Magnetic measurement results in R&D magnets for the Advanced Photon Source Upgrade*

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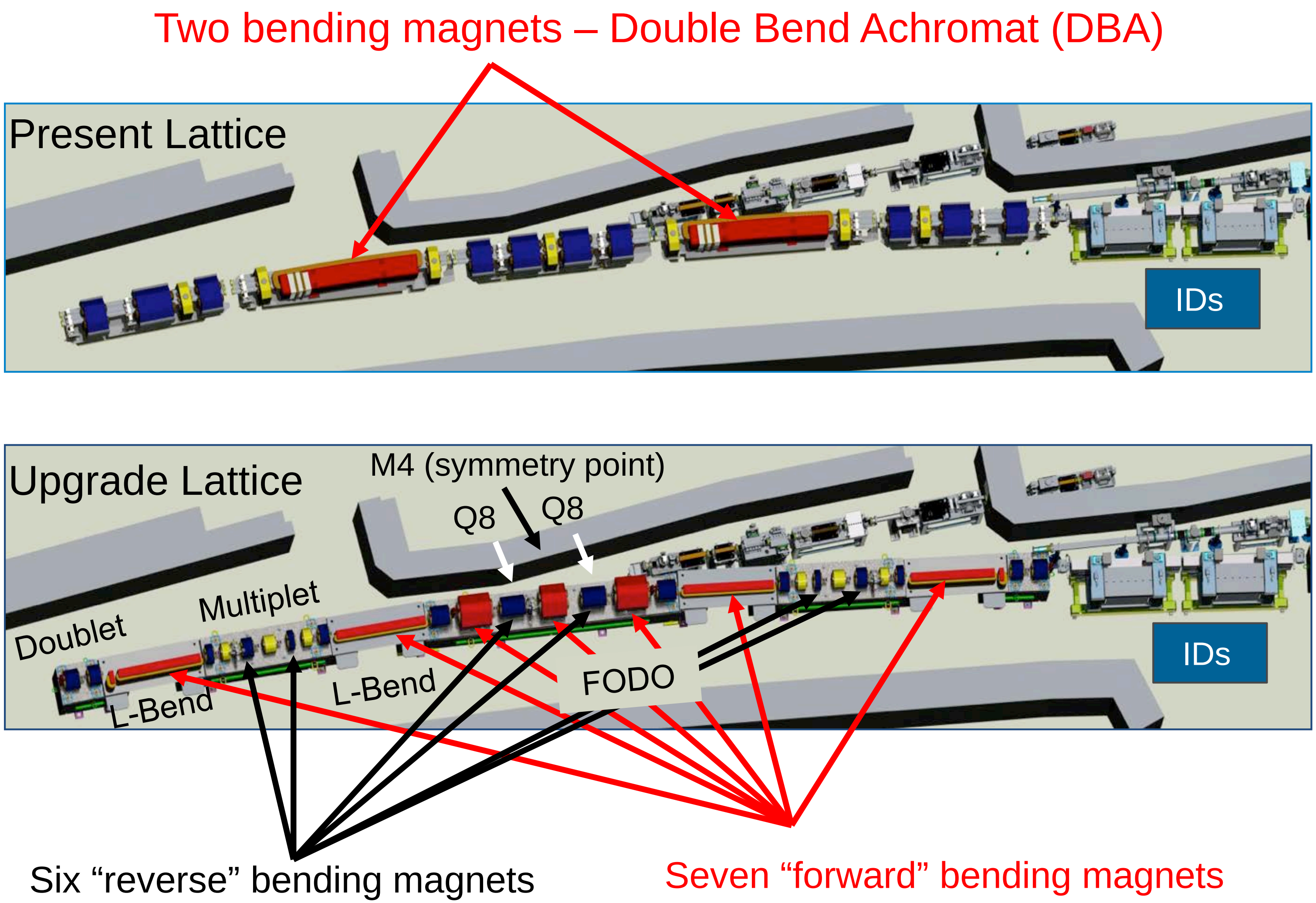
Advanced Photon Source Upgrade (APS-U)



4 longitudinal gradient dipoles (L-bends; dipole only)
3 transverse gradient dipoles (Q-bends; dipole + quadrupole)
6 reverse bending magnets (R-bends; dipole + quadrupole)

13 bends total (Multi-bend Achromat)

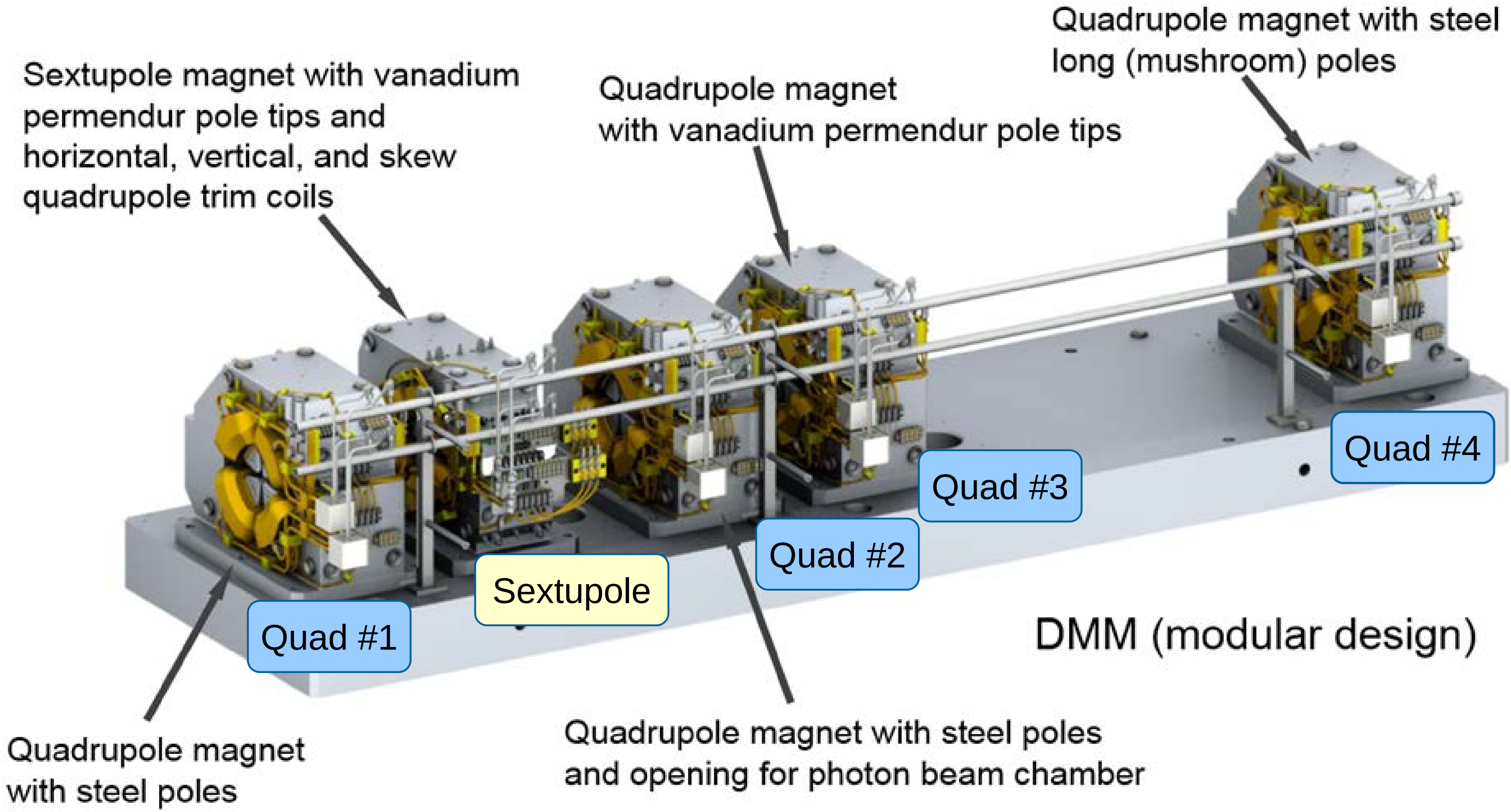
Outline

- Motivation for R&D
- Demonstration Modular Multiplet (DMM)
  - Saturation behavior
  - Field quality
  - Disassembly/reassembly tests
    (including recent results of Q8 magnet)
  - Axial profiles (Hall probe measurements)
  - Alignment tests (shimming and transportation tests)
- Summary

Motivation for R&D

- Accuracy of magnetic design calculations
- Mechanical tolerance stack up and its effect on magnetic performance
- Crosstalk between neighbouring magnets
- Alignment methods, alignment accuracy, and repeatability under disassembly/reassembly of magnets to simulate vacuum chamber installations
- Alignment stability after transportation of a magnet assembly on a plinth

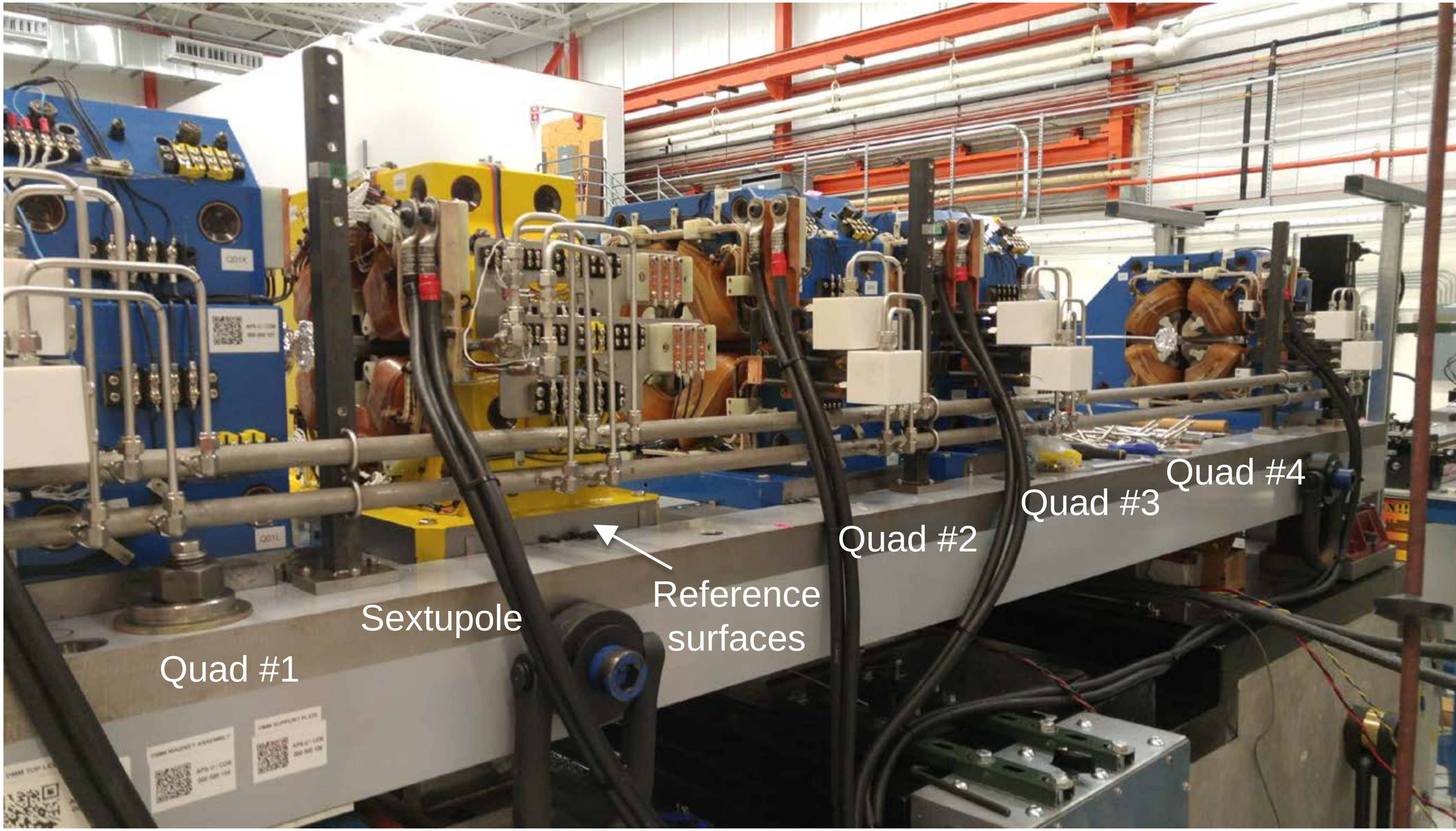
The DMM magnets and assembly



All quadrupoles differ slightly from each other, but use the same basic design.

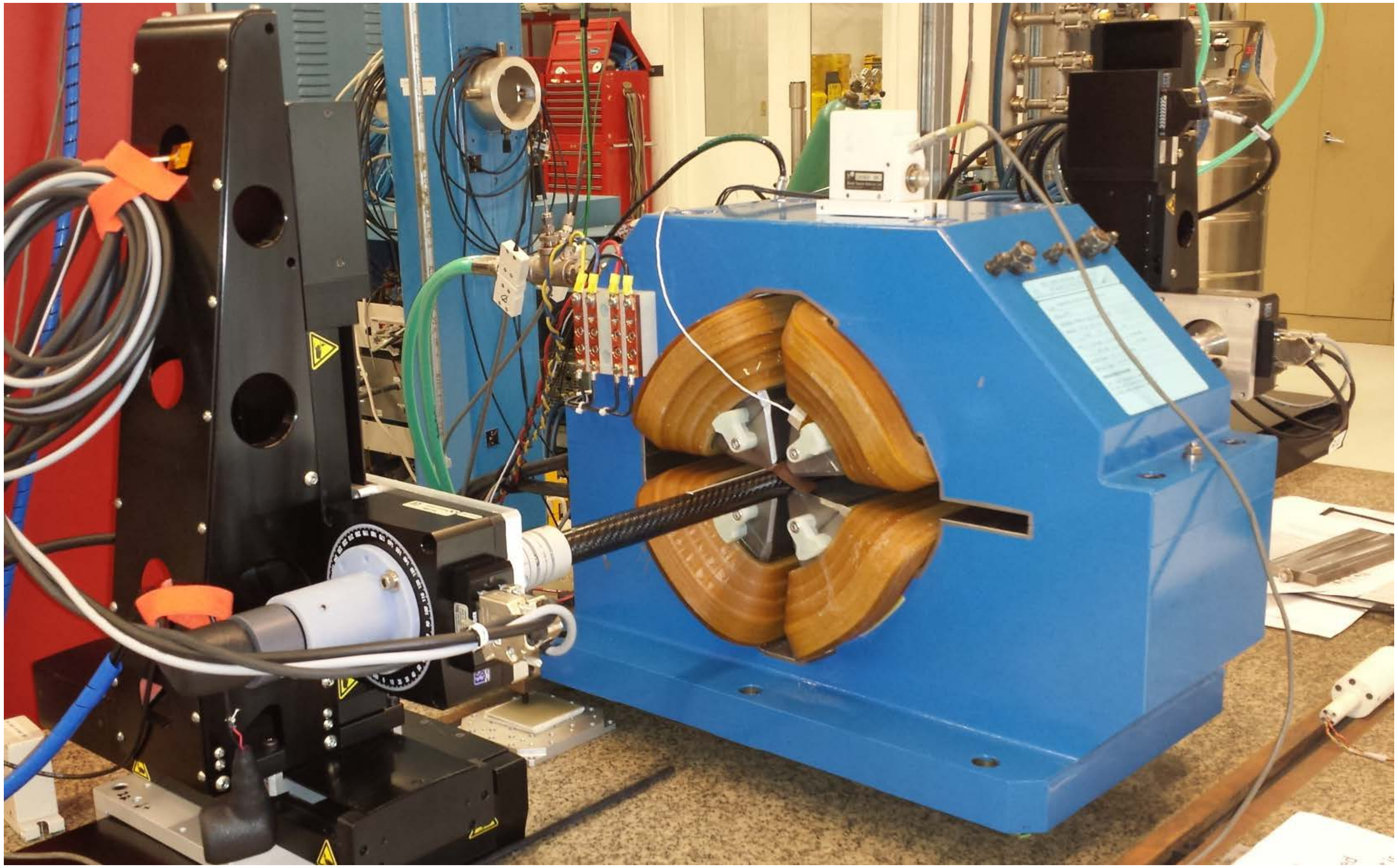
Initial alignment was done solely using reference surfaces. The required alignment of magnets on a common support structure is 30 μm RMS.

The DMM magnets and assembly (2)



Photograph of DMM magnets on steel support plate on top of concrete plinth

Rotating coil setup in a R&D APS-U quadrupole

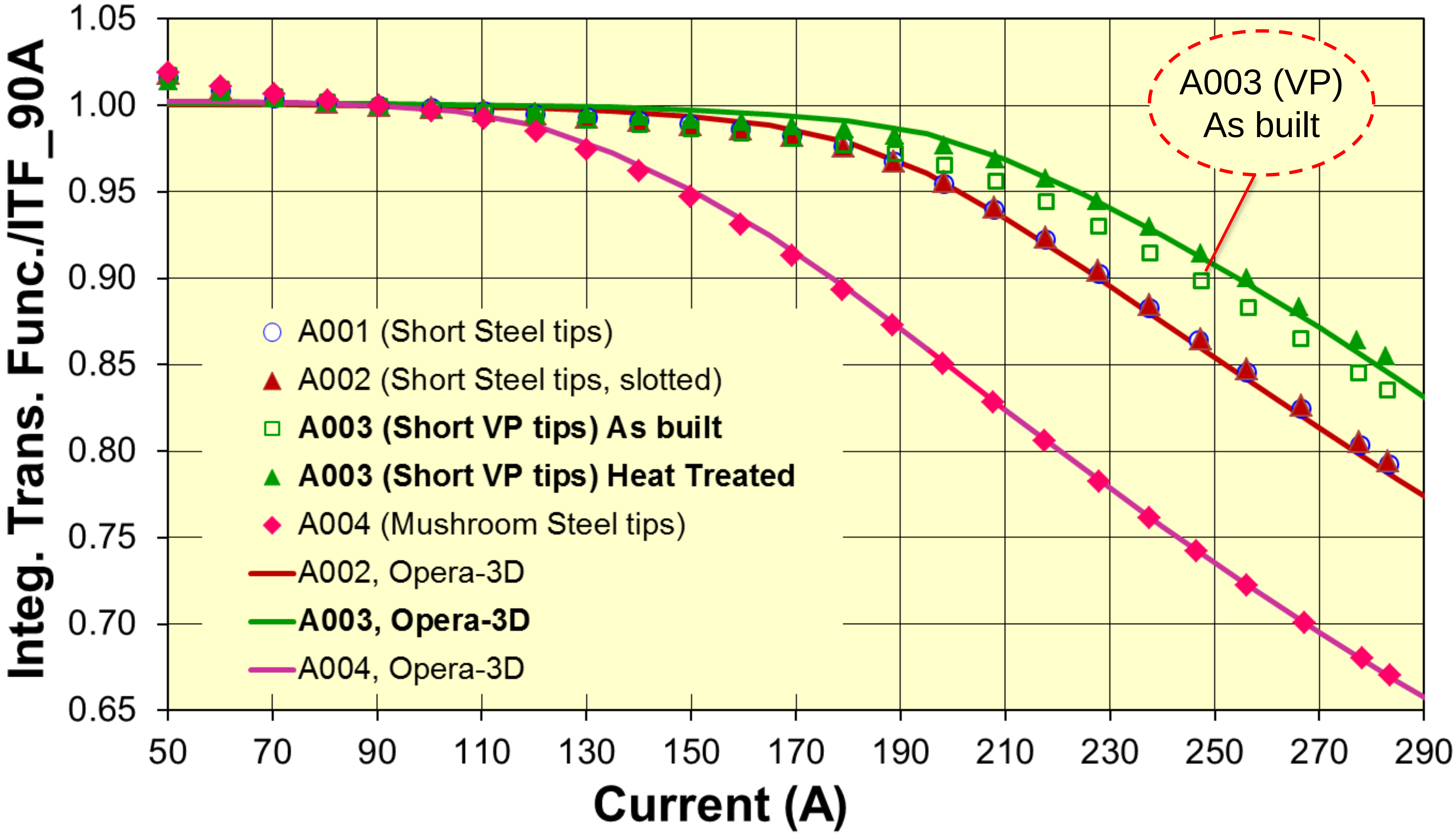


Active length = 425 mm; 14-layer printed circuit board, built by Fermilab

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

R&D DMM quadrupoles and sextupole were measured using this system.

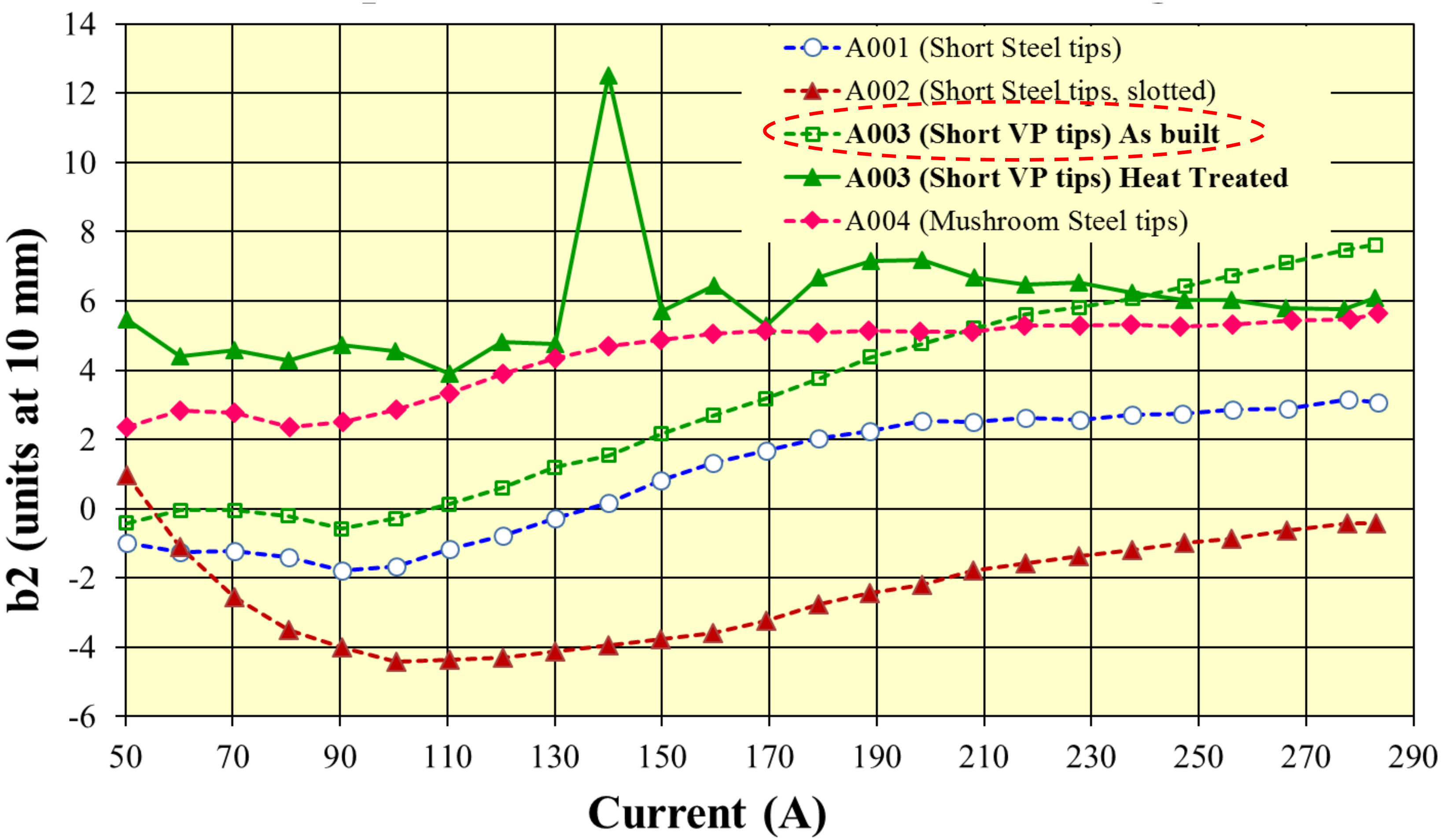
Saturation behavior of DMM quadrupoles



Saturation is as expected from Opera-3D calculations for all types of designs.

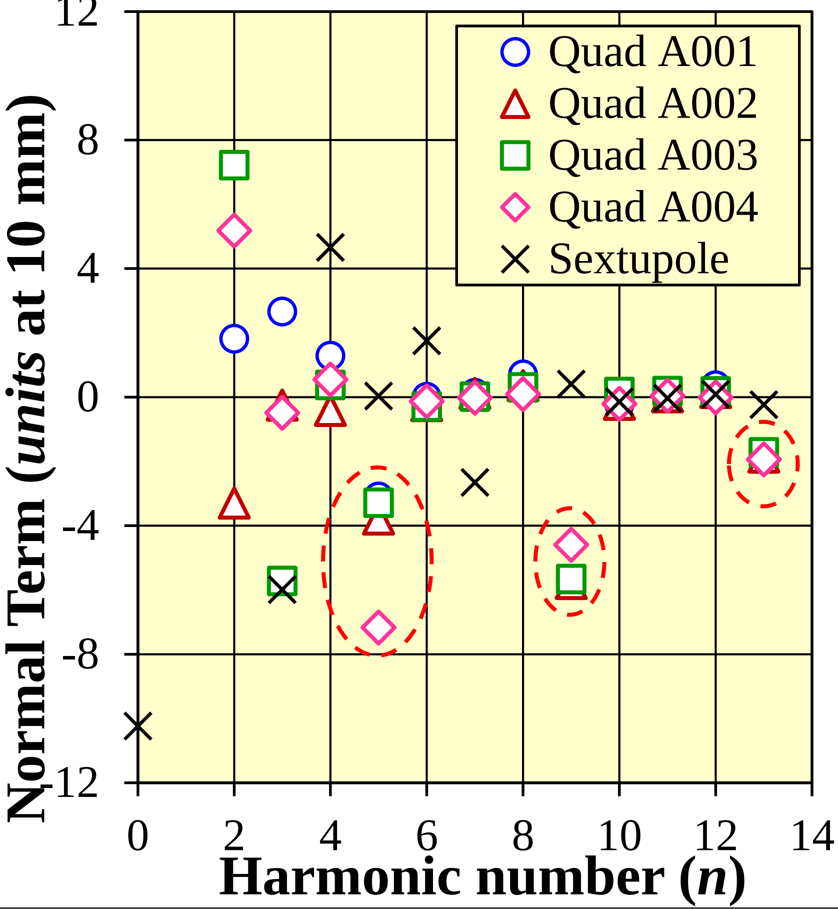
A003 (vanadium permendur) had material issues, but cured by heat treatment.

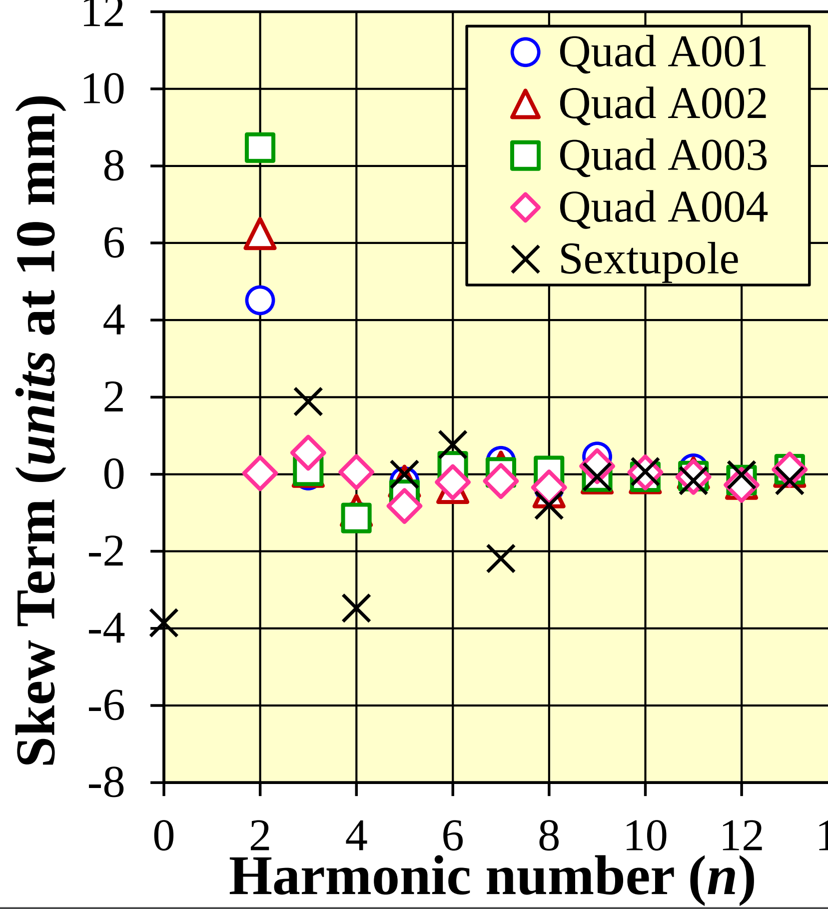
Sextupole term in DMM quadrupoles



Sextupole term showed a strong current dependence in the as-built quadrupole A003 with Vanadium Permendur pole tips. The current dependence was substantially reduced after a second heat treatment of the pole tips.

Field quality summary in DMM magnets





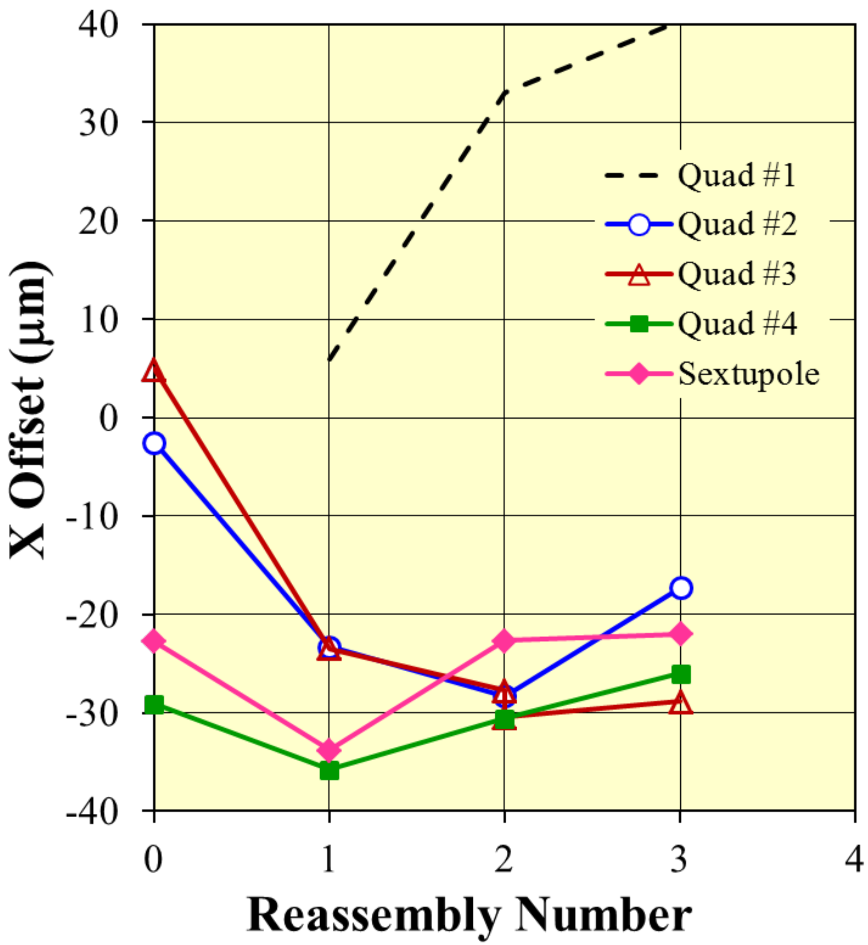
Normal and skew harmonics at 200 A in the DMM quadrupoles and 78 A in the sextupole.

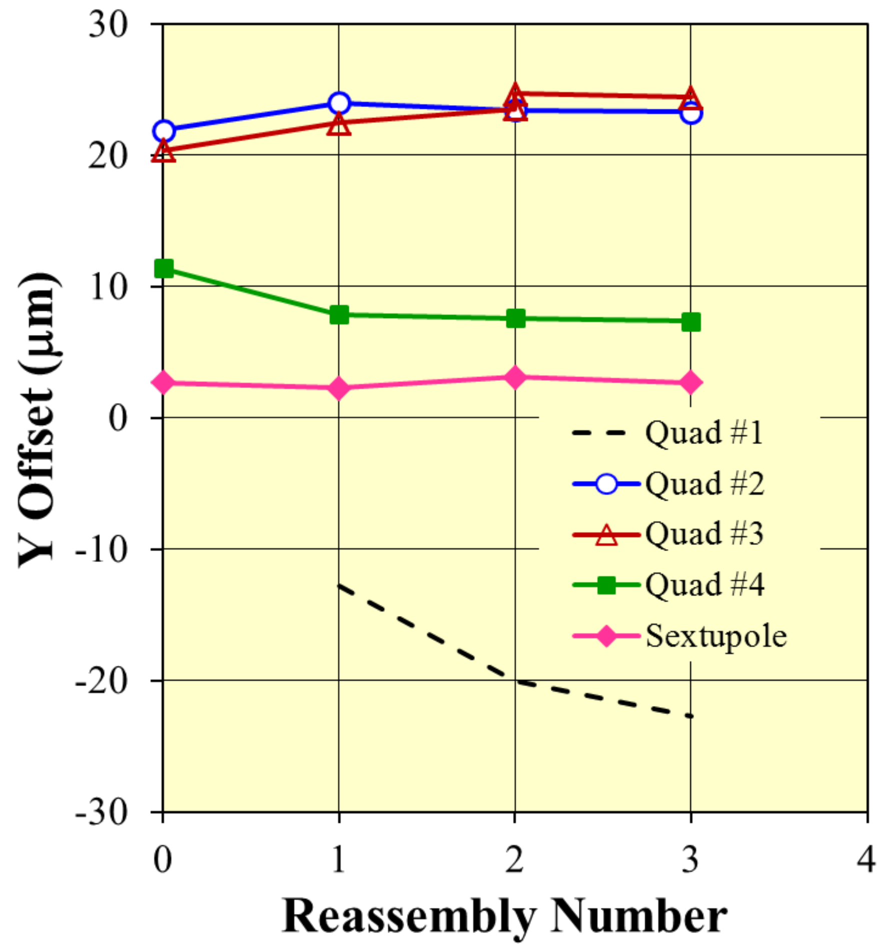
Design values of b5 ~ –2 units (~ *+4 units A004*), b9 ~ –4 units, b13 ~ –2.5 units in quads.

The b8 for the sextupole is ~ –300 units (not shown) due to design limitations.

Harmonic number *n* = 0 corresponds to the dipole term.

Magnet disassembly/reassembly tests

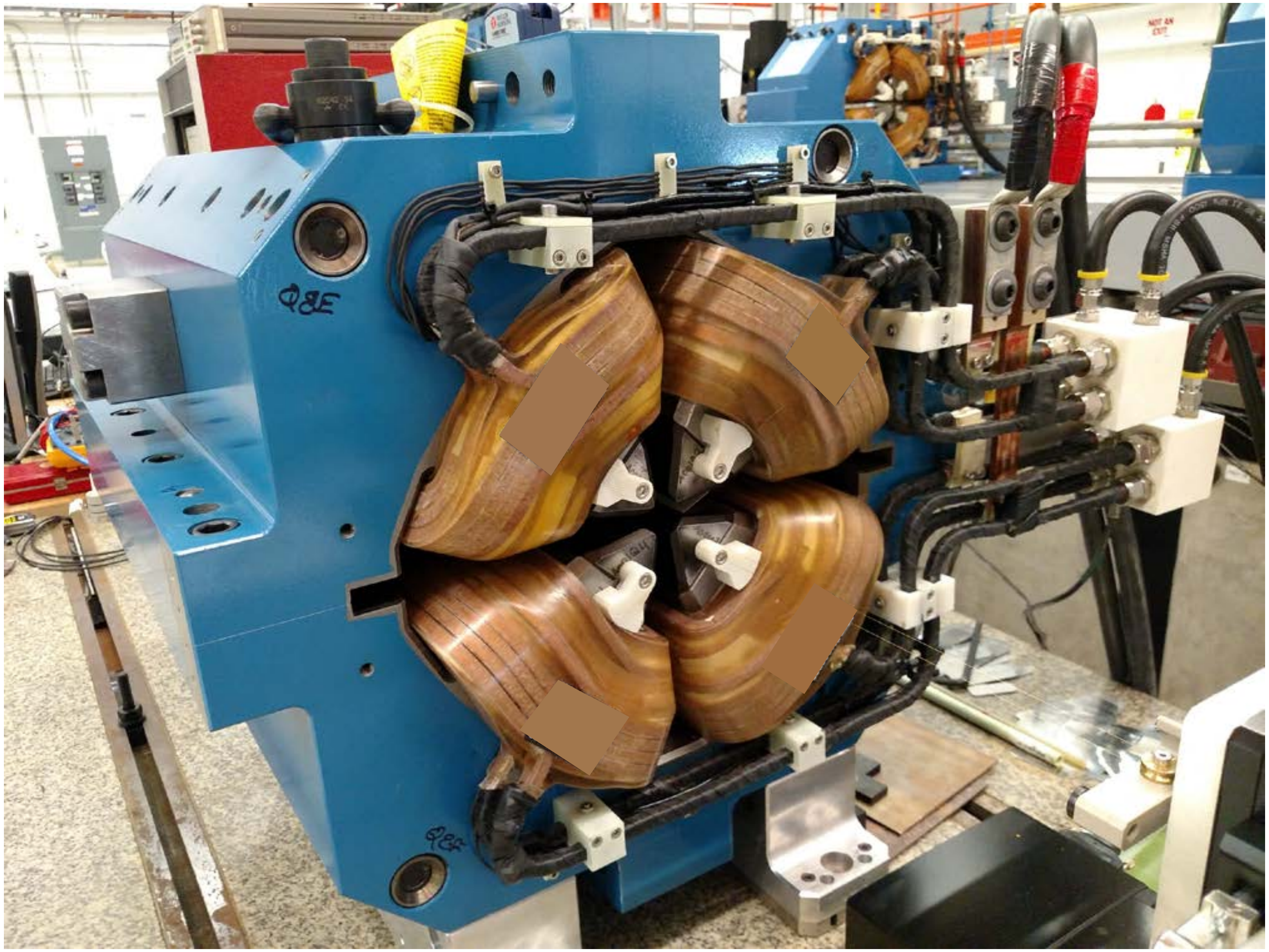




Quad #1 had poor reproducibility in X. Others had good reproducibility after the first reassembly. Reproducibility was good in Y for all magnets.

Pinning of top half to bottom half was improved in subsequent designs.

Q8 prototype quadrupole magnet



Photograph of the Q8 prototype 8-piece yoke design

Note: This prototype was designed for an earlier version of the APS-U lattice, and is a pure quadrupole. Q8 in the new APS-U lattice is a combined function magnet.

Reassembly tests in a Q8 prototype quadrupole

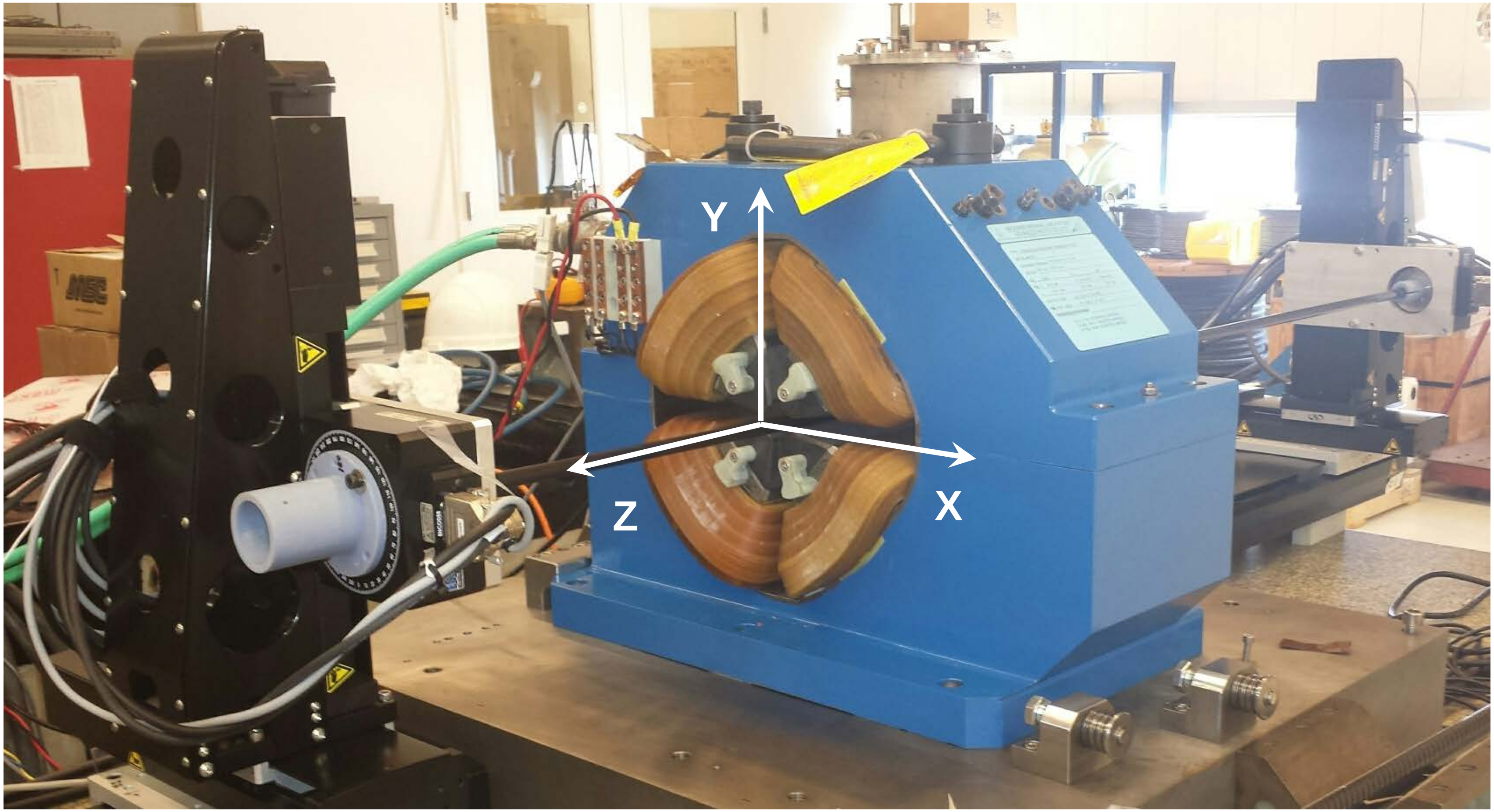
Measurements at 200 A on 3-May-2017 (Runs 1-3)

	Before	After 1	After 2	Max-Min
ITF	0.21185	0.21181	0.21177	**0.04%**
X0 (micron)	-0.2	-2.3	9.0	**11.2**
b2	2.67	2.80	2.67	**0.13**
b3	-1.62	-1.21	-1.17	**0.45**
b4	2.00	2.03	2.03	**0.03**
b5	-1.99	-2.00	-2.03	**0.04**
b6	-0.18	-0.16	-0.16	**0.02**
b7	0.19	0.19	0.17	**0.01**
b8	-0.47	-0.47	-0.47	**0.01**
b9	-2.17	-2.17	-2.16	**0.01**
b10	0.28	0.28	0.28	**0.00**
b11	-1.96	-1.96	-1.96	**0.01**
b12	-0.05	-0.06	-0.06	**0.00**
b13	-2.74	-2.74	-2.74	**0.01**
b14	-0.16	-0.12	-0.12	**0.04**
b15	-0.36	-0.36	-0.36	**0.01**

	Before	After 1	After 2	Max-Min
Fld.Ang (mr)	-1.61	-1.53	-1.80	**0.27**
Y0 (micron)	-0.2	0.5	-0.2	**0.7**
a2	4.03	3.74	3.47	**0.56**
a3	1.18	1.33	1.04	**0.30**
a4	-0.48	-0.52	-0.49	**0.04**
a5	2.17	2.10	2.19	**0.09**
a6	0.95	0.90	0.90	**0.05**
a7	-0.53	-0.63	-0.46	**0.18**
a8	0.39	0.34	0.35	**0.04**
a9	-1.03	-1.08	-1.01	**0.07**
a10	-0.13	-0.15	-0.14	**0.02**
a11	0.18	0.15	0.18	**0.03**
a12	-0.04	-0.06	-0.04	**0.02**
a13	0.31	0.31	0.30	**0.01**
a14	0.10	0.10	0.08	**0.02**
a15	-0.11	-0.12	-0.12	**0.02**

The Q8 prototype uses an improved 8-piece yoke design, and shows good reproducibility.

Hall probe setup in a DMM quadrupole

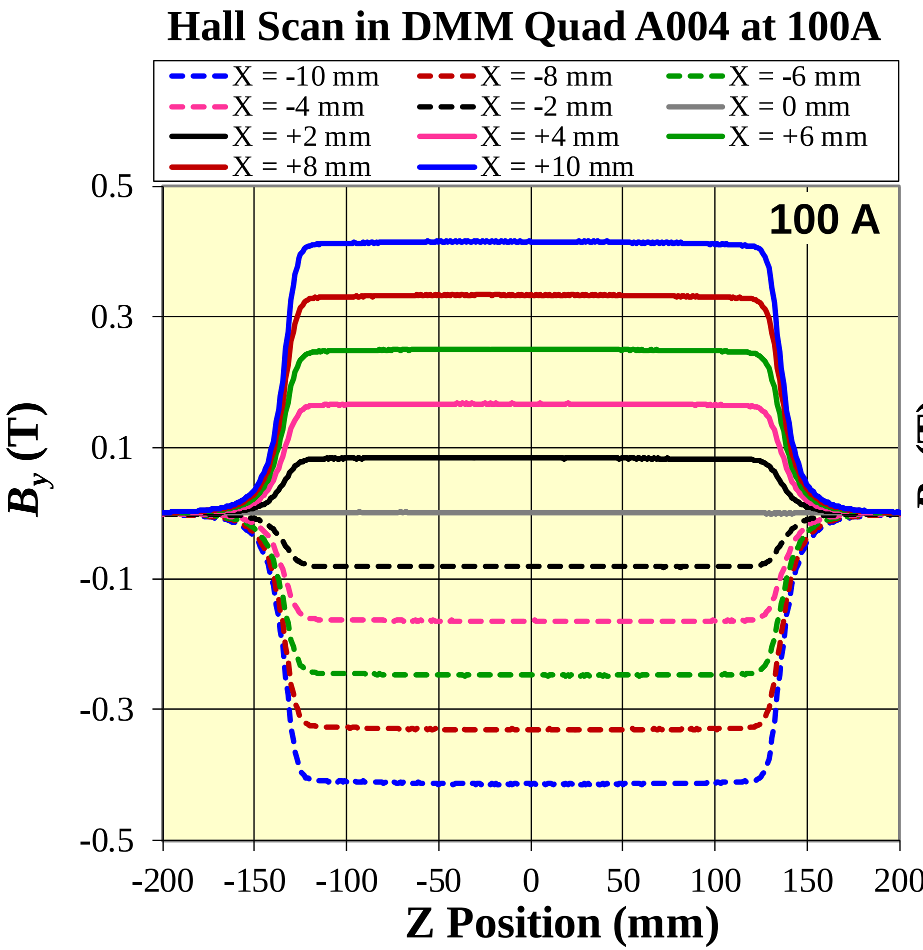


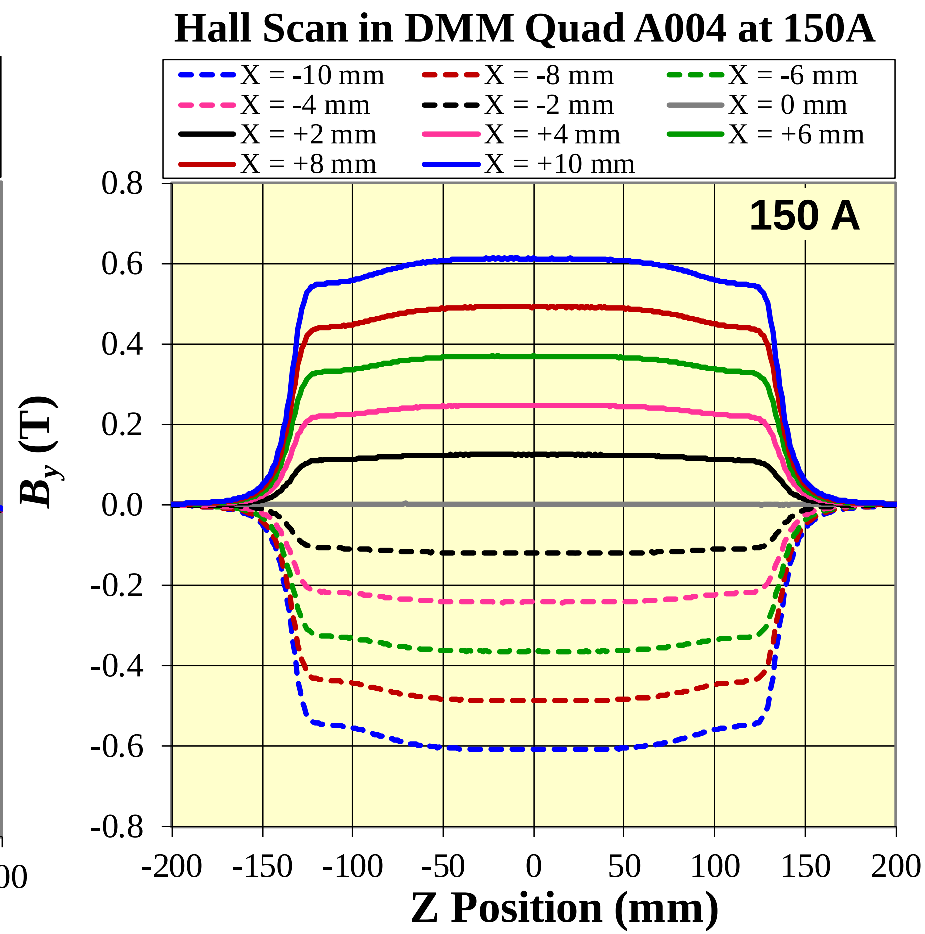
Demonstration Modular Multiplet (DMM) magnets were mapped at Y = 0 for:

–10 mm ≤ X ≤ +10 mm in 2 mm steps and -280 mm ≤ Z ≤ 280 mm in 1 mm steps

Only the B_y component was measured. (Stages reused from rotating coil setup.)

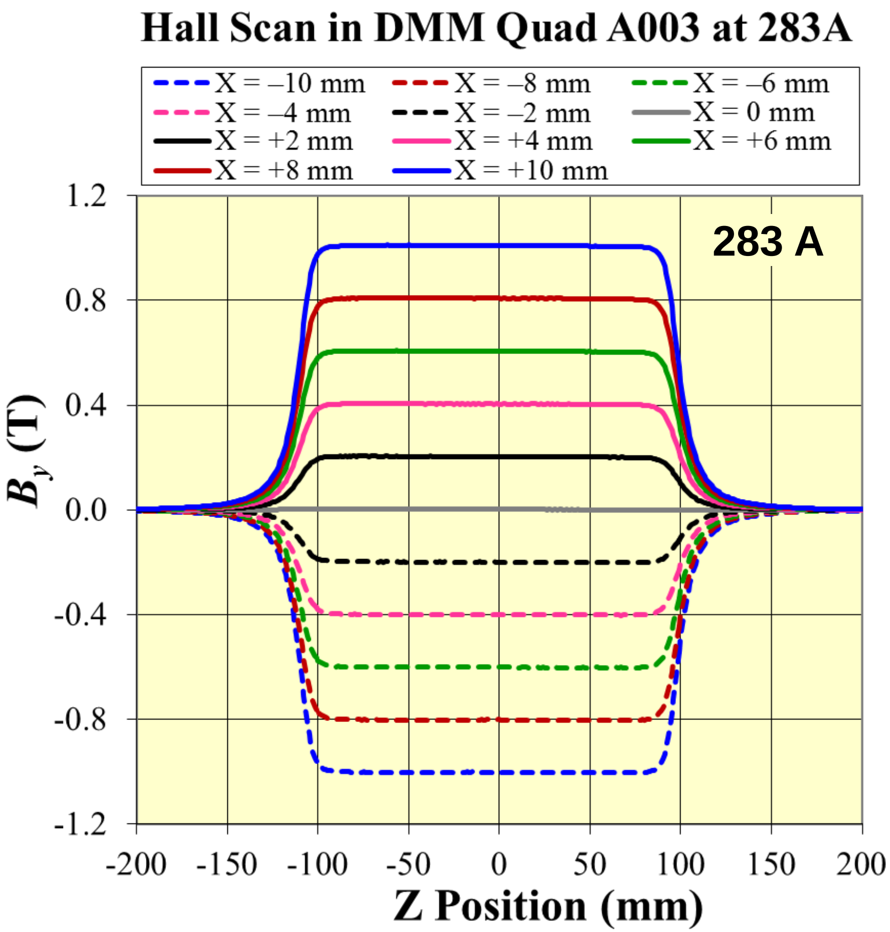
Axial profiles: "mushroom" tips (A004)

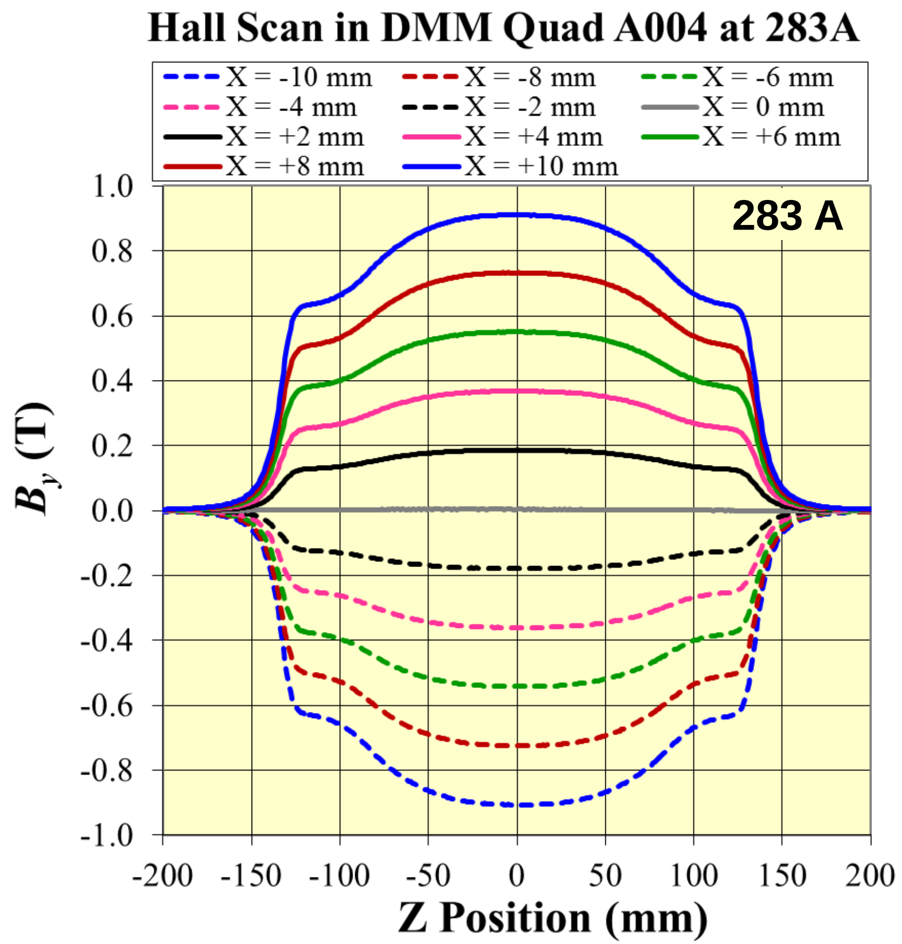




As the field is increased, the ends begin to saturate more than the body of the magnet, causing "shoulders" to appear in the axial profile.

Axial profiles: "short" vs "mushroom" tips



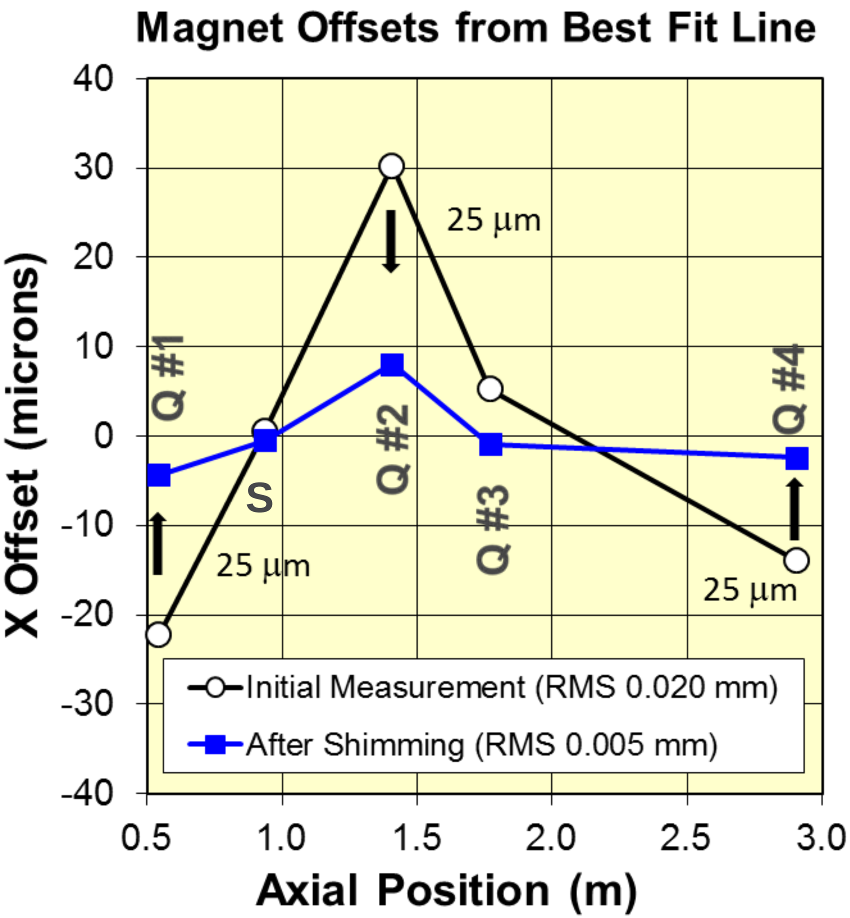


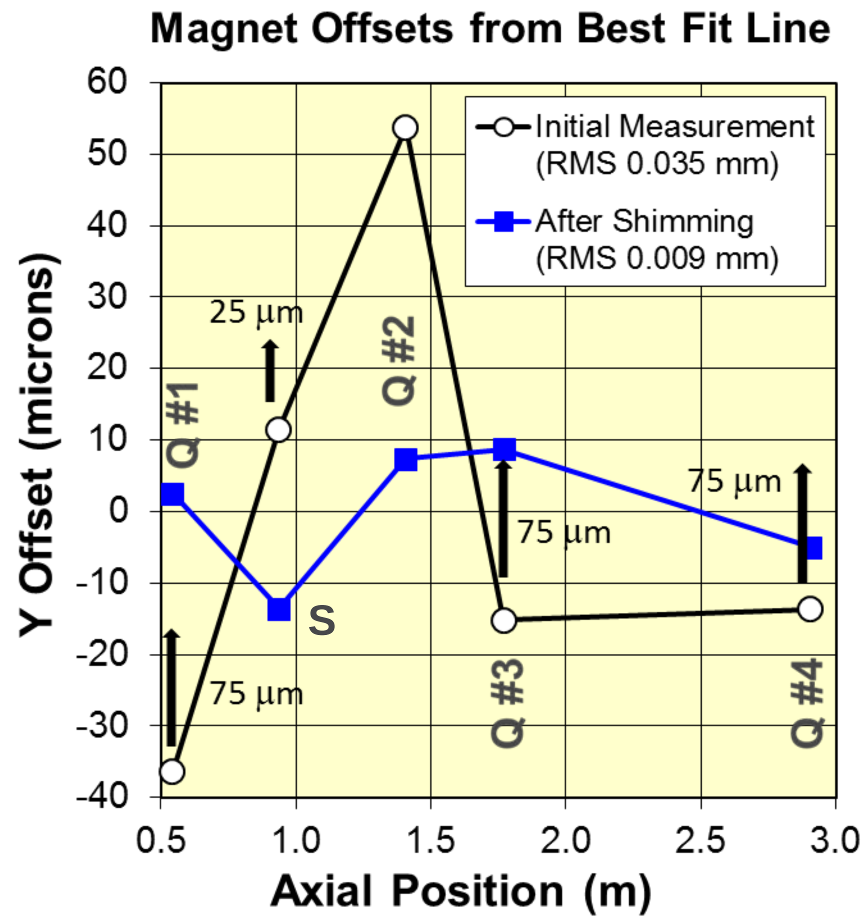
Short pole tips: Nearly flat field profile in the center, no "shoulders" in the ends.

Mushroom pole tips: Pronounced hump in the center, shoulders in the ends.

All production quadrupoles have been designed without mushroom ends.

DMM alignment: Measurements & shimming





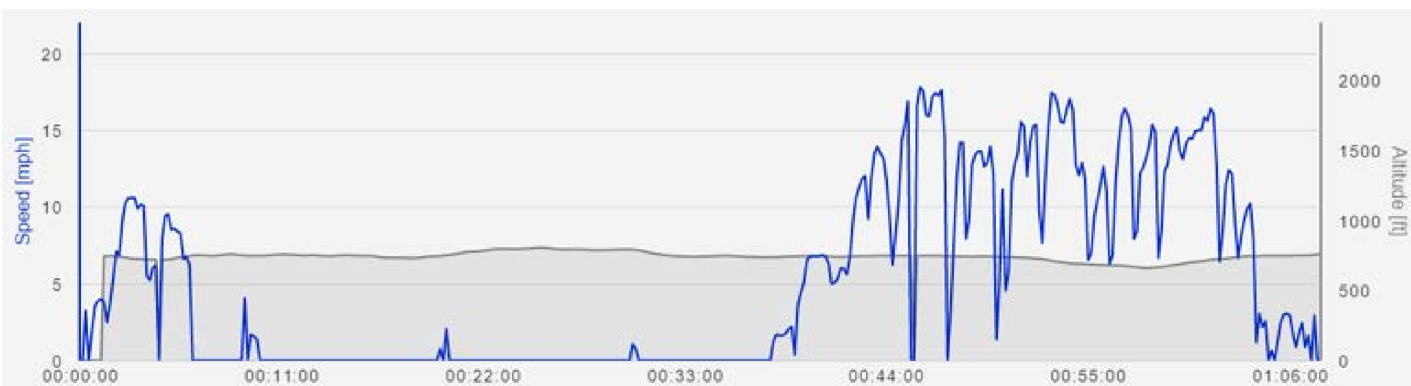
Initial assembly nearly met the tolerance despite known issues with Quad #2.

Shimming was not difficult to do although it could only be unidirectional.

Alignment of better than 10 µm RMS was obtained (using *n* x 25 µm shims).

DMM alignment: Transportation tests

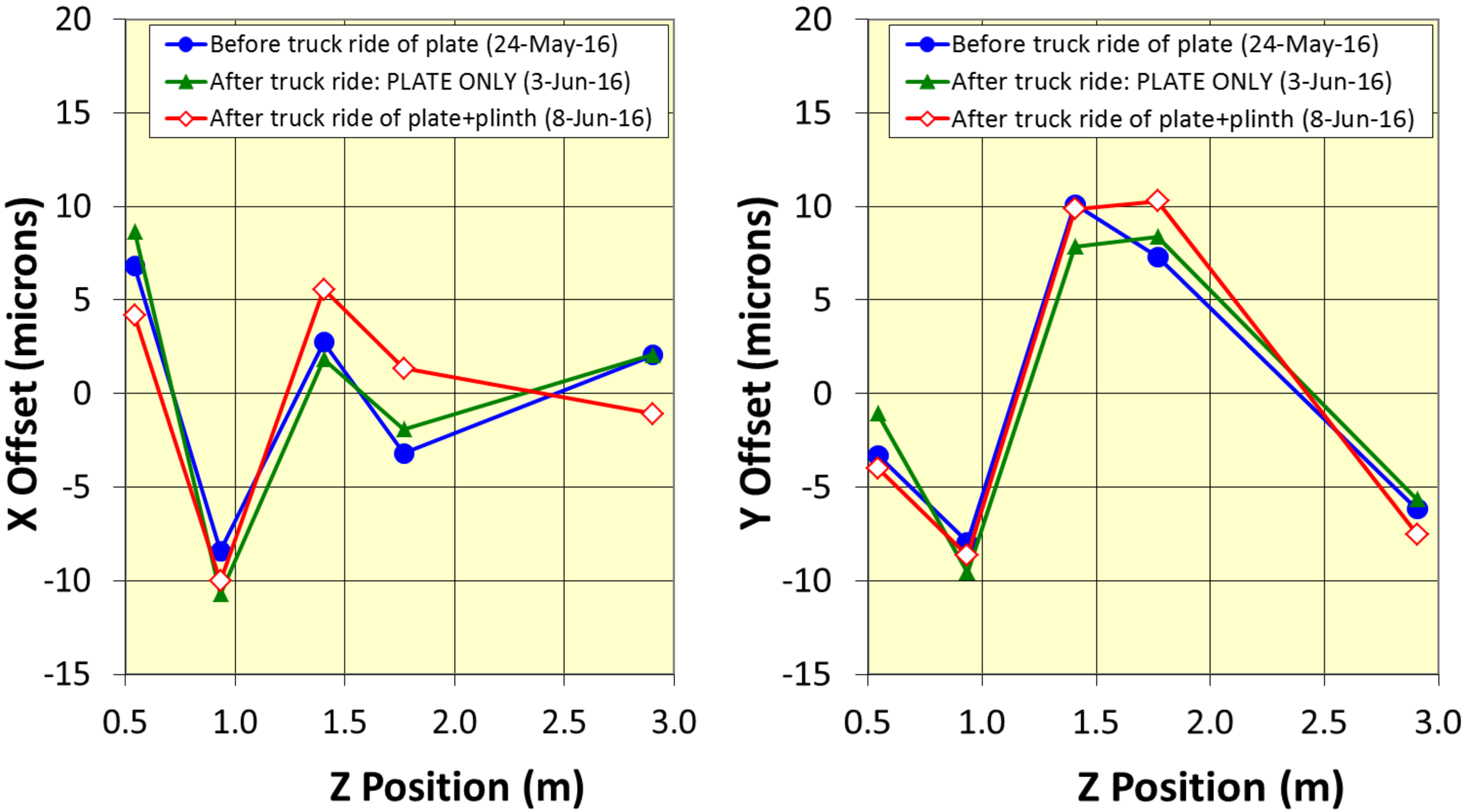
DMM assembly moved onto truck in building 314



DMM assembly was unloaded and reloaded on the truck, and driven ~ 5 miles.

Alignment was measured before and after the truck ride.

DMM Alignment: Transportation tests (2)



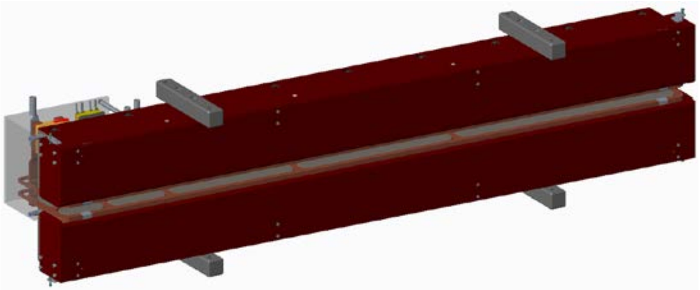
DMM assembly was unloaded and reloaded on the truck, and driven ~ 5 miles.

Alignment changes measured (< 5 μm) are within measurement uncertainties.

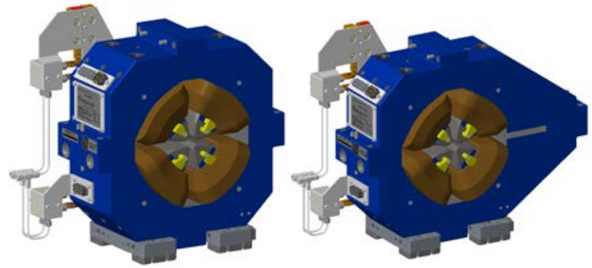
Summary

- Magnetic measurements of R&D magnets have proven that magnetic design simulations are accurate.
- The R&D magnets were successfully measured and all were shown to meet the magnetic field quality requirements.
- Alignment based on reference surfaces was shown to nearly meet the required tolerances (improved by mechanical shimming even though magnets were not designed to be adjusted).
- Alignment was shown to be stable under realistic transportation of the magnet assembly on a support plate as well as the entire plinth.
- Measurement results have guided design improvements made for production magnets (tested and proven in the Q8 prototype magnet).
- Future work will address magnetic measurement needs of transverse gradient (Q-bend) magnets and the FODO assembly of the APS upgrade.

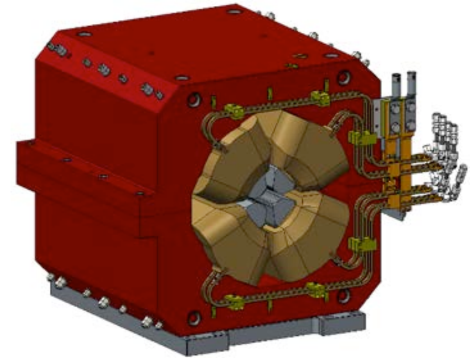
APS-U storage ring magnets scope (backup)



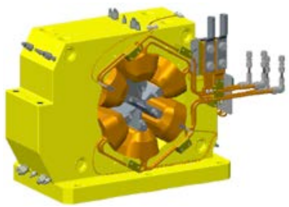
L-Bend Magnets (M1, M2)



Q1, Q2, Q3, Q6 and Q7 Quadrupole Magnets

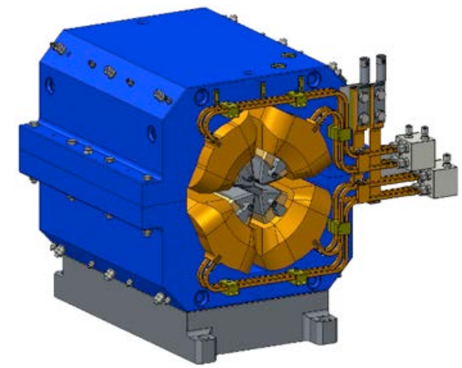


Q-Bend Magnets
M3,M4

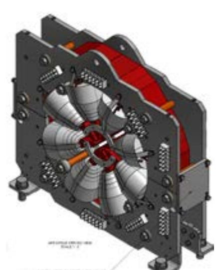


Sextupole Magnets
S1- S3

Item	ID	Types of Magnets	Pole tip material	Total Quantity
1	M1	Longitudinal dipoles	steel	80
2	M2	Longitudinal dipoles	steel	80
3	M3	Transverse-Gradient dipoles	VP	80
4	M4	Transverse-Gradient dipoles	VP	40
5	Q1	Quadrupole	VP	80
6	Q2	Quadrupole	steel	80
7	Q3 and Q6	Quadrupole (**similar to Q2**)	**steel**	160
8	Q4	**Reverse bend Quadrupole**	VP	80
9	Q5	**Reverse bend Quadrupole**	**steel**	80
10	Q7	Quadrupole	VP	80
11	Q8	**Reverse bend Quadrupole**	VP	80
12	S1 and S3	Sextupole	steel	160
13	S2	Sextupole	VP	80
14	FC1 and FC2	Fast Corrector	lamination	160
VP = vanadium permedur			Total Magnets 1320	



Reverse bend Quadrupole
Magnets
Q4, Q5, and Q8



8-Pole Corrector
(FC1 and FC2)

Items in red indicate changes from 67 pm to current 42 pm lattice.
Magnet lengths were also changed (from M. Jaski)