DESIGN AND MEASUREMENT OF THE NSLSII SEXTUPOLES*

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Abstract

The Sextupole magnets for the National Synchrotron Light Source II (NSLS-II) have stringent performance requirements. These magnets have a faceted pole profile that departs from the cubic shape due to constraints imposed by the vacuum chamber. Various geometric features were used to fine tune and minimize the harmonics. Prototypes have been built and measured and have satisfactory field performance.

INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) under construction at Brookhaven National Laboratory will be a new state-of-the-art 3 Gev electron storage ring designed to deliver world-leading intensity and brightness, and will produce X-rays more than 10,000 times brighter than the current NSLS at Brookhaven. The 792-meter circumference storage ring is comprised of approximately 1000 magnetic elements, 300 of which are sextupoles. The three variants are: 195 of the 68 mm aperture symmetric sextupoles, 75 of the 68 mm aperture wide sextupoles, and 30 of the 76 mm large aperture variety [1]. The 68mm aperture sextupoles are used in the low or non-dispersive regions while the large aperture sextupoles will be used in the high dispersion region. The specifications are listed in Table 1[2].

Table 1: Sextupole Prototype Specifications @25 mm

Description	Symmetric & Wide	Large Aperture
Aperture [mm]	68	76
Magnetic Length [mm]	200	250
Iron Yoke Length [mm]	178	225
Gradient [T/m2]	400	400
Approx. Pole Tip Field [T]	0.23	0.29
Amp.-Turns per Pole [NI]	2195	3064
Harm. b9** $[x10^{-4}]$	1.0	0.5
Harm. b15** $[x10^{-4}]$	0.5	0.5
Harm. b21** $[x10^{-4}]$	-	0.5

**Harmonic specifications defined as the integrated field errors normalized to the sextupole(n=3) term at a radius=25mm.

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DESIGN PHILOSOPHY

The good field region for the sextupole prototype magnets is ±20 mm horizontally and ±10 mm vertically. The design constraints of the large two-chambered vacuum vessel (see Fig. 1) and the small harmonic tolerances presented a difficult design challenge. A cubic pole tip was considered - but with the same overall field quality, b21 is smaller but b15 higher- and the pole grossly interfered with the vacuum vessel.

The following factors were considered for this design. First, it was determined that the magnet would consist of a two-piece lamination and shimmable center poles in order to minimize assembly errors and facilitate the assembly , removal and installation without having to break vacuum. The second consideration was the use of advanced manufacturing methods to minimize the surface variations in the laminations to assure good field quality. Cutting into the vacuum chamber was also a distinct possibility.

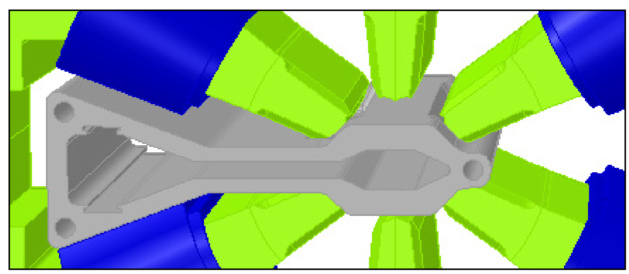

Figure 1: Two-chambered vacuum vessel.

2D MODELLING

For the initial 68 mm sextupole 2D model, the SLS (Swiss Light Source) sextupole was used as a starting point. The pole tip consists of four segments. Segment four (see Fig. 2) was constrained because it had to remain parallel to the surface of the vacuum vessel to minimize interference and aid in the mechanical inspection.

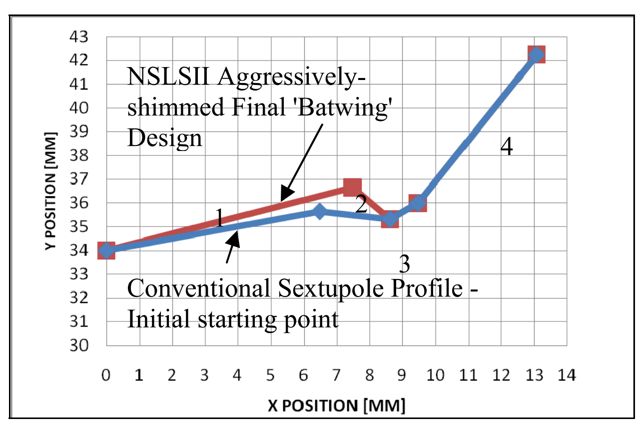

Figure 2: Final pole tip shape - 'Batwing' design.

A sextupole quadrant was modeled using Tosca 2D. Fixing the center pole point at the 34mm radius, the remaining points were moved in all directions. An iterative method was used to optimize the allowed harmonics and after a rather large but feasible encroachment into the vacuum chamber profile, the desired harmonics were achieved. The chamber was machined to accommodate the pole tip with a nominal 2 mm interstitial clearance.

This resulted in an aggressively shimmed pole tip end, referred to as 'bat wing' design due to its wing-like shape (see Fig. 3).

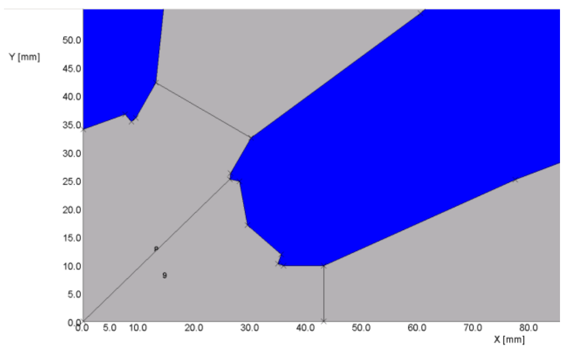

Figure 3: Final 2D pole tip shape- 'Batwing' design.

3D MODELLING

The 2D design (consisting only of points and lines) was used to create a 3D Tosca model by smoothing the pole shape by adding a 1.5mm radius between segments. The field harmonics were evaluated at a radius of 25 mm and met the integrated field harmonics of the symmetric and wide sextupole for the low dispersion region. There is no pole tip saturation because of the low field (0.23T).

LARGE APERTURE MODEL

The sextupole needed to be re-designed to meet the tighter harmonics specification for use in the high dispersion region. The allowed harmonics were expanded to include the 42 pole term (n=21).The logical course of action was to expand the aperture slightly which would increase the good field region. A study was undertaken to determine the optimum aperture to meet the specifications. A 76 mm diameter was chosen because the higher order terms (b15 and b21) approached zero. Retracting the poles in the radial direction while preserving the outer yoke envelope would leave the profiles of the various sextupoles unchanged throughout the ring.

Using the same pole profile, the aperture was increased from 68mm to 76mm. The poles were moved radially outwards and thickened slightly along their lengths to take advantage of the extra space afforded by the new aperture (see Fig 4).

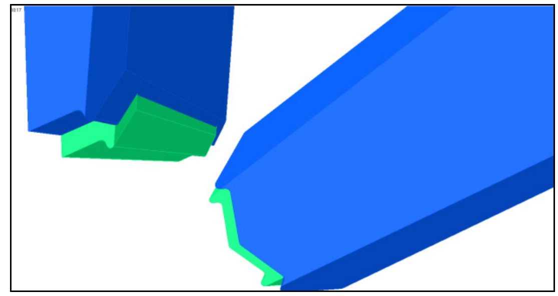

Figure 4: Comparison of 68 and the 76mm sextupole with poles radially pushed out and thickened.

FINE TUNING

Various geometric features were used for the fine tuning of the harmonics. The higher order allowed harmonics can be changed slightly ($< 0.5 \times 10^{-4}$) but remain driven by the 2D profile. Shims between the yoke and pole stem were introduced in the top and bottom center poles (see Fig. 5).

These were incorporated to minimize the dipole and decapole terms. A study was performed by shifting the center pole out and then in 50 microns for total shift of +-100 microns. The positive direction indicates the center poles pushed out while for a negative direction the poles were moved in toward the center. Graphing the results, they appear almost linear (see Fig. 6).

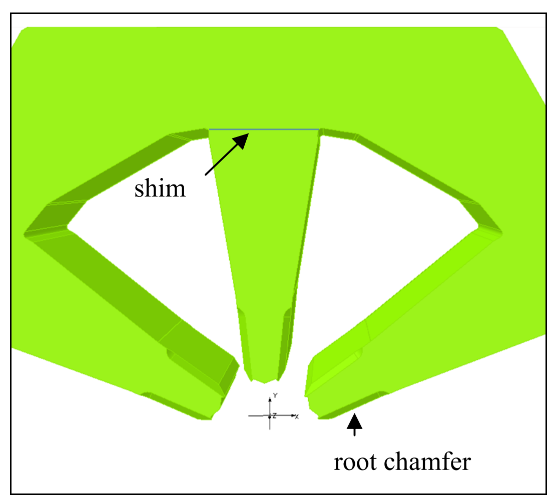

Figure 5: Sextupole with center pole shim.

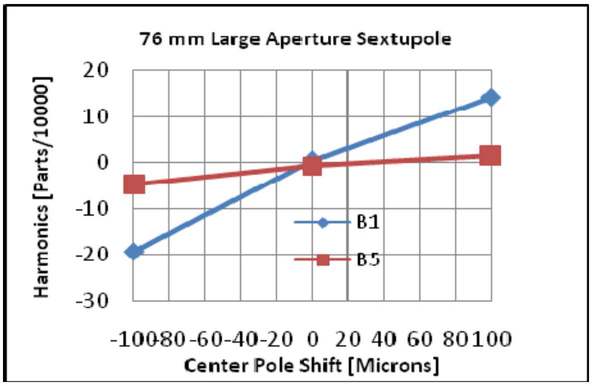

Figure 6: Harmonics vs center pole shift.

Another tool to trim undesirable harmonics is the mid-plane block (see Fig. 7). Small errors in the horizontal thickness of the mid-plane bracket on the order of 1 mm were found to affect mainly the dipole and decapole term (b1 and b5) and also slightly affect the allowed harmonics b9, b15, and b21. These effects were small, of the order of 0.1-0.2 x 10^{-4} for the allowed harmonics and 0.5x $10e^{-4}$ for the dipole and decapole terms. This trim could possibly be used for the very fine tuning of the b1 and b5 terms. The design of the pole tip was adequate and the mid plane bracket adjustment was not needed.

A third tool was the combination of the horizontal 'tip' chamfer and the vertical 'root' chamfer that runs along the edge of the pole stem [3] (see Fig. 7). The root chamfer is often used to accommodate the mechanical assembly of the coils and reduce saturation, however it has a significant impact on the first harmonic. The tip chamfer is used to trim the b9 harmonic. A study was performed on these two effects. They are linear but act in opposition. The root chamfer drives the b9 harmonic in the negative direction while the tip chamfer drives the b9 in the positive direction. By playing one chamfer against another, the absolute value of b9 can be reduced (b15 and b21 change very slightly) . Two iterations were sufficient to obtain a b9 that was slightly negative ($< -5x10^{-4}$). Next the tip chamfer was used to increase b9 toward zero. This was achieved after two more iterations. The only caveat is that by changing the root and tip chamfers, the magnetic length is also affected. It is best to minimize both of these chamfers to maintain the desired magnetic length.

MEASUREMENTS

Prototypes of the large aperture and the wide sextupole were produced and measured at BNL. An extra set of removable pole tips were also provided. The chamfering (tip only) was carried out at BNL. Two of the 76 mm sextupoles were produced, one each from two different vendors. A third vendor produced the 68 mm aperture wide sextupole. Having met the specifications, the prototypes were acceptable. A photograph of a sextupole prototype is shown in Figure 7.

Mid-plane block

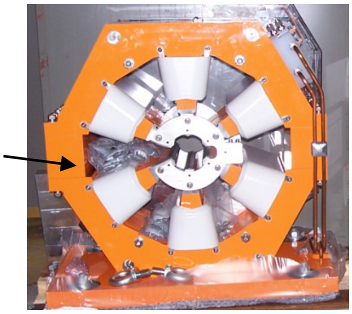

Figure 7: 76 mm prototype sextupole magnet.

Only one iteration was needed before a suitable tip chamfer was found. The results of the chamfering for the three prototypes and comparison to the Tosca 3D calculations are in Tables 3 and 4. The 3D calculations for the non-chamferable harmonics agree well with the prototype measurements except for the b15 term in the wide sextupole. The production sextupoles are due to arrive in the year 2010.

Table 3: Large Aperture Sextupole 3D Calculations vs Measurements

N	76mm 3D Tosca Calculation @25mm $x10^{-4}$	76mm Prototype 1 @25mm $x10^{-4}$	76mm Prototype 2 @25mm $x10^{-4}$
B9	-0.01	0.08	-0.39
B15	-0.21	-0.07	-0.21
B21	-0.50	-0.47	-0.47

Table 4: Wide Sextupole 3D Calculations vs Measurements

N	Wide 68mm 3D Tosca Calculation @25mm $x10^{-4}$	Wide 68mm Measured @25mm $x10^{-4}$
B9	-0.94	-3.8*
B15	-0.48	0.10

* Measured but not yet chamfered

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