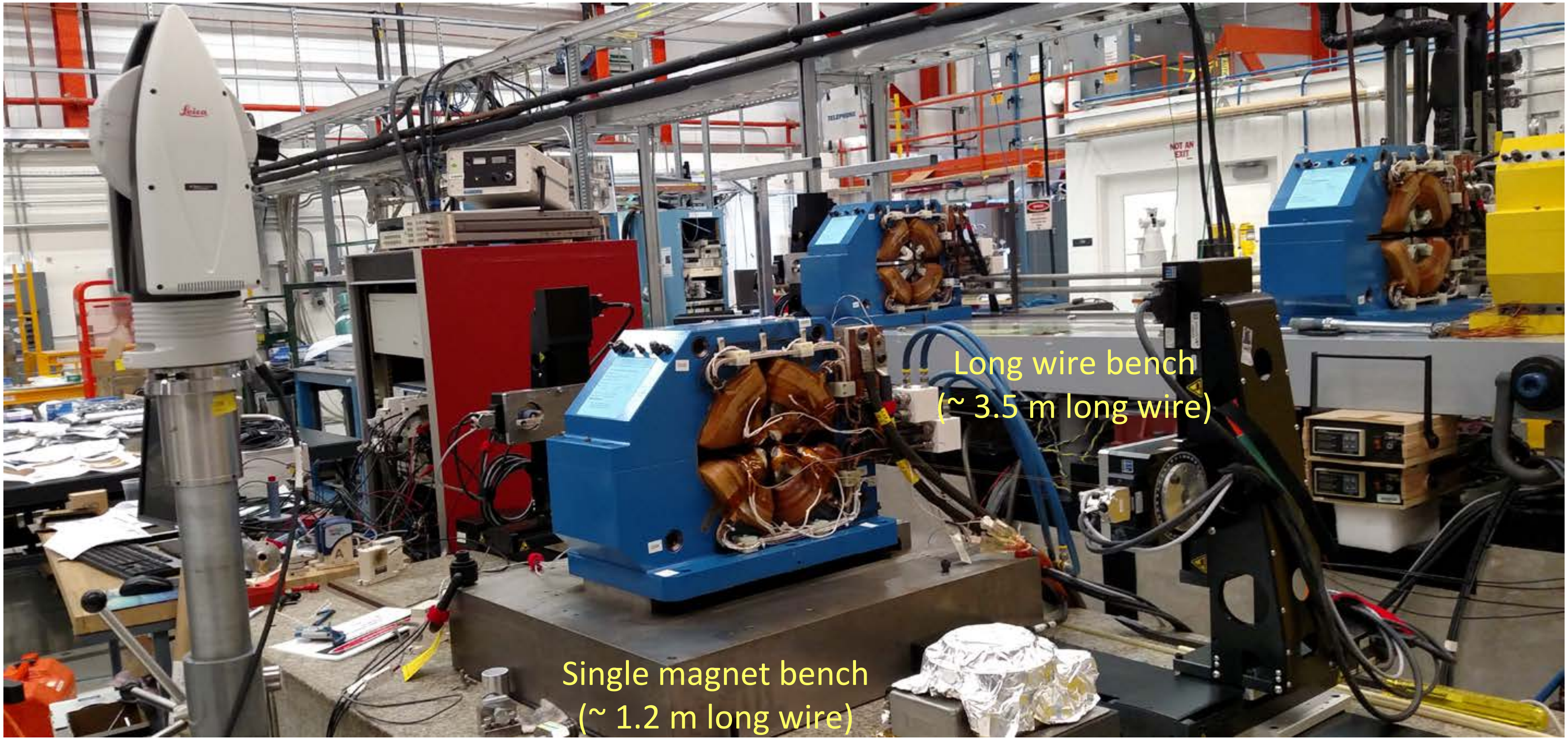


Based on data from *M. Jaski, APS*

Test of Q-bend axis measurement principle



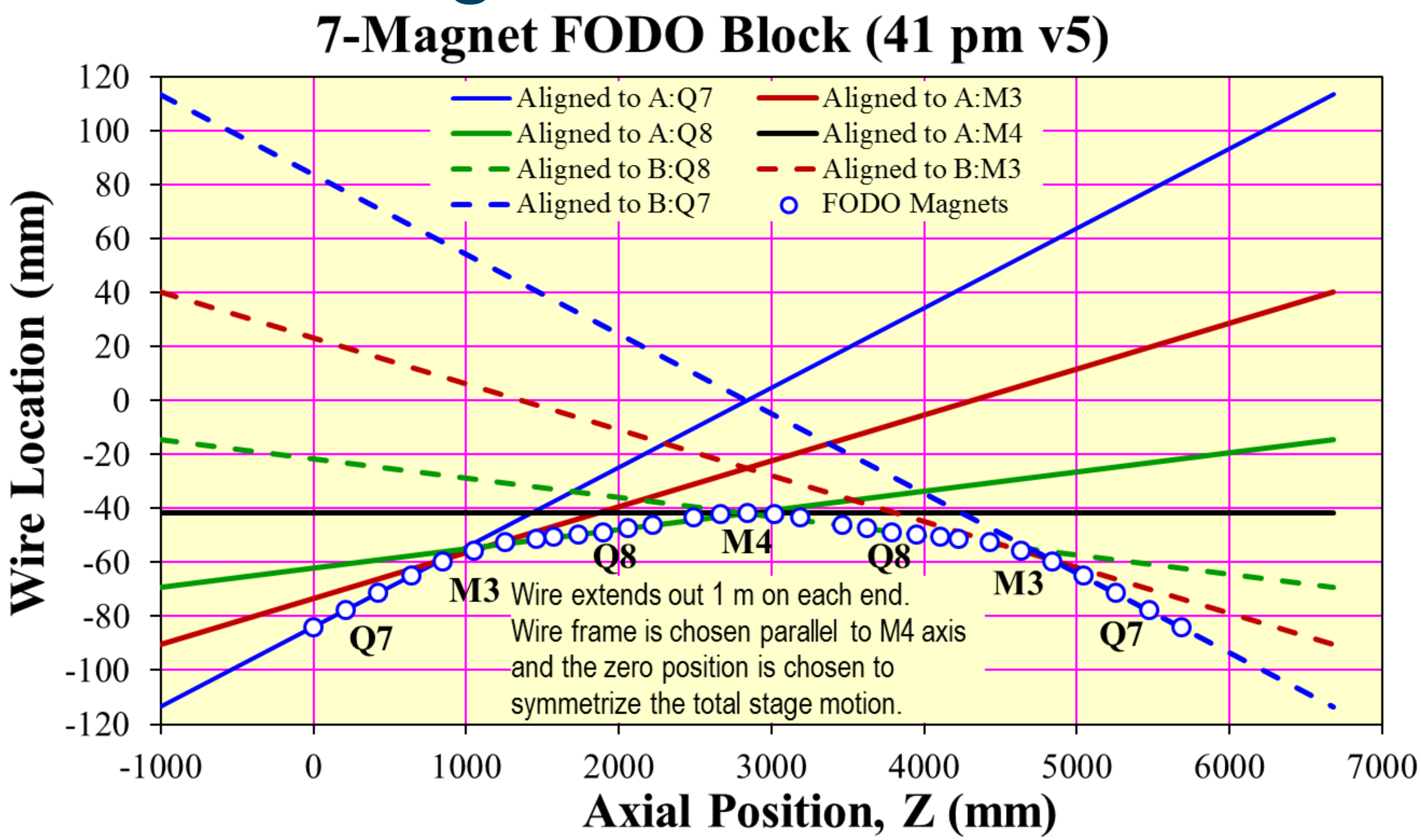
Rotating wire setup at APS



A rotating wire system can be used to measure the integrated dipole field as a function of X-position, and then derive the magnetic center.

See presentation by C. Doose in the "Alignment" session for more details on the rotating wire technique and results from magnet fiducialization experiments.

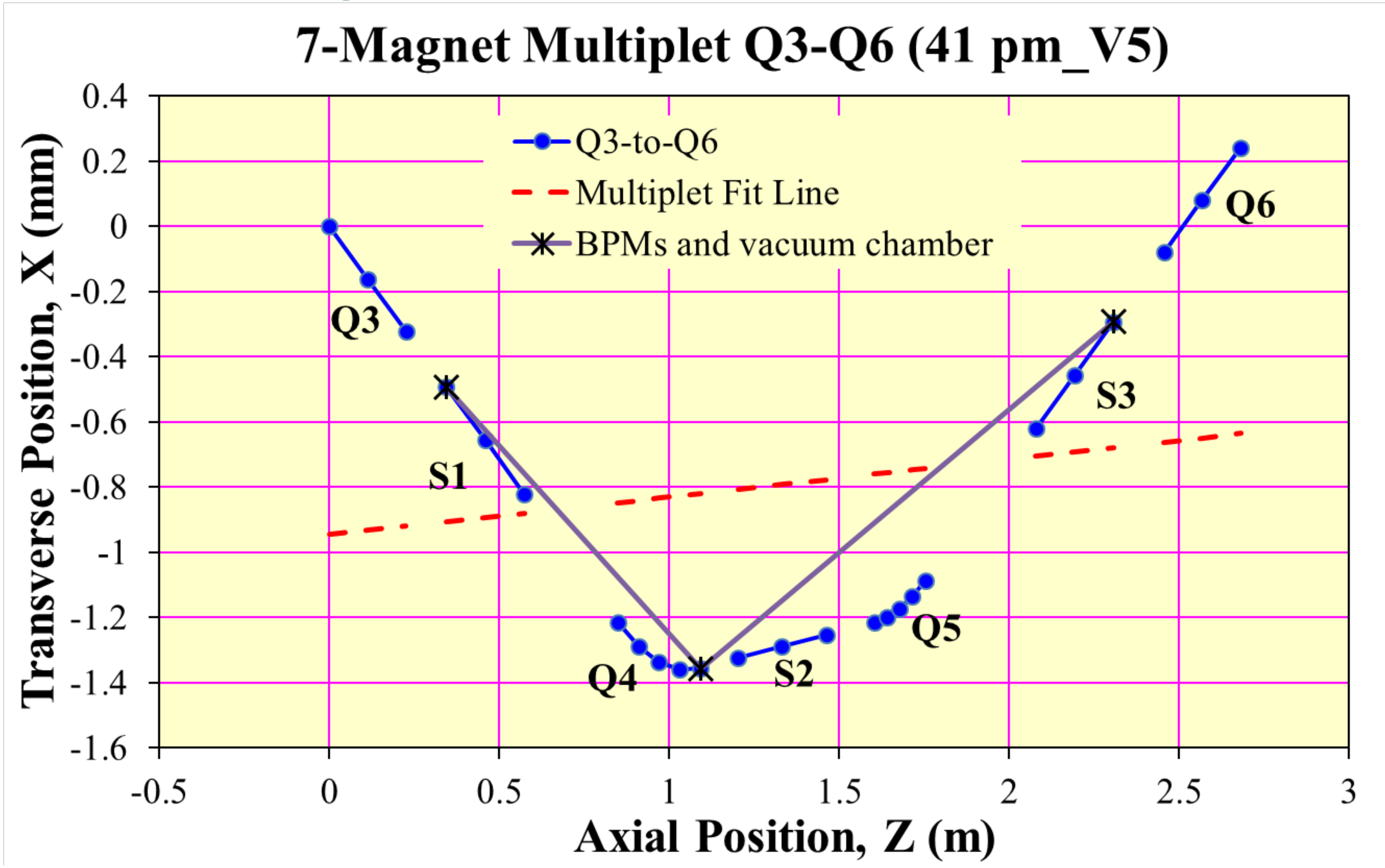
Measuring curved FODO section



- With the wire aligned to the axis of Q7 at one end, it is offset by ~ 168 mm in the Q7 at the other end, which is well into the yoke of the magnet.
- A very long wire (~8 m) is needed, and only ~2-3 mm motion is possible. Vibrating wire method is best suited for the geometry, but many difficulties in applying to combined function magnets.
- Wire stages with long (~300 mm) travel and precise motion with almost zero X-Y coupling will be needed.

In the case of FODO, it will be more convenient to fiducialize individual magnets, and then install by survey.

Measuring the curved multiplet section

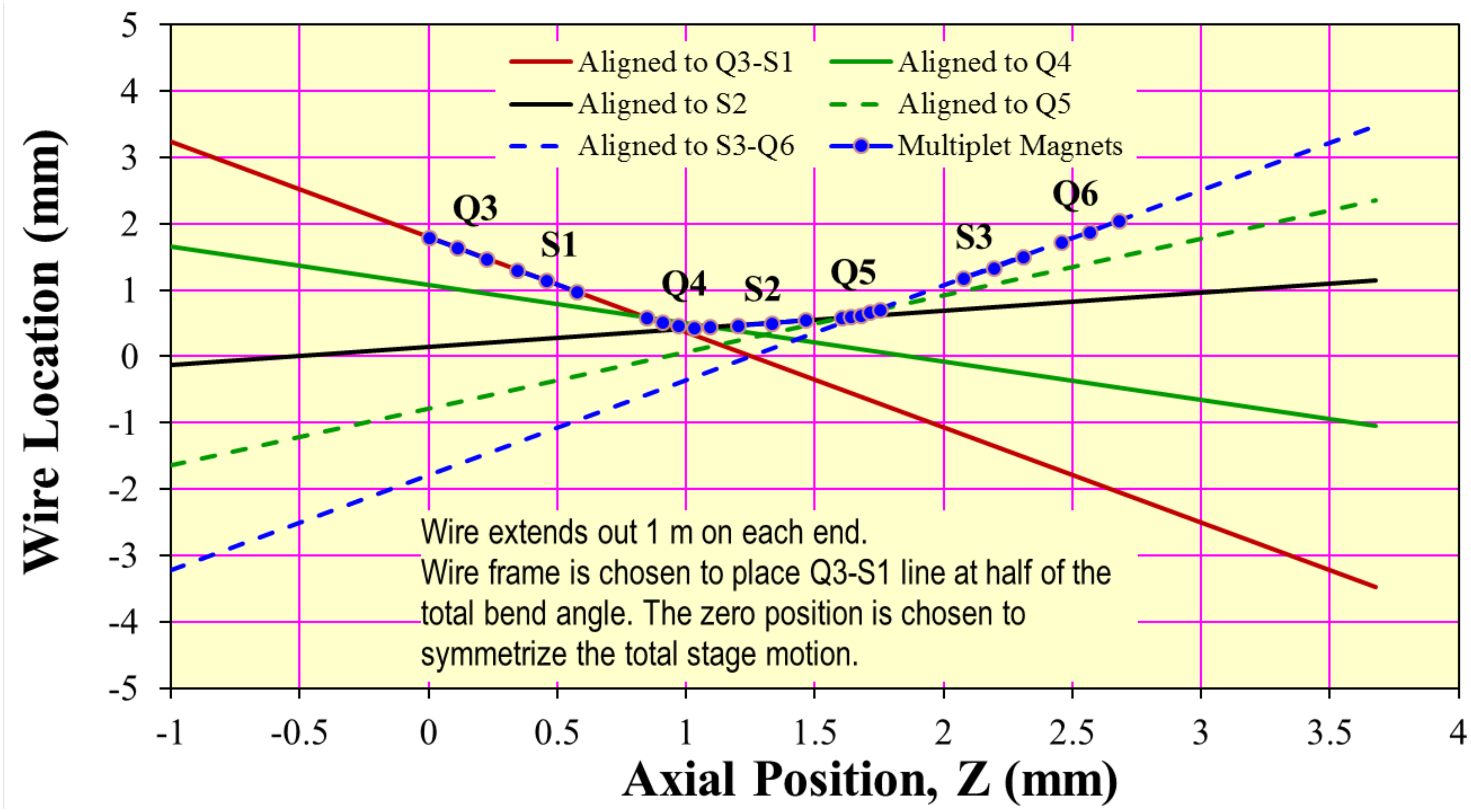


Total (reverse) bend angle = 0.1827 deg. (3.189 mr)

Q4 mechanical center is offset ~2 mm; Q5 mechanical center is offset ~5 mm. (Straight magnets)

Vacuum chamber may be offset by up to ~ 0.5 mm from the nominal beam axis.

Measuring curved multiplet section



With the wire aligned to the Q3-S1 axis, it is offset by ~ 4 mm in the Q6 magnet.

Rotation radius of the wire will be limited to only ~5-6 mm, but the magnetic centers of all magnets can be measured, even with the vacuum chamber installed.

Practical considerations may dictate that the multiplet section also be aligned as the FODO section, even though direct magnetic alignment is possible in principle.

Summary

- The upgrade of APS at Argonne will require measurement of 1320 magnets for the new storage ring.
- Approx. 85-90% of the magnets can be measured using well established rotating coil and Hall probe techniques.
- Curved combined function magnets pose significant challenges to measurement of the field quality and precise alignment.
- Schemes are developed to adapt rotating coil and wire based techniques to such magnets by using appropriate analysis of the data.
- These schemes were simulated using field maps from Opera-3D calculations, with promising results.
- Alignment of magnets in the curved FODO section will be done by fiducializing individual magnets and laser tracker survey.
- Aligning the multiplet section in the same way as the FODO may have a practical advantage during production, although magnetic alignment is possible in this case.