Performance of rotating wire magnetic alignment systems for the Advanced Photon Source Upgrade*

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Outline

- APS-U magnetic alignment requirements
- Review of wire-based alignment techniques
- Why rotating-wire?
- Rotating-wire measurement systems for APS-U
- Motivation for individual magnet fiducialization
- Laser Tracker fiducial measurements
- Results and lessons learned
- Conclusions

APS-U magnet alignment tolerances

Tolerances for the 42 pm-rad lattice

- The magnet-to-magnet transverse alignment tolerance has been set to 30 μm rms
- The girder-to-girder tolerance is 100 μm rms
- To meet these tolerances, two magnet alignment systems have been designed, built and tested.
- Some of the results of the testing will be presented in this talk

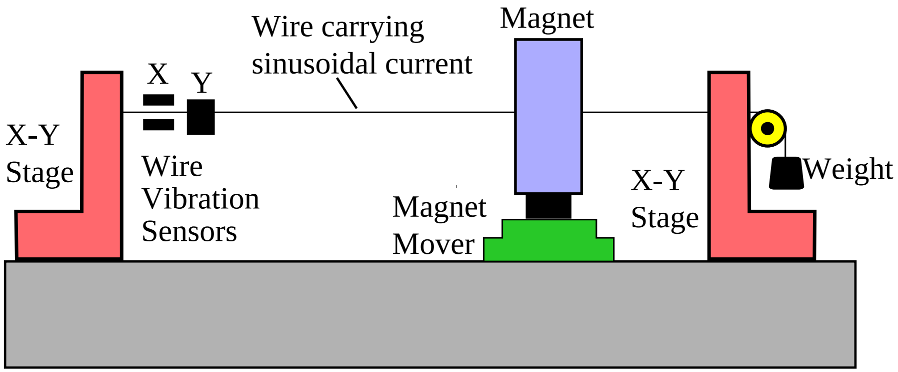
42 pm Magnet Parameters December 2016

Name	B_{min} T	B_{max} T	L m	θ	B' T/m
M1	-0.650	-0.148	2.223	0.0291	0.0
M2	-0.325	-0.156	1.986	0.0233	0.0
M3	-0.629	-0.629	0.780	0.0245	45.1
M4	-0.605	-0.605	0.650	0.0196	48.2
Q1	0.000	0.000	0.242	0.0000	-68.6
Q2	0.000	0.000	0.242	0.0000	52.3
Q3	0.000	0.000	0.242	0.0000	43.6
Q4	0.157	0.157	0.242	-0.0019	-65.0
Q5	0.106	0.106	0.242	-0.0013	-26.0
Q6	0.000	0.000	0.242	0.0000	46.9
Q7	0.000	0.000	0.418	0.0000	-76.1
Q8	0.168	0.168	0.600	-0.0050	-81.9

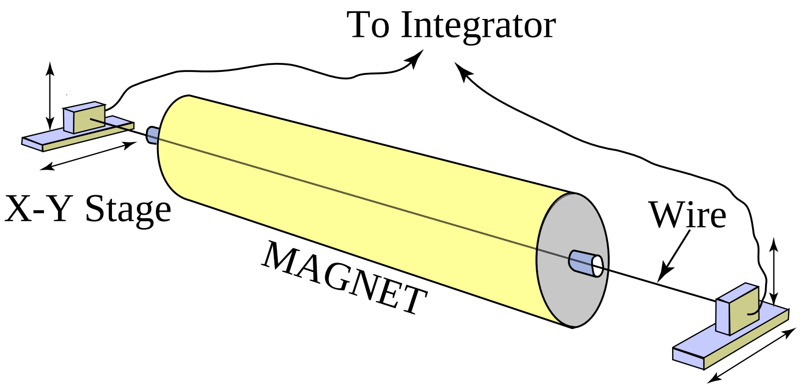
For details of magnet lattice, see talk by Animesh Jain 13:45 Monday: "Overview of magnetic measurements for the Advanced Photon Source Upgrade"

Review of wire-based magnet alignment 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



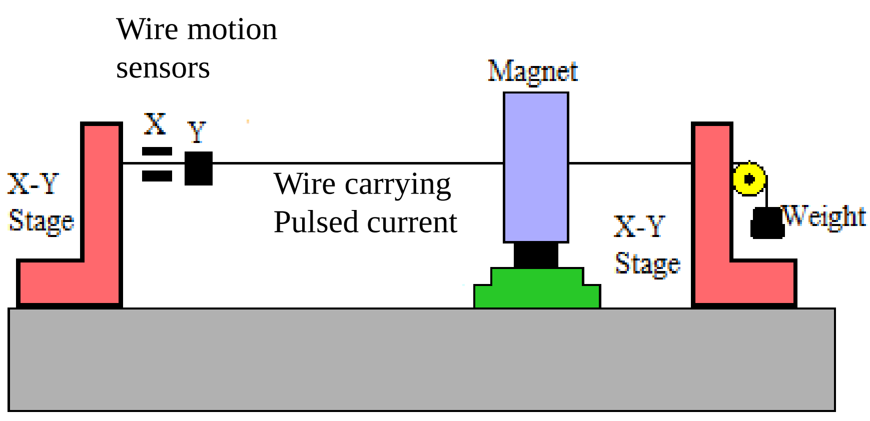
- Single Stretched Wire (SSW)
  - Wire moved transversely in magnet aperture, change in flux measured directly
  - Magnetic center determined from expected field symmetry



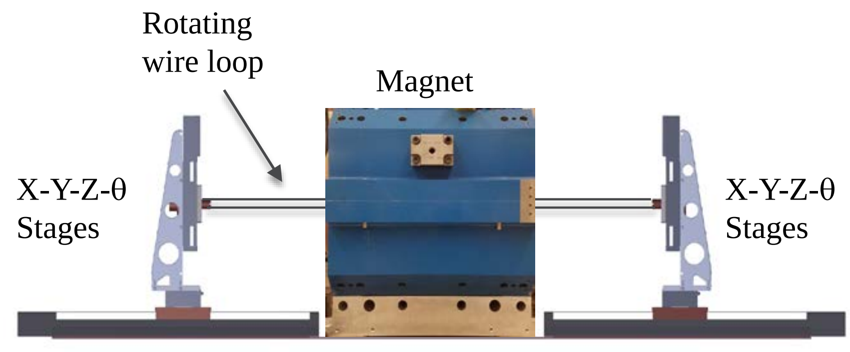
Figures courtesy of A. Jain

More wire-based alignment 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

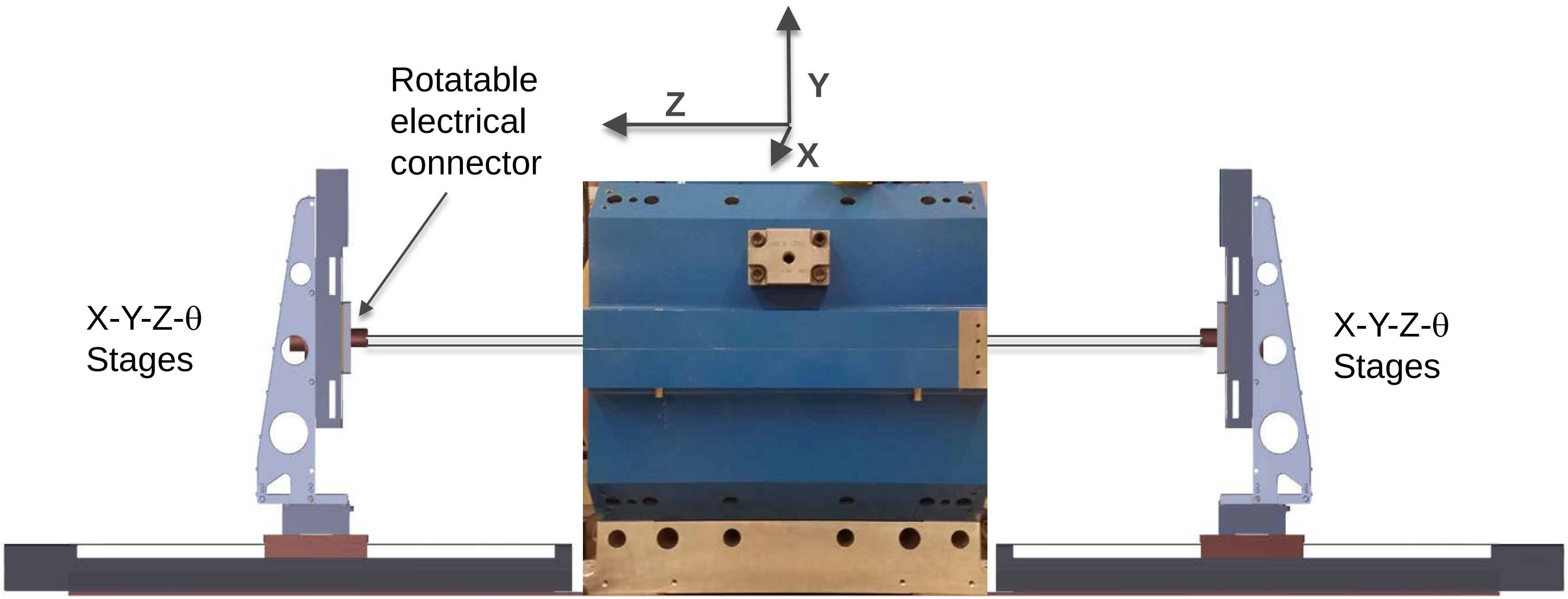


Why use rotating-wire alignment?

- With other non-rotating wire-based systems the ***location of the wire*** must be determined for magnet fiducialization.
- With rotating-wire, the wire ***rotation axis*** has to be determined, which is 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. (Errors ~0.1 mm OK for offsets < 0.5 mm)
- Not affected by higher harmonics, as FFT is used to separate out all terms

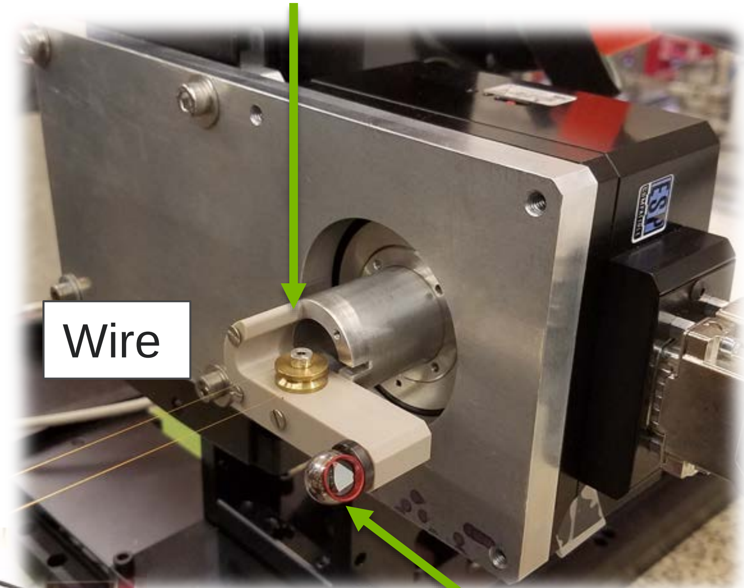
APS-U "Short-wire" system

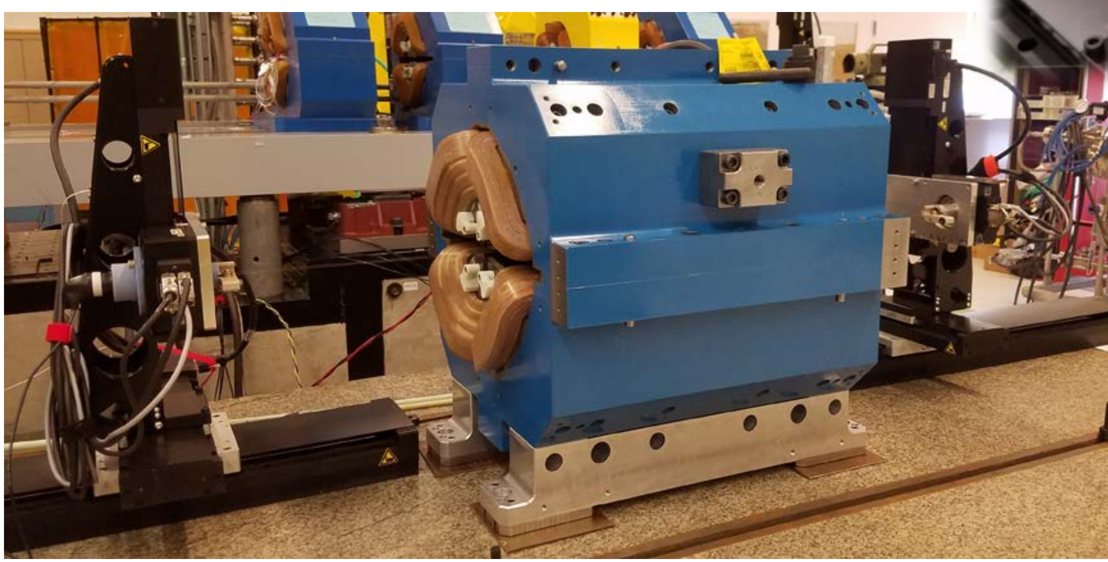
- Used for individual magnet FIDUCIALIZATION
  - Radial wire loop rotates in a circle using synchronized rotary stages
  - Return wire within 50 microns of rotation axis, outer can be located at any radius. (11 mm typ.)
  - Wire tensioned by moving Z-stages and measuring the wire resonant frequency
  - Wire rotation axis placed at magnetic center in X and at calculated sag value in Y
  - Wire rotation axis defined by center points of θ-stage rotation at wire ends
  - Wire length between 0.5 and 2 meters
  - National Instruments DAQ hardware and software, Newport motion stages.



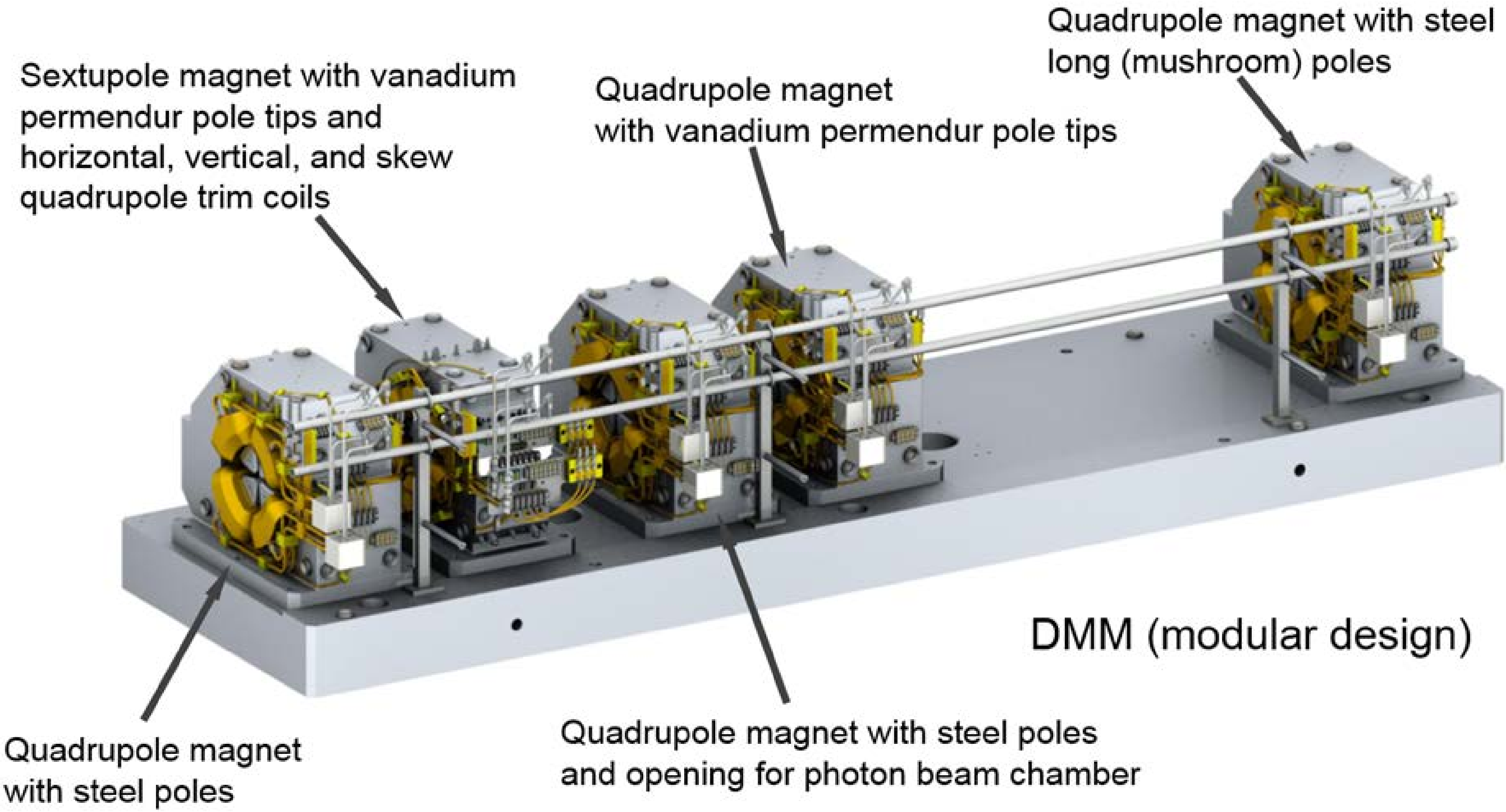
“Short-wire” system for the APS-U

- Wire rotation centers determined by fitting a circle to eight angular positions of the wire holders. *Idea proposed by B. Jansma, APS survey*
- Rotary stage eccentricity < 3 μm rms
- Laser tracker error < 10 μm rms





Demonstration Modular Multiplet (DMM)



All quadrupoles differ slightly from each other, but use the same basic design. Initial alignment was done solely using reference surfaces.

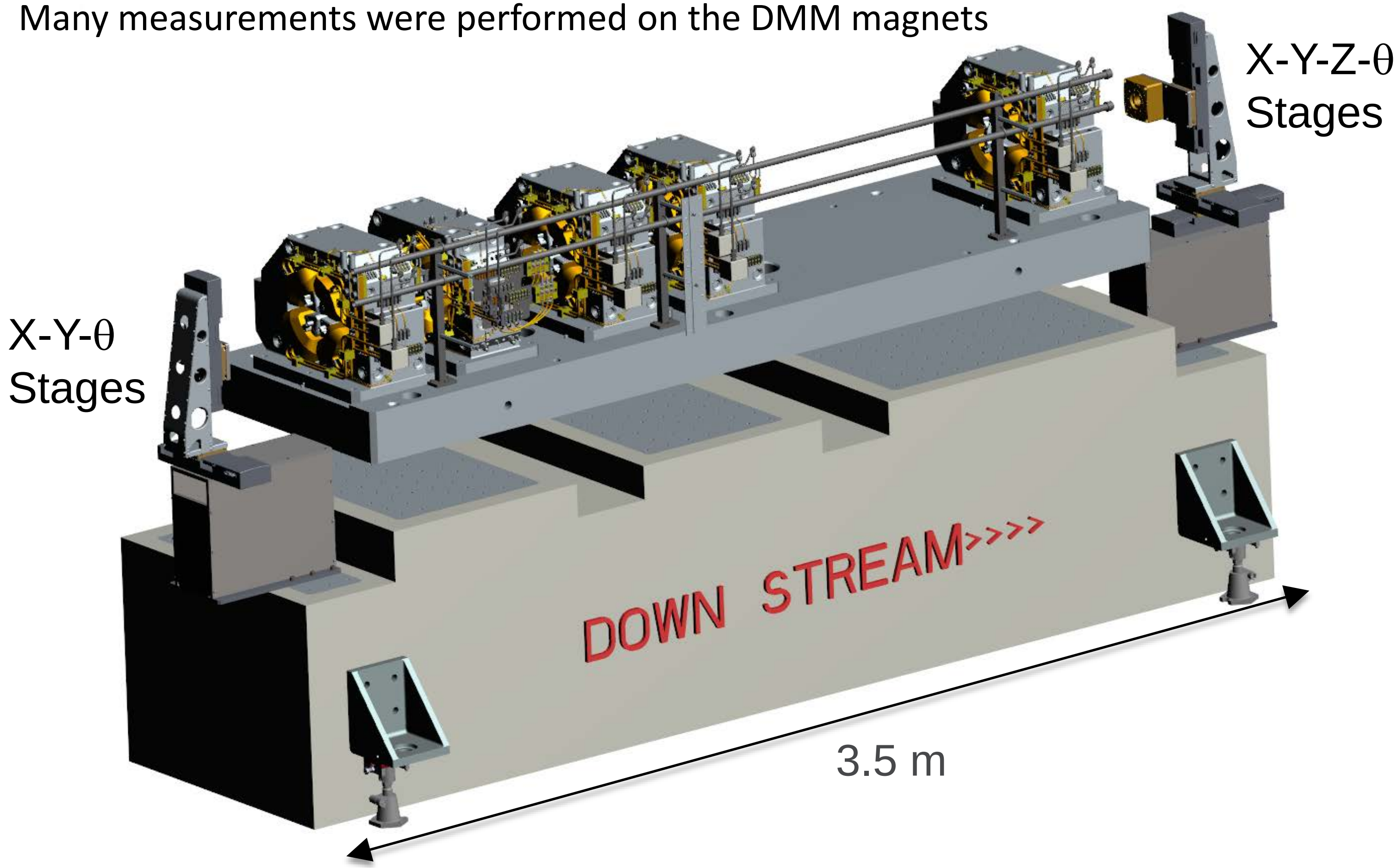
“Long-wire” magnetic alignment system

- Initially this alignment system was designed to measure alignment of magnets in straight sections of quadrupole and sextupole magnet assemblies.
- The latest APS upgrade lattice no longer has any straight assemblies of quadrupoles and sextupoles. The system, however, can still be used for the multiplet section.
- The long-wire system was extensively used to measure the five-magnet assembly of R&D magnets.

  See talk by R. Dejus 11:55 Thursday, “Magnetic measurement results in R&D magnets for the Advanced Photon Source Upgrade”.

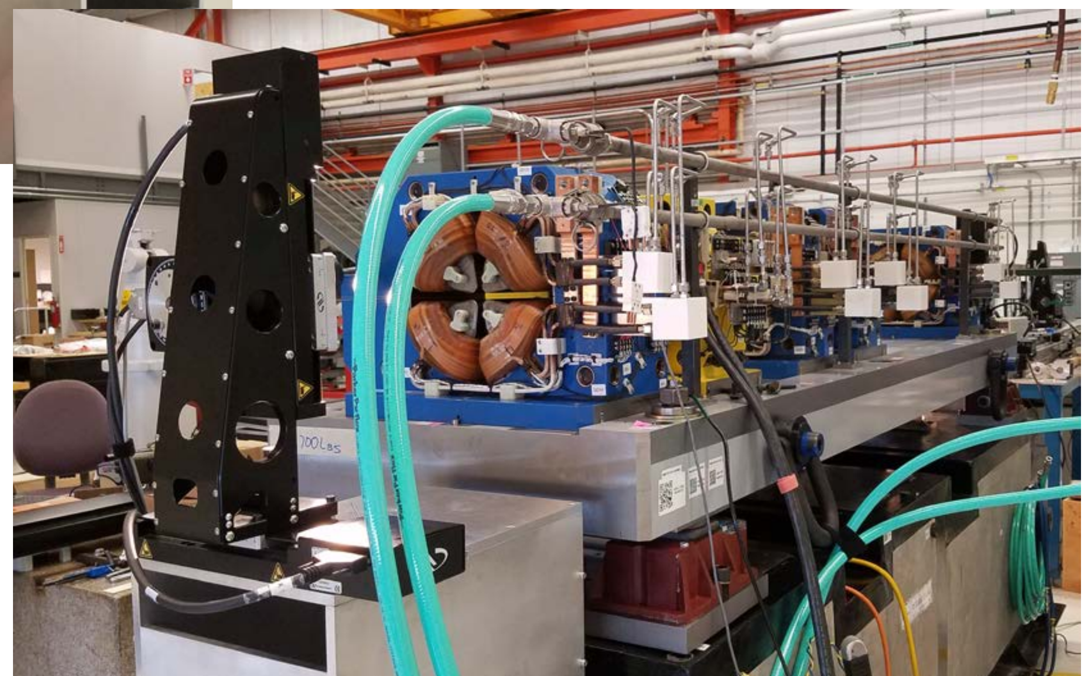
“Long-wire” magnetic alignment system

- Used for alignment of magnet assemblies up to ~4 m
  - Same hardware and software as “Short-wire” system
  - Z stage only on down-stream end
  - Many measurements were performed on the DMM magnets



"Long-wire" magnetic alignment system

Upstream and outboard end of DMM assembly



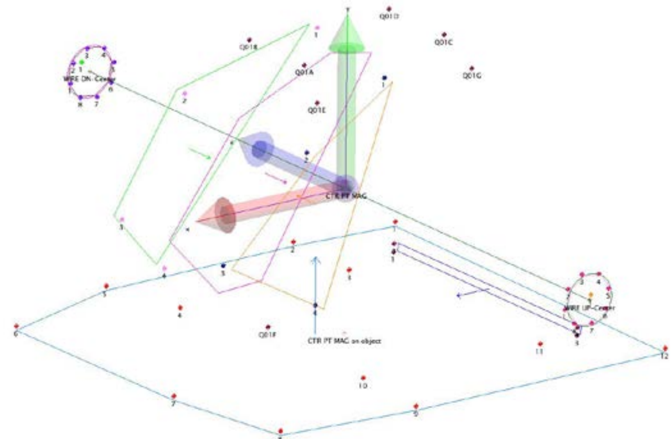
Upstream and inboard end of DMM assembly

Motivation for individual magnet fiducialization

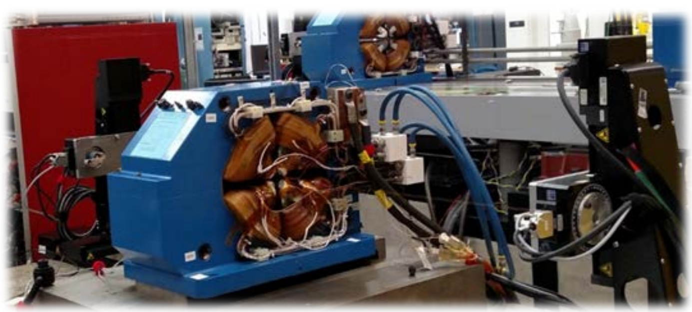
- We need to demonstrate that we will be able to replace a magnet in the ring, while meeting the 30 micron alignment requirement, should it ever become necessary.
- Magnet arrangement in the 42-pm APS-U lattice has become more complex with many more bends, including reverse bends, even in what was earlier a straight multiplet.
- Alignment of the FODO section will require individual magnet fiducialization because measuring the entire assembly is not practical.
- **How well can we fiducialize an individual magnet, and then align it to a series of magnets using survey data?**
- To answer this question, we used survey data obtained from the “short-wire” system to calculate shims to place a quadrupole onto the DMM. The “long-wire” system was then used to determine the relative magnet offset to the other four magnets.

Fiducialization using a laser tracker

- Laser Tracker data were taken with wire rotation axis centered in X and placed vertically at the calculated sag offset from magnetic center.
- The following fiducial points were measured:
  - All the visible fiducial nests
  - The machined –X side of the magnet base
  - Points on the US and DS ends of the magnet core
  - Points on the steel base plate
  - Eight angular positions of both the US and DS wire hold



- Origin defined by intersection of magnet vertical mid-plane and wire rotation axis.
- A frame was created in order to determine the distance from the magnetic center to the base plate and to the –X side machined reference surface.
- With the Vertical and Horizontal distances determined, shims were calculated in order to have the magnetic centers be collinear when mounted on the DMM plate.

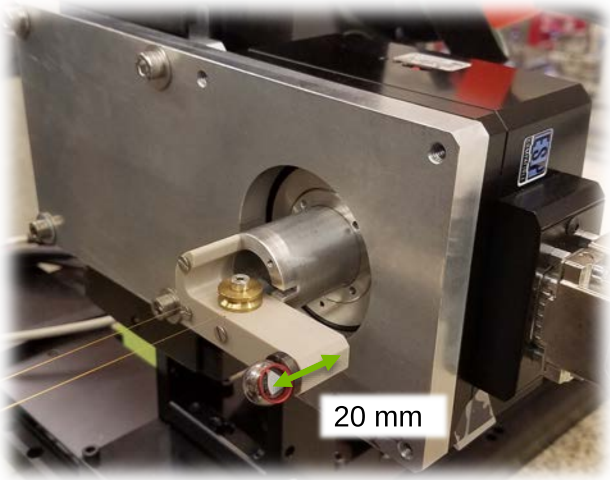


Unexpected discrepancy between long and short measurement systems

- After determining the required shims from the survey data from the short-wire system, the magnet was installed on the DMM.
- The long-wire measurement system showed the vertical offset was 87 microns low relative to the other previously aligned DMM magnets.
- We tried several different tests to determine the cause of the systematic difference, but ultimately it was discovered (by Animesh) that the planes described by the rotating-wire holders were tilted (up to 9 mrad) with respect to the wire axis. This caused an error in the determination of the rotation axis position.
- With the survey group’s help we used the laser tracker to align the stages in both measurement systems to about ~0.5 mrad or better.
- With the stages aligned there was very good agreement between the two measurement systems

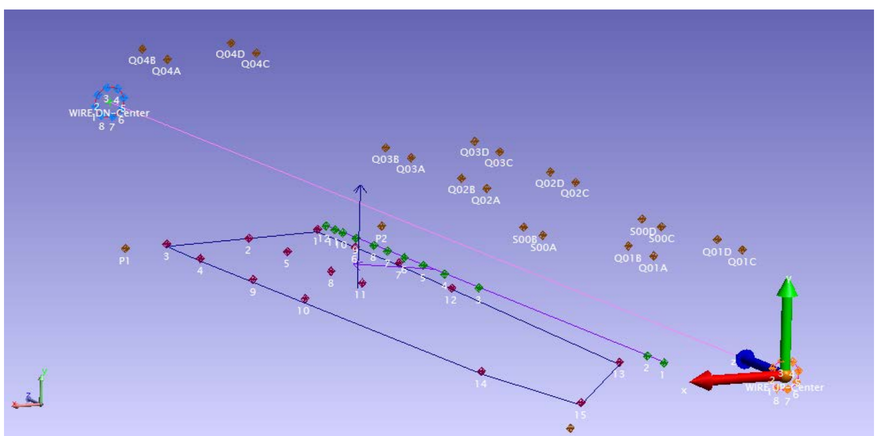
Lessons learned

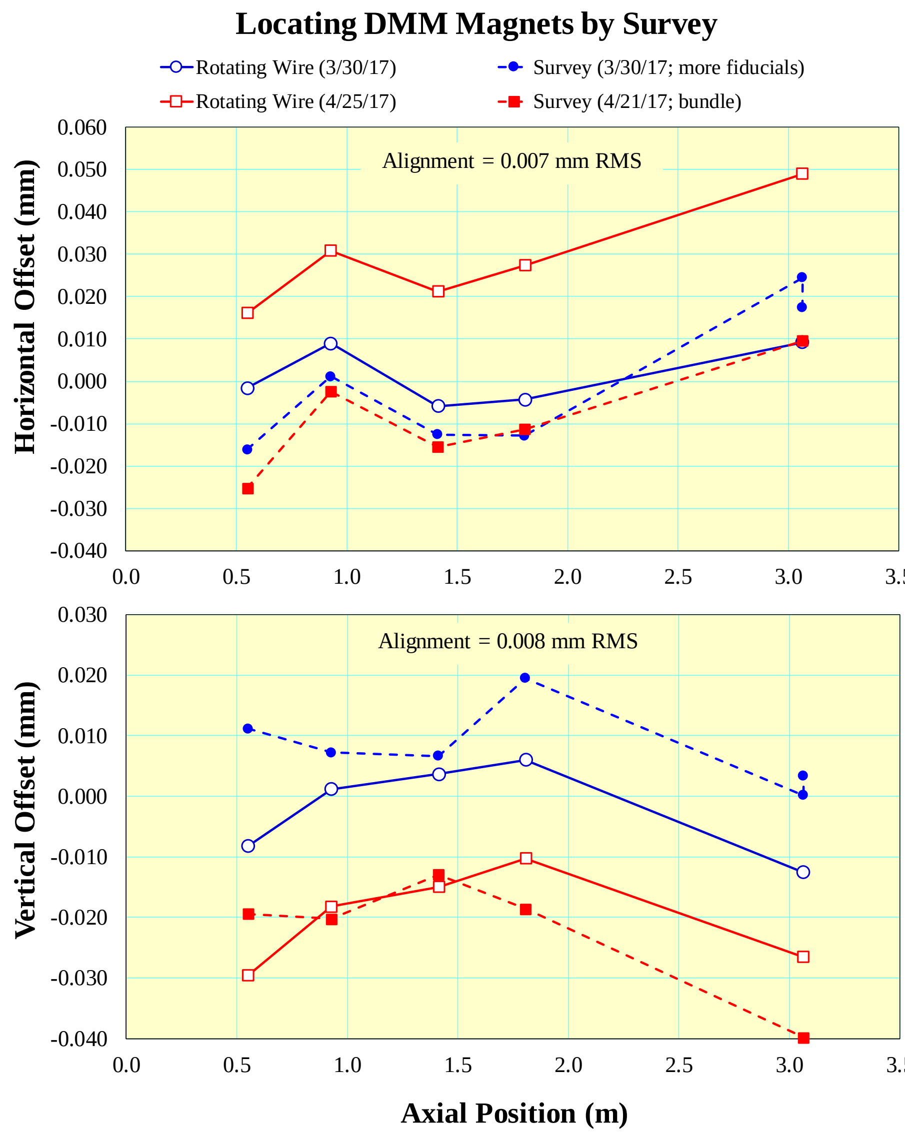
- Yaw and pitch of the rotary stages relative to the overall rotation axis produced errors in fiducialization.
- The cause of the fiducialization error was a 20 mm difference in the longitudinal location of the planes of rotation of the wire ends and the retro-reflector, coupled with the mis-alignment of the stages.
- We now have well aligned stages and a retro-reflector mount in the same plane as the wire ends to eliminate these errors.



DMM magnet offsets using survey data

- “Rotating Wire” refers to measured magnetic offset data from long-wire DMM measurement system.
- “Survey” refers to calculated magnetic offset relative to wire axis from fiducialization data.
- Shims based on fidcialization data give magnetic offsets <10 μm rms.
- Survey can determine magnetic center within 10 μm.





Conclusions

- A rotating-wire system has been chosen for APS-U magnet fiducialization and alignment due to speed, accuracy and ease of determining rotation axis.
- We have demonstrated the ability to individually fiducialize four quadrupoles and one sextupole and then place them on a plate (DMM) according to the survey data with alignment of ~10 μm RMS.
- Magnetic centers determined from survey data agree with direct magnetic measurements within ~10 μm.
- These results pave the way for aligning the magnets in the most challenging curved FODO assemblies for the APS-U.