

## FLEXIBILITY IN THE DESIGN OF THE NSLS-II LATTICE\*

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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]. The lattice design uses a 30 cell DBA structure with a periodicity of 15, with alternating long and short straight sections. All cells are tuned achromatic to maximize the emittance reduction achieved as damping wigglers are added to the ring. Recent optimization of the lattice consisted of increasing the number of possible hard X-ray beam ports using three pole wigglers, reducing the number of magnets (quadrupoles and sextupoles) and shifting the magnets to allow easier extraction of the photon beams. The impact of the reduction of magnets on the lattice flexibility will be presented in terms of the tuning range possible for the lattice parameters: tune, emittance, chromaticity, and beta function matching to user insertion devices (IDs). This flexibility is important for optimizing the lattice linear and nonlinear properties, the dynamic aperture, and its impact on beam lifetime, as well as matching the user source requirements and for value engineering of magnets and power supplies.

### INTRODUCTION

The NSLS-II light source, which has started construction in FY2009, is a new 3<sup>rd</sup> generation light source that will replace the two operating 2<sup>nd</sup> generation light sources at BNL. It has been designed to provide major improvements in the existing beam properties from IR to hard X-rays, with leading edge electron beam properties of:

- Ultra-small emittance  $\epsilon_x < 1.0\text{nm}$  (achromatic),
- Diffraction limited vertical emittance at 12 keV,
- Stored current  $\geq 500\text{mA} \pm 1\%$  with top-off injection,
- and  $> 24$  straight sections (SS) with  $> 5\text{m}$ , for IDs.

The storage ring is a 30 cell DBA lattice with a super periodicity (SP) of 15, with alternating long (9.3m, LSS) and short (6.6m, SSS) straight sections. The ultra-low emittance is obtained not from breaking the achromatic condition for the lattice (as in most existing rings), but by using a novel approach of increasing the synchrotron radiation damping using damping wigglers, DW, (3-8 7m 1.8T wigglers and user insertion devices) in the achromatic straights to reduce the lattice emittance in steps, as these devices are added[2]. This means that basic lattice need have only relatively low emittance and therefore lower natural chromaticity. This will result in greater dynamic aperture (DA) when the chromaticity is reduced with sextupoles. The low beam energy of 3 GeV

requires large DA and momentum aperture to maintain a reasonable lifetime and minimize the injection frequency for the top-off injection process. To maximize the emittance reduction obtained from the DW's, low field dipoles are used [1]. This gives a low critical energy of the emitted Xrays from the dipoles, which is ideal for the IR and VUV users, since the power on their optics is lower. However, this required the introduction of three pole wigglers (TPW) to be added to the dispersion region ahead of the second dipole, in order to provide more hard X-ray beam ports. This space was provided by eliminating one family of chromatic sextupoles, since the remaining pair provided adequate control of 1<sup>st</sup> and 2<sup>nd</sup> order chromaticity,  $\xi$  and  $\xi'$ . Table I presents a summary of the parameters for the basic NSLS-II lattice.

Table I: The NSLS-II basic ring parameters

Energy	3 GeV
Circumference	791.96 m
Harmonic Number	1320
Bending Radius	25.019 m
Dipole Energy Loss $U_0$	286.5 keV
Emittance Bare Lattice $\epsilon_0$ : Hor/Ver	2.05 / 0.01 nm-rad
Emittance for 8-DWs $\epsilon_{nat}$ 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 ( $Q_x, Q_y$ )	(33.42, 16.36)
Chromaticity ( $\xi_x, \xi_y$ )	(-103, -40)
Peak Dispersion	0.462 m
$\beta$ Function at 9.3m ID ( $\beta_x, \beta_y$ )	20.4 / 3.3 m
$\beta$ Function at 6.6m ID ( $\beta_x, \beta_y$ )	1.8 / 1.1 m

### BASIC LATTICE REQUIREMENTS

The basic lattice must achieve low emittance with an achromatic tune and small chromaticity. This basic lattice cell with super periodicity of 15 is shown in Fig. 1.

In the LSS it must provide a range of beta function for: injection, DW, RF and other user long, large gap IDs and low but variable beta functions in the SSSs. For an achromatic lattice with a fixed (bare lattice) emittance, the average of normalized dispersion,  $H$ , is fixed therefore fixing the ratio of  $(\eta^2/\beta)$  in the center of the dispersion region. Since there are only a pair of quadrupole families in the dispersion region, the peak  $\eta_x$  and  $\beta_x$  are constrained by the emittance.

The basic cell was optimized to provide a bare emittance  $< 2.1\text{nm}$ , low  $\beta_{x,y} \sim 1-2\text{m}$  in the 6.6m SSS for in

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vacuum undulators (IVU) and a  $\beta_y \sim 3\text{m}$  in the LSS to minimize the tune shift from installed DW's, but only slightly below the maximum vertical acceptance for a 7m long DW. The dispersion was tuned to minimize the peak dispersion (in order to reduce the 2<sup>nd</sup> order dispersion in the SSS) while providing adequate beta function separation in the chromatic sextupoles for correction of  $\xi_{x,y}$ . The strength of the central horizontally focusing quadrupole in the SSS was reduced below the maximum strength by removing one of the geometric sextupoles in the SSS and moving the QD quad closer to the dipole and increasing its separation from the central QF quad.

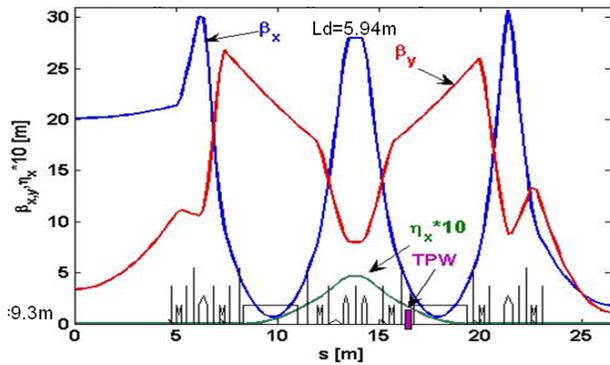


Figure 1: Twiss parameters for one cell of the NSLS-II lattice, with ID's of length 9.3 m(left) and 6.6 m(right).

In order to explore a range of working points (for DA optimization)[3], while maintaining the above parameters within a close range, a script was developed using Elegant to scan the horizontal and vertical tunes over a grid of tunes around the above value by  $\pm 1$  unit in  $Q_x$  and  $Q_y$ . Figure 2 shows the beta function variations for this scan of tunes.

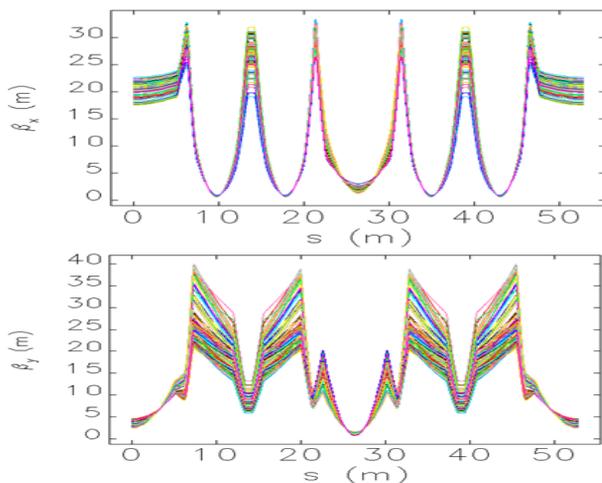


Figure 2: Variation  $\beta_x$  (top) and  $\beta_y$  (bottom) functions in a super period as the total ring tune is varied  $\pm 1$  unit, while maintaining the low emittance ( $\sim 2\text{nm}$ ) and natural chromaticity for the lattice.

Once the tune has been selected for DA optimization and the beta functions in the basic cell selected the emittance and chromaticity will be determined from these fits. The variations shown above assumed all 15 super

periods are tuned the same, but some user applications will desire changes in the beam size in separate straight sections.

All quadrupoles will be powered by individual power supplies, allowing considerable variation in the beta function optimization in the different SS's. However, tuning individual straight sections to different beta functions will have to be done without making major changes in the tuning of other ID's nor the dispersion region (emittance). Figure 3 shows the range of  $\beta_x$  tuning available to the user without impacting the emittance or other ID beta functions. Since there are only three quadrupoles families in the SS's, as the  $\beta_x$  is reduced,  $\beta_y$  will increase by a factor of 4.6. The ratio of the vertical to horizontal beam size can be changed by a factor of 3.0 under these constraints and within the available range of the quadrupole power supplies. Further changes in this ratio will require that beta functions in the adjacent SS's to be changed to match this modification which will obviously require user agreement. The tune shift introduced by including one or two SSS with these low  $\beta_x$  in the ring can easily be accommodated by small changes in the phase advance in all the other SSS of the ring.

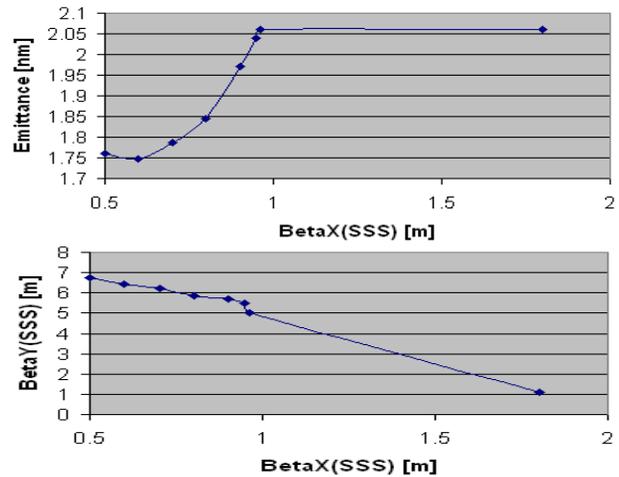


Figure 3: Changes in  $\beta_x$  (top) in the SSS, with its impact on the emittance (SP=15 lattice) and the resulting change in  $\beta_y$  (bottom) in the SSS.

Similarly the  $\beta_y$  can be reduced from 1.1 to 0.6 (within the power supply range) for the inner vertically focusing quadrupole, but this will increase the  $\beta_x$  in this ID. This change is less useful since the beta function will increase more rapidly, limiting it to short undulators or large gaps.

In the LSS,  $\beta_x$  can be lowered a factor of 10X from 20 to 2m, with  $\beta_y$  changing only 3%. The range of  $\beta_y$  tuning is only a factor of 3X from 3.3 to 1.0, while  $\beta_x$  varies a factor of 5X. All of these are possible within the specified power supply range and without impacting the emittance or adjacent SS's. However, some slight adjustment of the beta functions in the other SS's will be required to compensate the tune shift of this change, but it will be distributed equally among the other SSS's.

## DW AND TPW LATTICE CORRECTION

The DW used in NSLS-II will have a period length of 90mm and peak field of 1.8T. They will have a basic length of 3.5m, with up to two installed in one LSS. For  $\beta_y \sim 3.3\text{m}$ , one DW will introduce a vertical tune increase of  $\sim 0.03$  and will change the beta functions at the sextupoles, impacting the dynamic aperture. Initially correction for linear lattice shifts of the DW's was done using a global quadrupole method, but this has been shown to drive quadrupole resonances and limits the DA. More recently the correction for the linear impact of the DW's using local quadrupole families has been implemented, which maintains larger DA. This method is discussed in reference [4].

The low value of dipole field ( $\sim 0.4\text{T}$ ) yields a low critical energy  $\sim 2.4\text{ KeV}$  for the users. To increase the number of hard X-ray beam ports, up to 30 three pole wigglers (TPW) can be installed ahead of the 2<sup>nd</sup> dipole in the DBA lattice, see Figure 1. These will have a peak field of 1.1T over a central pole with 2mrad of bend and weaker outer poles (to reduce the emittance increase). The tune shift is very small ( $\sim 0.0002$ ) per TPW but it does change the achromatic condition. This is easily adjusted using the adjacent pair of the four chromatic quadrupoles in the dispersion region, made possible since they are individually powered. There is a small increase in the emittance of  $\sim 0.6\%$  per TPW, since they are installed in the dispersion region of the lattice. This can be compensated by adding a small horizontally focusing gradient in the TPW that increases the  $J_x$  at about the same rate as the quantum diffusion increases per TPW [5].

## CANTING OF THE DW'S

The high power radiated by the DW's make it possible to split them into two half length DW's with an angular separation ( $\sim 3.5\text{mrad}$ ) between them. This will allow two beam lines to share a common straight section, but will require some care in order to minimize the increase in emittance resulting from the dispersion in the DWs introduced by the separator bend magnets. This is planned to be handled by using back leg windings on the dipoles to reduce the bend angle by half the canting angle (before and after the DW straight section) and adding a full canting angle dipole between the two half DW's. By retuning the ID quadrupoles the dispersion can be minimized in the DW's causing less diffusion and therefore less emittance increase than if a normal three bump canting was used. For the assumed 3.5mrad canting angle, the emittance increase is only 11% compared to the non-canted emittance for 5-7m DW's.

## NONLINEAR LATTICE REQUIREMENTS

The dynamic and momentum aperture are critically important to maximize the Touschek lifetime. The low emittance of this lattice, produces a large natural chromaticity, which must be compensated by the

chromatic sextupoles. By appropriately placing these sextupoles in the dispersion region the three sextupoles with individual power supplies will provide linear chromaticity tuning, while minimizing the second order chromaticity. The chromaticity dependence for the ring tuned to linear  $(\xi_x, \xi_y) = (2.7, 0.1)$  is shown Fig. 5, using the displaced 3<sup>rd</sup> chromatic sextupole to reduce 2<sup>nd</sup> order chromaticity and tune shift with amplitude.

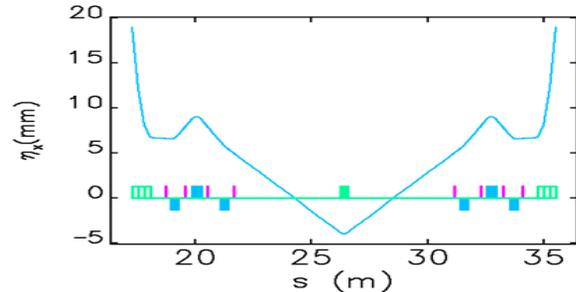


Figure 4: Dispersion in the long ID for a 3.5mrad cant angle for two DW, for reduced emittance increase.

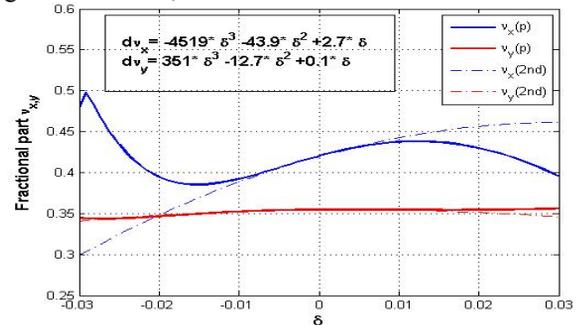


Figure 5: The tune shift with momentum for the lattice optimized for reduced 2<sup>nd</sup> order chromaticity.

## CONCLUSIONS

The NSLS-II lattice has been optimized to provide a wide range of tuning of the beta functions in the normal cells, as well as providing a flexible tuning range in individual cells. The individual powering of the quadrupoles has made this possible and will be used to optimize the beam performance for individual undulators and wigglers.

## REFERENCES

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