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NSLS-II Design: A Novel Approach to Light Source Design

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NSLS-II DESIGN: A NOVEL APPROACH TO LIGHT SOURCE DESIGN *

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Abstract

The NSLS-II storage ring will be a replacement for the existing two NSLS light sources, which although innovative when proposed, have been exceeded by modern light source designs. NSLS-II design takes a new approach toward providing users with the very bright beams after commissioning and a strategy of evolving to higher brightness beams as more ID devices are installed during its operations. This is achieved not by pushing the basic lattice to lower emittance, an approach that hits severe limits in the control of the dynamic aperture of an ever increasing non-linear lattice. Our approach is rather to reduce the natural emittance using damping wigglers, in addition to damping from the user undulator's. Details on the lattice design are presented.

INTRODUCTION

NSLS-II is the proposed replacement of the NSLS light sources that have been operating for more that 23 years. The storage ring requirements of the lattice are:

Ultra-low horizontal emittance ε_x <1.0nm (achromatic),
Diffraction limited vertical emittance at 12KeV,
$I_o \geq$ 500mA, Top-off injection, and
More than 24 ID straight section $\geq$5m, for IDs,

After several years of study a DBA lattice with 30 cells has been selected. This lattice while not reaching the emittance goal by itself has been designed to achieve this goal using damping wigglers (DWs) rather than the lattice functions. This avoids the difficulty in dealing with high chromaticity and low dynamic aperture (DA) that limits ultra-low emittance lattice designs. The DA impact of the DWs and undulators must be handled for any lattice and have less impact on the DA than the strong sextupole of alternate lattice designs. Also the number of cells provides for sufficient beam ports for our current VUV and Xray ring users, when those ring are decommissioned.

LINEAR LATTICE CHOICE

The basic light source lattices that can be used are: double bend (DBA) and triple bend (TBA) achromatic lattices. For *M* cells the theoretical minimum emittance is given by [2]:

$$\varepsilon_{MEDBA} = \frac{\gamma^2}{M^3}(0.77\ pm-radians) \qquad (1)$$

$$\varepsilon_{METBA} = \frac{\gamma^2}{M^3}(0.151\ pm-radians) \qquad (2)$$

where γ is the relativistic energy and the horizontal partition factor J_x is assumed unity. For low emittance, the lowest possible energy is preferred, this is possible due to the advances with in-vacuum, small gap and short-period undulators pioneered at the NSLS [3]. The Xray energy range of 2-20 keV can now be achieved with ~3 GeV beam energy, lowering the RF power and shielding cost for either ring.

A 24-cell TBA, with a potentially factor of five lower emittance per cell, was initially preferred. Due to difficulties in achieving large DA, the emittance goal had to be relaxed [4]. At that time a bold suggestion was made by S. Krinsky [1], to provide the initial emittance with a DBA lattice and use the extra straight sections for DWs to lower the emittance. Although this was a novel approach for new 3rd generation light sources, this idea has been used in colliders [5,6] and previously proposed for light sources [7,8]. This is the approach taken for NSLS-II, using a 30 cell DBA lattice with alternating long and short ID straight sections, one cell is shown in Figure (1).

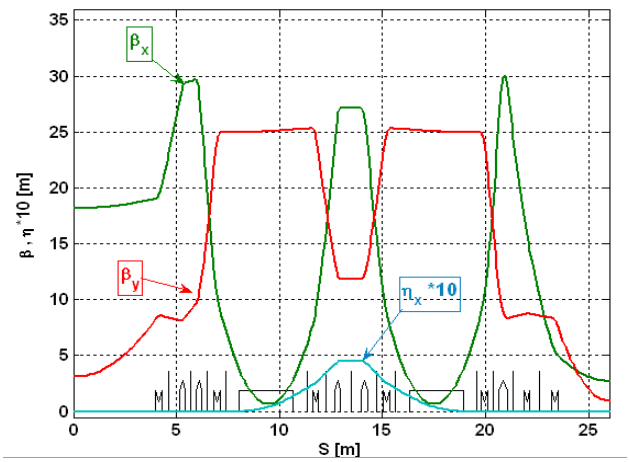

Figure (1) Twiss parameters for one cell of the DBA(15x2) lattice, with 8 and 5m ID lengths.

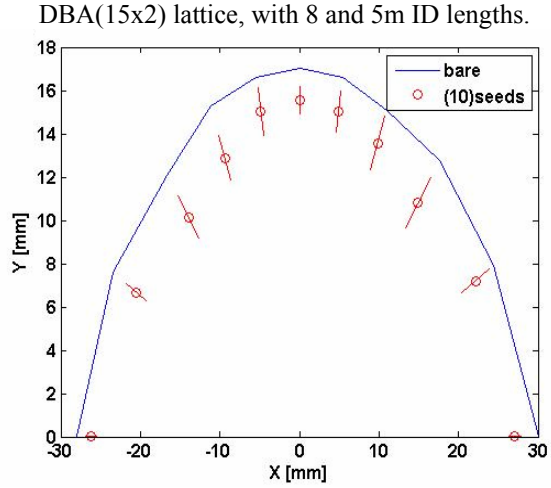

Figure (2) DA for the lattice with alignment tolerances (no field errors) and synchrotron oscillations (δ=0). Orbit distortions are corrected with beam based aligned BPMs.

This lattice was optimized for efficient use of the DWs for reducing the emittance, using weak dipole magnets

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with a bend radius of ρ_o = 25m. A quartet of quadrupoles is used in both the long and short ID straight sections to cancel the phase and beta function modulations from undulators and wigglers. Eleven families of sextupoles are powered to provide a large DA in the presence of realistic engineering and alignment errors. Figure (2) shows the DA for the bare lattice, as well as for the lattice (10 seeds) with alignment tolerances listed in Table I, with the resulting orbit distortions corrected using beam based aligned beam position monitors (BPMs).

Table I Lattice design parameters for NSLS-II

Energy [GeV]	3
Circumference [m]	780
Bending Radius [m] Dipole Energy Loss U_o [keV]	25.019 286.5
Bare Horizontal Emittance, ε_o /Vertical [nm]	2.05 / 0.01
Hor. Emittance w. 8-DWs, ε_{nat} /Vertical [nm]	0.51 / 0.008
Momentum Compaction	0.000368
Bare RMS Energy Spread / with 8- 7m DWs [%]	0.051 / 0.099
Tunes (Q_x , Q_y)	(32.35,16.28)
Chromaticity (ξ_x , ξ_y)	(-100, -41.8)
Peak Dispersion [m]	0.45
Long 8m ID (β_x, β_y) [m]	18/3.1
Short 5m ID (β_x, β_y) [m]	2.7/0.95
Alignment Tolerance Girder & Dipole (x, y, Φ) [mm, mrad]	(0.1, 0.1, 0.5)
Alignment Tolerance. Quad. & Sext.. (x, y, Φ)) [mm, mrad]	(0.03, 0.03, 0.2)

DW'S FOR EMITTANCE REDUCTION

The impact of damping wigglers added into an achromatic straight section is basically to enhance the damping of the lattice without significantly increasing the quantum excitation. The equilibrium values for the energy spread and the emittance depend not only on the wiggler peak field B_w,(bend radius ρ_w) and length L_w, but also on ρ_o , i.e. the dipole energy loss U_o= 7.17[MeV]/ρ_o[m]. The fractional change of the horizontal emittance ε_{nat} relative to the bare lattice emittance ε_o is given by

$$\frac{\varepsilon_{nat}}{\varepsilon_o} = \frac{1+f}{1+\frac{L_W}{4\pi\rho_o}\left(\frac{\rho_o}{\rho_W}\right)^2} \approx \frac{U_o}{U_o+U_W} \qquad (3)$$

where f in most cases is a small correction factor [1],
U_w is the energy radiated by the wigglers and
$U_w+U_o= U_T$ is the total radiated energy.

Thus the emittance can be reduced by increasing U_w or reducing U_o. Since RF power will limit U_T, the emittance reduction can be enhanced by reducing U_o. For undulator beam-lines, the brightness of the higher order harmonics will be reduced if the beam energy spread increases beyond 0.1%, further limiting the total emittance reduction. The fractional change of the beam energy spread, δ_W, relative to the bare lattice value δ_o, is given by

$$\frac{\delta_W}{\delta_o} = \sqrt{\left[U_o + \frac{8U_W}{3\pi}\left(\frac{\rho_o}{\rho_W}\right)\right]\left[U_T\right]^{-1}} \qquad (4)$$

For $\rho_w < \rho_o$, δ_W will increase with U_w. Increasing ρ_o will have the added benefit of reducing δ_o, allowing lower values of ε_{nat} to be reached before the δ_W <0.1% limit. Figure (3) shows the dependence of these two parameters on the wiggler radiated power, for two values of ρ_o: 25 and 16.68m (1 and 1.5X NSLS-II dipole field). This clearly shows the advantage of the lower dipole field and shows a natural progression of the lattice to lower emittance as DWs or IDs increase U_w for the ring. Clearly a factor of 3-5 reduction is possible within the limitations listed above. A similar reduction is not easily achieved if one has to change the lattice functions, since the DA for strong sextupoles must to be solved.

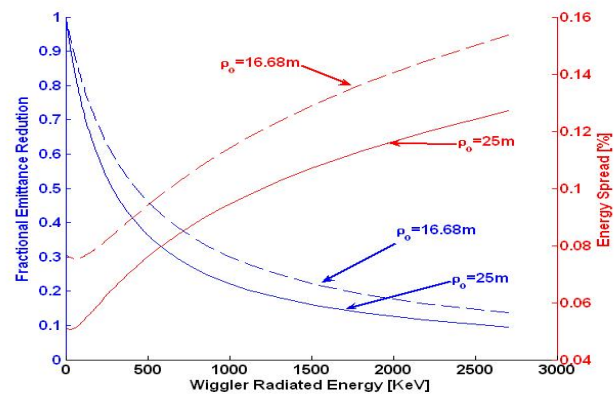

Figure (3) Change in ε_{nat} and δ_W with wiggler radiated energy for B_w = 1.8T and two values of dipole radius ρ_o.

The actual emittance will be limited by the bunch current dependent intra-beam scattering (IBS), a disadvantage of low beam energy. Increasing ρ_o or U_w beyond some point will become ineffective in further reducing the total emittance, $\varepsilon_{x,tot}$, as ε_{nat} approaches the IBS emittance value, ε_{IBS}. The value for $\varepsilon_{x,tot}$ is the emittance resulting from the equilibrium of the radiation damping rate and the quantum plus IBS diffusion rates given by

$$\varepsilon_{x,tot} = \tau_x < H \cdot D_{\delta,SR} > + \tau_x < H \cdot D_{\delta,IBS} > \qquad (5)$$

where τ_x is the horizontal synchrotron damping time,
H is the invariant dispersion amplitude and
$D_{\delta,SR}$ and $D_{\delta,IBS}$ are the radiation and IBS energy diffusion coefficients.

The first term in Eq. (5) is just ε_{nat} , from Eq.(3). The IBS energy diffusion term has been shown [9,10] to be inversely proportional to the equilibrium emittance, $\varepsilon_{x,tot}$ and proportional to a scattering integral of the small angle Möller scatter rate within the energy acceptance (at the scatter point). Factoring out $\varepsilon_{x,tot}$ from the 2nd term in Eq. (5) this term becomes $\varepsilon_{IBS}^2 / \varepsilon_{x,tot}$, where ε_{IBS} is the emittance when the damping reduces the ε_{nat} to zero. Eq. (5) can then be solved for the scaled total emittance

$$\frac{\varepsilon_{x,tot}}{\varepsilon_{IBS}} = \left[\frac{\varepsilon_{nat}}{2\,\varepsilon_{IBS}} + \sqrt{\left(\frac{\varepsilon_{nat}}{2\,\varepsilon_{IBS}}\right)^2 + 1} \right] \qquad (6)$$

Reference [9] shows that ε_{IBS} can be estimated using the weak dependence of the diffusion term $D_{\delta,IBS}$, on the energy acceptance and the vertical beam emittance. The diffusion coefficient times H can be averaged over the NSLS-II lattice functions for an assumed maximum beam current of 500mA in 1000 bunches. This yields ε_{IBS} in the range of 0.2 to 0.25nm, which we take as a constant at the maximum value. Figure (4) shows the dependence of $\varepsilon_{x,tot}$ on ε_{nat} as expressed by Eq.(6). For fixed U_T, as the dipole field is reduced, U_o is reduced as does $\varepsilon_{nat}/\varepsilon_o$, Eq.(3). Figure (4) shows that as $\varepsilon_{nat} \rightarrow 0$, the fractional reduction of $\varepsilon_{x,tot}$ becomes less effective. The optimum value appears to be

$$\varepsilon_{nat} \approx (2\ to\ 3)\varepsilon_{IBS} \;\Rightarrow\; (U_o/U_T) \approx (2\ to\ 3)(\varepsilon_{IBS}/\varepsilon_o)$$

which for U_T= 1MeV and ε_{IBS} = 0.25nm yield the range ρ_o ~ (20-30)m, 25m was chosen for NSLS-II.

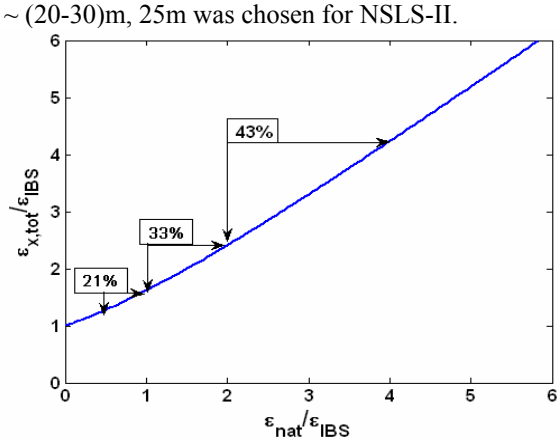

Figure (4) Total emittance reduction with IBS growth for 500mA ring current.

Table II Expected beam properties as the DWs are added

#-DW	ε_{nat} [nm]	$\varepsilon_{x,tot}$ [nm]	U_T [keV]	δ_W [%]	$\Delta\nu_y$
3	0.91	0.98	673.8	0.072	0.119
5	0.63	0.72	932.5	0.09	0.199
8	0.5	0.61	1320	0.1	0.318

The initial design for NSLS-II includes 3- 7m long DWs with B_W = 1.8T and λ_W =100mm. The beam parameters for this and future increases in number of DWs is shown in Table II. These simplified estimates are supported by calculations using computer codes that don't assume ε_{IBS} is constant [11]. Reducing the ρ_o further would make several properties of this lattice less desirable. The critical energy of the Xrays for ρ_o =25m is 2.4 keV, while not adequate for hard Xray beams, these will yield bright sources for our soft Xray and VUV users from NSLS. The DWs will provide high flux and brightness hard Xray beams, far exceeding beams from higher field dipoles. Another disadvantage is the reduced damping rate which could increase the impact of high current instabilities. This rate will increase as DWs are installed, helping to stabilize high current operations. Finally the increased cost for a slightly larger circumference (low uncertainty) needs to be balanced by the greater risk of achieving this performance with lattice changes that drive highly nonlinear lattices and small DA.

LATTICE EFFECTS OF DW

The impact of installing the DWs in the lattice will be similar to those of the user ID devices for which the ring is being designed. These include 1st and 2nd order tune shifts and the vertical betatron function modulation. The linear tune shift is large for this energy and long DW and is approximated by

$$\Delta\upsilon_y \approx <\beta_y> L_w/[4\pi\,\rho_w^2] \approx 0.038$$

While significant it can be locally corrected using a pair of quadrupoles. The beta function modulation is $\leq$ 8%[12] but this can also be locally corrected with another pair of quadrupoles. For this reason we have used four quads in the ID straight section to minimize these linear distortions and maintain the careful sextupole cancellation of higher order driving terms that yield the large and robust DA.

The nonlinear impact of the DWs can be estimated from

$$d\nu_y/d\,J_y \approx \pi <\beta_y^2> L_w/[2\,\lambda_w\,\rho_w]^2 \quad .$$

While significant, this term is only ~30% of the tune shift expected for the λ_w =19 mm undulators, that are planned for the NSLS-II beams. It has been show that by correcting for the linear tune and beta modulation with the four ID quads, this restores much of the DA of the lattice, including the effects of engineering tolerances [13].

There was concern that this large reduction of emittance would cause low Touschek lifetime, requiring too frequent injections to meet the ΔI/I goal. This proved not to be the case, since the scattering rate remains almost constant or slightly reduced, as was pointed out in Ref.[9].

CONCLUSIONS

The lattice design for NSLS-II has taken a novel approach toward achieving the ultra-low emittance goals with a natural progression to these values as DWs and IDs are added to the ring. This approach has been shown to be a less risky approach to the DA problem of these ultra-low emittance lattices and should keep NSLS-II at the fore of the emittance frontier for some time to come.

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