DESIGN AND MEASUREMENT OF THE NSLS II QUADRUPOLE PROTOTYPES*

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Abstract

The design and measurement of the NSLS-II ring quadrupoles prototypes are presented. These magnets are part of a larger prototype program described in [1]. Advances in software, hardware, and manufacturing have led to some new level of insight in the quest for the perfect magnet design. Three geometric features are used to minimize the first three allowed harmonics by way of optimization. Validations through measurement and confidence levels in calculations are established.

INTRODUCTION

The 3 GeV National Synchrotron Light Source (NSLS II) under construction at Brookhaven National Laboratory is a new third generation, medium-energy electron storage ring designed to deliver world-leading intensity and brightness. The ring has 240 quadrupoles with 66 mm aperture and 60 quadrupoles with a 90mm aperture for high dispersion regions where tighter tolerances are required

DESIGN

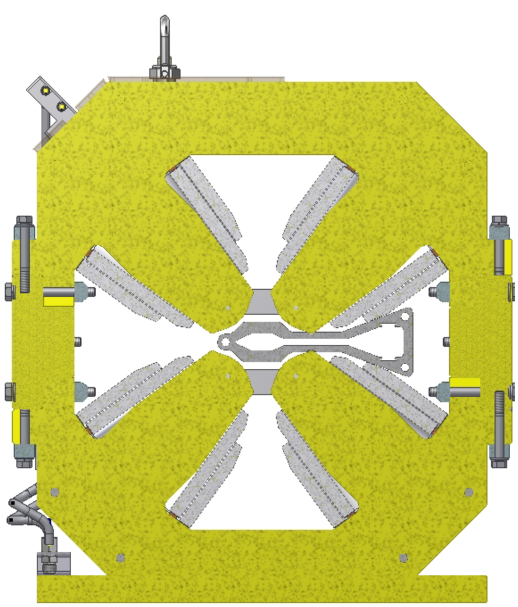

Figure 1: 90 mm Aperture Quadrupole.

Magnets are powered with independent DC power supplies. The coils are water-cooled copper conductor insulated with fiberglass. The yoke laminations are made of 1 mm thick low carbon steel. The 90 mm quadrupole cross-section is shown in figure 1. Top and bottom halves of the magnets are connected with magnetic iron brackets. This allows the use of the same laminations for the pole tips in different magnets of the same family. A non-magnetic bracket would have induced additional allowed harmonics (octupole) present in figure eight magnets.

The magnet's lengths are relatively short given their aperture and a 3D treatment from the onset is in order. These magnets were designed using models with parametric geometry to suit optimization in OPERA. The present approach consists of identifying significant parameters and finding the combination of these parameters that will minimize the first three allowed harmonics b6, b10, and b14. For long magnets b10, b14 are minimized in a 2D optimal profile after which b6 is reduced with end chamfers. There is however a small amount of coupling between the three harmonics. A 3D procedure where all three harmonics are minimized will result in even lower allowed harmonics.

Constraints

The pole tip shape is that of the scalar equipotential, a hyperbola. The ends of the pole tip are determined by the beam tube and the space needed to slip coils without further splitting the yoke to minimize assembly errors. The beam tube imposes particularly severe constraints. Tight space requirements in the lattice prevent the installation of lumped pumps and a distributed pumping has to be implemented. The antechamber has to be wide enough to allow the passage of synchrotron radiation fan and for the installation of distributed pumping in the form of NEG (non evaporative getter) strips, therefore these magnets are more constrained than in other similar machines.

Table 1: Protoype Quadrupole Specifications at 25 mm

Margin	Q66-250	Q66-400	Q90
Length [mm]	250	400	250
B' [T/m]	11/22	22	15
B'L [T]	2.76/5.52	8.8	3.75
NI [At]	4864/9864	9864	12208
b6 X10^{-4}	1	1	1
b10 X10^{-4}	4.5	4.5	0.5
b14 X10^{-4}	4	4	0.1

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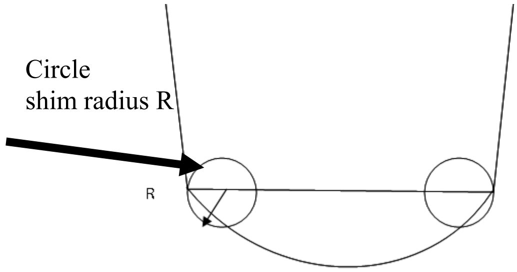

Figure 2: Termination of transverse pole profile with circular shim.

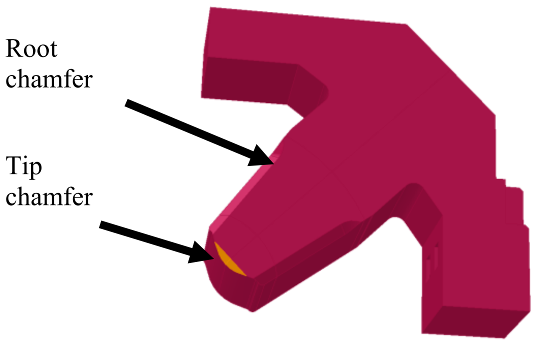

Figure 3: Tip and root chamfers.

Objectives and Parameters

Specifications for allowed harmonics are given in Table 1. The field quality is defined in terms of integrated harmonics normalized in "units" of $10^{-4}$with respect to the quadrupole field at a reference radius of 25 mm. This definition is compatible with the input to dynamic aperture codes used at NSLS-II. Harmonic values are highly sensitive to some geometric features, three of which have been retained as design parameters. They are the radius R (figure 2), and at the ends, a tip chamfer and a "root" chamfer (figure 3), both 45 degrees.

Variations with R

Figure 4 shows that as R increases, b6 is most sensitive by far, followed by b10 and b14 to a lesser extent.

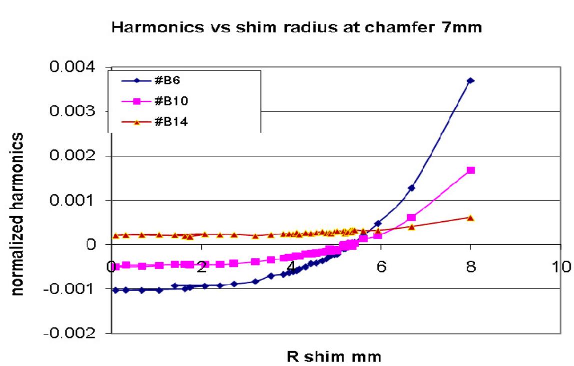

Figure 4: Harmonics versus shim radius.

In order to keep the parameterization simple, the customary flat surface used as reference to check alignment has been omitted.

Variations with Tip Chamfer

Usually, but not in the case of the ring sextupole, the first harmonic is negative in the unchamfered magnet. A chamfer increases b6 and a value can be found that will minimize its absolute value. b10 is also changed to an extent numerically significant here while b14 can be considered invariant.

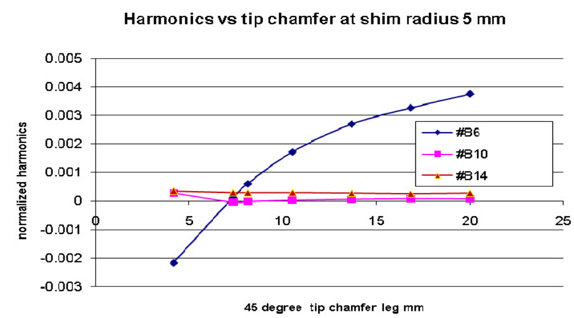

Figure 5: Harmonics versus tip chamfer.

Variations with Root Chamfer

The "root" chamfer is used mainly as a mechanical feature to reduce saturation and space taken up by the coils. That its impact on the first allowed harmonics is comparable to that of the common tip chamfer is first reported here to the best of our knowledge.

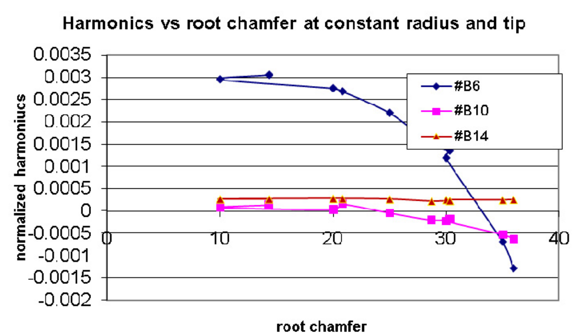

Figure 6: Harmonics versus root chamfer.

General Control of Harmonics

The preceding findings are summarized below:

- the shim of the pole profile increases b6 and b10 and is the best way to control b10
- the tip chamfer is used to increase b6
- the root chamfer reduces b6 and b10 to a lesser extent.

These findings are not limited to a quadrupole and apply to the sextupole design [2]. The root chamfer was mandatory there since b9 was positive for the unchamfered magnet. A fixed root chamfer was introduced in order to drive b9 in the negative range. The tip chamfer, which is cut in a removable end piece, was then used to reduce the absolute value of b9.

Optimization

The perfect design is reached when b6, b10, b14 all are zero for the same set of parameters: R, tip and root chamfers. To assist in this quest the OPERA module OPTMIZER with Pareto optimality was used. The geometry defined with parameters is built in the OPERA module MODELLER. Zero absolute values for the first three harmonics are chosen as objectives and the parameters are allowed to vary within predetermined bounds. OPTIMIZER is an efficient time saving finishing mathematical tool. At comparable field quality, one has the option to choose the set of harmonics with least impact on dynamic aperture. The set of harmonics with lower b14 and higher b10 could be the preferred choice if the impact of the third allowed harmonic on dynamic aperture is significant. The module is also a convenient tool for perturbation studies, correlating manufacturing tolerances to variations in harmonics.

NUMERICAL CONFIDENCE

Several measures were taken to assert the robustness of the numerical model. Harmonics were obtained for the scalar potential, which is directly calculated in OPERA, instead of using field quantities introducing numerical error through differentiation. Harmonics calculated at different reference radii are in agreement with values obtained by scaling with radius *r* or aperture *a* according to $b_n(r_1,a_1)/b_n(r_2,a_2)=(r_1a_2/r_2a_1)^{n-N}$, N=2 quad., N=3 sext...

It is verified that the sum of the first three harmonics converges to the value of the field error after which the truncation error remains constant and under a fraction of one unit. Harmonics of higher order (>b30), given sufficient sampling, are an artifact of a mesh size that is too coarse.

PROTOTYPES

Four types of prototypes were built: one 66 mm aperture, 250 mm long (S), one 250 mm long 66 mm aperture wide quadrupole (S W), one 66 mm aperture 400 mm long (B), and two 90 mm aperture, 250 mm long (I and B).

Measurements

Rotating coil measurements taken at BNL show that the allowed harmonics are all below the specifications (Baseline). The unallowed terms b3 and b4 are more prevalent in the Q90 I design than in the Q90 B design where the assembly procedure lead to a magnet of greater symmetry. The unallowed baseline harmonics were obtained form other machines, in particular the SLS. These preliminary specifications are remarkably close to measured normal bn terms but slightly underestimated the skew an terms, in particular a3.

Table 2: Q66, Harmonics in "units" of 10^{-4} at 25 mm

	Specs	Calc.	Q66 S	Q66 S	Q66 B
a3	1		0.5	-7.3	1.0
b3	3		-0.8	1.4	-0.1
b4	1		2.4	3.2	0.4
b6	1	-0.75	-0.6	-1.3	3.1*
b10	4.5	-2.66	-2.6	-2.7	-1.61
b14	4	-1.17	-1.1	-1.1	-1.1

*Q66 Buckley quadrupole does not have a final chamfer.

Agreement with calculated values is excellent.

Table 3: Q90, Harmonics 10^{-4} at 25 mm

	Specs	Calc.	Q90 I	Q90 B
a3	1		-1.19	0.32
b3	3		1.78	-0.39
b4	1		-1.96	0.51
b6	1	-0.24	-0.82	-0.24
b10	0.5	-0.10	-0.04	-0.06
b14	0.1	0.00	0.00	0.00

CONCLUSIONS

Design methods relying on computer-aided design, 3D parametric modeling, and new 3D optimizer have been used to minimize allowed harmonics. These tools are more than convenience as they lead to identification of parameters controlling harmonics. The concept of "root" chamfer as a control for harmonics instead of a mere mechanical feature has been introduced. Measurements have confirmed predictions with an excellent agreement. Confidence in numerical tools and in their application has been established.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Skaritka et al., “Design and Construction of NSLS-II Magnets,” Pac’09, MO6PFP008.
[2] C. Spataro et al., “Design and Measurement of NSLS II Sextupoles,” Pac’09, MO6PFP010.