RE-EXAMINATION OF THE NSLS-II MAGNET MULTIPOLE SPECIFICATIONS*

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Abstract

The NSLS-II magnet multipole specifications were determined based on the measurement results of the prototype magnets. The required field quality does not exceed what was specified for the existing light sources. While the prototype magnets are close to the ideal design, the magnets from mass production could have bigger errors. Recently we have relaxed the required momentum aperture from 3% to 2.5%. In this paper we discuss the acceptable range of the magnet multipoles based on the new requirement.

INTRODUCTION

The design and optimization of a lattice, to a large extent, is based on the design and technology of the magnets, which comprise the major part of an accelerator. For example, the magnet to magnet interference is considered small if the magnet separation is 2$\sim$3 times the magnet bore diameter. At NSLS-II the drift spaces between magnets are reduced to $\sim$ 17.5cm to save the vital longitudinal space; one of the driving factors is the 6$\sim$7cm magnet bore aperture. Combined function magnets were not adopted for the NSLS-II storage ring to avoid cross-talking caused by the magnet nonlinearity. The third example concerns the effective dynamic aperture. The dynamic aperture (DA) is usually a function of the magnitude of the magnetic and installation errors. For NSLS-II the 15mm injection aperture is achieved with the specified magnetic and engineering tolerances, such as the field deviation up to 25 mm is limited to a few units of 10^{-4}, and the magnetic centers are aligned on the girder to $\pm 30\mu m$ and 0.5mr.

The lattice considerations, on the other hand, impose a range for the magnet parameters. From physics perspective the key parameters of a magnet are the strength tuning range, the field quality in terms of harmonics, and the alignment errors. For NSLS-II the tuning range is derived from the lattice flexibility requirements, and engineering tolerances are specified to assure a sufficient DA for injection and to provide >3 hours Touschek lifetime [1, 2]. It is worth mentioning that the error tolerances, in most cases, are not deterministic. The blurry boundary is owing to two facts: the DA variation with error is a slow function; and the effects of errors are correlated. For example, the effect of one growing harmonic error can be partly compensated by the reduction of the other harmonics. Another example is that the multipole error effects on DA are not severe unless the closed orbit is off-centered to some level. Therefore even though all the specifications stem from physics considerations, some tolerances are specified as what can be achieved with the state-of-the-art technology, and some are determined through comparison of the effects between different sources. This methodology also makes it possible for fine adjustment during the production phase.

The magnet design and fabrication have been in rapid evolution in the past decades. While 2-D calculation and laser tracker were used for magnet design and installation when the early 3rd generation light sources were built [3], 3-D calculations have become a design routine to account for the asymmetric errors and edge effects [4]. Laser cutting and Electric Discharge Machining (EDM) are widely used to control the fabrication precision. At NSLS-II the vibrating wire technique [5, 6] is applied for magnet alignment. The magnet field quality is affected by saturation, pole face machining error, asymmetric frame and structure, and pole asymmetry in terms of geometry, length, and packing factor. A good magnet design should not only provide good field quality, but also simplify the fabrication and installation process; consequently minimize random errors and save cost.

FEEDBACK FROM MAGNET PRODUCTION

The production of the NSLS-II magnets has started since late 2010, depending on the individual schedule of the vendors. During interaction with the vendors, we have paid close attention to the key parameters, besides the other specifications. The integrated strength of a magnet can be well controlled if the yoke length is within specification. The number of laminations of a yoke can be adjusted to fit the length. With a lamination thickness of 0.5 mm and the total yoke length of >200 mm, one calculates the variation should be less than 0.25%. We found strong correlation between the total strength and the pole length. The magnetic length can be calculated from $L_m = L_y + 2g/n$, where L_m is the magnetic length, L_y the yoke length, g the bore diameter, and n is the number of poles. The result is surprisingly good, even with slight end-chamfering. The coil resistance, however, usually differs from calculation by a few percent. The NSLS-II power supplies are designed with a margin of $\sim$20%; therefore the resistance variation is not a problem.

The field quality of a magnet is characterized by the higher-order harmonics, which can be measured by a rotating coil to a precision of better than 10^{-4}. Two kinds of multipoles are usually found in the production magnets with large amplitudes. The first category includes the lower order terms, such as the dipole, the octupole and the de-

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capole components. These low-order harmonics are generated due to asymmetric structure, such as the base plate, the installation error between the upper half yoke and the lower half, unevenness among the poles, and field saturation. This type of harmonic error exists in both quadrupoles and sextupoles. The second type is the symmetry-allowed terms. These terms emerge basically owing to the finite pole width, or, imperfection in design. For example, quadrupoles would have 12-pole, 20-pole, and 28-pole components; and we usually see large 18-pole, 30-pole and 42-pole terms in a sextupole magnet. The rest of the harmonics are usually very small.

Several techniques have been developed to compensate the multipole errors. The so-called pole shimming technique is commonly used to correct the lower order terms. This method requires insertion of a thin metal sheet inbetween the contact surfaces, in order to adjust the position of the poles, or the roll of the upper and the lower halves. For example, the b_5 and a_4 terms of a sextupole can be effectively adjusted by shimming the upper and the lower poles. One the other hand, the b_4 and b_5 terms can be compensated by shimming the two spacers between the upper and the lower yoke. However, this method is very time consuming because the magnet has to be disassembled. The thickness of the shim is usually in steps of tens of microns; therefore, there will be residual harmonics even after shimming. And in principle shimming generates even higher order terms, unless the mechanical error is exactly eliminated after shimming.

The symmetry allowed terms can be compensated in two ways. One way is to shape the 2D pole profile to introduce counteracting systematic multipoles [7]; another way is to chamfer the two ends of the magnet pole [8]. In practice there are errors associated with both methods. For the pole profile optimization method, abrupt shape profiles are usually needed in order to obtain higher order components, and sharp edges are susceptible to machining errors, even with the latest machining technology, such as EDM. The end chamfering method is effective only on the first symmetry-allowed harmonic, and it also has limitation in correction strength. Essentially end chamfering is a coarse way to introduce the next symmetry-allowed harmonic term. Despite its simpleness to apply, it increases the fringe fields, and reduces the strength of the magnet; therefore the pole face shaping method is preferred.

In summary, we found in production that only the lower order terms and the symmetry-allowed terms have large amplitudes. In the following we will explore the allowable range for the harmonics, especially those that could be potentially large.

EFFECTS OF THE MULTIPOLE ERRORS

The effects of the multipole errors on the dynamic aperture have been discussed in [1, 2]. Here we briefly review it and show another conclusion. We have understood that the main effect on the DA by the multipoles is a detuning effect occurring for the particles with large transverse excursion. This can be illustrated through the Hamiltonian. The Hamiltonian of a multipole component, take the 20-pole as an example, can be expressed as

$$H_{10} = -\frac{K_9}{10}(x^{10} - 45x^8y^2 + \cdots)$$

where $K_9 = \frac{1}{B\rho}\frac{1}{9!}\frac{\partial^9 B_y}{\partial x^9}$ is the 20-pole strength, $B\rho$ is the rigidity of the beam, B_y is the vertical component of the magnetic field, and $x = x_{c.o.} + x_\beta$, where $x_{c.o.}$ denotes the horizontal closed orbit, and $x_\beta = \sqrt{2\beta_x J_x} cos\psi$ is the betatron oscillation amplitude. Because $x \gg y$, the Hamiltonian is dominated by the first term. And the tune change due to this term is

$$\begin{aligned}\nu_{10} &= \frac{1}{2\pi}\frac{\partial}{\partial J_x}\langle H_{10}\rangle \\ &= -\frac{1}{2\pi}\frac{K_9}{10}\sum_{i=1}^{5} iC_{10}^{2i}x_{c.o.}^{10-2i}(2\beta_x)^i\langle\cos^{2i}\psi\rangle J_x^{i-1}\end{aligned}$$

Note that J_x is small, therefore only large $x_{c.o.}$ leads to significant effect. The orbit deviation of the off-momentum particles is large at large dispersion locations. Therefore the multipoles at large dispersion will enhance this effect. That is the reason large bore aperture is designed for the NSLS-II magnets at the peak dispersion locations. On the other hand, the $i = 5$ term is independent of $x_{c.o.}$, therefore this term would affect the on-momentum particle if the betatron oscillation amplitude is large. It is worth noting that small effects were also seen in the vertical plane.

Interestingly, this detuning effect is related to the sign of the multipole; hence one might ask if cancellation occurs among the magnet families when they have different polarity. This is confirmed in simulation. We use a test lattice with chromaticity (4.6,4.6), including three damping wigglers and misalignment errors. Three cases were tested with the following multipole error configurations: run 2, with all multipole errors; run 1, the signs for the same error in run 2 are switched between the even cells and the odd cells; therefore the average strength of each multipole component is zero; run 0, with no multipole errors. The amplitude-tune relation is plotted in Fig 1 and 2. One can

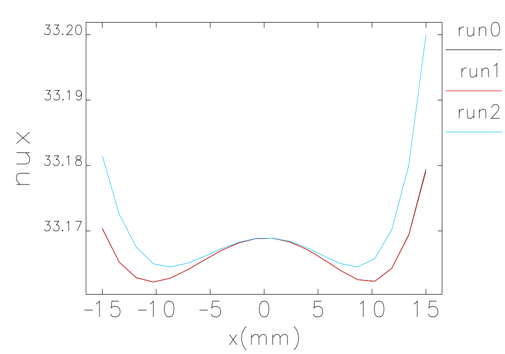

Figure 1: Amplitude-tune dependence at $\delta = 0$

see that the results almost overlap for run0 and run1; therefore cancellation indeed exists. The indication of this result

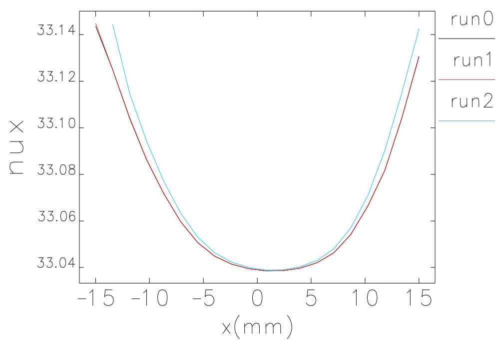

Figure 2: Amplitude-tune dependence at $\delta = -2\%$

is that the random errors are reduced by cancellation; therefore we are more concerned about the systematic multipole errors.

We have run many configurations in the simulation. The multipole errors can be grouped in five categories: quadrupole and sextupole magnet, normal and large aperture, normal and skew component, lower order and higher order, and systematic and random in terms of sign and strength. Essentially the origin of the multipole errors does not matter; the errors in the large aperture magnets have more impact because dispersion is large; the skew components introduce coupling, but in most cases they are not as detrimental because the required DA in the vertical plane is small; the lower order terms, such as octupole and decapole, are more harmful than the other harmonics because they are the leading terms for the amplitude-tune shift. Figure 3 shows the DA variation at $\delta = -2.5\%$ versus the magnitude of the multipole errors. Note that at 3% the DA reduction is much larger. We have also checked frequency map, Touschek lifetime, and long term stability with damping and quantum excitation, and we found that the perturbation due to the specified multipole errors is acceptable.

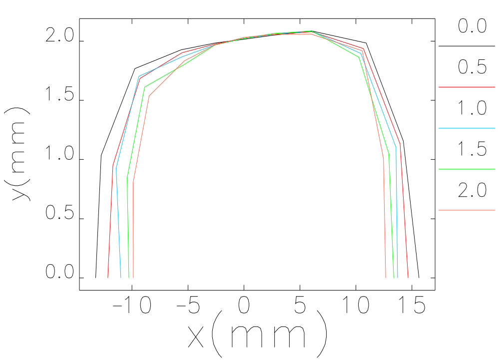

Figure 3: Dynamic aperture at $\delta = -2.5\%$ when the multipole errors listed in Table 1 and 2 are multiplied by a factor of 0,0.5,1.0,1.5, and 2.0, respectively.

THE REVISED SPECIFICATION

The revised specification is listed in Table 1 and 2. In conclusion, we are able to relax the multipole specifications, due to the relaxation of the momentum aperture from 3% to 2.5%, the 3 hour Touschek lifetime can still be achieved.

Table 1: Revised Multipole Specifications for the NSLS-II Quadrupoles (r=25mm, unit: 10^{-4})

	Normal Aperture		Large Aperture	
n	norm	skew	norm	skew
Symmetry-allowed				
6	3	0	0.5	0
10	3	0	0.5	0
14	3	0	0.1	0
Symmetry-unallowed				
3	2	2	3	1.5
4	2	1	2	1
5	1	1	0.3	0.1
6	-	1	-	0.1
7-9	1	1	0.1	0.1
10	-	1	-	0.1
14	-	1	-	0.1
11-13,15	0.5	0.5	0.1	0.1

Table 2: Revised Multipole Specifications for the NSLS-II Sextupoles (r=25mm, unit: 10^{-4})

	Normal Aperture		Large Aperture	
n	norm	skew	norm	skew
Symmetry-allowed				
9	2	0	0.5	0
15	1	0	0.5	0
Symmetry-unallowed				
1	30	15	15	10
4	2.5	1	3	3
5	1	1	1	1
6	1	1	1	0.5
7-8	1	1	0.5	0.5
9	-	1	-	0.2
10-11	0.5	0.5	0.1	0.2
12-14	0.5	0.5	0.1	0.1
15	-	0.5	-	0.1

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