SPECIAL MAGNET DESIGNS AND REQUIREMENTS FOR NEXT GENERATION LIGHT SOURCES*

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Abstract

This paper describes significant developments in iron-dominated magnet designs, magnet alignment and measurements and calculations of closely packed magnetic elements in the National Synchrotron Light Source II (NSLS-II) now under construction. A dipole design has been developed which significantly increases magnetic length for the same mechanical length of the magnet. The quadrupole and sextupole magnets must be aligned and positioned to better than 30 microns. This paper presents a brief status of the progress made. Another concern has been the distortion of field quality due to the small (~150 mm) axial spacing between the iron yokes of two adjacent magnets. The results of calculations and measurements of the field quality in the presence of other magnets and other machine components in close proximity are presented.

INTRODUCTION

NSLS-II will be a state-of-the-art synchrotron radiation source [1] at Brookhaven National Laboratory (BNL) that will produce x-rays more than 10,000 times brighter than the current NSLS. It will have an energy resolution of 0.1 MeV and spatial resolution of 1 nm. The most visible feature of the complex will be a 3 GeV electron storage ring having a circumference of 792 meters. The storage ring consists of approximately 1000 magnetic elements [2], including 60 dipoles, 300 quadrupoles [3], 300 sextupoles [4], 300 multi-function correctors [5], etc. A variety of these magnets will be placed with an axial spacing between them smaller than ever before in any machine. The interference harmonics due to proximity of magnets should be accurately known for ease of commissioning and reliable performance of the machine.

DIPOLE DESIGN

In the next generation synchrotron radiation sources, such as the NSLS-II at BNL, the space for magnets is limited, as is the strength of the dipole field. Increasing magnetic field is not desirable as that will increase the loss due to synchrotron radiation which is currently under 2 MeV per turn. To overcome these challenges an innovative magnet

Figure 1: Prototype magnet for NSLS-II with "*extended pole*" or "*nose*". The dotted line shows the boundary between the nose piece and the main laminations.

design (see Fig. 1) has been developed where the magnetic length becomes significantly longer than the mechanical length. In NSLS-II, it allows the mechanical length of the dipole to be reduced by 180 mm (for a total savings of ~10 meter or ~1.3% in the storage ring) without increasing the central field. The design is referred to here as "*extended pole*" design or design with a "*nose*".

Magnetic models of the upper half of the yoke (with magnetic field superimposed on the iron surface) along with the upper and lower coils for three cases are shown in Figs. 2-4. Fig. 2 is for the case without any nose piece, Fig. 3 is for the nose piece of optimized length (68.5 mm) and Fig. 4 is for a nose piece which is too long. One can see that a nose piece that is too long could create a situation where the iron in nose piece may saturate. Fig. 5 shows the dipole field along the nominal beam axis from the middle of the dipole in these three cases. One can clearly see the increase in magnetic length due to a nose piece. One can also see that when the nose piece is too long the dipole field in the nose region drops. This is due to the saturating iron, as can be seen in Fig. 4 (see the place in the nose where it meets the magnet yoke). A survey of the literature revealed that a somewhat similar pole extension has been used in quadrupole magnets placed inside a drift-tube Linac [6].

A nose piece also provides a convenient way to modify the ends of the magnet. One application is to convert a magnet with parallel ends, which is generally easier to construct, to a sector magnet with a simple angular cut in the nose piece. This feature has been incorporated in a prototype NSLS-II dipole. Geometric shaping of nose piece along the beam axis can be used to adjust the field fall-off to obtain a better match between the end profiles of 35 mm and 90 mm aperture dipoles

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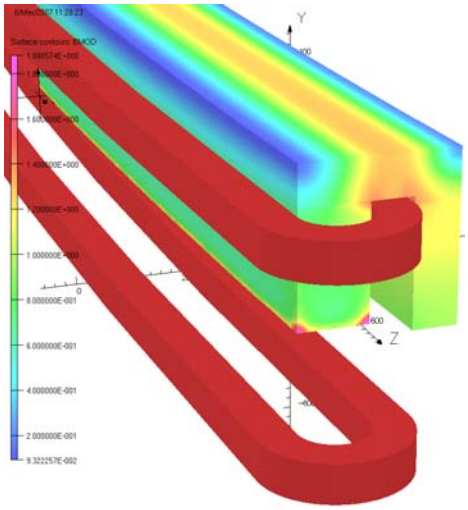

Figure 2: Magnetic model of the upper half of the yoke (and upper and lower coils) without “*nose*” piece.

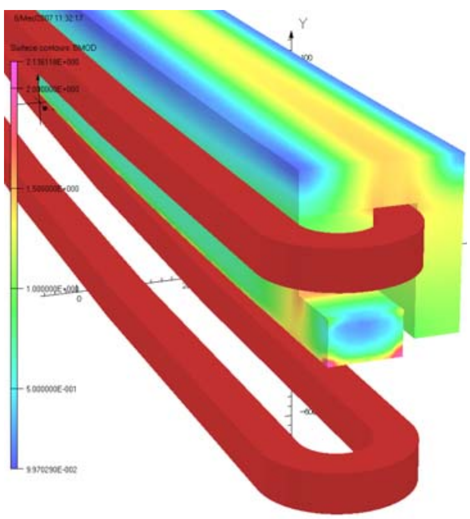

Figure 3: Magnetic model of the upper half of the yoke (and upper & lower coils) with optimized “nose” piece.

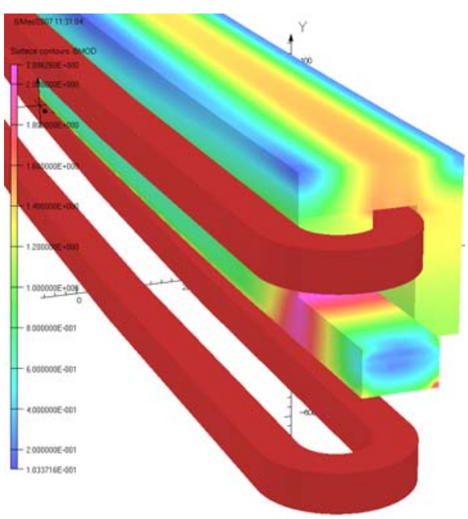

Figure 4: Magnetic model of the upper half of the yoke (and upper and lower coils) with a “*nose*” piece that is too long and causes saturation.

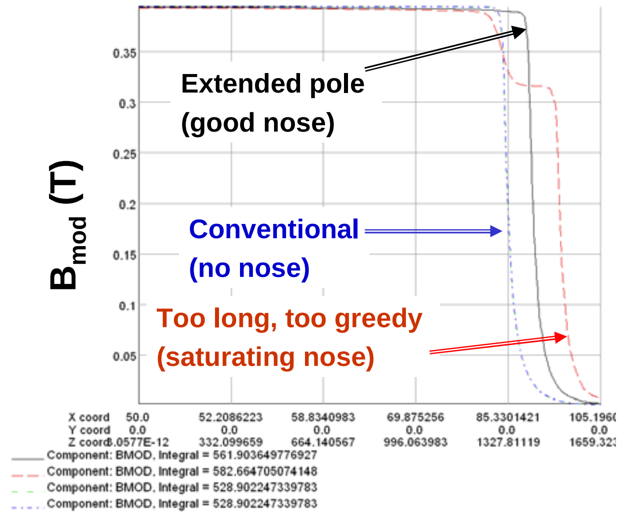

Figure 5: Dipole field (magnitude) along the beam axis from the middle of the dipole in these three cases.

WIDE SEXTUPOLE AND QUADRUPOLE

Quadrupole and sextupole designs have been described in detail elsewhere [3, 4]. Wide sextupoles and wide quadrupoles allow space for X-ray transport to beam lines. They, however, break the ideal magnet symmetry. In sextupoles such breaking of six fold symmetry creates “non-allowed” or “semi-allowed” harmonics b_1 (normal dipole), b_5, b_7, etc. We have developed a method [7] to compensate for this break in symmetry by another controlled break in symmetry. The poles on the vertical axis are moved away from the center (see Fig. 6 for a model of ¼ of the magnet) to compensate for the missing iron on the horizontal axis. This adjustment is natural for the vertical floating pole design as present in the NSLS-II sextupoles to aid assembly of the coils in the magnet. An adjustment in the amount of correction is obtained by adjusting the size of the shims between the floating poles and the yoke. It may be noted that only a small amount of pole adjustment (~70 microns) is required to compensate for a rather large amount of missing iron at the midplane.

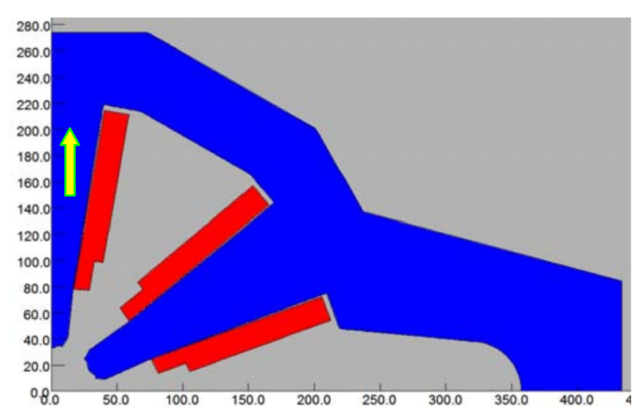

Figure 6: Magnetic model of a quadrant of the 68 mm aperture wide sextupole for NSLS-II. Poles must be moved vertically away from the center (see arrow) to compensate for the break in symmetry caused by a large cut-out in the iron yoke to allow X-ray transport.

This is due to the fact that in iron dominated magnets, perturbations at the magnet poles are much more effective than those at the midplane. Table 1 gives the harmonics before and after this compensation. The goal was to minimize b_5 harmonic, however, other symmetry breaking harmonics are also reduced in the process. A similar method can be used in wide quadrupoles.

Table 1: Symmetry breaking harmonics in 68 mm aperture wide sextupole (model shown in Fig. 6) before and after correction obtained by a 70 micron vertical displacement of upper and lower poles away from the center.

Harmonic	Before Correction	After Correction
b_1	-37.6	-8.1
b_5	-4.5	0
b_7	-0.36	-0.25

INTERACTION HARMONICS

The NSLS-II storage ring is a tightly packed machine with very small gaps (~150 mm) between adjacent magnets and other hardware (such as vacuum chamber supports and ion pumps, etc.). This, in some cases, generates significant field distortions (or interaction harmonics) that could have an impact on the performance of machine. A program to measure these interaction effects has been carried out using the magnets received on loan from other synchrotron radiation sources [8] and also some prototype magnets for NSLS-II. Measurements of interaction harmonics between various combinations of quadrupole, sextupole and dipole corrector magnets were performed. Calculations have also been performed in some cases. Results from the measurements and calculations are summarized.

Interaction between Quadrupole and Corrector

The interaction between the NSLS-II 156 mm corrector (horizontal and vertical) dipoles [4] and the Swiss Light Source (SLS) quadrupole [8] has been examined. For measurements, the quadrupole was kept at a fixed position and the corrector dipole was moved. The minimum distance possible between the yokes of two magnets was 130 mm because of the coils. The maximum effect on the integral quadrupole gradient was seen when the corrector was not powered. In this case the integral field harmonics indicated only small overall field distortion.

For calculations, the corrector magnet was modelled without the magnet coils which allowed the distance between the two yokes become less than 130 mm. Fig. 7 shows a model of SLS quadrupole with coils and NSLS-II corrector magnet without coils. To reduce the computational errors due to modelling, "*without corrector model*" is simply the material of corrector iron changed to air in "*with corrector model*". Beam axis is z-axis and the magnet cross-section is in xy plane. To compare the quadrupole gradient in the fringe field region with and

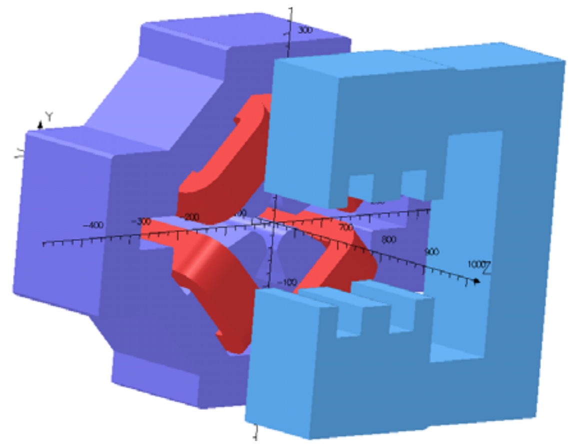

Figure 7: Magnetic model used for studying interaction harmonics between SLS quadrupole and NSLS-II 156 mm prototype corrector dipole. The corrector dipole is not powered and the coils are not shown.

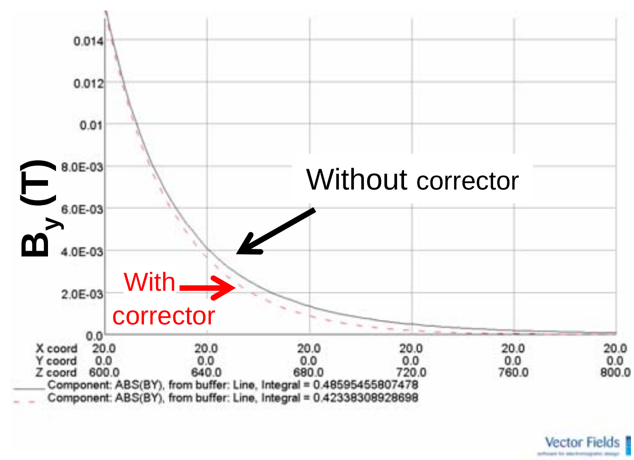

Figure 8: Vertical field component (B_y) parallel to magnet axis (x=20 mm, y=0 mm) outside SLS quadrupole without and with NSLS-II corrector dipole in proximity (yoke-to-yoke gap=130 mm).

without the corrector, we plot the vertical component of the field (B_y) as a function of z at x=20 mm and y=0 mm in two cases (see Fig. 8). Iron of the corrector magnet provides a shunt path to the fringe field of the quadrupole and reduces its local gradient (see Fig. 8) and hence integral strength. The yoke-to-yoke gap between the quadrupole and corrector magnet (when present) was 130 mm. We compare the calculations and measurements in Fig. 9 for the change in integral transfer function as a function of distance between the yokes of the two magnets. The integral transfer function decreases by ~1 part in 1,000 when the iron to iron separation is ~130 mm. Good agreement between calculations and measurements is seen as the two differ by only a few parts in 10,000, which is the limit of accuracy of both measurements and calculations.

Interaction between Quadrupole and Sextupole

Fig. 10 shows a setup when two sextupoles are placed on either side of the quadrupole. Iron of the sextupole (not

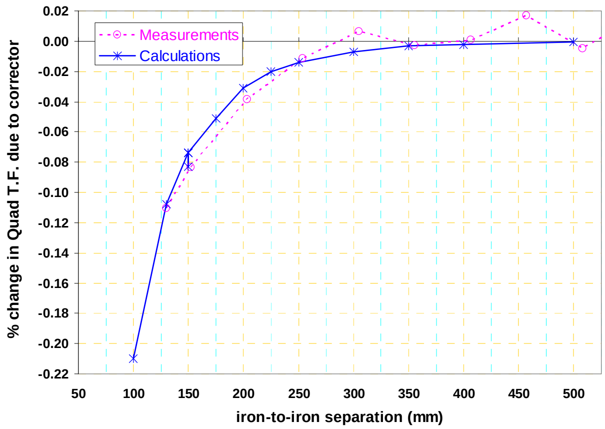

Figure 9: Comparison between calculations and measurements for the drop in integral quadrupole transfer function due to the presence of the corrector dipole (not powered) as a function of yoke-to-yoke separation between the two magnets.

Figure 10: SLS Quadrupole and sextupole on the measuring stand to study interaction harmonics between the magnets.

powered for this analysis) provides a shunt path to the fringe field of the quadrupole and reduces its local gradient and integrated strength. The sextupole, because of its much smaller aperture (66 mm), causes significantly more distortion in the quadrupole field than that caused by the corrector dipole (presented in the previous sub-section) with much larger aperture (156 mm). Fig. 11 shows the contour plot of the magnitude of the radial component of the field in a plane perpendicular to the magnet axis at the location where the sextupole iron starts. One can see the distortion caused by the sextupole iron in the quadrupole field. The poles of the quadrupole and sextupole are projected here.

Fig. 12 shows the angular dependence of the radial component of the field at a radius of 25 mm. This is computed in a plane perpendicular to the magnet axis and at the location where the sextupole iron starts. One can clearly see from Figs. 11 and 12 that the presence of sextupole iron reduces and distorts the quadrupole fringe field. The most prominent term created by this field distortion is octupole (which is not allowed in ideal quadrupole geometry). The measured integral octupole (b_4) as a function of yoke-to-yoke gap between two magnets is plotted in Fig. 13.

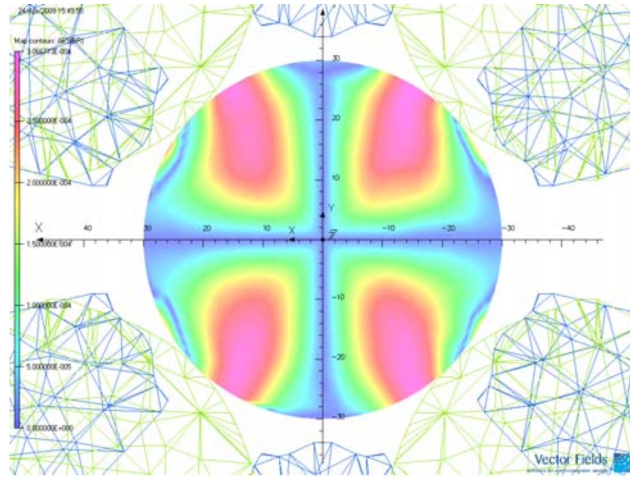

Figure 11: Contour plot of the magnitude of the radial component of the field in a plane perpendicular to the magnet axis at the location where the sextupole iron starts. The poles of the quadrupole and sextupole are projected here. Only the quadrupole is powered.

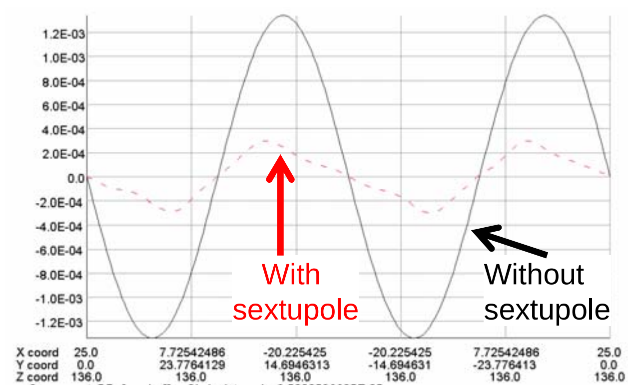

Figure 12: Radial component of the field as a function of angle at R=25 mm in a plane perpendicular to the magnet axis at the location where the sextupole iron starts.

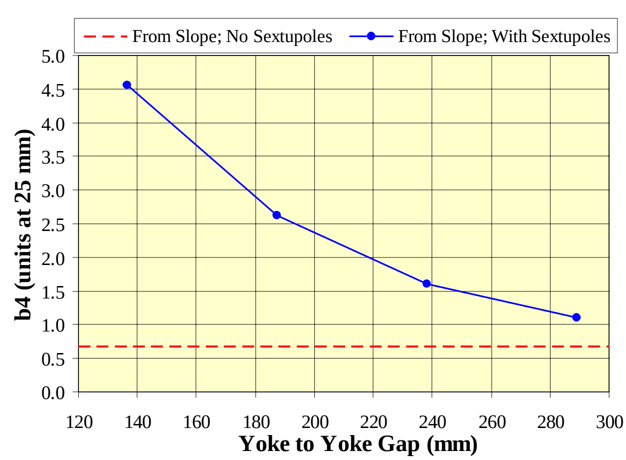

Figure 13: Measured integral octupole (b_4) harmonic in quadrupole as a function of yoke-to-yoke gap when a sextupole (not powered) is placed in the vicinity (blue solid line). Inherent b_4 is shown by red dashed line.

Interaction between Magnets and Hardware

Field quality in magnets can also get significantly distorted if the hardware contains some magnetic material and is placed in a close proximity. Of particular interest is the possible change created when the magnets are placed on the girder, close to the vacuum pump and the support structure for vacuum chamber. Measurements revealed that only the proximity of the vacuum chamber support structure (based on an earlier design) gave prominent harmonics. The chamber support is now being redesigned with alternate geometry and alternate mixture of materials (invar and stainless steel) to minimize this effect. These measurements were helpful as they pointed out and avoided a potential problem during commissioning.

MAGNET ALIGNMENT

For optimum performance, the magnetic axes of quadrupoles and sextupoles in NSLS-II should be aligned to better than ±30 microns. Optical survey accuracy (50-100 micron) is inadequate to achieve the required tolerance. It is difficult and expensive to maintain the required machining and assembly tolerances in a long support structure (~5 m long girder) holding several magnets.

An advanced system based on vibrating wire technique, originally developed at Cornell [9] has been built to achieve the required alignment tolerances using direct magnetic measurements in a string of magnets. In such a system, an AC current is passed through a wire stretched axially in a series of magnets. Transverse magnetic field causes vibrations, which are enhanced at resonance frequencies. The vibration amplitudes are studied as a function of wire offset to determine the transverse field profile, from which the magnetic axis can be derived.

The vibrating wire setup at BNL is shown in Fig. 14. It is described in more detail elsewhere [10]. An absolute accuracy in the center of quadrupole and sextupole magnets of better than 5 microns has now been demonstrated in this state-of-the-art vibrating wire system. This is sufficient to meet the NSLS-II specifications.

SUMMARY

This paper reported a number of significant developments in low field, iron dominated magnet technology. Introduction of nose piece in dipole magnets freed-up about 1.3% space in the machine, and from providing some additional benefits. Progress has been made in alignment technique based on vibrating wire that now provides an absolute accuracy of ~ 5 microns. NSLS-II storage ring has a tightly packed lattice. The possible influence of nearby magnets and other materials has been systematically studied. This knowledge should help in commissioning of NSLS-II.

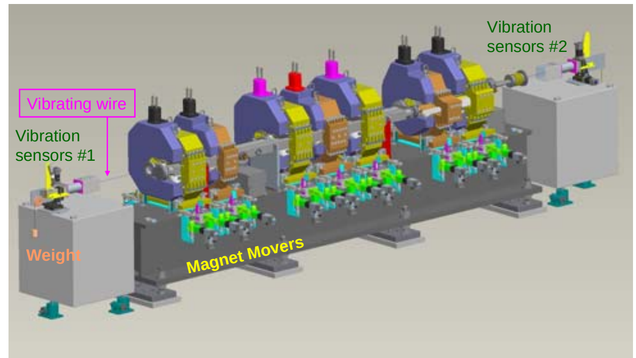

Figure 14: Vibrating wire system at BNL for measuring and adjusting centers of sextupoles and quadrupoles.

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