SPECIFICATIONS AND R&D PROGRAM ON MAGNET ALIGNMENT TOLERANCES FOR NSLS-II*

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Abstract

The NSLS-II light source is a proposed 3 GeV storage ring, with the potential for ultra-low emittance [1]. Despite the reduced emittance goal for the bare lattice, the closed orbit amplification factors are on average >55 in both planes, for random quadrupole alignment errors. The high chromaticity will also require strong sextupoles and the low 3 GeV energy will require large dynamic and momentum aperture to insure adequate lifetime. This will require tight alignment tolerances (~30μm) on the multipole magnets during installation. By specifying tight alignment tolerances of the magnets on the support girders, the random alignment tolerances of the girders in the tunnel can be significantly relaxed. Using beam based alignment to find the golden orbit through the quadrupole centers, the closed orbit offsets in the multipole magnets will then be reduced to essentially the alignment errors of the magnets, restoring much of the dynamic aperture and lifetime of the bare lattice. Our R&D program to achieve these tight alignment tolerances of the magnets on the girders using a vibrating wire technique[2], will be discussed and initial results presented.

INTRODUCTION

The NSLS-II light source, which has started construction in 2009, is a new 3rd generation light source that will replace the two operating 2nd generation light sources at BNL. It has been designed to provide major improvements in the existing beam properties from IR to hard Xrays, with leading edge electron beam properties:

- Ultra-small emittance ε_x <1.0 nm (achromatic),
- Diffraction limited vertical emittance at 12 KeV,
- Stored current ≥ 500mA ±1% with top-off injection,
- and > 24 straight sections with >5m, for IDs.

The storage ring is a 30 cell DBA lattice with super periodicity 15, of alternating long (9.3m) and short (6.6m) ID straight section. The ultra-low emittance is obtained not from breaking the achromatic condition for the lattice (as usually done), but by using a novel approach of increasing the synchrotron radiation damping using wigglers (and user IDs) in the achromatic straights to reduce the lattice emittance in steps, as these devices are added[3]. This means that bare lattice tuning can have relatively low emittance and lower chromaticity and nonlinear distortions. The low beam energy of 3 GeV makes the lower emittance easier to obtain, but makes the requirement of large dynamic aperture (DA) essential to maintain a reasonable lifetime and minimize the injection frequency for top-off injection. Table I summarizes the ring parameters and Fig. 1 shows the twiss parameters for the super period of the ring.

Table I: The NSLS-II Basic Ring Parameters

Energy	3 GeV
Circumference	791.96m
Harmonic Number	1320
Bending Radius	25.019 m
Dipole Energy Loss Uo	286.5 keV
Emittance Bare Lattice ε_o: Hor/Ver	2.05 / 0.01 nm-rad
Emittance for 8-DWs ε_{nat} Hor./Ver	0.51 /0.008 nm-rad
Momentum Compaction	0.000368
RMS Energy Spread: Bare Lattice / Energy Spread with 8-DWs	0.051% 0.099 %
Tunes (Q_x , Q_y)	(32.42,16.36)
Chromaticity (ξ_x , ξ_y)	(-103, -40)
Peak Dispersion	0.462 m
β Function at 9.3m ID (β_x, β_y)	20.4 / 3.3 m
β Function at 6.6m ID (β_x, β_y)	1.8 / 1.1 m

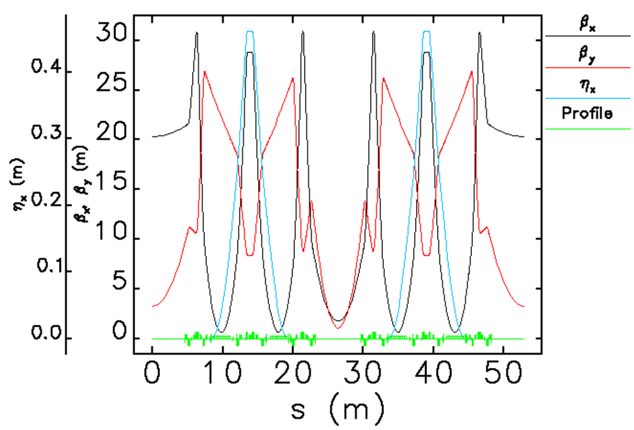

Figure 1: Twiss parameters for one superperiod of the NSLS-II lattice, with 9.3 m and 6.6m (center) ID lengths.

CLOSED ORBIT AMPLIFICATION FACTORS

When a quadrupole (strength K_1 and length l) is misaligned by an error δu_q in the storage ring, it drives a closed orbit error $u(s)$ (where u is x or y for the plane of the error) resulting from the closed orbit angular kick, $\theta=(K_1 l)\,\delta u_q$. For misaligned quadrupoles around the ring the closed orbit can be expressed as integral of all the normalized kick angles, $f(\varphi)=\beta^{3/2}\,\theta(\varphi)$, for the azimuthal angle $\varphi = {2\pi s}/{C}$, where C is the ring

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circumference. The closed orbit distortion (COD) at location ϕ is given by Ref. [4]

$$u(\phi) = \frac{\nu\sqrt{\beta}}{2\sin(\pi\nu)} \int_{\phi}^{\phi+2\pi} f(\varphi)\cos[\nu(\pi+\phi-\varphi)]\,d\varphi \quad (1)$$

where ν is the ring tune. The expectation value for the square of the closed orbit is

$$< u(\phi)^2 >= \left(\frac{\nu}{2\sin(\pi\nu)}\right)^2 \beta(\phi) \int_{\phi}^{\phi+2\pi}\int_{\phi}^{\phi+2\pi} < f(\psi) f(\varphi) > \cos[\nu(\psi-\varphi)]\,d\psi\, d\varphi \quad (2)$$

where $< f(\psi) f(\varphi) >$ is the correlation between the quadrupole kick errors distributed around the ring. For random (uncorrelated alignment) errors, the correlation term in Eq. (2) is zero except for the same quadrupole, Eq. (2) then becomes a sum over k quadrupoles in the ring

$$< u(\phi)^2 >= \frac{\beta(\phi)}{4\sin^2(\pi\nu)} \sum_k \beta_k \theta_k^2 \quad (3)$$

The Quadrupole Closed Orbit Amplification Factor (QCOAF) is then the square root of Eq. (3) per unit of quadrupole misalignment error, δu_q, which drives the errors (assuming all quads have the same error). This is shown in Fig. 2, for the NSLS-II lattice for one cell (half period). The average values are shown as dotted lines with <X>=Xa=55 and <Y>=Ya=58, this means that state of the art alignment errors of $\pm$0.1mm will drive CODs of 2.5 to 8.5 mm in the lattice. These distortions in the sextupoles drive phase and beta function distortion that will reduce the already limited dynamic aperture (DA) of this highly nonlinear lattice.

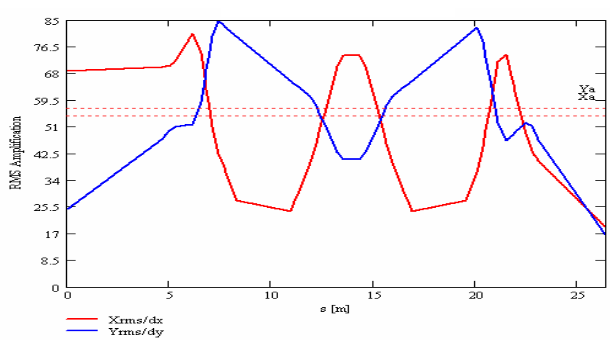

Figure 2: QCOAF for random quadrupole misalignments errors for one DBA cell.

In NSLS-II the plan is to align the quadrupoles on girders with better resolution than they can be aligned in the tunnel directly. This will correlate the positions of the 3 or 4 quads on a girder and the orbit distortion will be partly cancelled by the horizontal and vertically focusing quadrupoles producing opposite kicks for the same displacement. The expected value for the COD could be solved using Eq.(2) but is easier solved by numerically computing the rms closed orbit distortion averaged over a large number of random lattice layouts of the girders using lattice codes that allow girder definitions[5,6]. The resulting rms COD per unit of random alignment error of the both ends of the girders, is defined as the Girder Closed Orbit Amplification Factors (GCOAF) and are shown in Fig. 3 for the NSLS-II lattice.

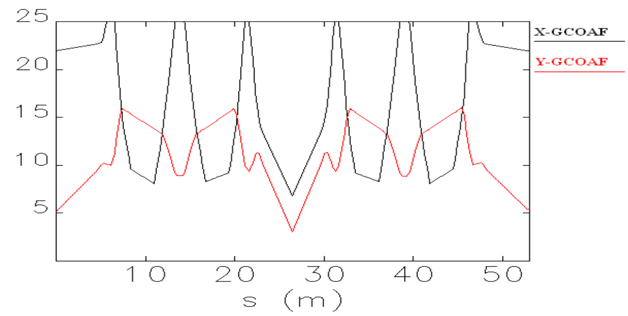

Figure 3: GCOAF for the NSLS-II lattice computed by Elegant [5] for 1000 sets of random lattice errors.

The average values are 17 and 12 or a factor of 3.2 and 5 reduction compared to the QCOAF's, for horizontal and vertical planes, respectively. The NSLS-II procedure of tighter tolerances of quadrupoles on the girders will have a reduced impact on the COD and the DA.

MULTIPOLE ALIGNMENT TOLERANCES

An estimate of the alignment tolerances for the sextupoles can be made by calculating the reduction of the DA versus random strength error of the lattice quadrupoles ($\delta K_1/K_1$). This was estimated to be ~5x10^{-4} for an 80% reduction of the DA [1]. Since a closed orbit error in the sextupoles contributes a focusing error to the lattice of $\delta(K_1\ l) = (K_2\ l) * (\delta x$ or $\delta y)$, then using the QCOAF to relate the quadrupole alignment error to the closed orbit error this impact would require the alignment of quadrupoles to δu_q < 5μm. This overestimates the impact since the COD will have a strong correlation around the tune spatial frequency, but it shows that alignment tolerances are of critical concern.

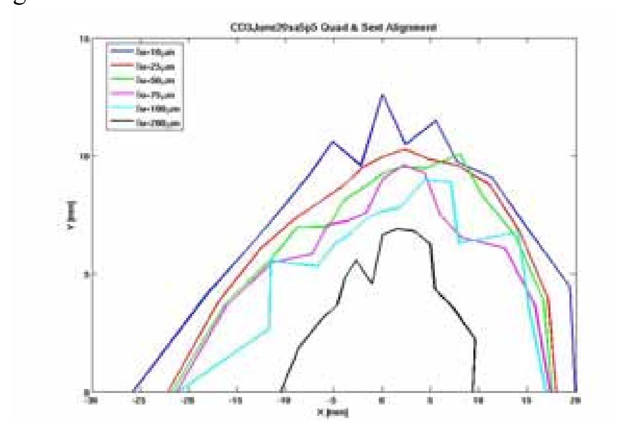

Figure 4: Changes in the lattice DA vs multipole alignment tolerances, with COD correction.

A better estimate of the tolerances is obtained by randomly distributed misalignment of the quadrupoles and sextupoles by the same rms error, correcting the COD to the BPM's and calculating the reduction of the DA as the rms error is increased. We have limited the reduction of DA to ~80% of the bare lattice DA as the tolerance. Figure 4 shows that the tolerance of <30 μm is needed to meet this goal. This is tighter than what can be reasonably achieved with laser tracker alignment in a large tunnel.

To ensure that the alignment requirements are met, NSLS-II has taken the approach that several multipole magnets will be aligned to a straight line on a girder in a highly controlled environment. Then making use of the lower GCOAF, the girders are aligned to more easily achievable tolerances in the tunnel. These tolerances are listed in Table II below for all magnets, girders and BPMs (assuming a beam based alignment BBA errors). The impact on the DA is shown in Fig. 5, for the specified alignment tolerances. The real challenge is to meet these tight tolerances for the large number of magnets and girders that need to be produced.

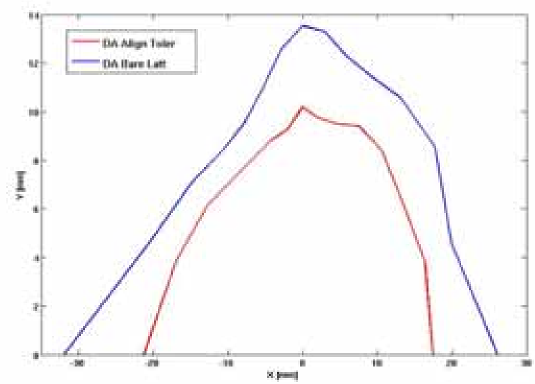

Figure 5: The lattice DA for alignment tolerances listed in Table II, with COD correction.

Table II: Alignment Tolerances for NSLS-II

Element	δx, δy [mm]	Roll angle [mrad]
Quadrupoles	0.03, 0.03	0.2
Sextupoles	0.03, 0.03	0.2
Dipoles	0.1, 0.1	0.5
Multipole Girder	0.1, 0.1	0.5
BPM BBA error	0.01, 0.01	0.1

ENGINEERING SOLUTION

The solution adopted to meet the tight alignment tolerances is to build on the idea of the vibrating wire technique developed and used at other labs [7, 8], which has demonstrated the potential to measure the magnetic center to the required resolution. In this technique, the vibrations in a wire stretched in the magnet aperture and carrying an AC current at a resonant frequency of the wire are analyzed to measure the field seen by the wire. By scanning the wire in the magnet aperture, the field profile can be obtained, and the magnetic center can be determined. A prototype system has been setup to measure the resolution of this technique for quadrupoles and sextupole magnets. Figure 6 shows the measured profile in a sextupole magnet using two sets of vibration sensors. The magnetic center, defined as the point of zero slope in this case, is measured by two independent sensors that agree within ~1µm. The absolute accuracy of magnetic center is estimated to be within ~5 µm.

Finding the center of a magnet is only part of the problem. Multiple quadrupoles and sextupoles must be positioned and maintained to the line in space defined by the wire, over girders of up to 5 m in length. A detailed engineering solution has been worked out (see Ref. [2] for details): where magnets are rough aligned to the girder, allowed to come to thermal equilibrium ($\pm$ 0.1° C) in an environmentally controlled room, the centers are measured with the vibrating wire, magnets are moved to position their centers to the line (sag compensated) defined by the wire, and the magnets are locked into the desired position to better than $\pm$5µm repeatability. The prototype system has performed to better than the required tolerance. Although the goals of alignment of magnets on the girder has been demonstrated for a couple of magnets on one girder, a work plan has been provided for achieving this resolution for a large number of magnets and girders.

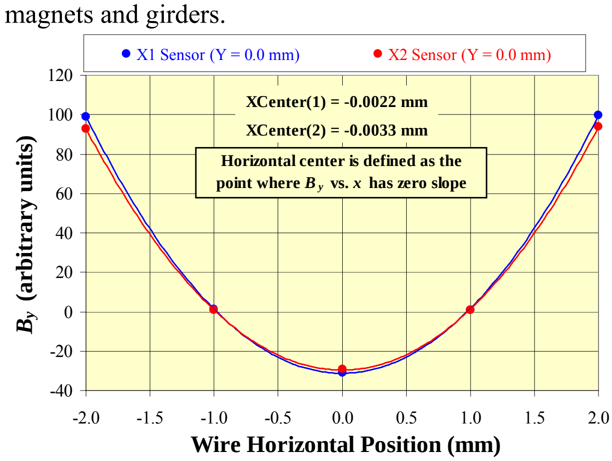

Figure 6: Vibrating wire scan in horizontal plane of a sextupole showing a parabolic field profile.

CONCLUSIONS

The push to ultra-low emittance for NSLS-II will require extreme care in all aspects of design and construction. The critical issue of multipole alignment will be solved by accurately centering the magnets on rigid girders and aligning the girders as a unit to the reference orbit in the tunnel, with easily achievable tolerances. The R&D program has demonstrated this is achievable in single units and a plan has been worked out to achieve these tolerances for a large number of magnets and girders.

REFERENCES

[1] Work presented on behalf of the NSLS-II Design Team, CDR(2006), CD2(2007) and CD3(2008).
[2] A. Jain et al, International Workshop on Accelerator Alignment, Tsukuba, Japan, Feb.11-15, (2008).
[3] S. Ozaki, et al., Proceedings PAC07, p. (2007).
[4] E. Keil, CERN 77-13, p. 52 (1977).
[5] BETA code, J. Payette, CEA-LNS, jpayet@cea.fr
[6] Elegant code, M. Borland, ANL, borland@aps.anl.gov
[7] A. Temnykh, NIM A399, p. 185 (1997).
[8] Z. Wolf, SLAC Note LCLS-TN-05-11, (2005).