ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK014

DIPOLE FRINGE FIELD ANALYSIS OF THE NSLS-II STORAGE RING*

J. Choi†, Y. Hidaka, W. Guimei, C. Spataro and T. Shaftan, BNL, Upton, NY

Abstract

In the NSLS-II storage ring, the effect of the dipole fringe field is not negligible and was considered already at the design phase. Especially in the vertical direction, the standard simulation codes are using the parameter called FINT (fringe Field INTegral) and, if there is no specific information, it is usually set to 0.5 which is considered as the reasonable average. With the hall-probe measurement data of the NSLS-II storage ring dipoles, we evaluated measured FINTs and applied them to the beam simulation. The paper shows the resulting FINTs and their effects.

INTRODUCTION

NSLS-II is a 3rd generation light source commissioned in 2014 [1]. It has a double bend achromat lattice with 30 cells on a 792 m circumference. The 30 straight sections are alternatively long and short with high and low horizontal beta values, and the ring consists of the 15 super-period.

The electron energy is 3 GeV and the nominal tunes are 33.22/16.26 and the beam emittances are 0.9 nm rad nad 8 pm for horizontal and vertical planes, respectively. The lattice design of one super-period of the NSLS-II storage ring is shown in Fig. 1. Each cell has 2 dipoles, 10 quadrupoles, 9 sextupoles and 6 mulit-function correctors.

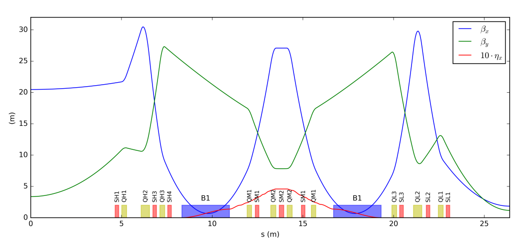

Figure 1: One super-period of NSLS-II storage ring.

Even with the circumference of 792 m, to minimize the beam emittance as the state-of-the-art synchrotron radiation source, the space of magnets is still limited and the innovative dipole magnet has been developed where the magnetic length becomes significantly longer than the mechanical length [2]. The design is referred as "extended pole" or design with a "nose". The new design freed up about 1.3 % space in machine by releasing about 190 mm per dipole magnet. In the NSLS-II storage ring there are 54 dipole magnets of 35 mm gap and 6 dipole magnets that have a gap of 90 mm as the infrared sources. Each dipole has magnetic length of 2.62 m with a field 0.4 T which gives the radius of curvature 25 m for the 3 GeV electron beam and bends the beam 6.0° with the sagitta of 35 mm [3].

* Work supported by the U.S. Department of Energy (DOE) under contract No. DE-SC0012704.

† jchoi@bnl.gov

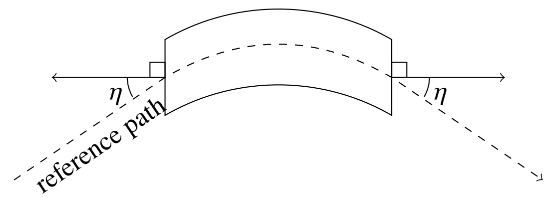

Figure 2: Schematic diagram of the rectangular dipole magnet and the ideal beam path.

Because of the concern about the effects from the 2 kinds of unconventional dipole magnets, the fringe field effects were already numerically analyzed at the design phase using the calculated 3D magnetic field map [4] and confirmed that the optics distortion can be fully accommodated. Now, we have the machine in operation and would like to analyze the effects on the optics to the first order with the measured data.

In simulation studies, the dipole magnet is frequently simplified to the hard edge model where the magnetic field is constant inside the magnet and vanishes outside, i.e., the fringe field region is infinitesimally thin. In this case, if the ideal beam path is not normal to the pole face, because of the excess or lack of curvature compared to the ideal path, the beam is focussed or defocussed at each end of the dipole as

$$\Delta x' = \frac{x}{\rho}\tan\eta \tag{1}$$

where ρ is the nominal radius of curvature and η is the injection or extraction angle shown as in Fig. 2.

Even with the hard edge model, we will have non-vanishing horizontal magnetic field, if η is not zero, by applying Ampère's law without the source, $\nabla \times \mathbf{B} = 0$, at the edge of the magnet. The resulting focussing strength can be written as

$$\Delta y' = -\frac{y}{\rho}\tan\eta. \tag{2}$$

When we move to the extended fringe field from the hard edge model, the horizontal focussing strength does not change to the first order but, in the vertical plane, the η in Eq. 2 needs to be corrected because η is the source of the asymmetry which induces the horizontal field and the field experienced by the particle is changing along the path. As the result, the vertical edge focussing is corrected in the first order as [5]

$$\Delta y' = -\frac{y}{\rho}\tan(\eta - \psi). \tag{3}$$

where

$$\psi = \frac{Kg}{\rho}\sec\eta(1+\sin^2\eta)$$
$$K = \int \frac{B_y(z)[B_0 - B_y(z)]}{gB_0^2}\,dz. \tag{4}$$

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK014

Here, g is the magnet pole gap size and z is the coordinate normal to the pole face. And B_0 is the magnetic field well inside of the magnet body. The integral for K should cover enough region around the edge from $B_y = 0$ to $B_y = B_0$ and the typical value of K for actual magnets may range from 0.3 to 1.0 [5]. K is also known as FINT in many particle tracking codes like MAD [6] and the default value is usually set to 0.5, which is considered as the reasonable average.

When the NSLS-II lattice was designed, we also used the hard edge model. The accurate dipole fringe field effect was not the primary concern and, furthermore, the machine is equipped with enough knobs, including the 1% dipole trim coils, to compensate all the expected fringe field effects.

In fact, even though all the set-point currents of the quadrupole magnet power supplies are away from the values obtained by the design field strengths and the unit conversions, the machine is running with target specifications. However, from the fact that the slight deviation of the tune can affect the machine performance, we expect the understanding the effects on the beam optics from the fringe fields of the 60 2.62 m dipoles still can help in improving the performance performance.

In this paper, we will estimate the focussing strengths of the extended fringe fields of the NSLS-II dipole magnets to the first order using the measured field data and discuss the effects on the beam optics.

DIPOLE FRINGE FIELD

The fields for all the NSLS-II storage ring dipole magnets were measured by the manufacturer (Buckley Systems Inc., New Zealand). Upon arrival at the NSLS-II site, among 54 35-mm gap dipoles, magnetic fields were measured for 17 samples using the hall-probe and the fields for all 6 90-mm gap dipoles were also measured.

In the measurement, the vertical magnetic field was measured in rectangular coordinate system where x in the horizontal direction, y in the vertical direction in the transverse plane and z in the longitudinal direction. The field was measured at three planes at $y = -10$, 0 and 10 mm along the ideal beam path assuming hard-edge model. In the z direction, they were measured at points from -1800 mm to 1800 mm relative to the magnet center with 5 mm step. In the x direction, the fields were measured at 13 points for the given y and z. The center point in x direction is the ideal beam path and the step is 5 mm. The overall measured field values B_y at $y = 0$ plane are shown in Fig. 3

For the NSLS-II storage ring, one magnet power supply is providing the current to all 60 dipole magnets around the ring, but each magnet has independent trim coils which can compensate up to 1% of the bending angle. By numerical integration, it can be shown that the integral of the vertical magnetic field along the ideal beam path of each magnet is well within 1% of 6° ($2\pi/60$).

The typical fringe field profiles for 35 mm and 90 mm gap dipole magnets are shown in Fig. 4 and 5. The z in the figures is the longitudinal direction in the rectangular coordinate system, normal to the pole face. The profiles are also shown together with the approximated Enge function [7]. As the reference, Fig. 6 shows the typical short-tail and long-tail fringe field profiles Enge suggested. Compared to the typical profiles of Fig. 6, both 35 mm and 90 mm profiles show different characteristics and the reason is considered to be the non-conventional nose-type design.

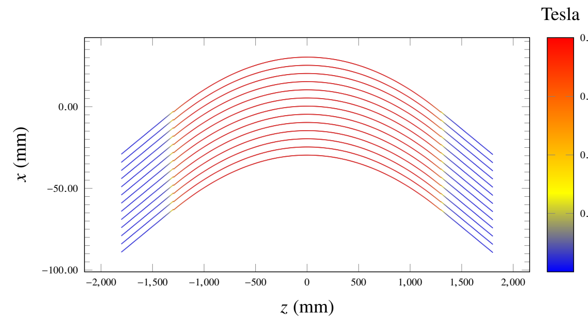

Figure 3: Hall-probe field measurement data of a sampled NSLS-II 35-mm gap dipole at $y = 0$.

By numerical integrations, we obtained the corrections in the vertical focussing strengths due to the finite fringe field range, K (FINT) in Eq. 4, from the measurement data and the results are 0.9445 ± 0.01 for the 35-mm gap dipole and 0.35 ± 0.0022 for the 90-mm gap dipole. These values are placed at the ends of the range $0.3 \sim 1.0$ which is the range of the values which the FINTs of actual magnets are expected to have [5]. As the references, the FINTs from the typical short-tail and long-tail fringe field profiles of Fig. 6. are 0.42 and 0.48, respectively.

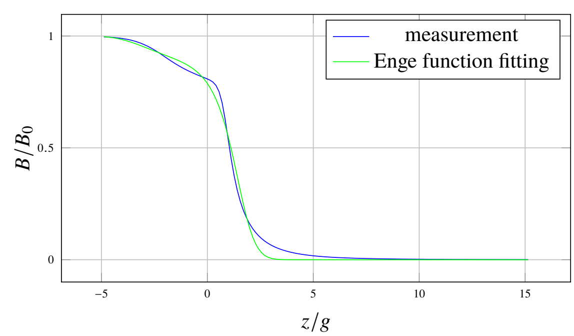

Figure 4: Typical fringe field profile of the 35-mm gap dipole along the z direction where z=0 is at the pole face and g is the pole gap size.

EFFECTS ON THE STORAGE RING OPTICS

By using the FINTs obtained in the previous section in Eq. 3 and 4, we can correct the vertical focussing strengths at dipole edges and recalculate the Twiss parameters. Even though the FINTs, 0.9445 and 0.35, from 35-mm gap and 90-mm gap dipoles, are very different each other, we can see the difference is coming from the denominator of the integrand of the second equation of Eq. 4. In calculating the

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK014

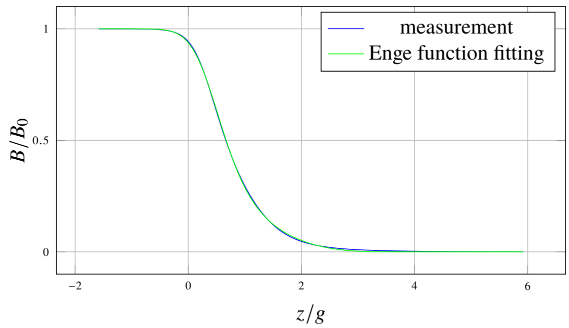

Figure 5: Typical fringe field profile of the 90-mm gap dipole along the z direction where z=0 is at the pole face and g is the pole gap size.

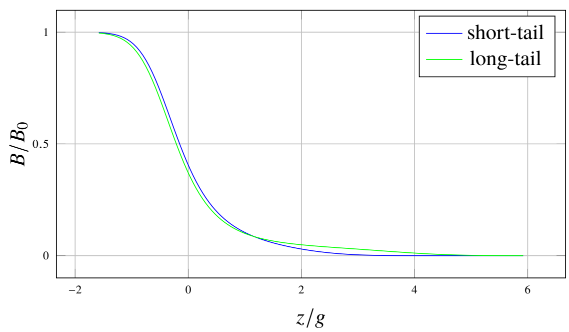

Figure 6: Typical short-tail and long-tail fringe field profiles.

focussing strengths, the difference is compensated by the first equation of Eq. 4 and the corrections from finite fringe field effects to the 35-mm gap and 90-mm gap dipoles are becoming similar.

On the other hand, if we put 0.5 for both dipoles as in the conventional simulation, the effects in Eq. 4 will be 1.9 times over-estimated for the 35-mm gap dipole and 0.7 times under-estimated and the results will show symmetry breaking in the vertical plane optics.

Using the design values of the NSLS-II storage ring, we calculated deviations in vertical β values at beam position monitor (BPM) positions with different dipole fringe field effects. Relative deviations in β values for the cases where 0.5 was put as FINT for all dipoles and FINT from the measurement data are shown together in Fig. 7.

As can be seen in the Fig. 7, when we put the conventional value 0.5 for all FINTs, the β_y function has 3-fold symmetry with overall lower deviation. When we apply the measured data, the symmetry is restored but the overall deviation is increased. The overall deviation from the design β_y values (beta beating) are 0.44% and 0.63% for each case.

The vertical tune of the design model is 16.26 when no correction is applied. It is changed to 16.253 for 0.5 as the FINT and becomes 16.249 when the FINTs from the measured data are applied.

SUMMARY

We reviewed the corrections in the focussing strengths at the dipole edges due to the extended fringe fields.

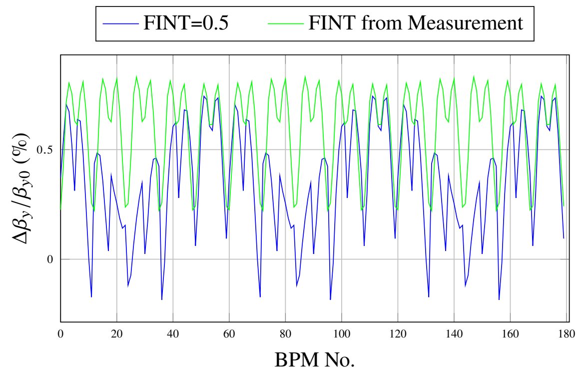

Figure 7: Deviations in the vertical β values from the hard-edge design values depending on the dipole fringe field effects.

In the horizontal plane, the correction from the hard-edge model is not needed to the first order. However, in the vertical plane, the correction using the field integral values (FINT) is needed to the first order. If the pole-gap is given for the dipole magnet and the specific information about FINT is not available, the usual tracking codes use 0.5 as the FINT and correct the vertical focusing strengths at the dipole edges.

By comparing the vertical β values and tune to the design values of the NSLS-II storage ring, the correction using either FINT, the code default 0.5, or the values from the measured data, affect the vertical ring optics only slightly and, if needed, the lattice can be corrected easily. The concern is the fact that if we blindly try to correct the operation lattice to the design optics, where the default FINT is used, the resulting optics can have the 3-fold symmetry. Therefore, using the correct values for the FINTs is still desired.

REFERENCES

[1] F. Willeke, "Commissioning of NSLS-II," in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, paper MOYGB3, pp. 11–16

[2] R. C. Gupta, A.K.Jain, "Magnet Designs and Requirements for Next Generation Light Source," in *Proc. 23th Particle Accelerator Conf. (PAC'09)*, Vancouver, British Columbia, Canada, May 2009, paper TU1RAI01, pp. 614–618

[3] S. Dierker, "NSLS-II Preliminary Design Report," Nov. 2007

[4] Y. Li, S. Krinsky, M. Rehak, "Numerical based linear model for dipole magnets," in *Proc. 23th Particle Accelerator Conf. (PAC'09)*, Vancouver, British Columbia, Canada, May 2009, paper TH6PFP016, pp. 3732–3734

[5] K. L. Brown, "A First and Second Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers," *Adv. Part. Phys.* 1, pp. 71–134, 1968

[6] MADX, http://madx.web.cern.ch/madx

[7] H. A. Enge, "Effect of extended fringing fields on ion-focusing properties of deflecting magnets," *Rev. of Sci. Inst.* 35 (3), pp. 278–287, 1964