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

R. Dejus, for the APS-U magnet group
Physicist
Argonne National Laboratory

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Advanced Photon Source Upgrade (APS-U)

Two bending magnets – Double Bend Achromat (DBA)

Present Lattice

Upgrade Lattice

M4 (symmetry point)

Six “reverse” bending magnets

Four longitudinal gradient dipoles (L-bends; dipole only)

Three transverse gradient dipoles (Q-bends; dipole + quadrupole)

Six reverse bending magnets (R-bends; dipole + quadrupole)

Seven “forward” bending magnets

13 bends total

(Multi-bend Achromat)

Measurement results in R&D magnets for APS-U; IMMW20; June 4-9, 2017
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
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 $30 \, \mu \text{m} \, \text{RMS}$. 
The DMM magnets and assembly (2)

Photograph of DMM magnets on steel support plate on top of concrete plinth
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 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 $b_5 \sim -2$ units ($+4 \text{ units } A004$), $b_9 \sim -4$ units, $b_{13} \sim -2.5$ units in quads.

The $b_8$ for the sextupole is $\sim -300$ units (not shown) due to design limitations.

Harmonic number $n = 0$ corresponds to the dipole term.
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)

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</table>

The Q8 prototype uses an improved 8-piece yoke design, and shows good reproducibility.
Demonstration Modular Multiplet (DMM) magnets were mapped at Y = 0 for:
\(-10 \text{ mm} \leq X \leq +10 \text{ mm}\) in 2 mm steps and \(-280 \text{ mm} \leq Z \leq 280 \text{ mm}\) 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 assembly: 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 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.
Items in red indicate changes from 67 pm to current 42 pm lattice. Magnet lengths were also changed (from M. Jaski)