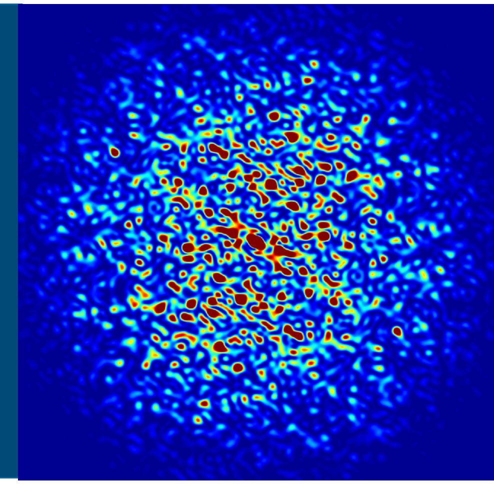
Magnetic measurements of the Advanced Photon Source Upgrade (APS-U) storage ring magnets*



Animesh Jain
Argonne National Laboratory

Talk presented at NSLS-II, Brookhaven National Laboratory, October 29, 2019

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APS-U magnet measurements team

Gentillo Curescu (measurement technician)

Joe DiMarco (FNAL)

Chuck Doose (Electro-Mechanical Engineer)

Scott Izzo (Mechanical Engineer)

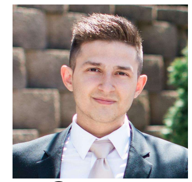
Bill Jansma (Survey)

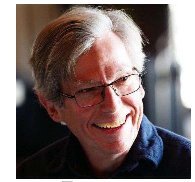
Tyler Malas (measurement technician)

Spiro Skiadopoulos (Survey)

Robert Soliday (Software)

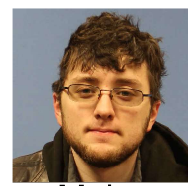
Mathew Virgo (Software)

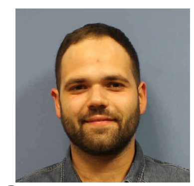

Curescu


Doose

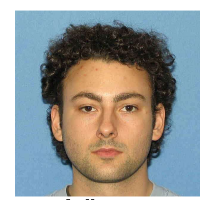

Izzo


Jansma


Malas


Skiadopoulos


Soliday

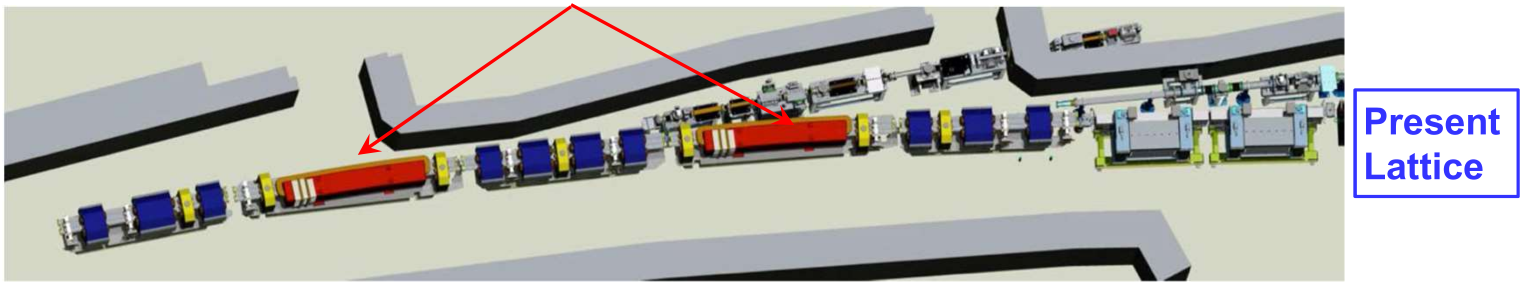

Virgo

Introduction

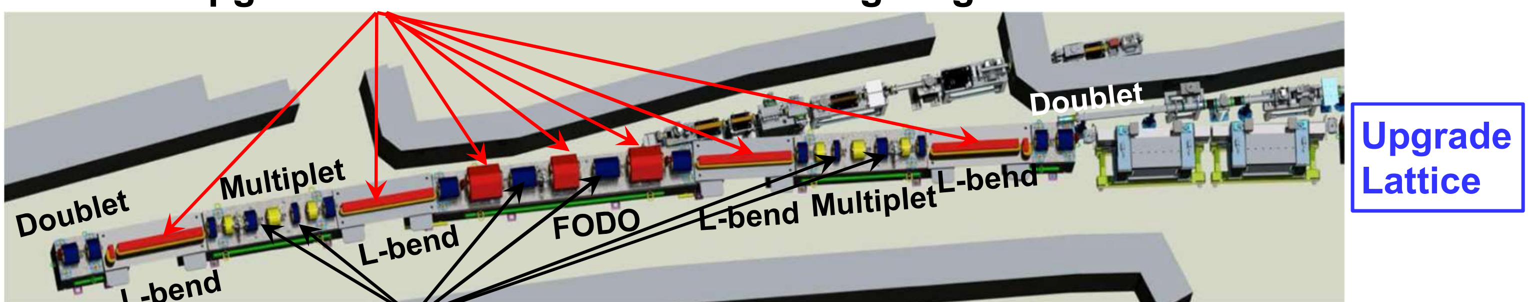
- It is planned to upgrade the Advanced Photon Source (APS), currently operating at Argonne National Laboratory, to provide much brighter beams of X-rays (the APS-U project).
- As part of this upgrade, the entire storage ring will be replaced with a new storage ring based on a 42 pm Multi-bend Achromat (MBA) lattice.
- The new storage ring will contain over 1300 new magnets, which will have to be measured and aligned in 200 modules containing several magnets each.
- The project received "Critical Decision 3" approval in July 2019. However, several magnet types were already under production starting in July 2017 under a previous "CD-3b" authority.
- A new magnetic measurement laboratory is built and is operational with three benches for the measurements and fiducialization of the storage ring magnets.
- Status of magnetic measurements for APS-U is presented in this talk.

Advanced Photon Source Upgrade (APS-U)

Present lattice: 2 bending magnets (Double Bend Achromat)



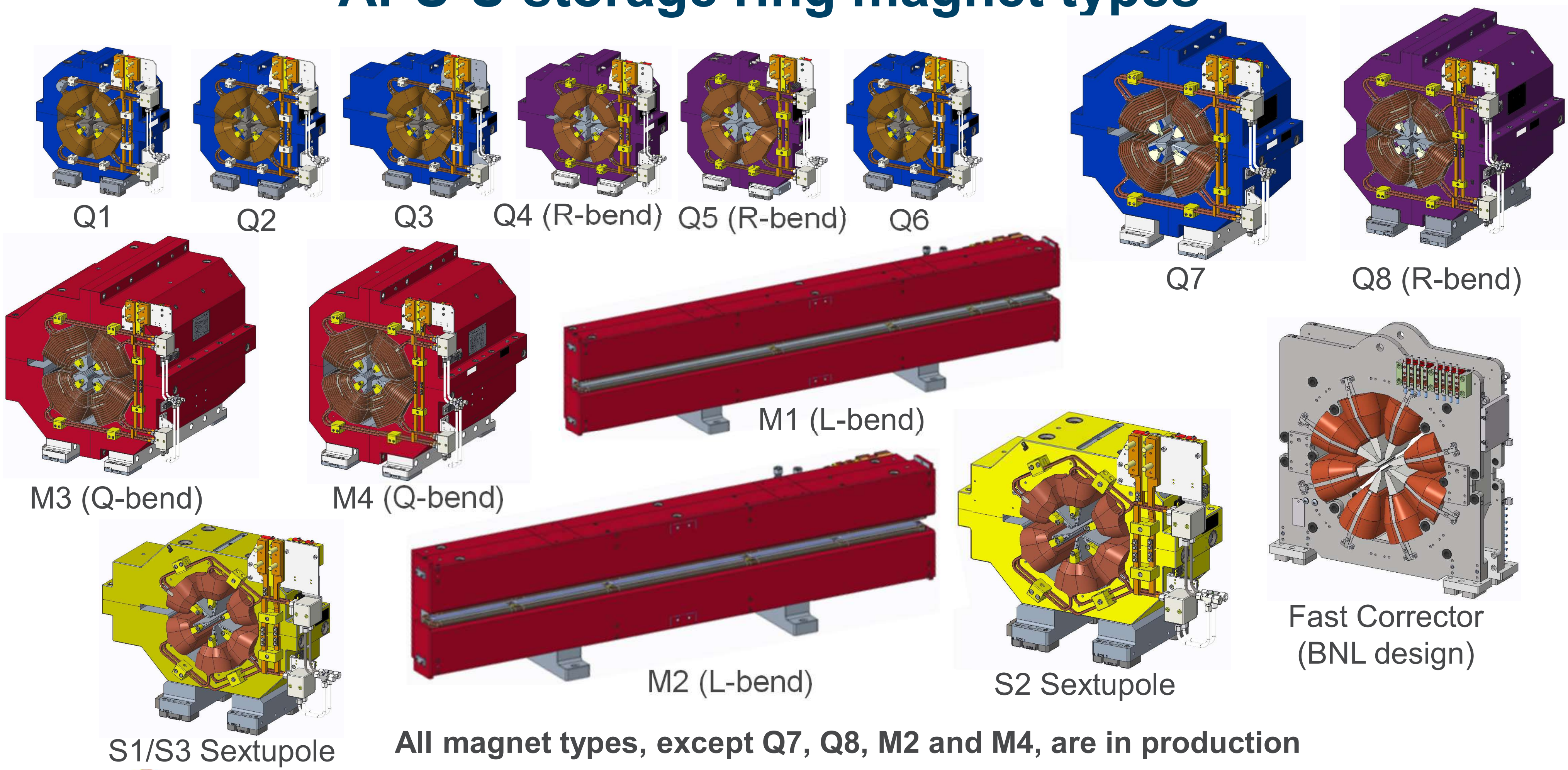
Upgrade lattice: 7 "forward" bending magnets



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)

APS-U storage ring magnet types



All magnet types, except Q7, Q8, M2 and M4, are in production

Status of magnet procurements (as of October 18, 2019)

Magnet Type	Quantity Ordered	Quantity Received
8-pole fast correctors	162	1
Q1	82	82
Q2	81	72*
Q3	83	0
Q4	82	1
Q5	82	1
Q6	82	1
S1/S3	164	1
S2	82	1
M1	82	0
M3	82	0
Total	**1064**	**160**

* 10 of 72 failed incoming inspections and were returned for repairs.

Magnets remaining to be ordered (needed CD-3 approval)

Magnet Type	Quantity to be Ordered
Q7	82
Q8	82
M2	82
M4	41
Total remaining	**287**

All magnet designs are completed.

Four magnet types are currently in the procurement process

~80% of all magnets are already ordered

Field quality measurements are completed in all magnets that were delivered to ANL, and that passed incoming inspections.

Field quality and alignment requirements

- Maximum field deviation in terms of integrated field harmonics is $\pm 10\times10^{-4}$ relative to the nominal field, at 10 mm radius about the designed orbit position. (*APS-U Accelerator Functional Requirements Document*)
  - The random errors specifications are more stringent (*APS-U Preliminary Design Report*)
  - Goal is to measure field harmonics with a resolution of well below 1×10^{-4} of the main field (1 "unit") at a reference radius of 10 mm (< 0.1 unit is achievable with current state-of-the-art equipment).

- Alignment requirements (*APS-U Accelerator Functional Requirements Document*):

Girder to girder alignment			
DLM to FODO; 1 sigma cutoff	μm rms	100	(by survey)
QMQ to DLM or FODO; 1.5 sigma cutoff	μm rms	50	(by survey)
Elements within a girder			
Magnet to magnet (2 sigma cutoff)	μm rms	30	(magnetic + survey)
Dipole roll	mrad	0.4	(survey of poles + mechanical)
Quadrupole roll	mrad	0.4	(magnetic + mechanical)
Sextupole roll	mrad	0.4	(magnetic + mechanical)

New magnetic measurement laboratory for APS-U

- The existing space that was used for measurements during R&D phase is not big enough to accommodate the needs of the full APS-U production.
- We need space for four rotating coil benches, two fiducialization benches, and one Hall probe bench, in addition to space for incoming mechanical and electrical inspections, pre-survey of dipoles, and storage of some magnets to match the measurement throughput of approximately one week.
- A portion of an existing building at Argonne was identified as a suitable candidate around January 2018, but the space was being used for other purposes at that time.
- The space was vacated, existing unwanted structure was demolished, and the space was re-built according to the needs of the measurement laboratory.
- We received final occupancy of the new space in April 2019.

Magnet measurement lab: Incoming inspection area

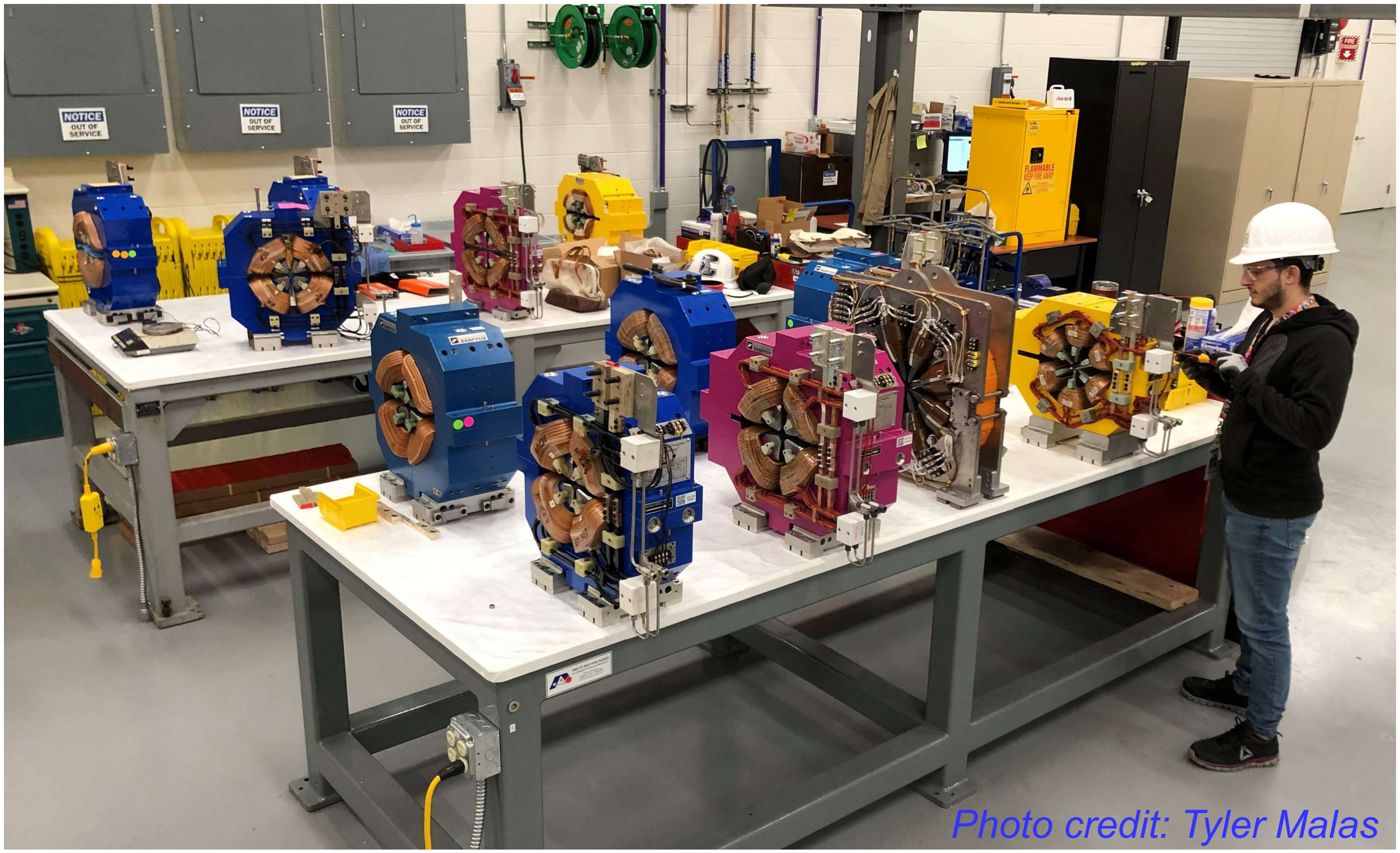


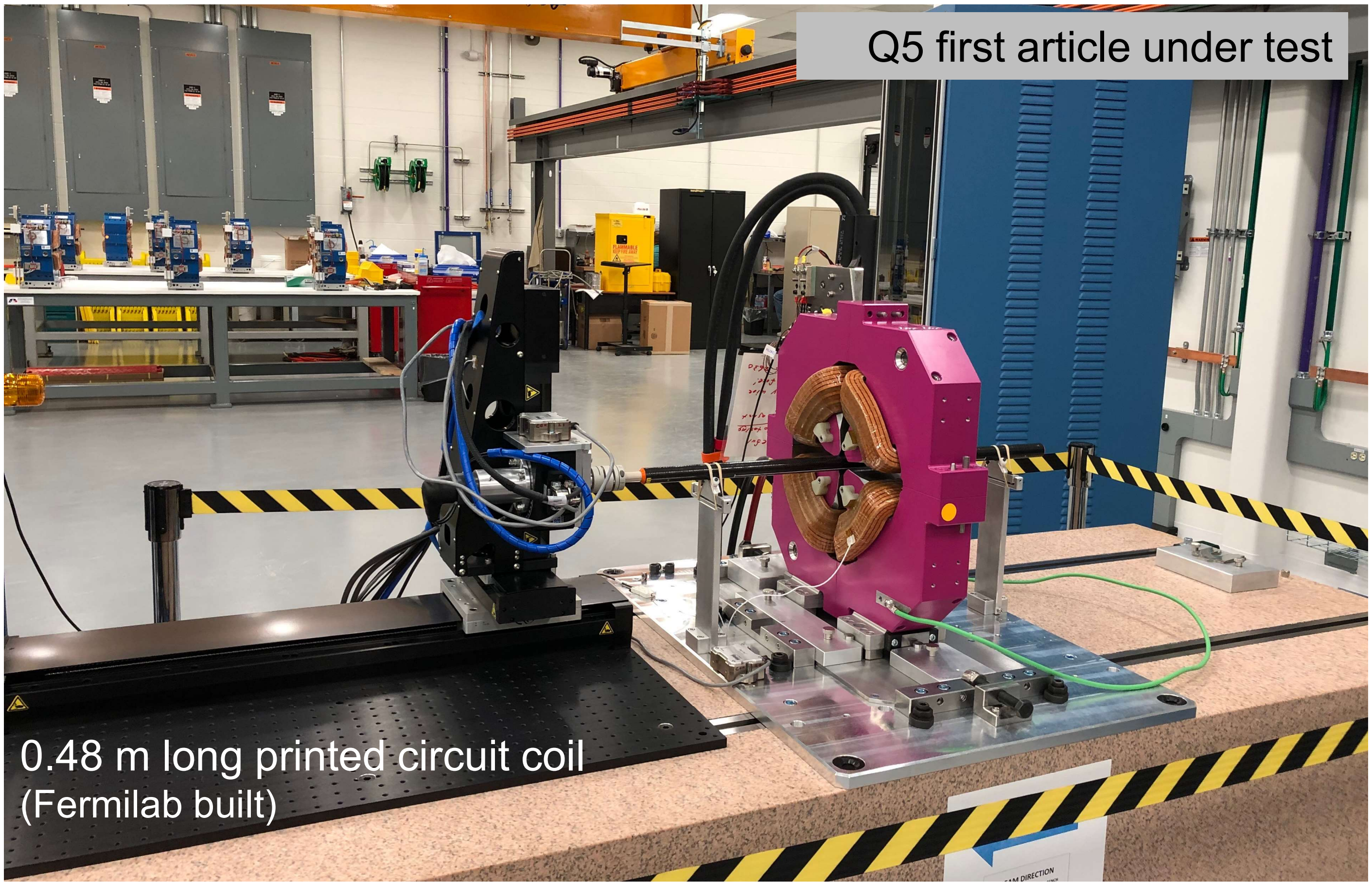
Photo credit: Tyler Malas

All magnets received so far have been mechanically inspected.

The magnet manufacturers are responsible for meeting only the mechanical requirements, and not field quality, since all magnet designs are by Argonne, and the magnets are supplied under a **"build-to-print"** contract.

However, in the end, field quality is important and magnetic measurements are essential.

Magnet measurement lab: rotating coil benches



0.48 m long rotating coil
Newport motion stages
National Instruments DAQ

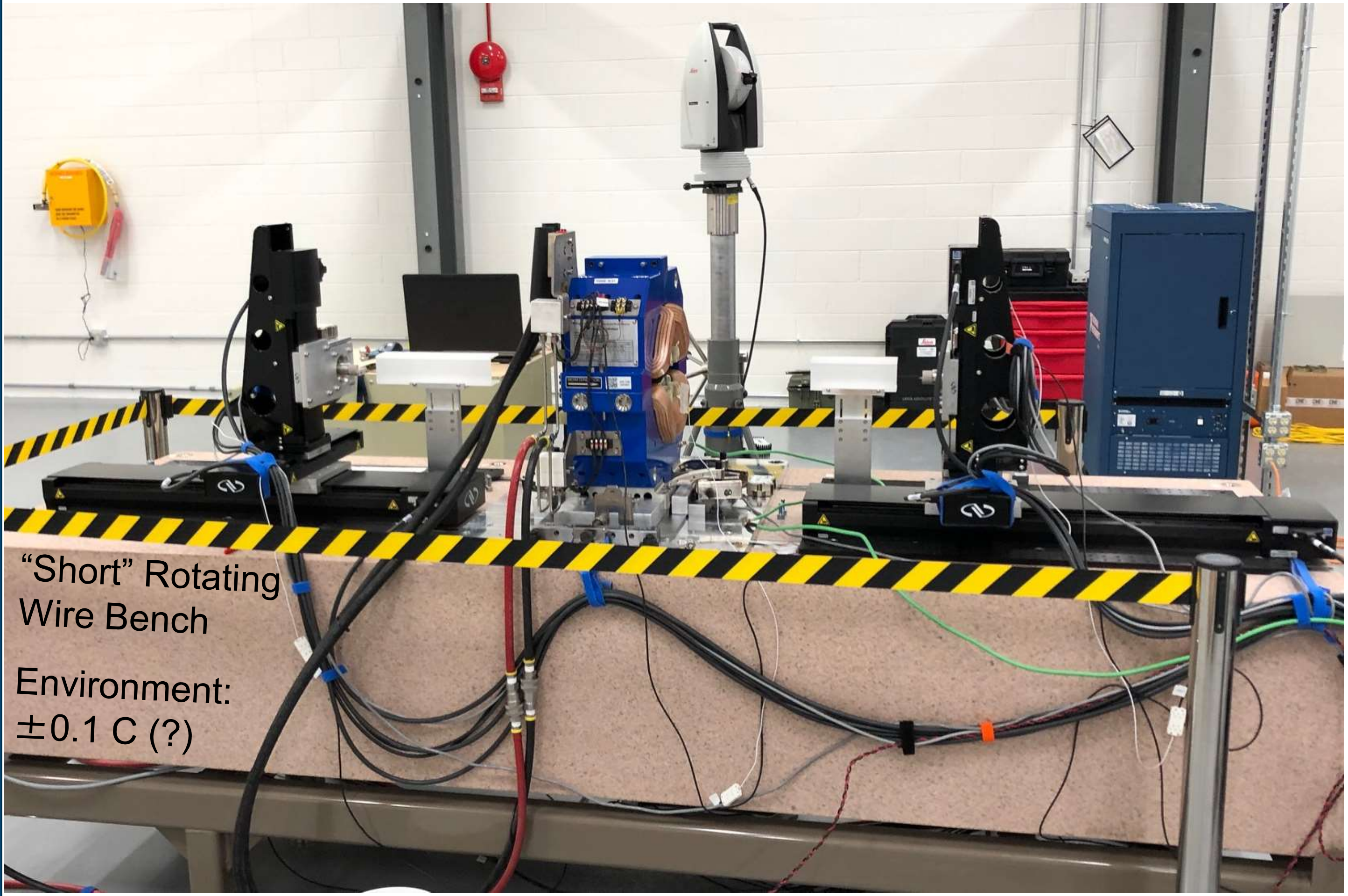
Routine measurements started on June 17, 2019

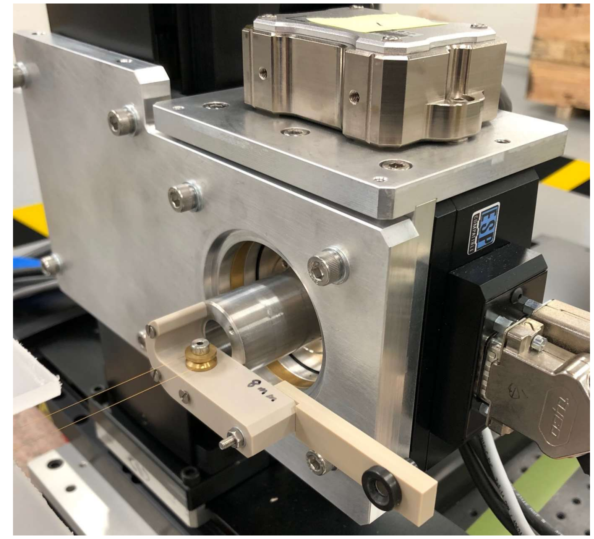
Designed to measure Q1-Q6 magnets

A second identical bench is also operational now.

Designed to measure Q1-Q6, S1-S3 and fast corrector magnets

Magnet measurement lab: Fiducialization room





The bench is operational and is being used to fiducialize Q1 and Q2 magnets.

Wire length: 1.27 m

A second bench for longer magnets will be similar.

Simple measurements with rotating coils

Magnet Type	Length (m)	Quantity	Bend Angle (mr)	Comments
Q1	0.250	82	--	Quadrupole
Q2, Q3, Q6	0.225	246	--	Quadrupoles
Q4*	0.244	82	-1.7069	Sagitta = 0.046 mm
Q5*	0.150	82	-1.1575	Sagitta = 0.016 mm
Q7	0.424	82	--	Quadrupole
Q8*	0.646	82	-5.3586	Sagitta = 0.392 mm
S1, S3	0.229	164	--	Sextupole
S2	0.260	82	--	Sextupole
8-pole Fast Correctors	0.160	162	--	Normal and skew dipole; skew quad
Total		**1064**	**(~79% of all magnets)**	

** Sagitta is small and simple integral measurements are sufficient.*

Two rotating coil lengths (0.48 m and 1.0 m) will cover all of these magnets.

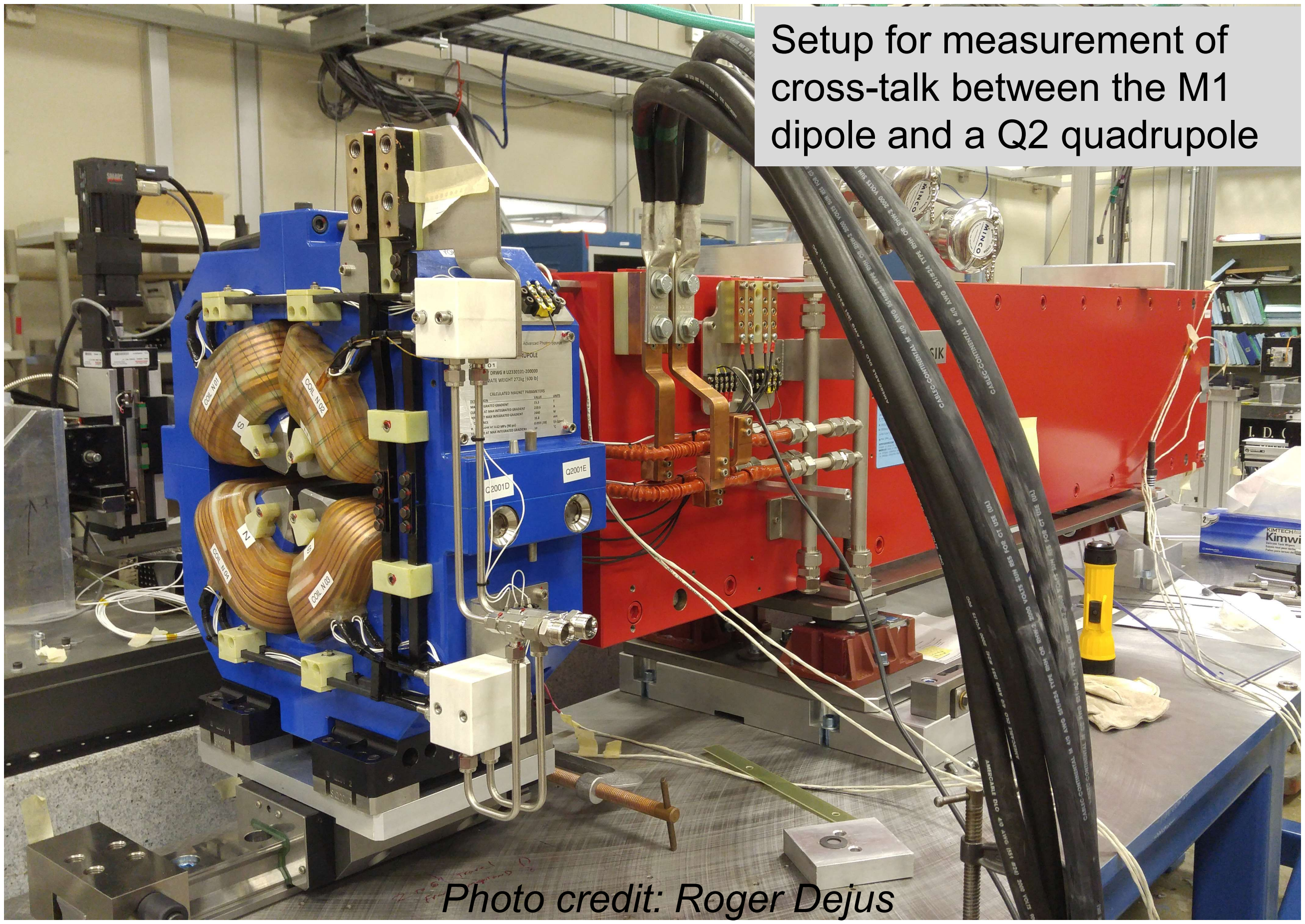
- Two benches with 0.48 m long coils (completed)
  - Q1-Q6, S1-S3, 8-pole corr.
- One bench with 1.0 m long coil (being fabricated)
  - Q7 and Q8 magnets

Simple measurements with Hall probes

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M1	2.225	82	28.5716	5-segment L-bend B_{max}/B_{min} ~ 4.6
M2	1.985	82	23.2944	5-segment L-bend B_{max}/B_{min} ~ 2
Total		164	(~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.

Hall probe mapping of a R&D M1 L-bend dipole



The bench used to measure the R&D L-bend magnets will be needed for insertion device measurements.

A new Hall probe mapping bench is being designed and will be fabricated in-house.

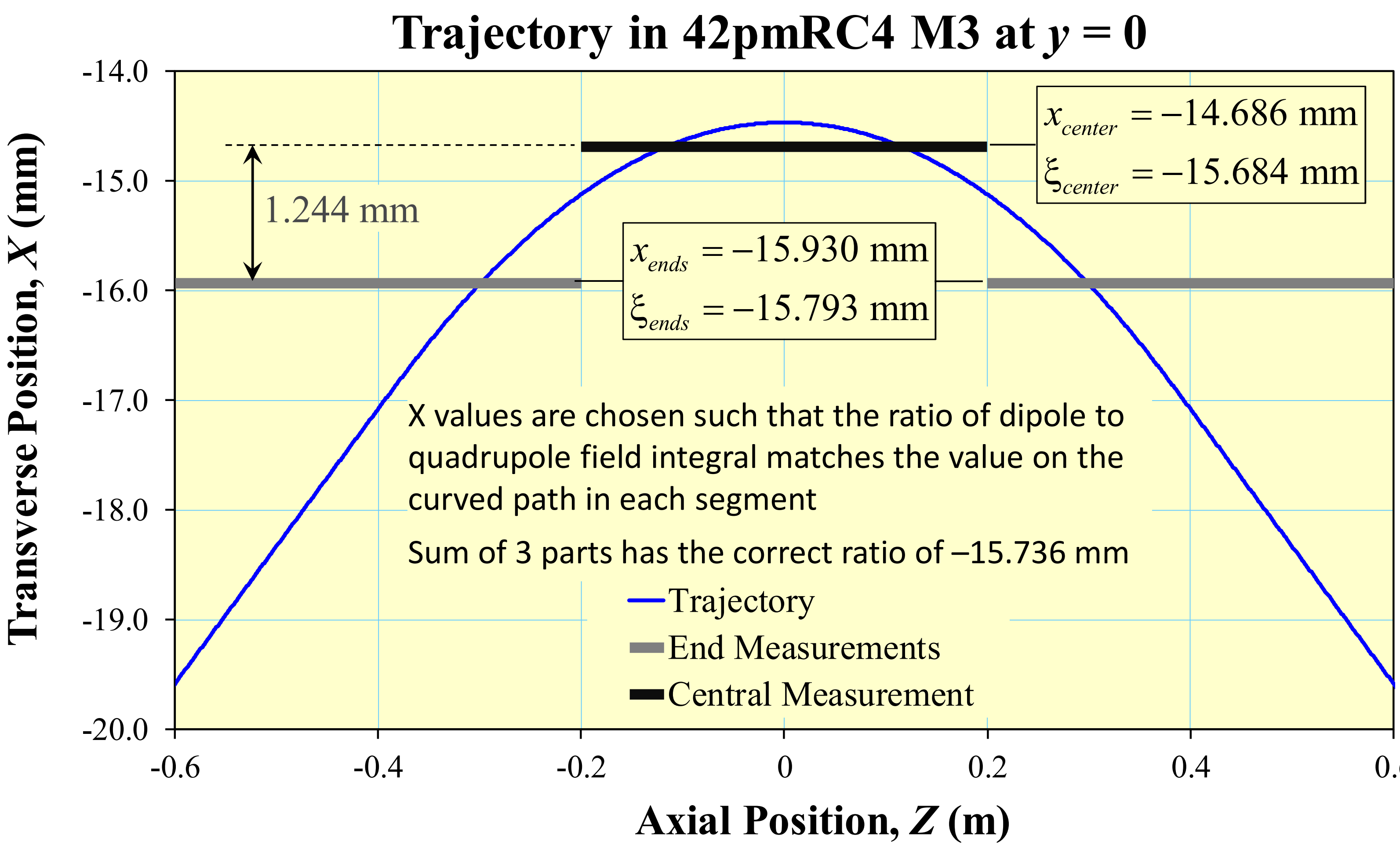
New bench is expected to be available in early 2020, in time to measure the M1 first article currently under production.

More challenging magnet types

Magnet Type	Length (m)	Quantity	Total Bend Angle (mr)	Comments
M3	0.820	82	25.0793	Sagitta = 2.405 mm
M4	0.700	41	19.6350	Sagitta = 1.584 mm
Total*		123	(~9% of all magnets)	

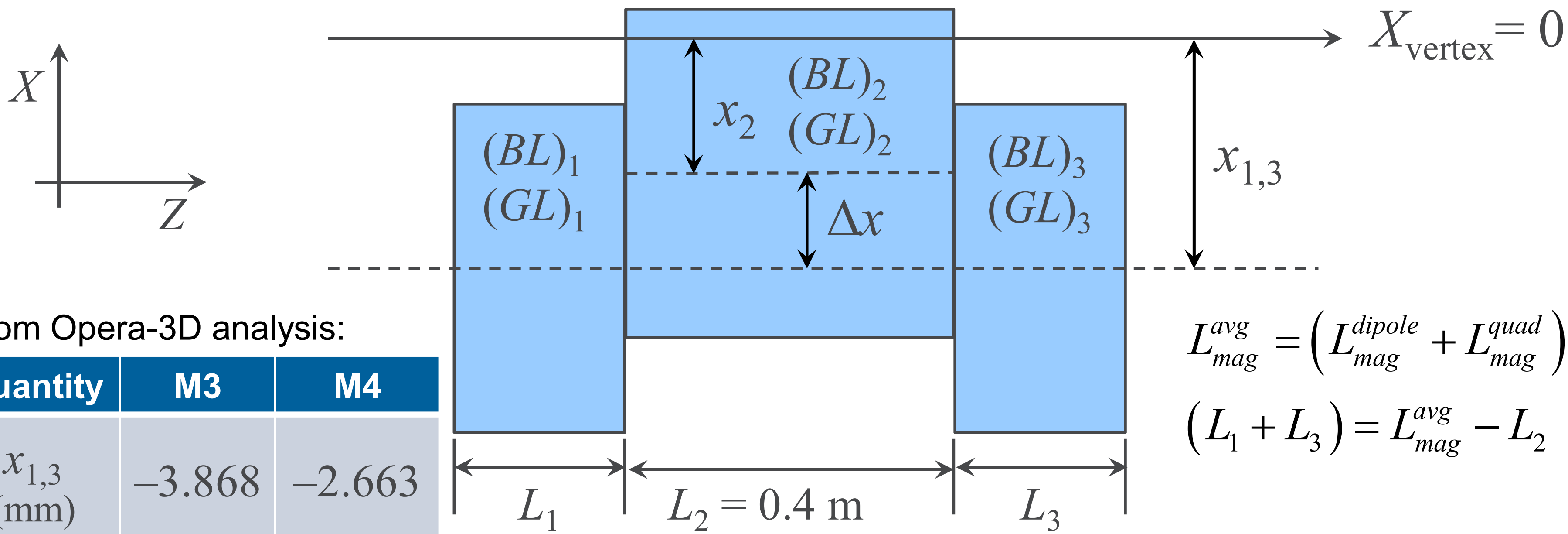
- These magnets have strong dipole and quadrupole components.
- Magnet yokes are built straight, but are fitted with curved pole tips.
- Hall maps are inconvenient to measure (no access from the side).
- Also need to locate the "magnetic center" precisely enough for aligning to other magnets in the same FODO assembly to 0.030 mm rms.
- 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. **(See talk at IMMW20, UK, 2017)**

3-part measurement in M3 magnet (M4 is similar)



$$\xi = \left(\frac{BL}{GL}\right)$$

3-part representation of the M3 and M4 magnets



$$L_{mag}^{avg} = \left(L_{mag}^{dipole} + L_{mag}^{quad}\right)/2$$

$$\left(L_1 + L_3\right) = L_{mag}^{avg} - L_2$$

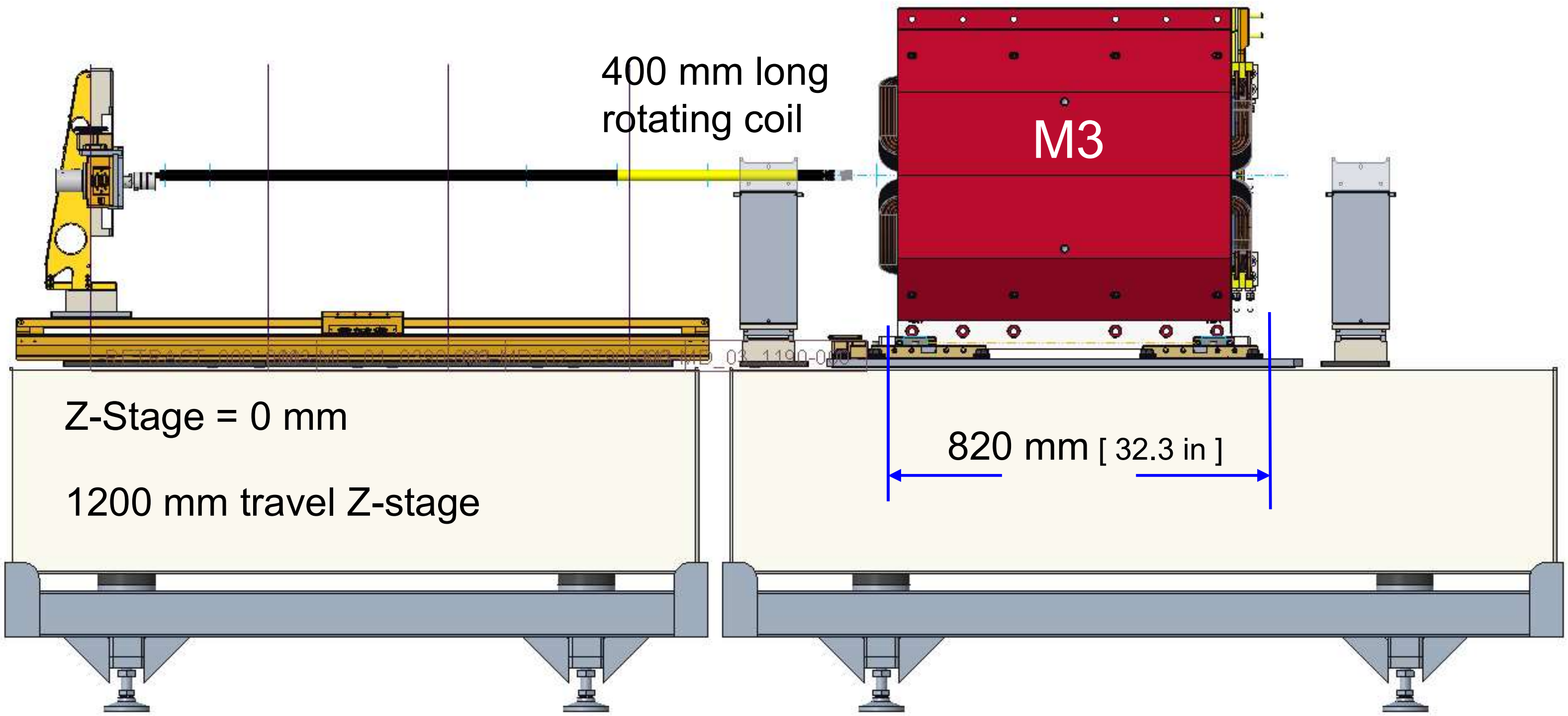
From Opera-3D analysis:

Quantity	M3	M4
$x_{1,3}$ (mm)	–3.868	–2.663
x_2 (mm)	–2.624	–1.787
L_1=L_3 (m)	0.1814	0.1206
Δx (mm)	1.244	0.876

$$L_1 = \left(\frac{1}{2}\right)\left[\frac{(BL)_1}{(BL)_1 + (BL)_3} + \frac{(GL)_1}{(GL)_1 + (GL)_3}\right]\left(L_{mag}^{avg} - L_2\right)$$

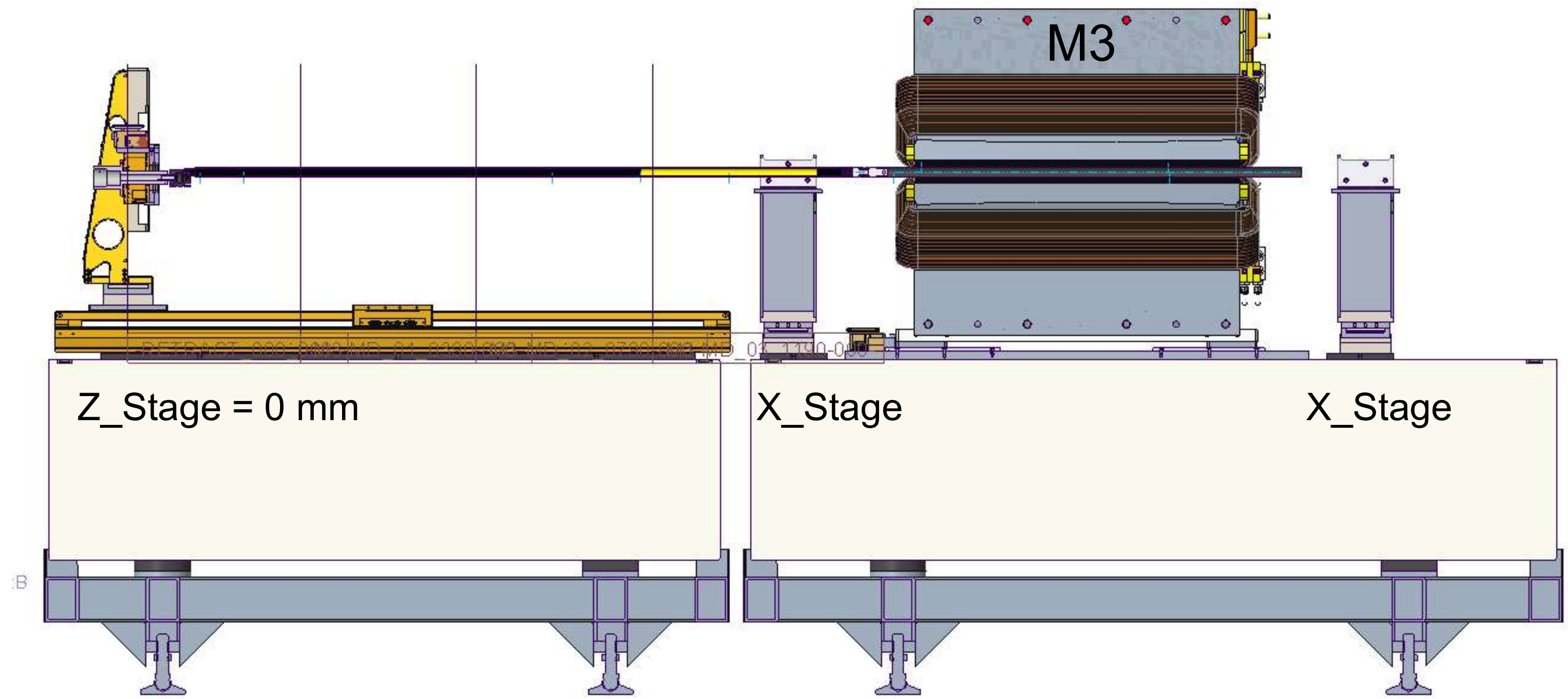
$$L_3 = \left(\frac{1}{2}\right)\left[\frac{(BL)_3}{(BL)_1 + (BL)_3} + \frac{(GL)_3}{(GL)_1 + (GL)_3}\right]\left(L_{mag}^{avg} - L_2\right)$$

M3-M4 Q-bend rotating coil system design



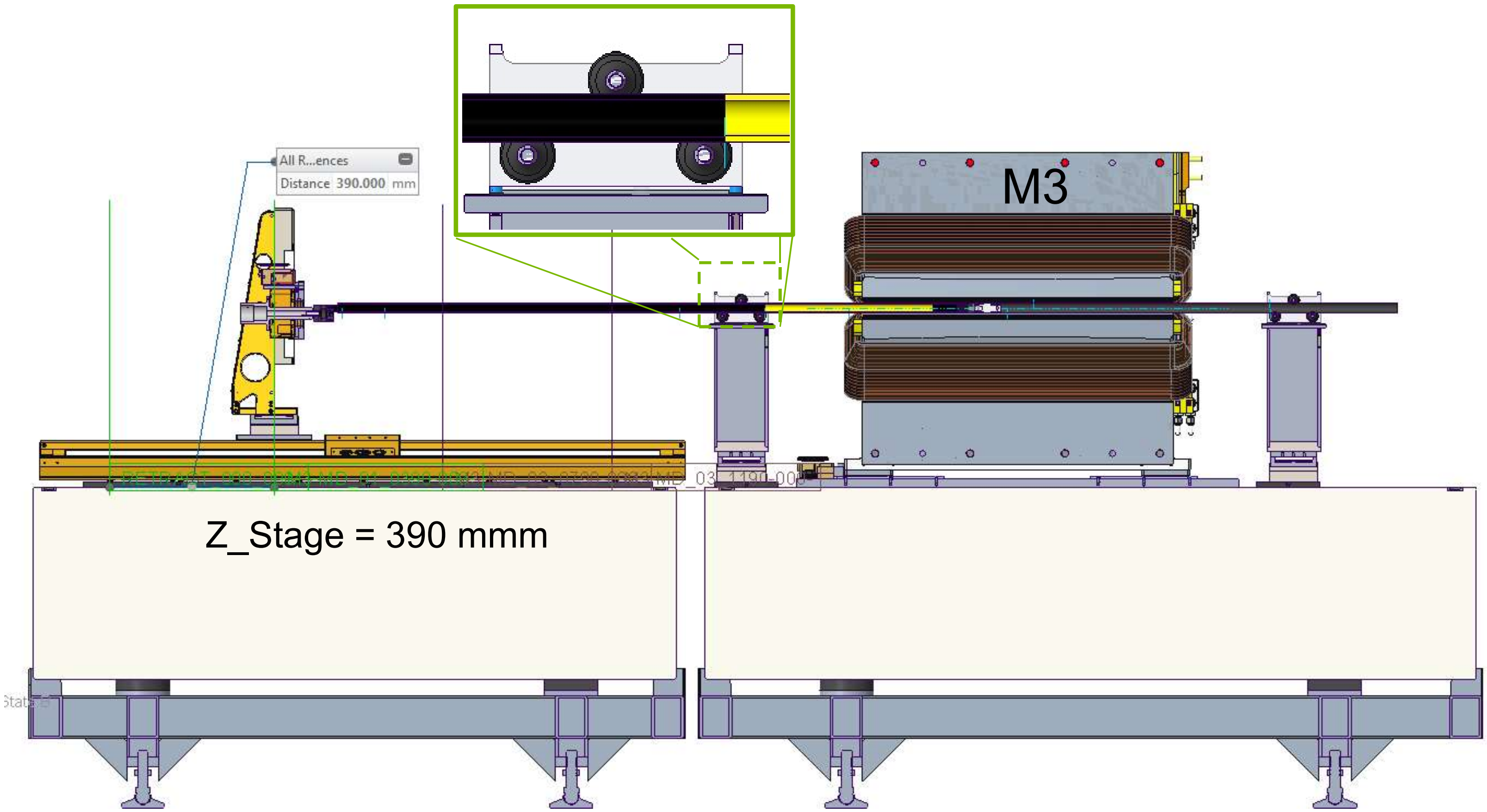
A similar concept is used for the Q7-Q8 rotating coil system

M3-M4 rotating coil system: with coil extension attached



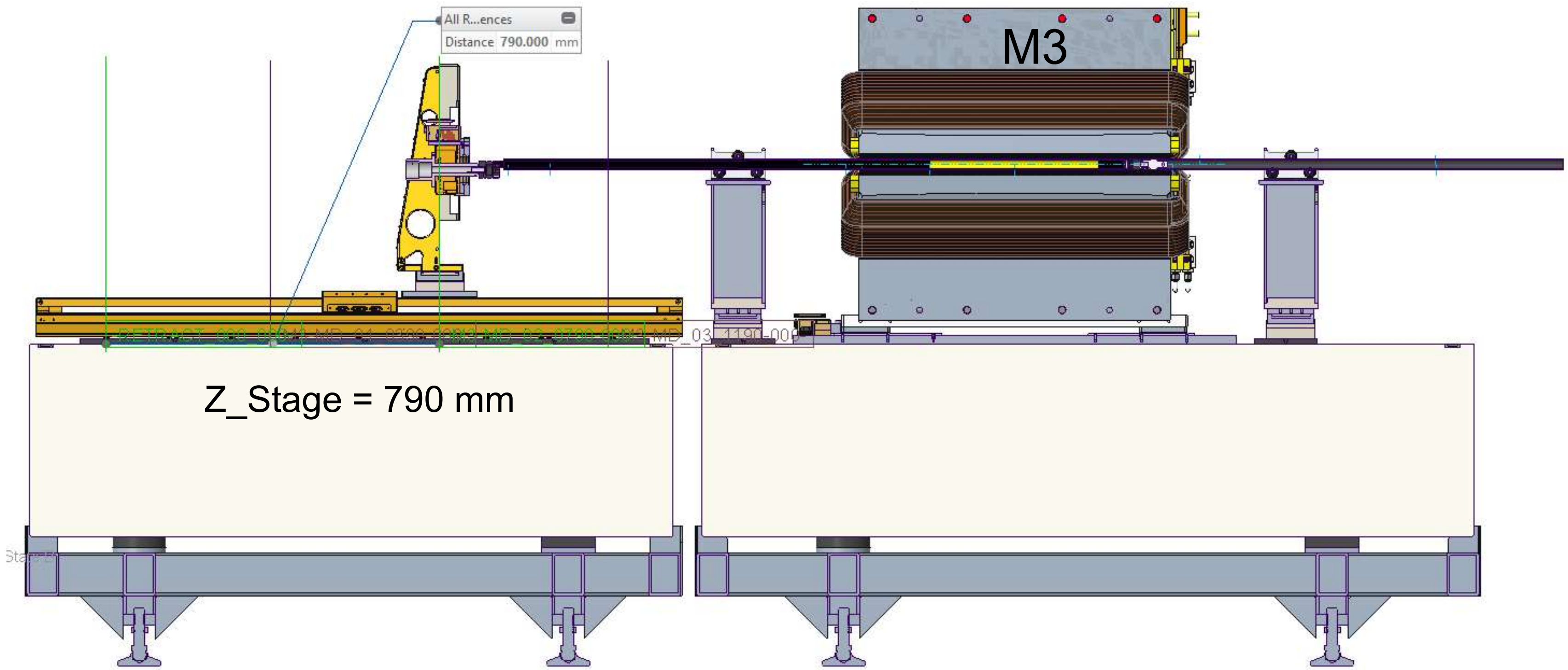
Granite block is segmented to keep the weights of individual pieces within the crane capacity (5 tons)

M3-M4 rotating coil system: 1st measurement position



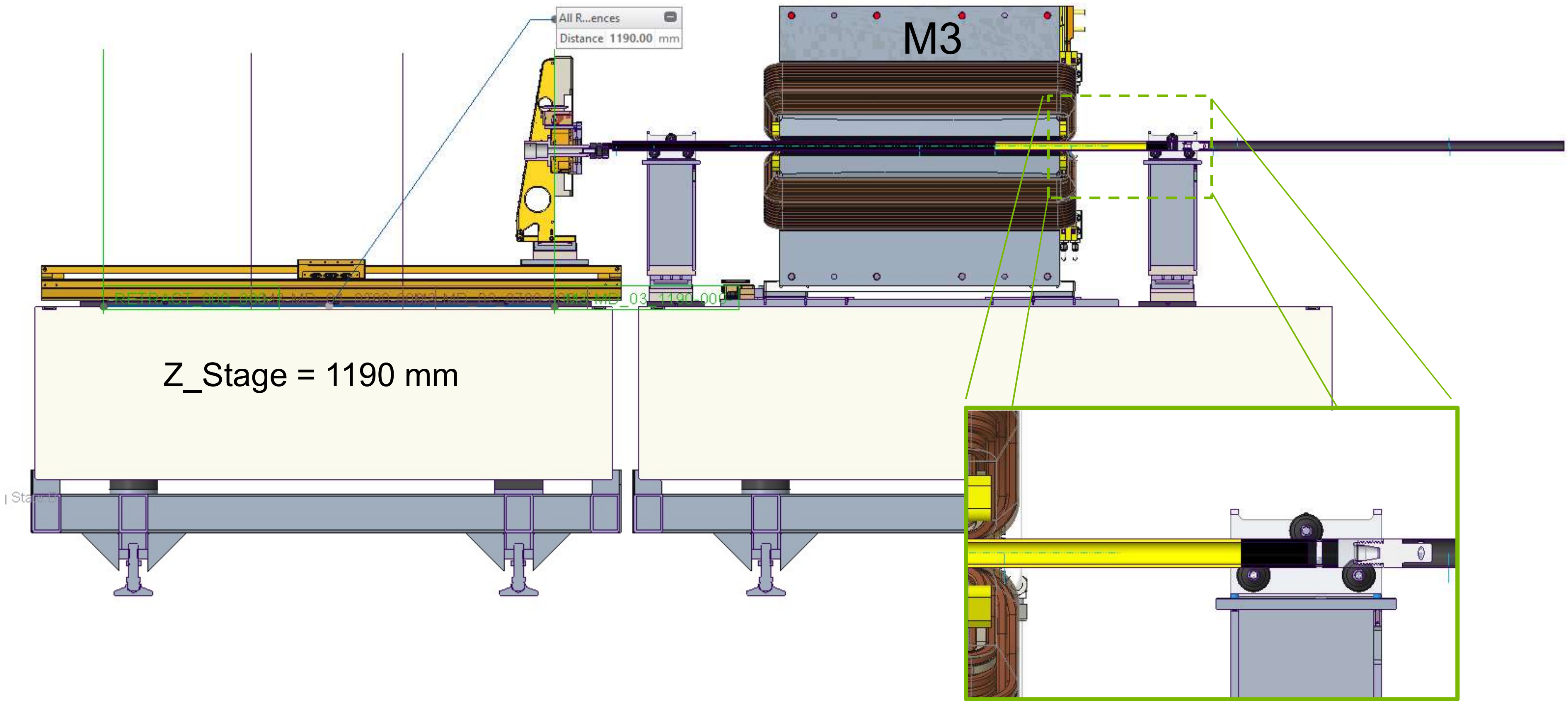
Rotating coil is secured at both ends in all measurement positions

M3-M4 rotating coil system: 2nd measurement position



The coil is moved in X as a function of Z-position, to approximate the curved beam path

M3-M4 rotating coil system: 3rd measurement position



Field quality summary in Q1 quadrupoles (82 magnets)

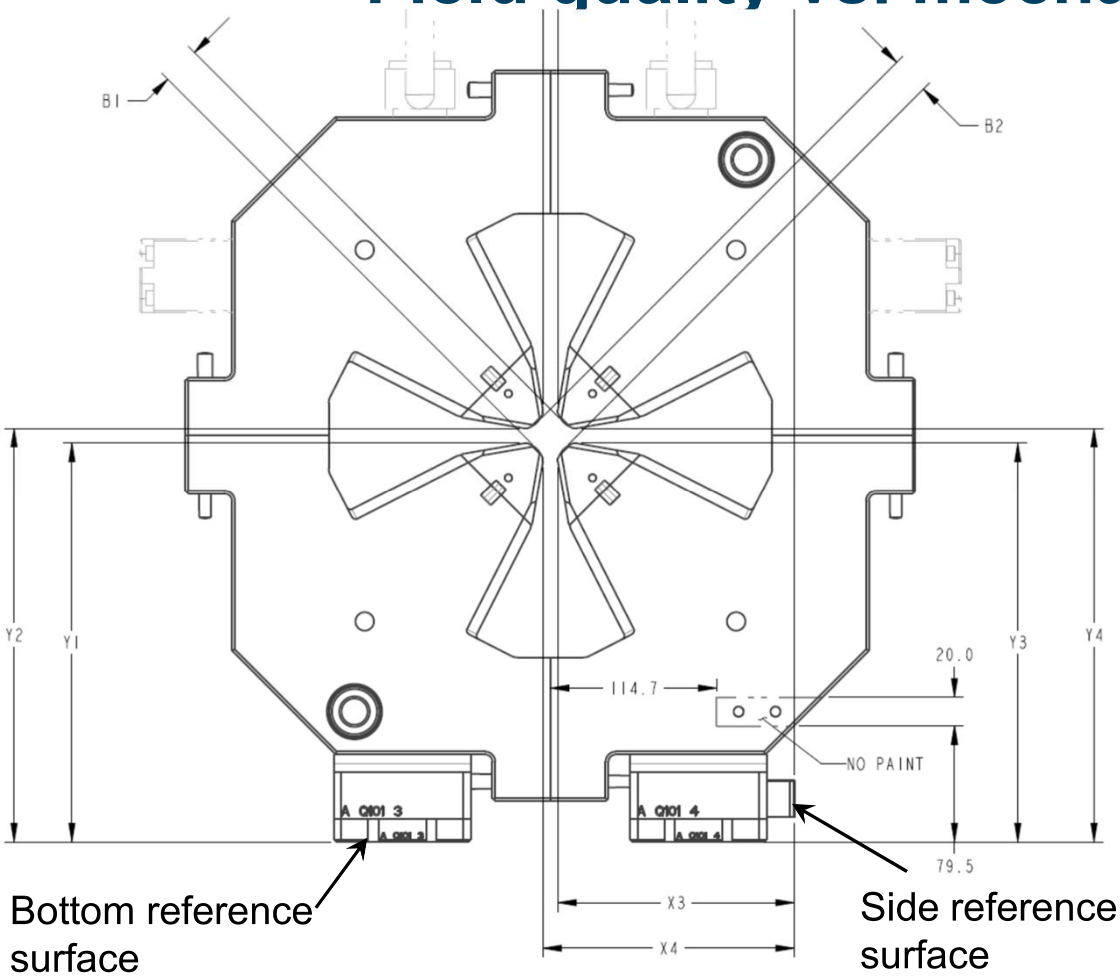
Quantity	Mean	Std. Dev
I.T.F. (T/A)	9.6131E-02	6.3211E-05
b0 (units)	--	--
b1 (units)	--	--
b2 (units)	0.17	1.13
b3 (units)	1.04	0.85
b4 (units)	-0.01	0.23
b5 (units)	-6.06	0.42
b6 (units)	-0.01	0.11
b7 (units)	0.02	0.06
b8 (units)	0.00	0.03
b9 (units)	-3.98	0.09
b10 (units)	-0.07	0.06
b11 (units)	0.03	0.03
b12 (units)	0.01	0.01
b13 (units)	-2.48	0.03
b14 (units)	-0.07	0.05
b15 (units)	0.01	0.01
b16 (units)	0.00	0.00
b17 (units)	-0.22	0.01

Quantity	Mean	Std. Dev
Field Angle (mr)	0.036	0.137
a0 (units)	--	--
a1 (units)	--	--
a2 (units)	0.47	1.86
a3 (units)	0.05	0.27
a4 (units)	-0.05	0.30
a5 (units)	-0.27	0.14
a6 (units)	0.00	0.11
a7 (units)	-0.01	0.08
a8 (units)	-0.01	0.04
a9 (units)	0.02	0.06
a10 (units)	0.15	0.04
a11 (units)	0.00	0.02
a12 (units)	-0.01	0.02
a13 (units)	0.01	0.03
a14 (units)	0.12	0.04
a15 (units)	0.00	0.01
a16 (units)	0.00	0.00
a17 (units)	0.00	0.00

Harmonics are at a reference radius of 10 mm (77% of aperture)

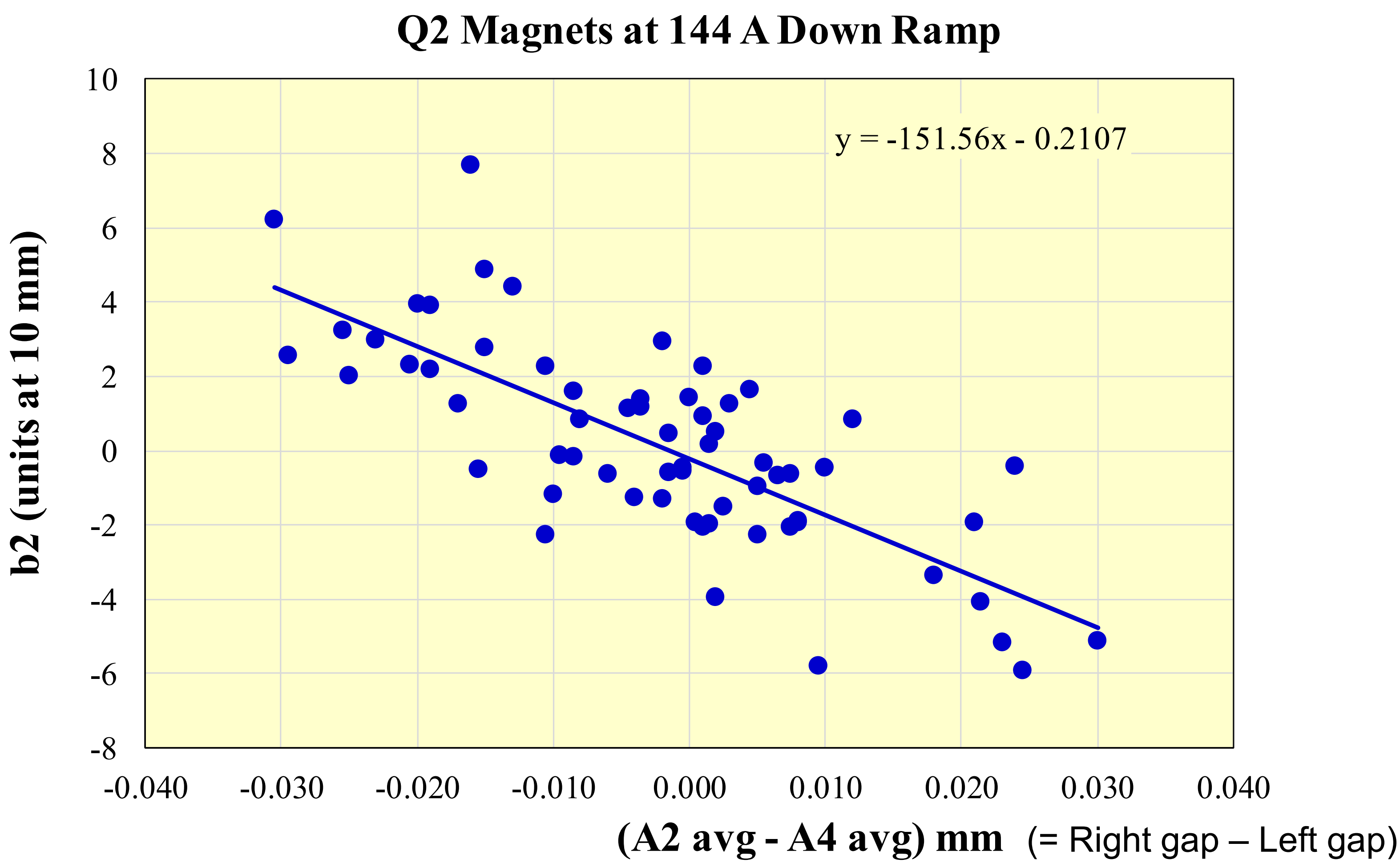
- Wire EDM was used to get high accuracy in mechanical dimensions (Vendor's choice).
- Unallowed terms are nearly zero.
- Standard deviations are well below what was assumed for beam physics simulations. (Conventional machining was assumed.)
- Systematic non-zero values of allowed terms (b5, b9, b13, b17) are due to limitations of the magnetic design.

Field quality vs. mechanical symmetry

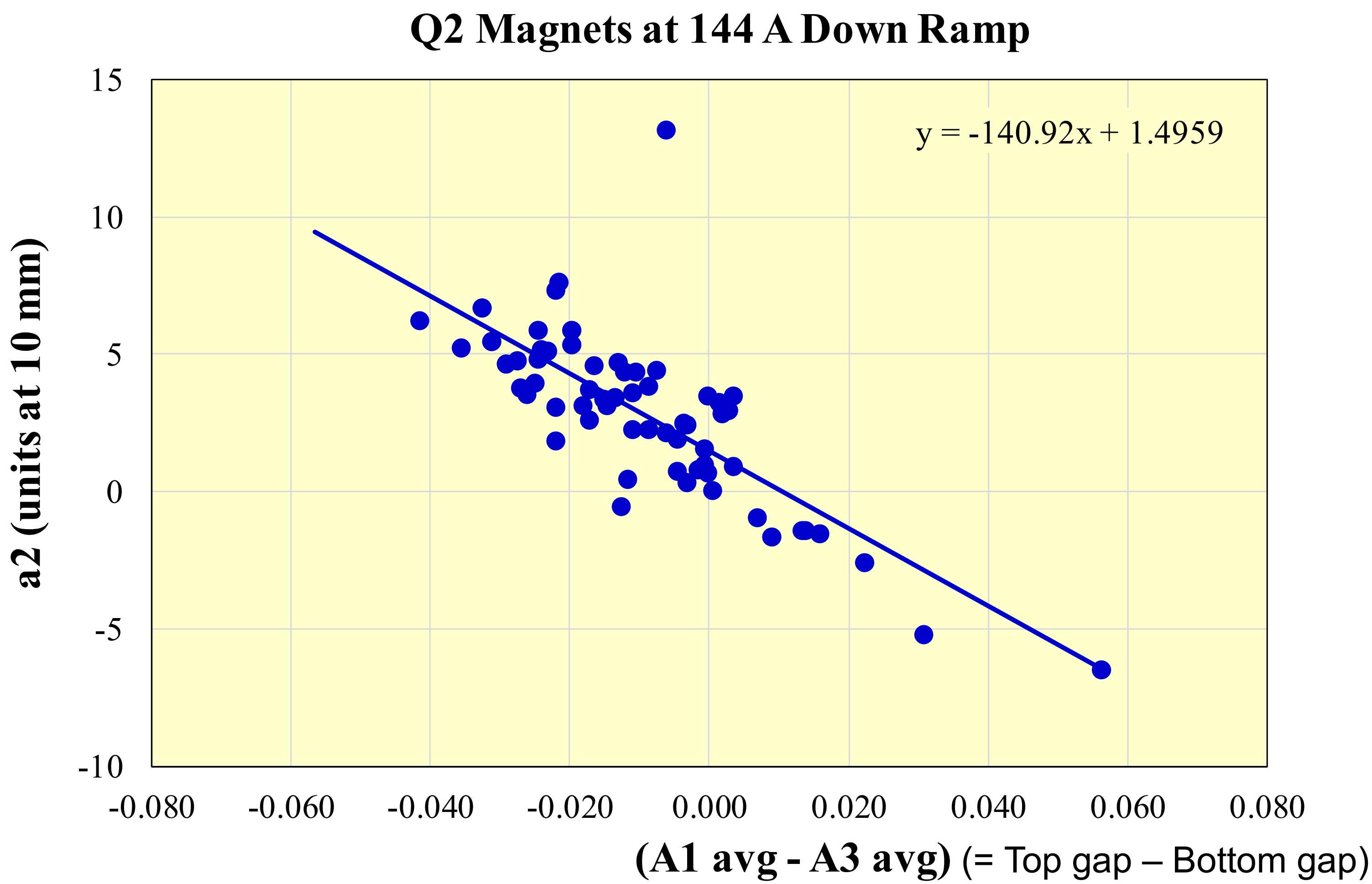


- "Build-to-print" approach relies on a good correlation between mechanical symmetry and field quality.
- A tighter tolerance is imposed on the *symmetry* between the left, right, top and bottom pole gaps, than on the absolute values of the gaps.
- This allows a relatively relaxed tolerance on individual parts, but a tighter tolerance on the assembly of pole tips. (Patented 8-piece quad design) US Patent 9,881,723, Jan 2018

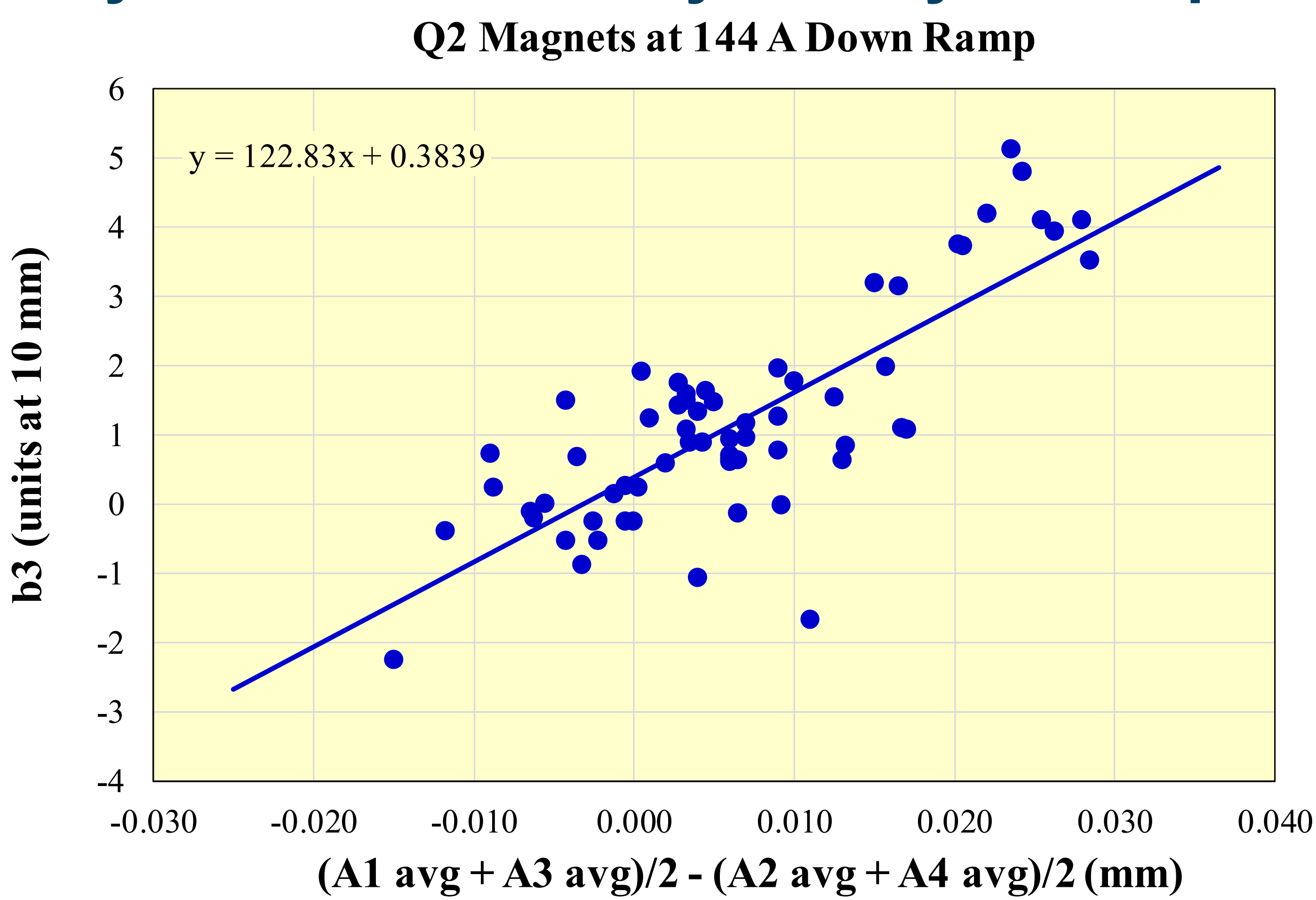
Field quality vs. mechanical symmetry in Q2 quadrupoles



Field quality vs. mechanical symmetry in Q2 quadrupoles



Field quality vs. mechanical symmetry in Q2 quadrupoles

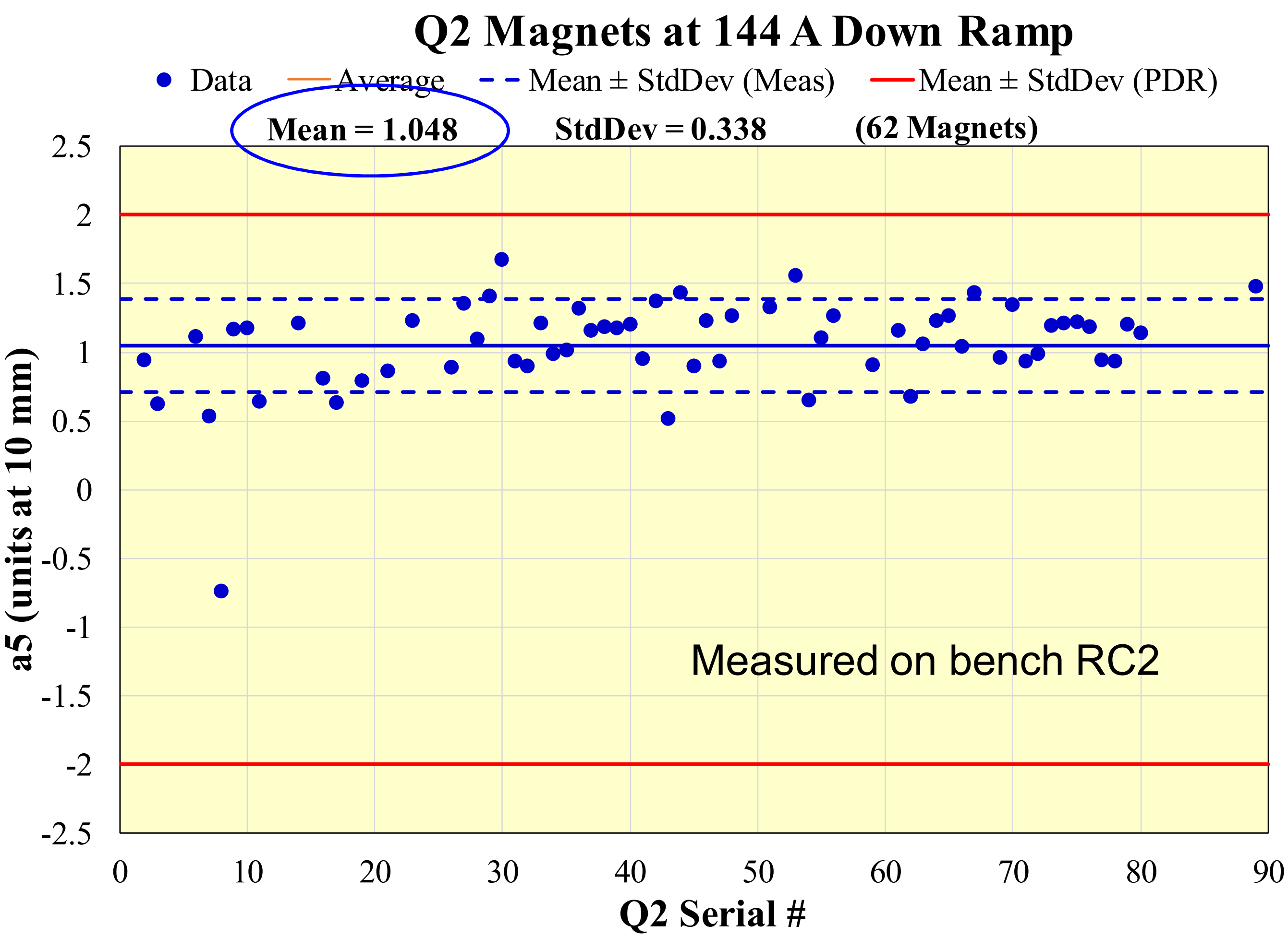


(Top gap/Bottom gap average) – (Left gap/Right gap average)

What makes the "easy" not always so easy?

- Although the rotating coil method is the well established, and the most precise method available to measure field harmonics, things can still go wrong.
- Typical resolution of good systems is ~0.01 units, or 1 ppm of the main field. Many things can go wrong at this level, and one has to keep a constant watch.
- The mechanical systems, including the construction of the rotating coil itself and the motion hardware, as well as the electrical systems must perform well and be in calibration over a long measurement campaign.
- The calibration of the rotating coil must be checked periodically to ensure there are no issues:
  - Fermilab printed circuit design has features for basic self-calibration of the coil.
  - Calibration of field angle is typically done once per week at APS-U, but more frequent calibration may be needed, depending on the performance of the system.
  - Many magnets may have to be measured again if problems with data are found later.

The case of skew 12-pole in Q2 magnets



Rotating Coil bench #2 (RC2) was allocated for measuring the Q2 quadrupoles.

The skew 12-pole in all Q2 magnets was measured to be ~1 unit.

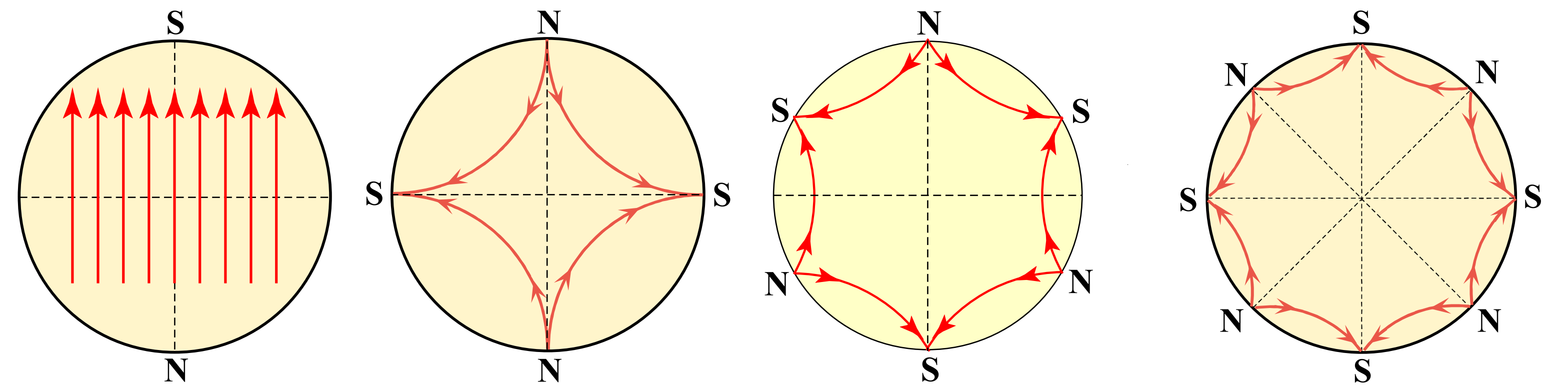
This was not a big concern, but still did not seem right.

The Q1 magnets, built by a different vendor, and measured on a different bench, did not show such large skew 12-pole.

Initially it was attributed to some unknown manufacturing issues.

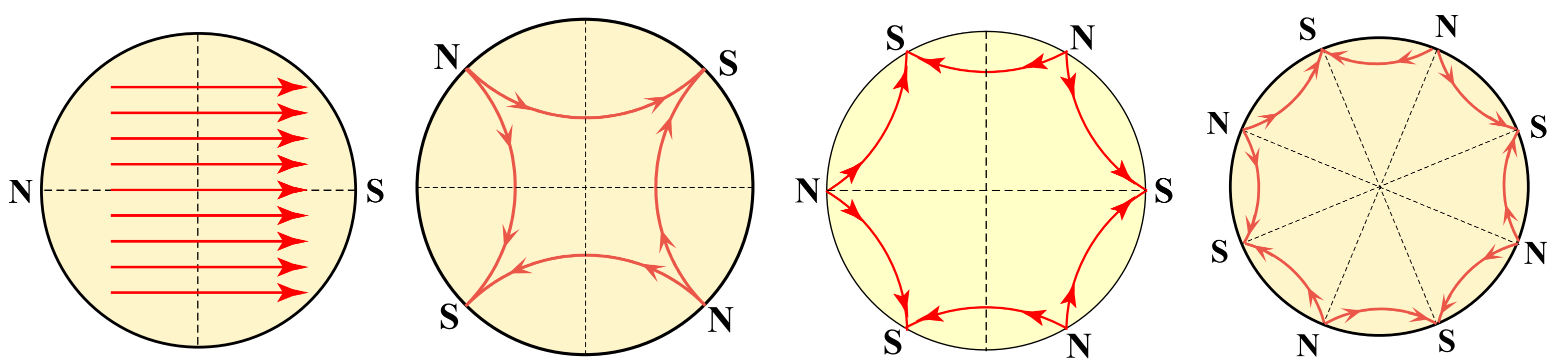
Subsequent investigation showed that it is a measurement error caused by a twist in the mounting of the printed circuit coil and coupling from large allowed normal 12-pole.

Using field symmetry to detect measurement errors



Normal Dipole (B_0) Skew Quadrupole (A_1) Normal Sextupole (B_2) Skew Octupole (A_3)

EVEN NORMAL and ODD SKEW harmonics look the same when viewed from either end of the magnet.



Skew Dipole (A_0) Normal Quadrupole (B_1) Skew Sextupole (A_2) Normal Octupole (B_3)

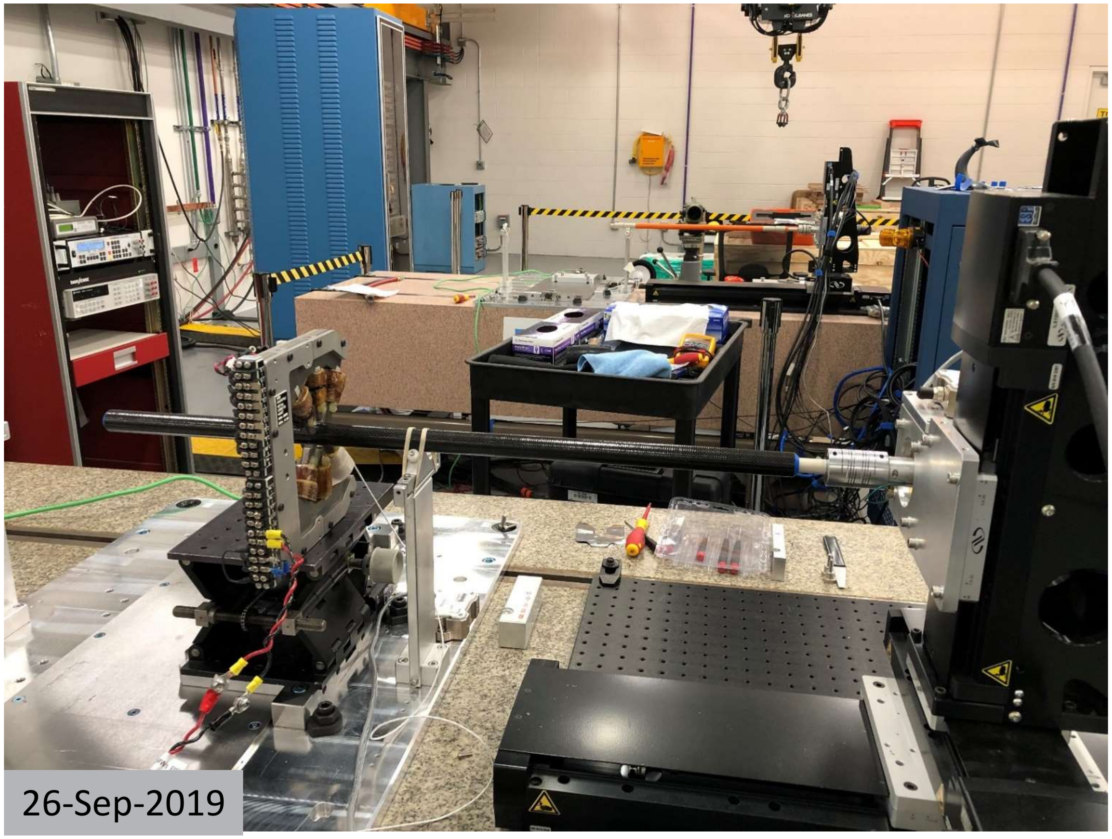
EVEN SKEW and ODD NORMAL harmonics look reversed when viewed from the other end

Measurements in “Normal” and “Flipped” orientations

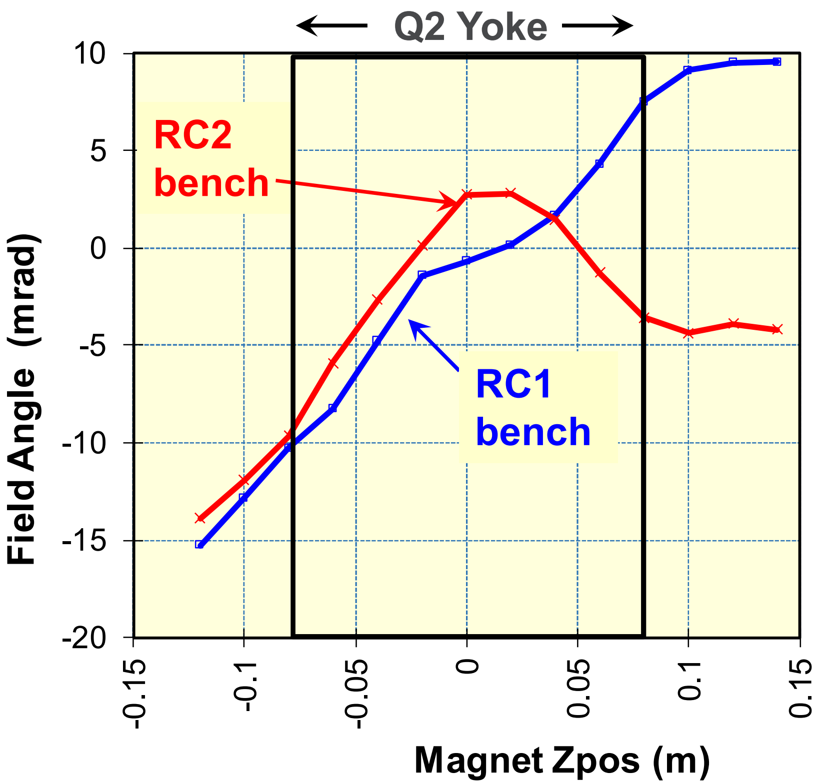
Q2 # 47 on 8/16/2019 Calib. runs 02 and 03 (Centered)							
Using Calibration of 15-Aug-2019 13:53:41							
Harmonic	**Normal**	**Flipped**	**Error**	**Harmonic**	**Normal**	**Flipped**	**Error**
b1	10000.00	-10000.00	0.00	**a1**	0.00	0.00	0.00
b2	-0.26	-0.17	-0.05	**a2**	2.35	-2.27	0.04
b3	1.02	-0.91	0.06	**a3**	0.46	0.45	0.00
b4	0.34	0.28	0.03	**a4**	-0.31	0.31	0.00
b5	-10.27	10.28	0.01	**a5**	0.91	-1.84	**1.38**
b6	-0.07	0.32	-0.20	**a6**	0.10	-0.10	0.00
b7	0.01	0.02	0.01	**a7**	0.04	0.04	0.00
b8	-0.06	-0.05	-0.01	**a8**	-0.06	0.06	0.00
b9	-3.84	3.81	-0.01	**a9**	0.17	0.19	-0.01
b10	-0.11	0.19	-0.15	**a10**	-0.02	0.05	0.01
b11	0.04	-0.03	0.01	**a11**	-0.05	-0.04	0.00
b12	-0.01	0.00	0.00	**a12**	-0.01	0.01	0.00
b13	-2.44	2.44	0.00	**a13**	-0.12	0.02	-0.07
b14	-0.14	0.14	-0.14	**a14**	-0.01	0.02	0.00
b15	0.00	0.01	0.00	**a15**	0.00	0.01	0.00

- **Odd normal** and **Even skew** terms **should change sign**.
- **Even normal** and **Odd skew** terms **should not change sign**.
- **Skew 12-pole (a5) should NOT change sign, but it does!**
- This indicates an error of ~1.4 units in the measurement of a5 term.
- Since the normal 12-pole term is large, an error in the phase angle can cause error in skew 12-pole.

Measurement of printed circuit board twist



A small corrector ~10 mm long was measured for several axial positions of the rotating coil on both RC1 and RC2 bench.



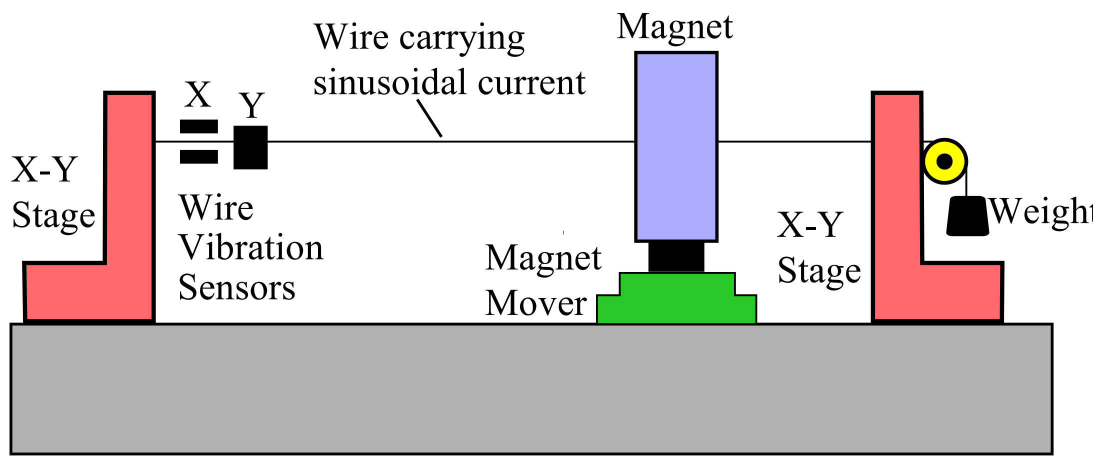
RC2 coil has a complex twist, which results in a phase error. The RC1 coil also has a large twist, but a uniform twist causes no error if the axial profile of field harmonic is symmetric.

Magnet alignment in a module assembly

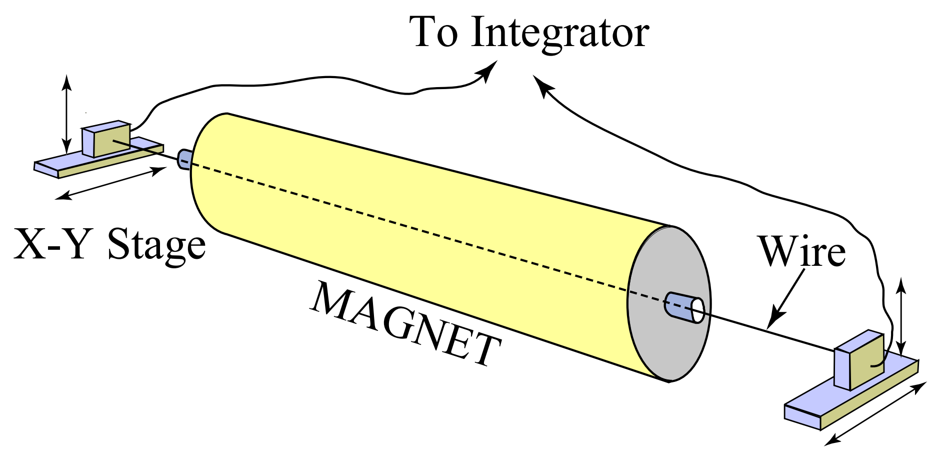
- All module assembly types are curved due to the presence of several bending elements.
- Alignment of magnets within a module is impractical using wire-based techniques, e.g. the vibrating wire technique, as was used for the NSLS-II girders.
- All magnets will have precisely located side and bottom reference surfaces, and the magnet support plates will have precisely machined top surface and horizontal stops.
- It is expected that machining accuracies will be sufficient to meet the alignment specification. However, magnetic alignment will be verified using fiducialization data.
- Individual magnets will be fiducialized using a wire based "rotating wire" measurement, to relate the magnet fiducials to the magnetic center.

Review of wire-based magnet measurement techniques

- Vibrating-wire
  - AC (near resonant frequency) passed through wire to excite wire motion
  - Sensors detect horizontal and vertical motion due to transverse field
  - Field determined from vibration amplitude as a function of position
  - Magnetic center derived from field profile

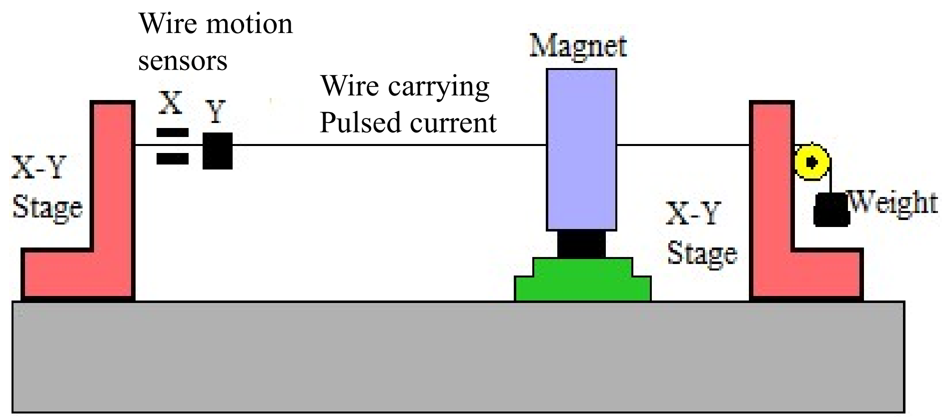


- Single Stretched Wire (SSW)
  - Wire moved transversely in magnet aperture, change in flux measured directly
  - Magnetic center determined from expected field symmetry

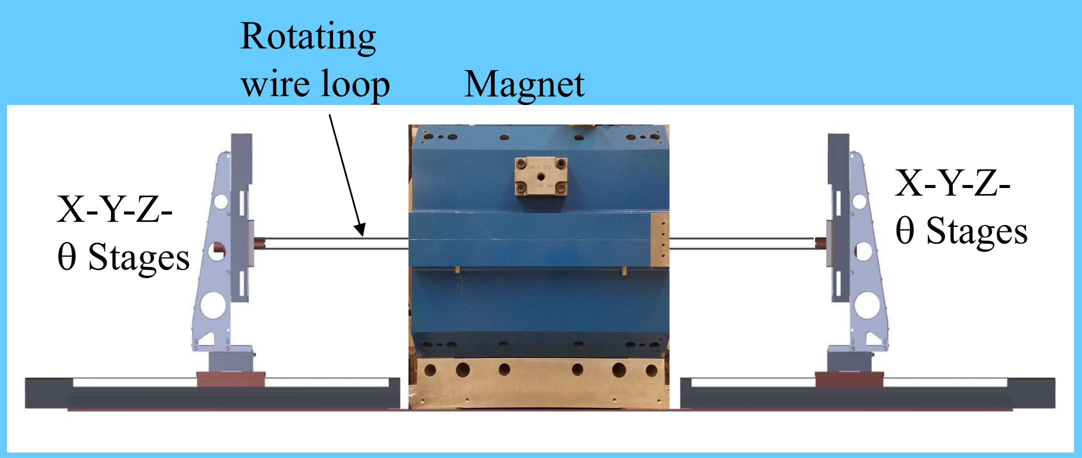


More wire-based measurement techniques

- Taut Pulsed wire
  - Short current pulse passed through wire
  - Sensors detect wire motion due to Lorentz force from transverse field
  - Field derived from detected wire motion and wire parameters
  - Magnetic center derived from field profile



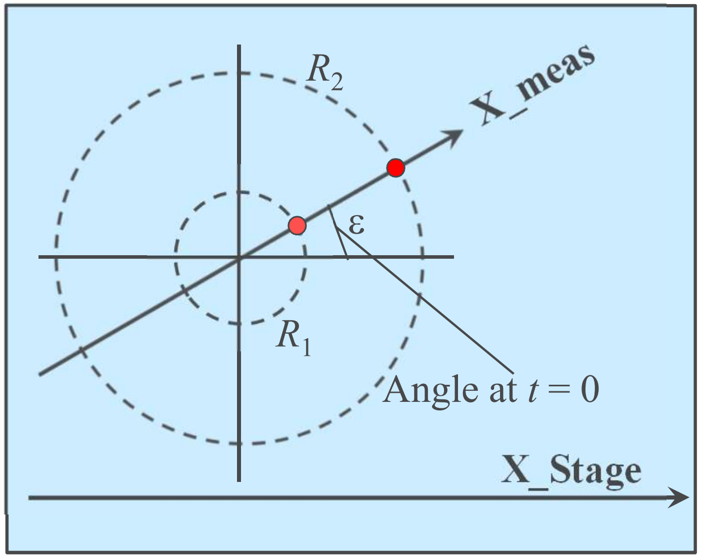
- Rotating wire (*chosen for APS-U*)
  - Radial or tangential wire loop rotates in a circle using synchronized stages
  - Field components derived from FFT of induced voltage or flux
  - Magnetic center derived from field components



Advantages of rotating-wire method

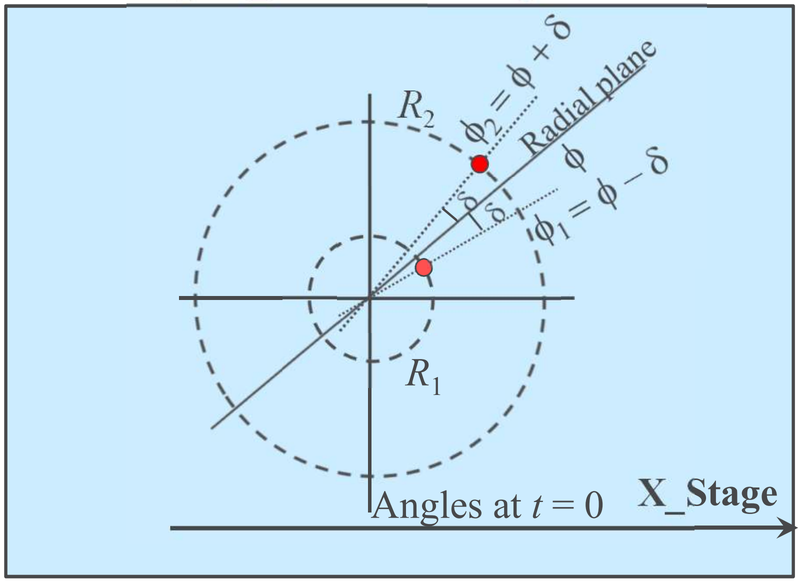
- With other non-rotating wire-based methods the ***location of the wire*** must be determined for magnet fiducialization.
- With rotating-wire, the wire ***rotation axis*** has to be determined, which is relatively easier to locate precisely.
- Knowing the wire rotation axis and the sag, the magnetic axis can be related to magnet fiducials.
- Short measurement time, 1 Hz rotation rate, typically 10-turn averages
- Sub-micron short-term repeatability in magnetic center measurement.
- All harmonics available with ~0.5 unit error or less.
- Relatively insensitive to small calibration errors of loop geometry at small magnetic offsets. (However, accurate calibration is required for Q-bends.)
- Not affected by higher harmonics, as FFT is used to separate out all terms.

Measurement errors due to wire loop geometry errors



Simplified description of a rotating wire loop:

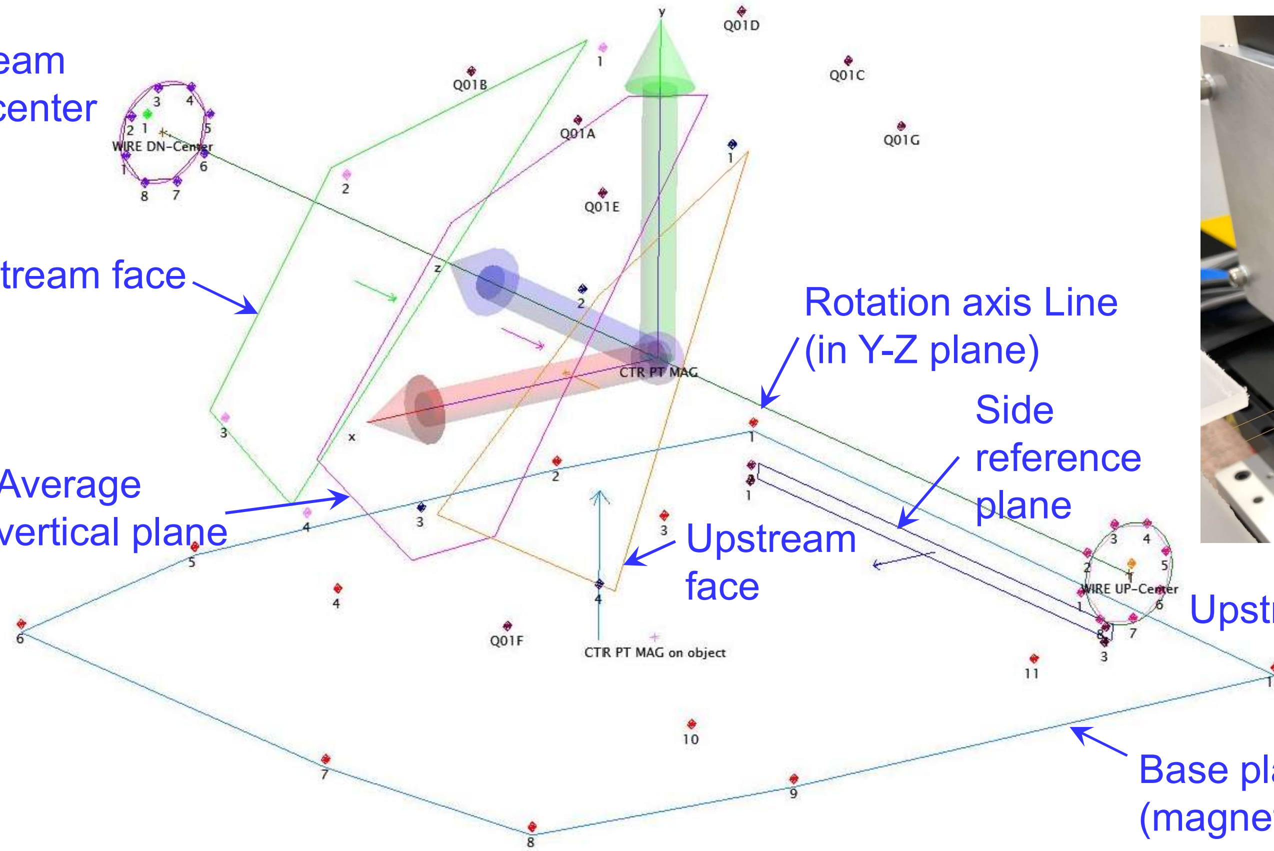
- Plane of loop is assumed to be perfectly radial
- Radii R_1 and R_2 are only approximately known.
- Error in center determination is negligible for simple quadrupoles and sextupoles, since we are looking for zero feed down.



Full description of a rotating wire loop:

- Plane of loop is not perfectly radial
- Radii R_1 and R_2 are only approximately known.
- Tilt of the plane, and radii R_1 , R_2 must be precisely known for combined function magnets.
- **A calibration procedure is developed for measuring combined function magnets**

The fiducialization process



Wire holder with retro-reflector nest

Magnetic center (chosen as origin) is the intersection of rotation axis line with the average vertical plane.

Questions related to magnet fiducialization

- **Question 1:** How *repeatable* is the fiducialization process?
- **Question 2:** If a magnet is subsequently installed in an assembly, and only the magnet fiducials are surveyed, how well can we locate the magnetic center, and thus the true magnetic alignment between various magnets? (*reliability*)
- These questions were studied extensively during R&D, and the studies were repeated with the new production measurement system.
- We fiducialized one Q1 magnet (serial #22) nine times to determine the repeatability (Question 1).
- For question 2, we can use any one of the nine measurements as the "fiducialization run", and the other eight as "future measurements".
  - Use the fiducials data in the "future" measurements to derive magnetic center
  - True magnetic center is (0,0,0) in all cases, so error in magnetic center is determined
  - There are 72 combinations possible, so the *error distribution* can be measured

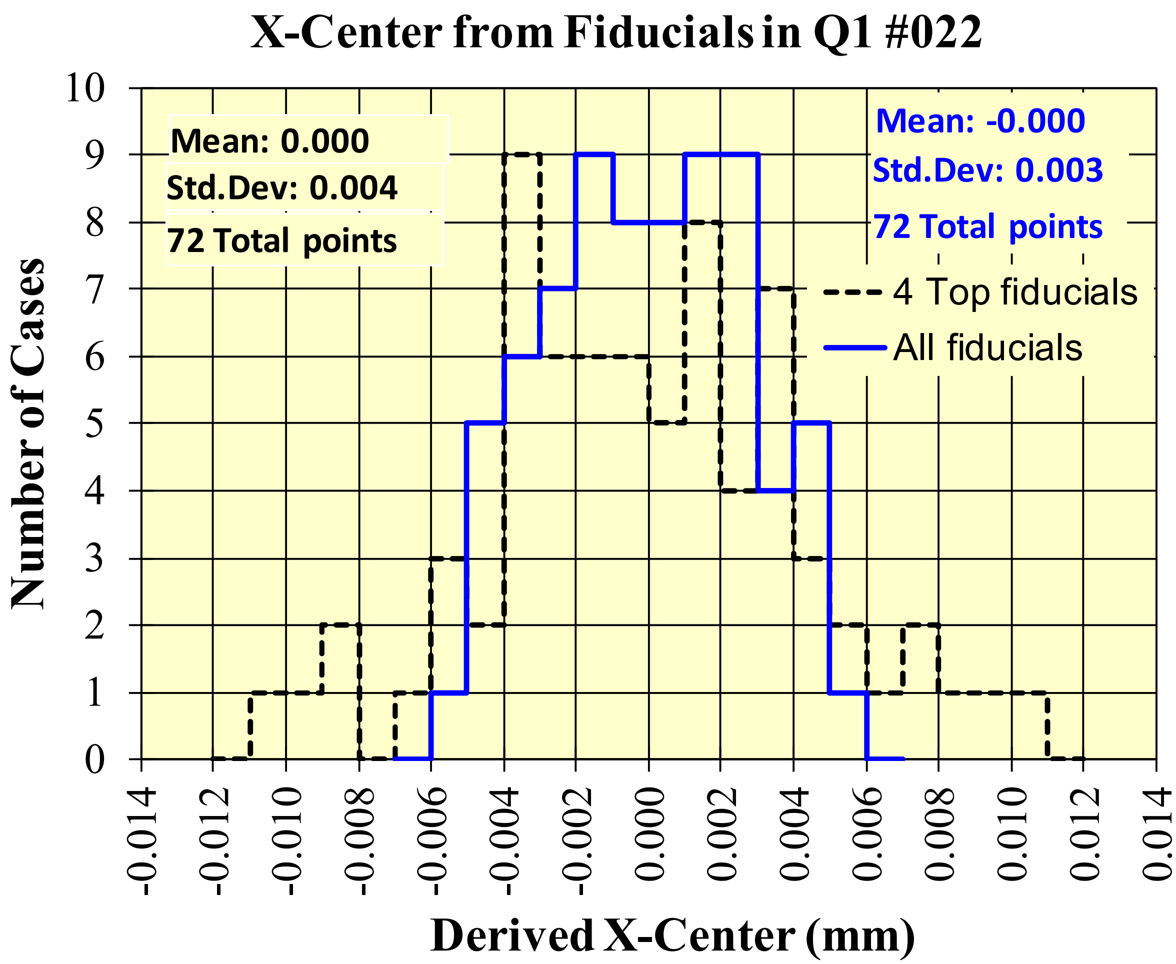
Repeatability of fiducialization (Q1 #22)

Measurement Number	Date	X from Side (mm)	Y from base (mm)
1	4-Sep-2019	168.033	279.524
2	4-Sep-2019	168.043	279.526
3	5-Sep-2019	168.048	279.526
4	5-Sep-2019	168.046	279.521
5	5-Sep-2019	168.047	279.521
6	5-Sep-2019	168.031	279.532
7	5-Sep-2019	168.027	279.529
8	6-Sep-2019	168.030	279.527
9	6-Sep-2019	168.038	279.532
Mean		**168.038**	**279.526**
Std. Deviation		**0.008**	**0.004**

Production Rotating Wire bench #1

- The measured offsets of X and Y reference surfaces is used as an indicator of repeatability.
- The uncertainty in X is similar to the results obtained during R&D.
- The uncertainty in Y is ~2X better than R&D, presumably due to better temperature control.
- The Y-offset may be more repeatable than X because the side reference plane is very small, partially obscured by the X-stops, and thus difficult to measure accurately.

Deriving magnetic center from fiducials: Q1 #22



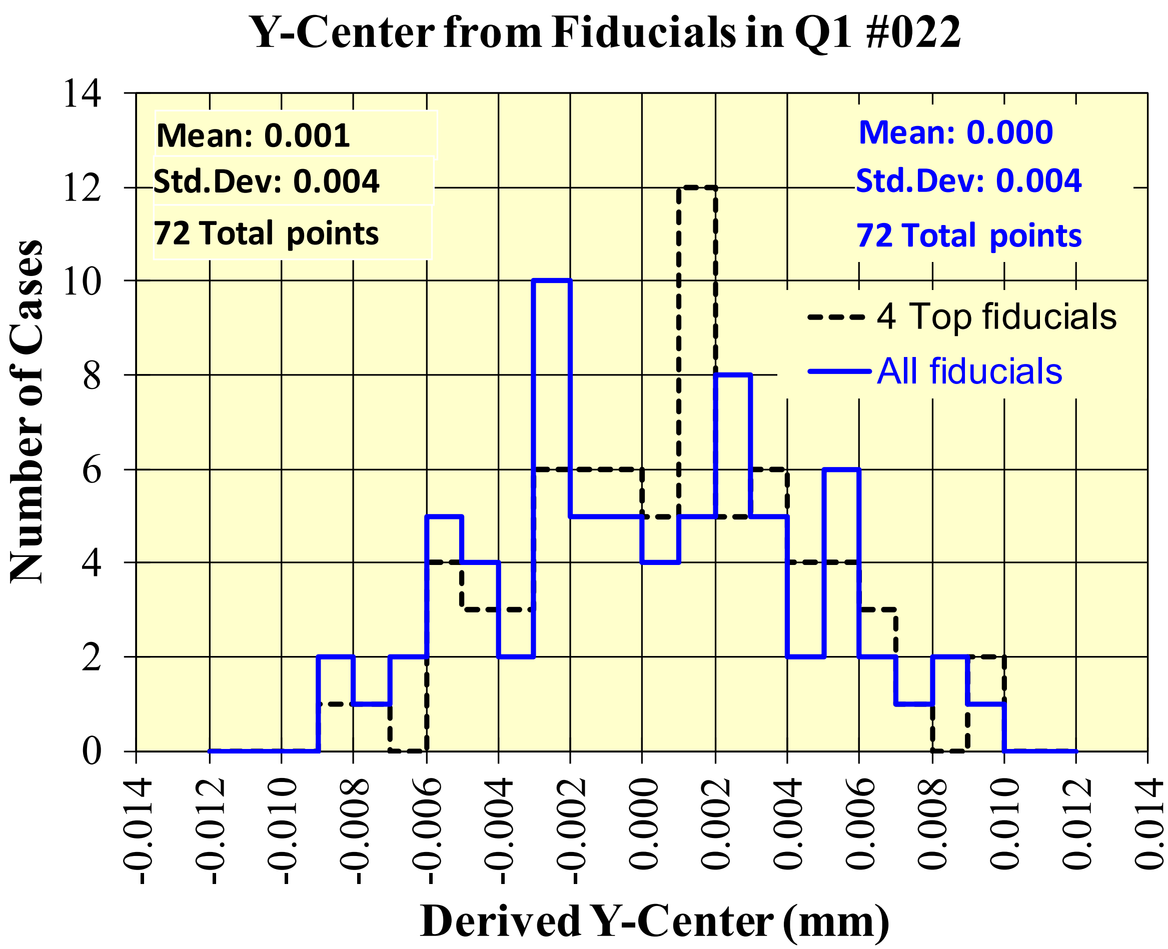
Production Rotating Wire bench #1

Standard deviation is ~2X smaller than what was obtained during R&D, presumably due to a better temperature control of the environment.

This demonstrates that the horizontal center can be determined with sufficient accuracy using fiducialization data.

Using more fiducials has a slight advantage over using only the four fiducials on the top of the magnet.

Deriving magnetic center from fiducials: Q1 #22



Production Rotating Wire bench #1

Standard deviation is ~2X smaller than what was obtained during R&D, presumably due to a better temperature control of the environment.

This demonstrates that the vertical center can be determined with sufficient accuracy using fiducialization data.

Only the four top fiducials are sufficient to locate the vertical center.

Summary - 1

- The upgrade of the Advanced Photon Source (APS) at Argonne will require measurements of ~1350 magnets for the new storage ring.
- A new magnet measurement laboratory is built to handle the high volume of magnetic measurements. All measurements are scheduled to be completed by the end of FY 2022.
- Two rotating coil and one rotating wire bench are in operation now.
- Four rotating coil, two rotating wire, and one Hall probe bench, for a total of seven benches, are planned. All benches should be available by the end of FY2020.
- So far, production batches of only the Q1 and Q2 magnets have been received. All magnets received have been measured for field quality. Fiducialization is in progress.
- The Q1 and Q2 magnets meet or exceed the field harmonics requirements.
- Mechanical asymmetry is found to be a good predictor of potential field quality issues. This is important for a "build-to-print" procurement of magnets.

Summary - 2

- Approximately 90% of the magnets can be measured using well established rotating coil and Hall probe techniques. However, one must keep watching for sources of error.
- Schemes are developed to adapt well established rotating coil and wire-based techniques to curved combined function magnets M3 and M4 using a 3-part description.
- All magnets will be fiducialized using rotating wire method, but quick alignment in a module assembly is expected to be achieved using precise reference surfaces.
- Accurate calibration of rotating wire loop geometry is essential for fiducializing combined function magnets. A procedure is developed for in-situ calibration of rotating wire.
- Alignment in a module assembly will be verified using laser trackers and fiducialization data. Any grossly out of alignment magnets will be shimmed as necessary.
- It is demonstrated that magnetic center can be determined with a standard deviation of < 5 microns by surveying the magnet fiducials. Even four fiducials on the top are enough.
- We are confident that all the measurement and alignment requirements can be met.