Field Harmonics Optimization of the NSLS-II Storage Ring Magnets

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Abstract:

The NSLS-II storage ring lattice magnets have stringent field harmonics requirements in order to achieve its performance requirements for beam emittance, dynamic aperture, and beam life time. Approximately 1000 of these magnets were built with very tight machining and assembly tolerances of the order of 10 µm. The pole profiles and shimming of the poles were guided by 3-D nonlinear magnetic field analyses. Various field anomalies found during the magnet production were also identified and corrected by detailed 3-D field analyses and magnetic measurements. In this paper we present case studies of various field harmonics optimization for the NSLS-II magnets.

1. Introduction

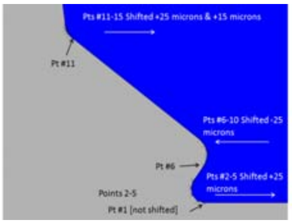
The National Synchrotron Light Source II (NSLS-II) under construction at Brookhaven National Laboratory will be a state-of-the-art 3 Gev electron storage ring designed to deliver world-leading intensity. The 792-meter circumference storage ring is comprised of quadrupole, sextupole, dipole and corrector magnets. All magnets were built to harmonic specifications. The magnet program entailed measurements at the vendor or BNL and necessitated the need for shimming and/or chamfering to meet the specifications. The allowed harmonic specifications for the quadrupoles, sextupoles, dipoles, and correctors are listed in Table 1.

Description	Quad 66 mm	Quad 90 mm	Sext. 68 mm	Sext. 76 mm	Dipole 35/90 mm	Corrector 100/156 mm
Good Field Region or Radius	25	25	25	25	±20 Hor/±10 Vert.	±20 Hor/±20 Vert.
Field Homogeneity [x10-4]	-	-	-	-	5	100
Harm. B6 [$x10^{-4}$]	3	0.5	-	-	-	-
Harm. B9 [$x10^{-4}$]			1	0.5	-	-
Harm. B10 [$x10^{-4}$]	3	0.5	-	-	-	-
Harm. B14 [$x10^{-4}$]	3	0.1	-	-	-	-
Harm. B15 [$x10^{-4}$]	-	-	0.5	0.5	-	-
Harm. B21 [$x10^{-4}$]	-	-	-	0.5	-	-

Table 1. Magnet harmonic specifications

3. Perturbation Studies

2-D perturbation studies of the 68mm sextupole and 66mm quadrupole were done to determine machining and assembly tolerances needed to meet the specifications. The sextupole's pole profile has small 'wings' at the corners.



	CASE 1 PTS 2-5 X=+25 MICRONS		CASE 2 PTS 6-10 X= -25 MICRONS		CASE 3 PTS 11-15 X=+25 MICRONS		CASE 4 PTS 11-15 X= +15 MICRONS		CASE 1+2+3		TOP CENTER POLE X=+25 MICRONS	
	a	b	a	b	a	b	a	b	a	b	a	b
1	-0.5	-0.1	0.2	0.0	-1.0	-0.6	-0.6	-0.4	-1.3	-0.6	2.6	10.1
2	0.7	-0.3	-0.2	0.1	0.7	-1.2	0.4	-0.8	1.1	-1.4	7.0	2.5
3	0.6	0.0	-0.2	0.0	-0.1	0.0	0.0	0.0	0.3	0.0	-0.2	0.0
4	0.5	-0.5	-0.1	0.2	-0.7	-1.0	-0.4	-0.6	-0.3	-1.2	-3.5	1.3
5	0.3	-0.5	0.0	0.2	-0.9	-0.4	-0.5	-0.3	-0.6	-0.7	0.6	2.5
6	0.1	-0.5	0.1	0.1	-0.8	0.1	-0.5	0.0	-0.5	-0.2	0.5	0.0
7	0.0	-0.4	0.1	0.1	-0.5	0.4	-0.3	0.2	-0.4	0.1	0.0	-0.2
8	-0.1	-0.2	0.1	0.0	-0.2	0.5	-0.1	0.3	-0.2	0.3	-0.3	0.0
9	-0.1	-0.1	0.0	0.0	0.1	0.5	0.0	0.2	0.0	0.3	0.0	0.3
10	-0.1	-0.1	0.0	0.0	0.2	0.3	0.1	0.1	0.2	0.2	0.2	0.0
11	-0.1	0.0	0.0	0.0	0.3	0.1	0.1	0.0	0.2	0.0	0.0	-0.2
12	-0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	-0.1	-0.1	0.0
13	-0.1	0.0	0.0	0.0	0.1	-0.1	0.0	0.0	0.0	-0.2	0.0	0.1
14	0.0	0.0	0.0	0.0	0.1	-0.1	0.0	0.0	0.0	-0.1	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	-0.1	-0.1	0.0	0.0

Fig. 1.a) Sextupole 'wing' shape b) Harmonic change from the 68mm base case

Three sets of points that comprise the center of the pole and the 'wings' were perturbed to simulate manufacturing errors. All three effects were then combined. The center pole was radially pushed out to simulate assembly errors. The delta in harmonics from the base case are listed in Fig. 1b. Out of spec harmonics are highlighted. Pole profile variations up to ~10 microns provide acceptable field performance beyond which the higher order harmonics begin to grow whereas assembly errors affect harmonics above n=5. The results of the 2-D study for the 66mm quadrupole were similar to the sextupole.

4.Machining Methodology

In order to meet the harmonics specifications, the iron quality, machining, and assembly tolerances are crucial in determining the final harmonics. The machining and assembly processes evolved over the course of the production.

One challenge was the results of perturbation studies that showed the pole spacing tolerances on the assembled magnet should be ~ 15 microns to meet harmonic requirements. Each multipole had to be disassembled to install the vacuum chamber. The repeatability for any reassembly of a magnet should produce field harmonics within ±20% of the original measured harmonics.

Traditional magnet fabrication techniques aren't capable of achieving this level of precision. Magnet fabrication traditionally employed the following operations: Lamination Stamping – Yoke Stacking and Bonding – Magnet Assembly. Magnets produced using this sequence achieve a mechanical precision of 50-100 microns. The goal was to minimize the fabrication and assembly variations. (See Table 2.)

Manufacturing Process	Achievable Tolerances (Microns)
Conventional Stamping	20-25
Fine Blanking	10-15
Laser Cutting	50-100
CNC Machining	10
Wire EDM	5
Mechanical Assembly	5-10

Table 2. Achievable tolerances.

All five magnet contractors implemented some form of secondary processing after yoke-bonding to successfully manufacture the storage ring magnets. The secondary manufacturing processes used to achieve the field harmonics were: machining the interface surfaces of top and bottom yokes to provide a precise flat mating interface, assemble yoke halves using an established bolt torque and tightening sequence to ensure consistent alignment of the magnet assembly, and final machining of the pole profiles after bonding to eliminate variations from lamination production and yoke stacking process. Achievable tolerances for various manufacturing processes for magnets of this size are shown in Table 2.

It's noteworthy to mention that one magnet vendor did not use secondary machining. Instead, after yoke bonding, highly specialized secondary processes were implemented to consistently achieve the field harmonics requirements.

5. Dipole Matching

The 35mm dipole design is unique. A 'nose' in the beam direction was added to the end of the yoke to save radial space, increase the integrated field , and used to match the lower order terms and the integrated field between the 35mm and 90mm dipoles. An Opera study was done to match the harmonics between the 35 and 90 mm dipole using a nose chamfer. A straight chamfer across the bottom edge of the nose adjusts the sextupole component while the chamfer angle will adjust the quadrupole component.

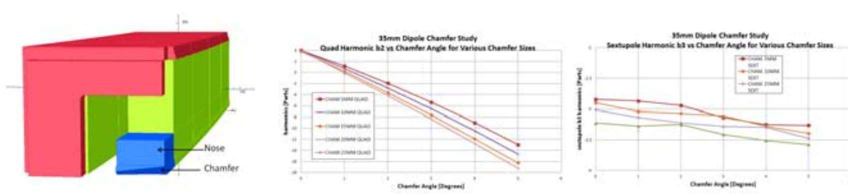


Fig. 2.a) 35mm dipole with angled chamfer b) Nose chamfer study results

Chamfer sizes up to 25 mm and angles up to 5 degrees were studied. The change in the quadrupole and sextupole terms can be seen in Figures 2a and 2b. The 90 mm magnets were measured and the average quadrupole and sextupole terms determined. Next, the 35mm dipole with the unchamfered nose was measured. In an iterative process, the nose was chamfered to match the 90mm quadrupole and sextupole terms. A match of 1/10000 was considered acceptable. The integrated field was measured. The length of the nose would be shortened to match the integrated strength of the 90mm dipoles.

The quad and sextupole harmonics of the 35mm and 90mm dipoles were the same magnitude. The quadrupole and sextupole contribution from the edge focusing were deemed close enough so that the nose did not have to be chamfered. (See Table 3.)

35 mm Serial Number	b2	b3	90 mm Serial number	b2	b3
41	1.01050E-03	-1.29775E-04	1	9.81261E-04	-1.15642E-04
42	9.66878E-04	-1.34188E-04	2	9.93664E-04	-1.21457E-04
43	9.77768E-04	-1.53388E-04	4	9.13684E-04	-1.28672E-04
44	8.51758E-04	-1.37700E-04	5	1.06556E-03	-1.39277E-04
45	9.30469E-04	-1.33789E-04	3	9.63076E-04	-1.22262E-04
46	9.65679E-04	-1.21721E-04	6	8.69447E-04	-1.14974E-04

Table 3. Quadrupole and sextupole terms due to edge focusing

5-2. **Multipole Shimming/Skimming**

Chamfering and shimming of the multipoles was done if the magnet did not meet specifications. Pole tip chamfering is required to minimize the first allowed harmonic (b9) in the sextupole and b6 in the quadrupole. A pole tip chamfer will drive the b6 or b9 positive. In contrast, a 'pole' chamfer along the sides of a pole will drive b6 or b9 negative. (see Fig. 3a) These two tools were used in the initial design. The pole chamfer is used first to obtain a slightly negative value of b6 or b9, then the tip chamfer is added to zero b6 or b9.

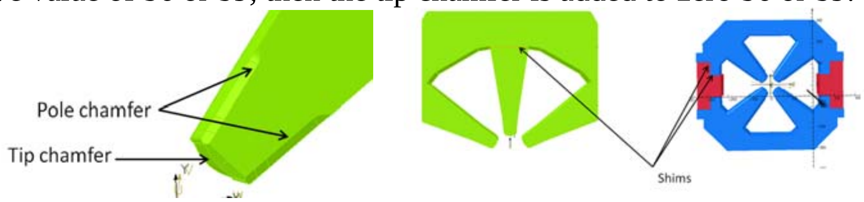


Fig 3. a)Tip and pole chamfer locations b) Shim locations

The sextupole required the adjustment of the center pole to meet the b5 and a4 harmonic. 3D Opera calculations were performed in order to ascertain a calibration of parts/micron movement of the center pole. Small horizontal shims were also used to adjust the b3 and b4 terms in the quadrupole. Small vertical shims were used to adjust the a3 term only. (see Fig. 3b).

6. Field Anomalies

The first measurements of the 35 mm dipole found a large field variation of about 3 gauss in the beam direction (see Fig. 4a). The cause was discussed in depth and could be attributed to: a machining error, steel laminations, packing factor, stacking process, welding along the length, or variations of the magnetic properties of the steel plate.

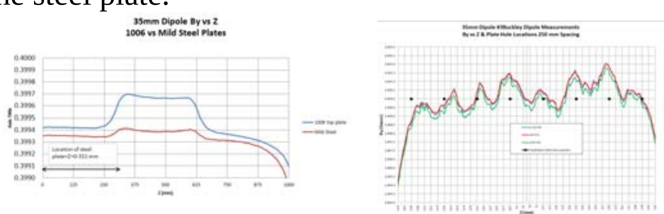


Fig. 4. a) Field variation in z beam direction. b) Tosca results with air gap

An Opera model and the yoke assembly drawings pointed to the cause of this field variation. The laminations/stacking were ruled out due to the long wavelength of the field anomalie. A machining error would have to be 35 microns. The gap was measured and found within spec. Models were run with a 1006 and mild steel plate lifted off of the yoke by a half mm. (See Fig. 4b). This produced a drop in field of about 1-3 gauss. The variation due to the material was 3 gauss. These variations are of the same order that were measured. The final clue was in the assembly drawings. The field variation appeared to be periodic with 250 mm distance between peaks. This approximated the bolt pattern in the top plate. The top plate was 1006, but the permeability can vary widely and it was not a machined surface. The conclusion: the bolting of the top plate to the laminated yoke produced gaps between laminations and plate. This gap resulted in a large reluctance and longer flux path. Where the plate was tight against the yoke near the bolt positions, the field was larger, where there a small gap between plate and yoke, the field dropped. Overlaying the field variation and the bolt hole positions, the cause and effect became obvious. The plates were machined for a better fit.

7. Harmonic Optimization - Quadrupole Saturation and Asymmetry

The quadrupoles were most troublesome due to their initial design and quantity – 300 throughout the storage ring. There was a large b6 variation with current. Modeling showed yoke saturation was the cause of current dependency. The top and bottom of the yoke were thickened and the magnets lengthened 20mm. The decrease in operating current brought the saturation down to a level of 3-4%.

Initial measurements showed a variation of a3 with current. This was due to a top-down asymmetry in the yoke. The magnet vendors used steel baseplates. 3-D modeling confirmed this and showed that a 3 mm stainless or aluminum shim would be enough to isolate the baseplate from the yoke (See Fig. 5.)

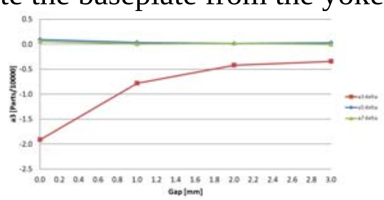


Fig. 5 a3,a5,a7 vs baseplate shim width

7-2. Harmonic Optimization - Quadrupole Machining Error

The quadrupoles produced by one vendor showed an upward trend of b8 from 0.2 to 1.5 units.(see Fig. 6a) The specification was 2 units. Perturbation results showed the b8 could be from an asymmetry in the poletip. The vendor insisted the milling machine worked fine and the program used to machine it was found to be correct. BNL insisted an aluminum pole piece be cut and measured with a CMM. The vendor discovered the five axes milling machine had a built in offset of 50 microns. When they fixed two of five axes, the offset disappeared. Using this machining technique, the b8 was successfully reduced to the 0.2 unit range.

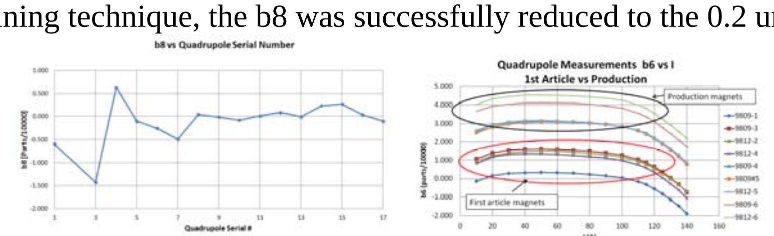


Fig. 6. a) b8 harmonic vs Ser. No. b) b6 first article and production

Halfway through production of the quadrupoles by a vendor, a sudden jump in b6 was found. (See Fig.6b) The chamfers were measured. The chamfers varied from 7.35 to 8.2 mm, the design value was 7.2mm. (See Table 4a.)

MAGNET	TOP LEFT	TOP RIGHT	BOTTOM LEFT	BOTTOM RIGHT
Chamfer [mm] 9809 #5	7.58	7.58	7.35	7.48
Chamfer [mm] 9812 #5	8.20	8.18	7.64	7.82

MAGNET	TOP LEFT	TOP RIGHT	BOTTOM LEFT	BOTTOM RIGHT
Chamfer [mm] 9812 #10	6.00	5.95	6.05	6.00
Chamfer [mm] 9812 #10	6.00	6.05	6.05	5.95

Table 4. Chamfer length a) Before and b) after machining method change

The vendor realized the technique they used to machine the chamfer was incorrect. The chamfer length varied with yoke length. The vendor changed the method which resulted in the correct chamfer being machined. (See Table 4b.)

The vendor produced 20 yokes with the wrong chamfer size. The chamfer size had to be reduced to drive the b6 lower but this was now impossible on the already-machined yoke. The solution was to use a ‘pole’ chamfer instead of the tip chamfer to reduce the b6 harmonic. Calculations showed a 1.5 mm pole chamfer would bring the b6 harmonic back into spec. The 20 yokes were re-machined. This not only saved the scrapping of 20 yokes, but also avoided a two month delay in completing the magnet contract.

7-3. Corrector magnet

A combined function horizontal/vertical dipole and skew quad corrector were manufactured and measured at BNL. A very large skew octupole term was found. An Opera model verified the measured results. The width and position of the quad coils, the number of turns, and the wire size were run in various model configurations. New coils were designed and tested, reducing the skew octupole from hundreds of units down to less than 50.

Looking forward, 3-D analysis has been an invaluable tool to aid in the design and manufacturing of the production magnets. Potential future additions in the form of higher order multipole correctors to the NSLS-II ring will clearly benefit from these type of 3-D simulations.

References

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