FIELD QUALITY FROM TOLERANCE STACK UP IN R&D QUADRUPOLES FOR THE ADVANCED PHOTON SOURCE UPGRADE*

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Abstract

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is planning to upgrade the existing Double-Bend Achromat (DBA) 3rd generation storage ring lattice to a 4th generation Multi-Bend Achromat (MBA) lattice [1]. In this paper we present a novel method to determine fabrication and assembly tolerances for quadrupole magnets through combined magnetic and mechanical tolerance analyses. We performed mechanical tolerance stack-up analyses using the Teamcenter Variation Analysis package [2] to determine part and assembly fabrication tolerances and finite element analyses (FEA) using OPERA [3] to estimate the effect of fabrication and assembly errors on magnetic field quality and to set tolerances to achieve desired magnetic performances. We present our analysis results and make comparison to magnetic measurements of fabricated R&D magnets in this paper.

INTRODUCTION

The APS upgrade project (APS-U) is preparing to replace the existing storage ring lattice with a hybrid seven-bend-achromat lattice that provides dramatically enhanced hard x-ray brightness and coherent flux [4]. Tight manufacturing and alignment tolerances will be required for the new storage ring magnets. For example, the multipole components of the low order harmonics, at a reference radius of 10 mm, are required to be less than 10 units (0.1% of the main field). Further the magnet-to-magnet alignment within a girder needs to be better than 30 μm RMS.

We present results of joint mechanical tolerance stack-up analyses and 2D magnet simulation using code OPERA of an R&D quadrupole magnet. The mechanical tolerance stack-up analyses allocate tolerances to parts and assemblies based on magnet alignment requirements. The FEA 2D magnetic analyses are performed to determine multipole errors and their distributions under different tolerance conditions. Our results led us to find out key factors for the magnet performance and to develop a new magnet design which can achieve high magnetic field quality but does not require high precision machining.

MECHANICAL TOLERANCE ANALYSIS

The R&D quadrupole magnets are made of a top and a bottom two-piece solid steel yoke with removable pole bases and pole tips [5]. The Teamcenter Variation Analysis software randomly generates parts within specified mechanical tolerances, virtually assembles parts using specified procedures, and virtually measures parts at specified locations. An example of distribution of a measurement is shown in Fig. 1(a). Two fabrication methods were simulated in detail: i) with the four pole tips assembled to the yoke and then machined tip profile using electrical discharge machining (EDM), and ii) with the four pole tips machined separately using regular CNC machine and then assembled to the yoke. The magnet mechanical center in the horizontal (X) direction are shown in Fig. 1(b) for two assembly tolerances: 20 μm and 50 μm (labeled A20 and A50, respectively) and three pole tip profile tolerances: ±15 μm, ±25 μm, and ±50μm (labeled P30, P50, and P100, respectively). The results for the vertical (Y) center are similar.

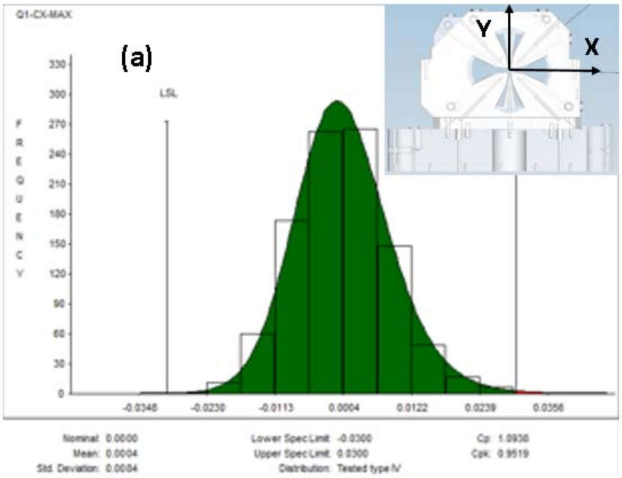

Figure 1: (a) Example of distribution of a measurement in mechanical tolerance analysis.

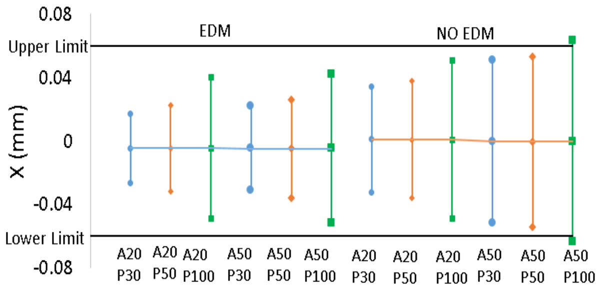

Figure 1: (b) Distribution of mechanical centers in X.

It was found in this study that the assembly tolerances for mating surfaces need to be better than 20 μm if EDM machining is not used. This in turn will be expensive and difficult to achieve for a series of production magnets. The assembly tolerances can be relaxed to 50 μm if EDM machining is used but this is expensive too and associated

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with certain dimensional restrictions. Thus for either case the fabrication costs appear inevitably high.

MAGNETIC TOLERANCE ANALYSIS

Systematic harmonic errors (the allowed terms) in quadrupoles and other multipole magnets arise mostly from limitations in the design, whereas random errors may come from excitation, fabrication and assembly errors. In this paper, only fabrication and assembly errors are considered. For a quadrupole, the allowed terms are the 12-pole, 20-pole, etc. (denoted by b5, b9, ...) [6].

Figure 2 shows details of pole tip geometries used in the simulations. The four pole tip profiles are allowed to vary between the outer and inner boundaries. Three different tolerance zone widths, ±15 µm, ±25 µm, and ±50µm were simulated. The tolerance zones include contributions from both geometrical errors caused by machining and orientation and positioning errors caused by assembly. They account for the combination of radial, azimuthal, and rotational perturbations of pole tips.

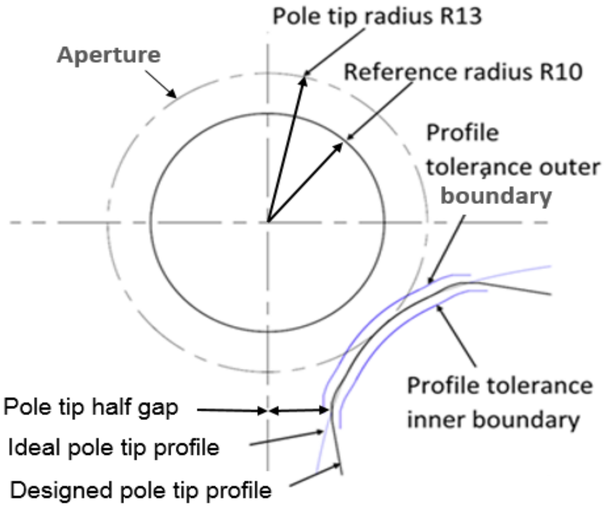

Figure 2: Pole tip configurations used in Opera-2D.

Since the magnet is a two-piece design, three possible displacement errors may exist: i) top half offset horizontally, ii) top half offset vertically, and iii) top half rotated relative to a fixed bottom half. For each condition the profile tolerance zone was added on top of two-piece assembly errors to see the effect of their combination on field quality. For each case the Opera optimizer was set to run 360 instances to find maximum multipole errors and their distributions.

Figure 3 shows the Opera-2D model and magnetic flux lines at 196 A (98% efficiency). The results were also used as input for lattice evaluation. For all cases no significant impact on the dynamic acceptance, the local momentum acceptance and beam lifetime was seen.

Figure 4 shows the standard deviation of multipole errors as a function of pole profile tolerance. It is seen that typical errors are at an acceptable level of ~1 unit rms or less for a tolerance zone width of 50 µm. The profile tolerance can therefore be relaxed to the 50 µm level (±25 µm) that a regular high-precision CNC machine tool can achieve and hence eliminate the need for EDM.

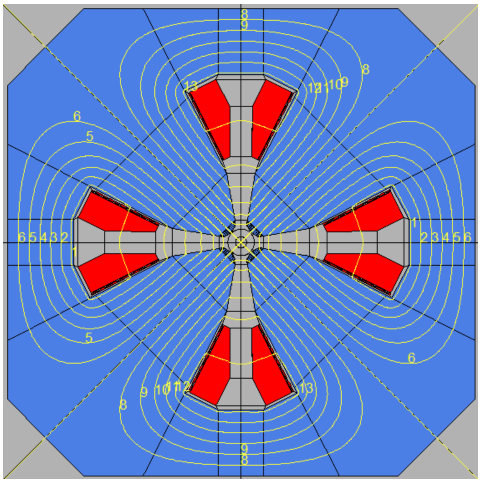

Figure 3: A 2D quadrupole model with flux lines.

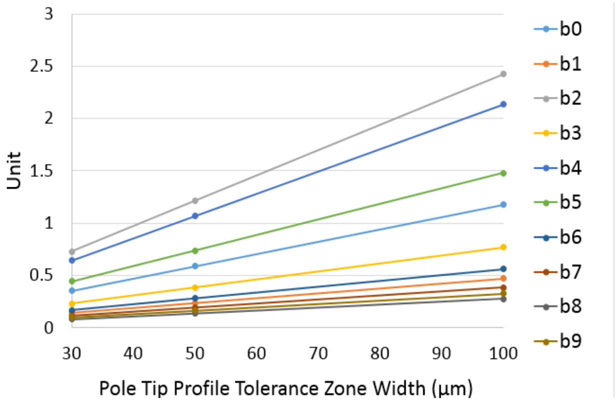

Figure 4: The standard deviation of b_n at a reference radius of 10 mm for different pole tip profile tolerance levels.

The harmonics were relatively insensitive to horizontal and vertical displacements of the two halves, except for the dipole term which resulted in a shift in magnetic center. For rotation, the sextupole term is the most significant. The rotation should to be kept below 0.1 mrad to keep the effect on the sextupole term below 1 unit.

PROTOTYPES AND TESTS

Four prototype R&D quadrupole magnets were built for the APS-U and studied in detail (see Fig. 5). All four magnets have the same pole tip geometry. The first quadrupole has steel pole tips. The second quadrupole is similar to the first one but has a left-right asymmetric yoke to provide a cutout for photon beam extraction chamber. The third quadrupole has vanadium permendur (VP) pole tips. The forth quadrupole has pole tips that are extended longitudinally up to the coil ends to provide extra field integral. All four magnets have pole tips that were EDM machined with profile tolerances of ±10 µm after installing in the yoke.

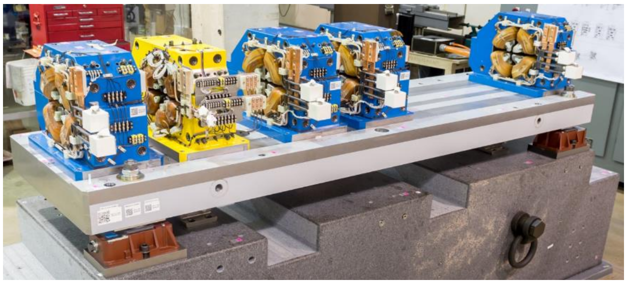

Figure 5: Photograph of four quadrupoles (blue) and one sextupole (yellow) prototypes built for the R&D program.

All four magnets met our designed performance goals and matched very well with the 3D magnetic simulations. The 3D magnet design simulations can be found in reference [5]. The measured multipole errors were small, the largest being the sextupole terms which were still below 10 units. Figure 6 shows the measured normal terms of the first prototype quadrupole magnet as a function of current. More details of the magnetic measurement results can be found in reference [7].

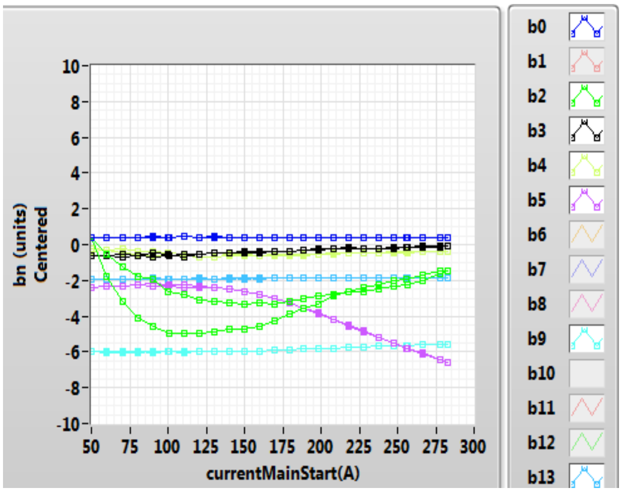

Figure 6: Variation of normal terms b_n as a function of current in a prototype quadrupole with steel pole tips.

It was found that the symmetry of the four pole tips is very important to achieve high magnetic field quality for a quadrupole. If we can align the pole tip symmetry to a high precision, then we can achieve satisfactory magnetic field quality even if the fabrication and assembly tolerances are relaxed.

Based on our analyses and test results a new 8-piece magnet mechanical design and an alignment method were developed. In the new design the yoke is divided into four quadrants, each quadrant contains one yoke and one pole tip. All parts are machined separately within CNC machine tool precision capabilities. During assembly the pole tips are aligned symmetrically to better than 10 µm to each other using gauge pins. The pole tip radii can be increased together but the four radii need be within 10 µm of each other. In the same manner, the four pole tip gaps will be aligned to better than 10 µm to each other. After alignment is completed the quadrants are clamped and pinned together using tapered dowel pins. Removable pads are added to the bottom for magnet center adjustments in the vertical direction and to the back side for the horizontal direction. The height and horizontal position of the mechanical center can be controlled within 25 µm by adjusting the thickness of removable pads. This new design achieves high magnetic field quality and exceeds the alignment requirements without ultra-high-precision manufacturing. In the new design, dowel pins for pole tip and pole base alignment are eliminated which saves additional machining cost. A prototype quadrupole magnet of the new design is under fabrication. The tolerance analyses for the new design are completed and the results are very encouraging.

CONCLUSION

Four R&D quadrupole magnets for APS-U were designed, fabricated, and tested. Tolerance analyses combining mechanical tolerance stack up and 2D FEA magnetic analyses were carried out to estimate parts and assembly tolerances for machining and assembly.

It was found that the symmetry of the pole tips as reflected in uniformity of pole tip radii and pole tip gaps are key factors for determining magnetic field quality. The multipole errors are not particularly sensitive to reasonable pole tip profile errors. If the symmetry of the pole tips can be ensured, then tolerances on parts and assemblies can be relaxed to reduce fabrication costs.

A new 8-piece design and assembly method were developed which keep the symmetry of the four pole tips and the pole tip gaps within 10 µm and the center location controlled within 25 µm relative to the datum references.

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