

MAGNETIC MEASUREMENTS OF STORAGE RING MAGNETS FOR THE APS UPGRADE PROJECT*

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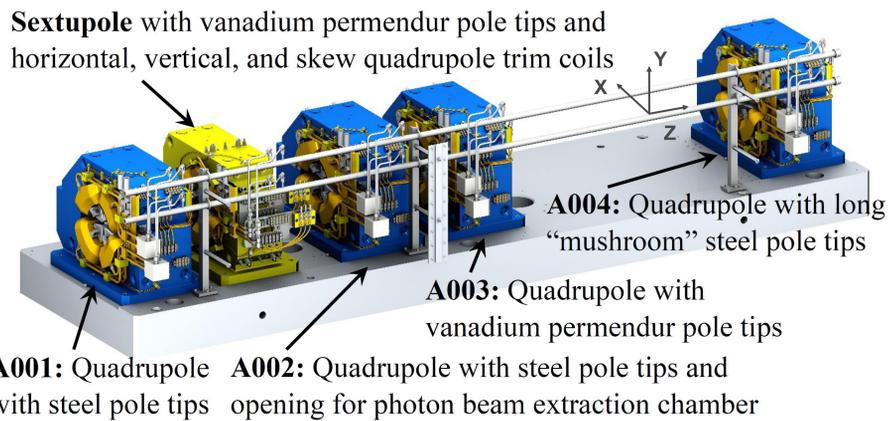
ABSTRACT

Extensive prototyping of storage ring magnets is ongoing at the Advanced Photon Source (APS) in support of the APS Multi-Bend Achromat (MBA) upgrade project (APS-U). As part of the R&D activities four quadrupole magnets with slightly different geometries and pole tip materials, and one sextupole magnet with vanadium permendur (VP) pole tips were designed, built and tested. Magnets were measured individually using a rotating coil and a Hall probe for detailed mapping of the magnetic field. Magnets were then assembled and aligned relative to each other on a steel support plate and concrete plinth using precision machined surfaces to gain experience with the alignment method chosen for the APS-U storage ring magnets. The required alignment of magnets on a common support structure is 30 μm RMS. Measurements of magnetic field quality, strength and magnet alignment after subjecting the magnets and assemblies to different tests are presented.

INTRODUCTION

A 3D rendering of the magnets on the steel support plate is shown below. All quadrupoles are 269 mm long and have the same pole tip shape but differ slightly in other manufacturing details:

- A001 has a symmetric yoke and steel pole tips that do not extend beyond the yoke in the longitudinal direction (short tips).
- A002 also has short steel pole tips but has a left-right asymmetric yoke to provide an opening in the core for a photon beam extraction chamber.
- A003 has a set of Vanadium Permendur (VP) short pole tips.
- A004 has a set of "mushroom" steel pole tips that extend out of the yoke up to the coil ends, a design feature to gain extra field integral value.
- Sextupole is 235 mm long and has VP pole tips. It also has vertical, horizontal, and skew quadrupole corrector coils.
- All pole tips were machined using electrical discharge machining (EDM) after bolting to the core to obtain a $\pm 10 \mu\text{m}$ machining tolerance.



R&D Magnets on Steel Support Plate

MAGNETIC MEASUREMENT TECHNIQUES/EQUIPMENT

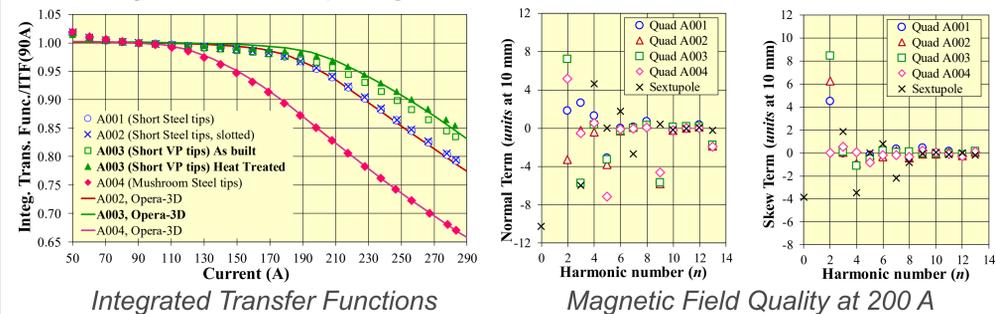
- The field harmonics in all of the magnets were measured using a radial rotating coil built using printed circuit technology.
- The field harmonics were expressed at a reference radius of 10 mm. Typical noise in the measurement of harmonics was below 10 ppm of the main field (0.1 unit).
- The vertical field profiles were measured in the horizontal midplane at several excitation currents using an I1A series Senis Hall probe.
- The relative alignment of magnets was measured using a 3.52-m-long rotating wire.



Rotating wire & coil setup

MAGNETIC MEASUREMENT RESULTS

Comparison of various DMM Quad Designs



Integrated Transfer Functions

Magnetic Field Quality at 200 A

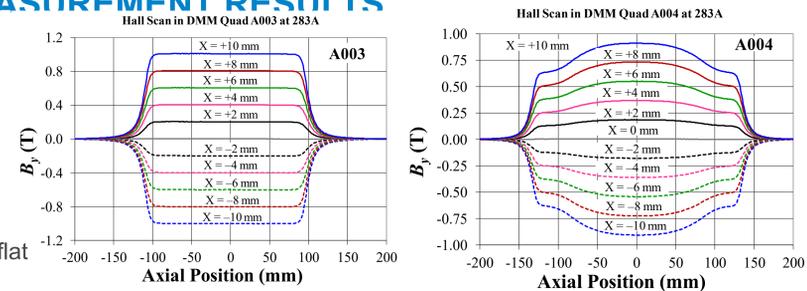
- Excellent agreement was found for the saturation behavior between measurements and Opera-3D simulations.
- The A003 quadrupole (with VP pole tips) initially had material issues but those were cured after a second heat treatment.
- All harmonics were within acceptable limits, with none of them being larger than 10 units at 10 mm radius (except for the b_8 in the sextupole magnet – acceptable for the storage ring).

MAGNETIC MEASUREMENT RESULTS



Hall probe mapping

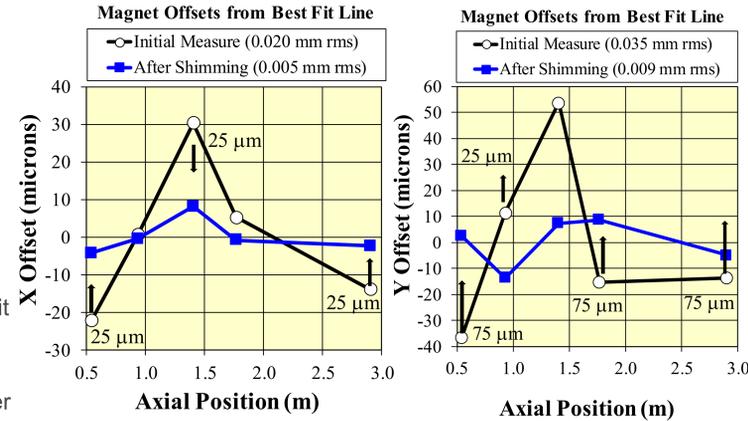
The A003 (with short VP pole tips) shows a nearly flat profile whereas the A004 shows a pronounced hump in the center and shoulders at the ends.



Hall Probe Measurements at 283 A

Alignment Results

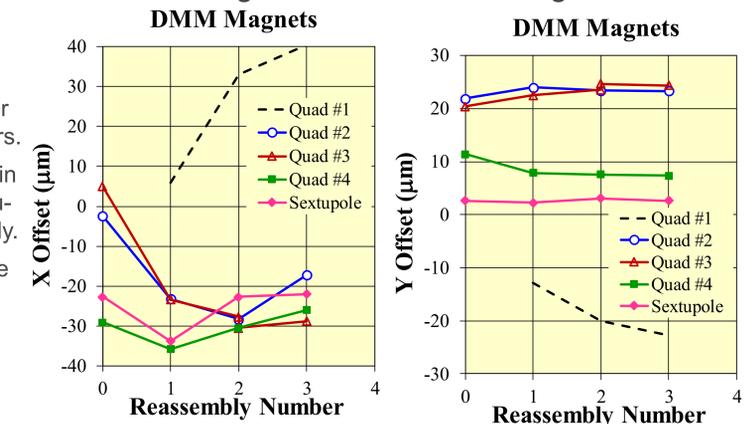
- Initial assembly of magnets nearly met the alignment tolerance of 30 μm RMS despite some assembly tolerance issues with A002.
- Shimming using 25 μm thick iron shims was not difficult although for the present magnet and mounting design it could only be unidirectional.
- Alignment of better than 10 μm RMS was obtained after shimming.



Alignment and Shimming

Reassembly Tests

- All magnets need to be split for installing the vacuum chambers.
- A001 had poor reproducibility in X. All others had good reproducibility after the first reassembly.
- Reproducibility was acceptable in Y for all of the magnets

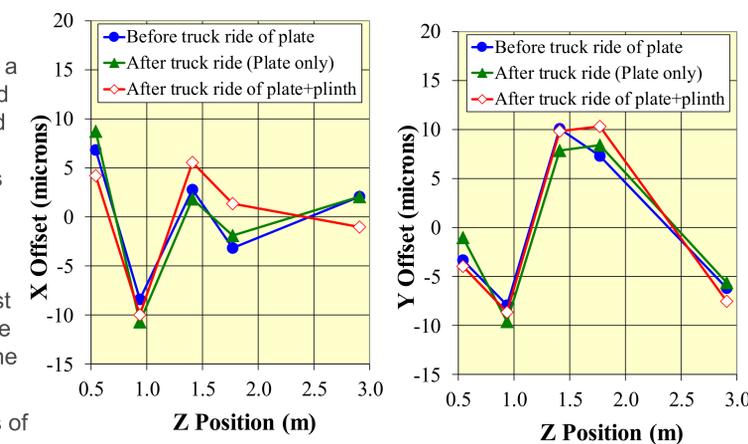


Disassembly and Reassembly Results

Transportation Tests



- The assembly was loaded on a truck, driven ~ 8 km, unloaded and reloaded on the truck and brought back for a recheck of the alignment. Two such tests were performed.
- In one test only the support plate with the magnets was transported. In the second test the entire system including the magnets, support plate and the plinth were transported.
- Measured alignment changes of less than 5 μm are within measurement uncertainties.



Transportation Tests Results

CONCLUSION

- All magnets were successfully measured and all were shown to meet the field quality requirements and integrated magnetic field strengths.
- Alignment based on reference surfaces was shown to nearly meet the alignment requirement of 30 μm RMS, with only one magnet being significantly misaligned in the horizontal direction. The alignment was easily improved to below 10 μm RMS by shimming.
- The alignment was shown to be stable under realistic transportation conditions of the magnets on the support plate as well as on the plate with the plinth assembly.
- The fabrication of R&D magnets and magnetic measurements have guided the design improvements for the production magnets of the APS-U. The quadrupole families Q1 and Q2 of the quad-doublet assembly, which are of designs similar to the R&D quadrupoles, are the first magnets to be manufactured and this work was particularly important for shaping their final designs.
- See J. Liu et al., NAPAC'16, paper WEP0B09, this conference for tolerance stack up analyses.

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