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) [1]. 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 support steel plate of the Demonstration Modular Multiplet (DMM) is shown in Fig. 1. The magnet lengths are based on the design version 3 of the MBA lattice but differ only slightly from the magnet lengths in more recent versions of the lattice [2]. All quadrupoles are 269 mm long and have the same pole tip shape but differ slightly in other manufacturing details:

- Quadrupole A001 has a symmetric yoke and steel pole tips that do not extend beyond the yoke in the longitudinal direction (short tips).
- Quadrupole 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.
- Quadrupole A003 has a set of VP short pole tips.
- Quadrupole 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.

All quadrupoles have also vertical and horizontal corrector coils but these will be eliminated in the final version of the design due to field quality issues. The sextupole magnet 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 ±10 μm machining tolerance.

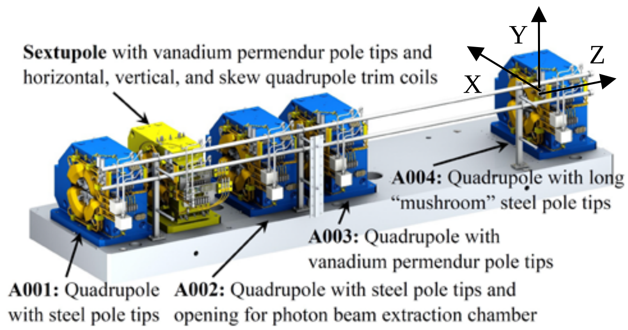

Figure 1: A 3D rendering of the DMM magnet layout on the support plate. The quadrupoles (in blue colour) are referred to as A001 thru A004 from left to right.

Among the many purposes for building the DMM assembly, checking for the following aspects was key:

- Mechanical tolerance stack up and its effect on magnetic performance.
- Accuracy of magnetic design calculations.
- 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.

MAGNETIC MEASUREMENT RESULTS

The field harmonics in all of the DMM magnets were measured using a radial rotating coil built using printed circuit technology. The coil also provided signals bucked for the dipole and the quadrupole terms (DQ bucked) and bucked for the dipole, quadrupole and sextupole terms (DQS bucked) to ensure measurements free of spurious harmonics in the quadrupoles and the sextupole. The main coil had an outer radius of 11.35 mm and 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 axial field profiles were measured in the horizontal midplane at several excitation currents using an I1A series Senis Hall probe [3].

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Integrated Transfer Functions

The integrated transfer functions (ITF) from rotating coil measurements of the 4 quadrupoles are compared to computer calculations using Opera-3D software [4] in Fig. 2. In order to account for small systematic differences between magnets due to construction tolerances, the ITF values are normalized to corresponding values at a relatively low current of 90 A. An excellent agreement was found for the saturation behaviour. The slight discrepancy at very low fields was due to remnant fields, which were not included in the computer simulations. The A003 quadrupole (with VP pole tips) initially had material issues (open squares in Fig. 2), but those were cured after a second heat treatment (filled triangles in Fig. 2).

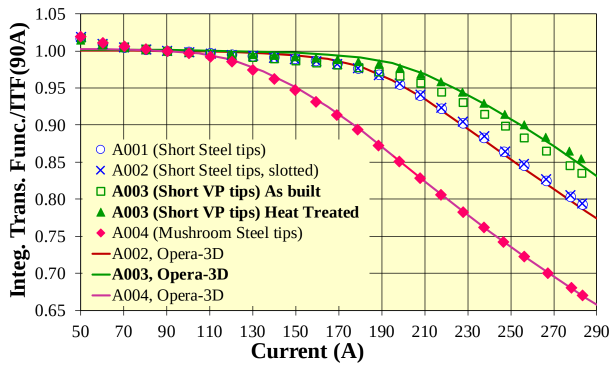

Figure 2: Measured integrated transfer functions normalized to 90 A compared to Opera-3D calculations.

Magnetic Field Quality

The normal and skew harmonic multipoles measured using a rotating coil are shown in Fig. 3. All harmonics were within acceptable limits, with none of them being larger than 10 units (one unit is 10^{-4} of the main field) at 10 mm radius, except for the 18-pole (b_8) in the sextupole magnet, which is ~ –300 units due to design limitations, and is not shown in Fig. 3. This large value of b_8 is deemed acceptable for the machine. Except for the low order terms, the random variation in harmonics is also small. It should be noted that there is a systematic difference in the allowed 12-pole term (b_5) between the quadrupole A004 with mushroom tips, and other quadrupoles with short tips. This is because the 2-D pole profile was kept the same in the two designs, whereas the end harmonics are different.

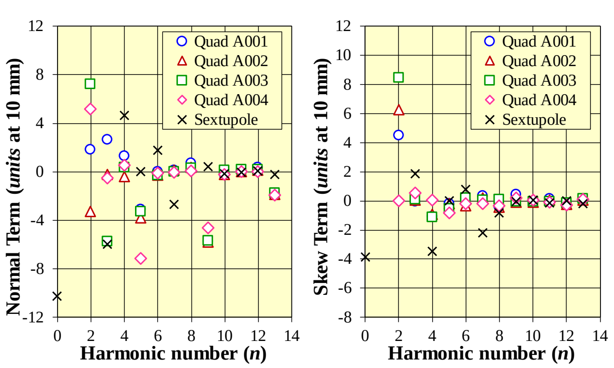

Figure 3: Normal (left figure) and skew (right figure) harmonics at 200 A in the DMM magnets. Harmonic number n = 0 corresponds to the dipole term.

Hall Probe Measurements

The vertical profiles of the A003 with short tips and the A004 with “mushroom” tips are compared in Fig. 4. The A003 shows a nearly flat profile whereas the A004 shows a pronounced hump in the center and shoulders at the ends. Due to potential machine performance issues with the humped profiles that are difficult to model, the production quadrupoles may not use the “mushroom” design.

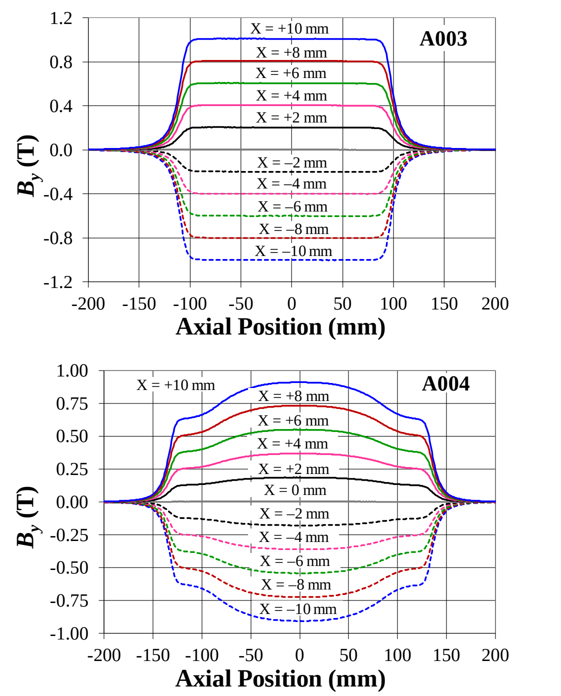

Figure 4: Vertical profiles in the vertical midplane of quadrupole A003 with short VP pole tips (top) and A004 with “mushroom” pole tips (bottom) at 283 A.

Alignment Measurements and Shimming

The magnets were installed on a steel plate and aligned to each other using reference surfaces on the magnets and the plate. The relative alignment of magnets in the DMM assembly was measured using a 3.52-m-long rotating wire. Initial assembly of magnets on the DMM support plate 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 to do although for the present magnet and mounting design it could only be unidirectional. Alignment of better than 10 μm RMS was obtained after shimming. Figure 5 shows the horizontal and vertical offsets before and after shimming. The production magnet design has been modified to incorporate features that would allow a better mechanical alignment to begin with, and also enable easy shimming for either positive or negative displacements if needed.

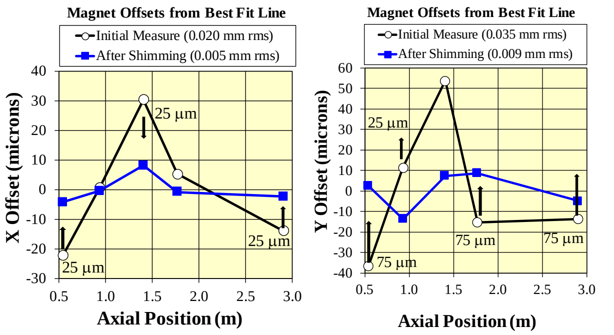

Figure 5: Magnet offsets in the horizontal (X) and vertical (Y) planes before and after shimming measured at 200 A.

Magnet Disassembly/Reassembly Tests

After verification of magnetic alignment in an assembly during production, all magnets will need to be split for installation of the vacuum chamber. In order to verify that the magnet alignment is not adversely affected by this procedure, each magnet was disassembled and then reassembled several times, and the relative alignment of magnets in the assembly was measured. The A001 had poor reproducibility in X, which is seen in Fig. 6. All others had good reproducibility after the first reassembly. Reproducibility was acceptable in Y for all of the magnets. Design modifications will be implemented in the production magnets to better control the horizontal alignment of the top and the bottom halves.

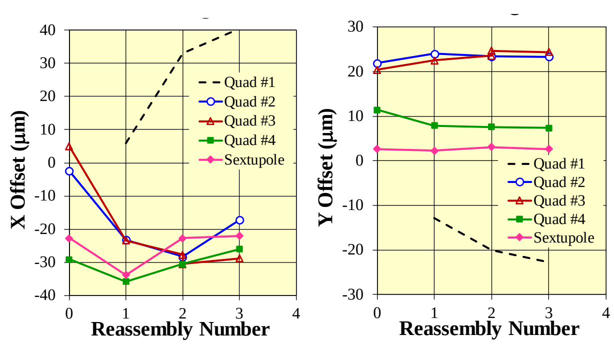

Figure 6: Magnet offsets in the horizontal (X) and vertical (Y) planes versus reassembly number measured at 200 A.

DMM Transportation Tests

During production the alignment in all magnet assemblies will be measured on the test bench. These assemblies will then have to be transported to the tunnel for installation. It is likely that the test benches will be located off site due to lack of adequate space on site, requiring travel of several kilometres. The DMM assembly was loaded on a truck and driven ~ 8 km, then unloaded and reloaded on the truck and brought back to the measurement area for a recheck of the alignment. Two such tests were performed. In the first test only the support plate with the magnets was transported. In the second test the entire magnets and support system including the support plate and the plinth were transported. The measured alignment changes of less than 5 µm shown in

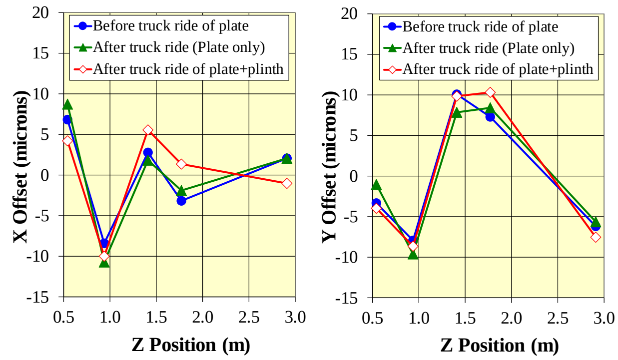

Figure 7: DMM transportation tests. The offsets were measured with the rotating wire setup at 200 A. No significant changes were measured.

Fig. 7 are within measurement uncertainties. These results demonstrate that the magnet alignment in the assembly is expected to remain stable during transportation.

CONCLUSION

All the DMM magnets were successfully measured and all were shown to meet the field quality requirements and integrated magnetic field strengths. The alignment based on reference surfaces was shown to nearly meet the alignment requirement of 30 µm RMS [5], with only one magnet being significantly misaligned in the horizontal direction. The alignment was easily improved to under 10 µm RMS by shimming, although the DMM magnets were not designed to be adjusted. Further the alignment was shown to be stable under realistic transportation conditions of the magnets on the support plate as well on the plate with the plinth assembly.

The fabrication of DMM 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 DMM quadrupoles, are the first magnets to be manufactured and this work was particularly important for their final designs.

REFERENCES

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