BNL-79159-2007-CP

Philosophy for NSLS-II Design with Sub-Nanometer Horizontal Emittance

S. Ozaki, J. Bengtsson, S. L. Kramer, S. Krinsky, V.N. Litvinenko

Presented at the 22nd Particle Accelerator Conference
Alburquerque, New Mexico
June 25-29, 2007

June 2007

National Synchrotron Light Source-II

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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Philosophy for NSLS-II Design with Sub-Nanometer Horizontal Emittance*

S. Ozaki[#], J. Bengtsson, S. L. Kramer, S. Krinsky, V. N. Litvinenko
BNL, Upton, Long Island, NY 11973 USA

Abstract
NSLS-II at Brookhaven National Laboratory is a new third-generation storage ring light source, whose construction is on the verge of being approved by DOE. When completed, NSLS-II with its ability to provide users with a wide range of spectrum, ranging from IR to ultra-high brightness hard x-ray beams will replace the existing two (20+ years old) NSLS light sources. While presenting an overview of the NSLS-II accelerator system, this paper focuses on the strategy and development of a novel <1 nm emittance light source.

INTRODUCTION

The basic mission requirements of the NSLS-II facility are the achievement of x-ray source providing 1 nm spatial resolution and 0.1 meV energy resolution with single atom sensitivity. A major part of this requirement for the resolution must be fulfilled from the beamline optics design but the storage ring must provide ultra-high brightness and stable synchrotron radiation. Translated into the storage ring design, the requirements for the accelerator complex are:

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

An extensive optimization of the performance and cost led to an adoption of a double-bend-achromatic (DBA) lattice with 30 cells as the basic configuration of the storage ring. This lattice achieves the emittance goal by using Damping Wigglers (DWs) and avoiding the difficulty of high chromaticity and low dynamic aperture (DA) which limit other low emittance lattice designs. The basic parameters of the storage ring are shown in Table 1 and include the following key aspects:

- the choice of DBA relative to TBA to increase the number of achromatic straights to install damping wigglers,
- the selection of soft-bend dipoles to enhance the effectiveness of damping wigglers,
- the introduction of Three-Pole-Wigglers to provide a number of high quality hard x-ray beams, and
- the introduction of wide-gap dipoles to provide large aperture beam ports for IR beam lines.

The storage ring consists of fifteen identical superperiods each consisting of two mirror symmetric cells. There are alternating ID straights of: 8.6-m long with high horizontal β for injection, RF, DWs, and lower brightness or higher flux user ID's, and 6.6-m long with low β for narrow gap ID's such as CPMU and EPU for high brightness and high flux x-ray beams. Three pairs of dipoles with gaps enlarged from 35 mm to 93 mm will accommodate large aperture, high flux far IR beamlines. The top-off injection will be made with a 200 MeV S-band linac and 3 GeV booster synchrotron with the circumference one fifth of the storage ring (158.3 m). With an anticipated beam life-time of 3 hours, injection of ~7 nC of charge every minute will be necessary to maintain the stored beam current at 500 ±5 mA.

Table 1: The NSLS-II storage ring parameters

Energy	3 GeV
Circumference	791.96 m
Harmonic Number	1320
Bending Radius	25.019 m
Dipole Energy Loss Uo	286.5 keV
Emittance Bare Lattice ε_0: 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)	(32.42,15.15)
Chromaticity (ξ_x , ξ_y)	(-99, -33)
Peak Dispersion	0.489 m
β Function at 8.6m ID (β_x, β_y)	18/3.8 m
β Function at 6.6m ID (β_x, β_y)	1.9/2.1 m
Alignment Tolerance Girder & Dipole (x, y, Φ)	(0.1, 0.1, mm, 0.5mrad)
Alignment Tolerance. Quad. & Sext..(x, y, Φ)	(0.03, 0.03 mm, 0.2 mrad)

LINEAR LATTICE CHOICE

For *M* cells, the theoretical minimum emittance for double bend (DBA) and triple bend (TBA) achromatic lattices are given by [1]:

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

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

where γ is the relativistic energy and J_x, is the horizontal partition factor that is assumed to be unity. For a given number of cells, lower energy yields a lower emittance. A beam energy of ~3 GeV is adequate, since the advances with in-vacuum, small gap and short-period undulators, pioneered at the NSLS [2], can produce x-rays in the energy range of 2-20 keV. The lower electron beam energy has a significant cost savings.

Our lattice guidelines were established to attain:

- minimum horizontal chromaticity per cell,
- maximum peak dispersion,
- horizontal and vertical dynamic acceptance (linearity),
- horizontal DA (top-off injection),

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ozaki@bnl.gov
*Work supported by U.S. DOE, Contract No.DE-AC02-98CH10886

- and maximum momentum aperture (Touschek lifetime), with control of nonlinear effects by sextupole correction (10 families) and parameter choice in IDs.

Although a TBA-24 lattice can potentially give an emittance five times lower per cell, this could not be realized with a ring of reasonable size due to difficulties in achieving adequate DA for realistic tolerances [3]. A DBA-30 lattice, with similar circumference as the TBA lattice, can have a reasonably small emittance and large DA. The extra ID straight sections can be used for DWs to lower the emittance [4]. This is a novel approach for 3rd generation light sources, which has been used in colliders [5,6] and proposed for light sources [7,8]. Figure (1) shows the lattice functions for one superperiod of the NSLS-II lattice.

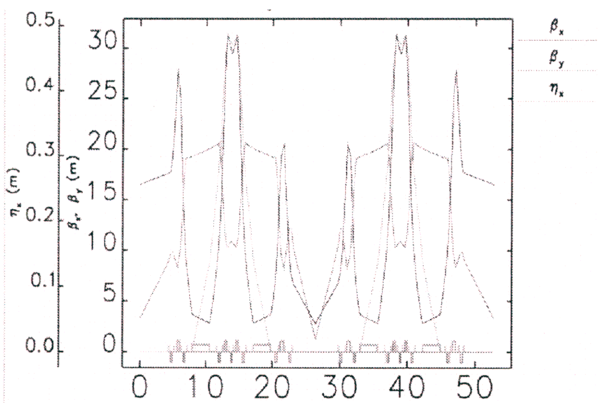

Figure (1) Twiss parameters for one superperiod of the DBA-30 lattice, with 8.6 and 6.6m ID lengths.

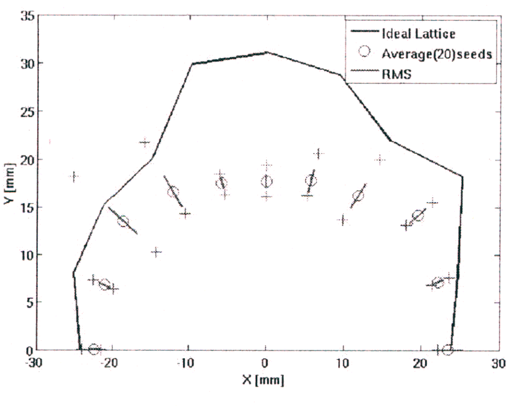

Figure (2) The lattice DA with alignment tolerances and synchrotron oscillations. The average (O), rms and extreme values (+) of the DA for 20 randomly seeded sets of errors are shown.

DW'S AND SOFT BEND FOR EMITTANCE REDUCTION

This lattice was optimized for efficient use of DWs for reducing the emittance, using weak dipole magnets with a bend radius of $\rho_0 = 25$m. Quadrupoles triplets in the long and short ID straight sections are used to cancel the phase and beta function beating introduced by undulators and wigglers. Ten sextupoles families are used to control the DA for a realistic lattice. Figure (2) shows the DA for the ideal lattice, as well as for the realistic lattice (20 seeds) with alignment tolerances listed in Table I, with the resulting closed orbit distortions corrected using beam based aligned beam position monitors.

The impact of damping wigglers in the dispersion free straight section is 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 change of the horizontal emittance ε_{nat} relative to the bare lattice emittance ε_o is given by [1]

$$\frac{\varepsilon_{nat}}{\varepsilon_0} \approx \frac{U_0}{U_0 + U_w} \qquad (3)$$

where 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 most efficiently enhanced by reducing U_o. For NSLS-II we reduced U_o by using low field dipoles and large U_w , with initially 21 m and ultimately with 56 m of DW's with 1.8 T peak field.

The beam energy spread, δ_w, relative to the bare lattice value δ_o, 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. The emittance reduction and energy spread increase are shown in Fig. (3) of Ref. [9], as a function of dipole radius and installed DW power. This showed an emittance reduction factor of 3-5 is possible for reasonable RF power and δ_w.

With a low energy and high current storage ring, the intra-beam-scattering (IBS) can present a limit on how small an emittance one can achieve. Namely, increasing ρ_o or U_w beyond some point will become ineffective in further reducing the total emittance, $\varepsilon_{x,tot}$, the emittance resulting from the equilibrium of the radiation damping rate and the quantum plus IBS diffusion rates, as ε_{nat} approaches the IBS emittance value, ε_{IBS}. One of the authors showed 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[10]. The diffusion coefficient times *H,* the invariant dispersion amplitude, 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. For these assumptions the dependence of the slope of $\varepsilon_{x,tot}$ with ρ_o is shown in Figure (3). For fixed U_T, as ρ_o increases (reduced dipole field), U_o and $\varepsilon_{nat}/\varepsilon_o$ are reduced. This shows that as $\rho_o \rightarrow \infty$ ($\varepsilon_{nat} \rightarrow 0$), the fractional reduction of $\varepsilon_{x,tot}$ becomes less effective. The optimum value for U_T = 1MeV and ε_{IBS} =

0.25nm appears to be $\rho_o \sim$ (20-30) m, where 25m was chosen for NSLS-II.

The change in beam properties as one increases the length of DWs is shown in Table II. These simplified estimates are consistent with calculations using computer codes that don't assume ε_{IBS} is constant [11]. In addition, the DWs will provide high flux and brightness hard x-ray beams, far exceeding beams from higher field dipoles, and will be highly useful sources for user beamlines that are designed to handle this high power.

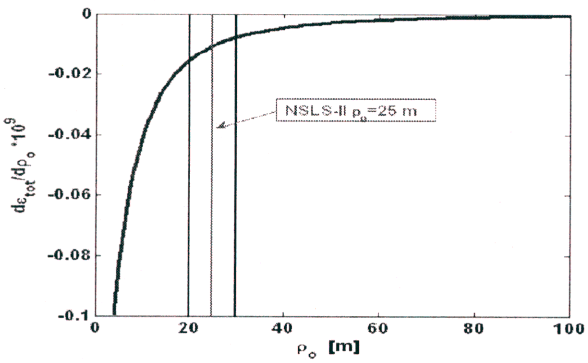

Figure (3) The change of total emittance with IBS growth for 500mA ring current per unit of change of the dipole bend radius. The optimum range is shown, with the NSLS-II value.

Table II Expected beam properties as DWs are added

DW[m]	ε_{nat} [nm]	$\varepsilon_{x,tot}$ [nm]	U_T [keV]	δ_W [%]	$\Delta\nu_y$
21	0.91	0.98	673.8	0.072	0.119
35	0.63	0.72	932.5	0.09	0.199
56	0.51	0.61	1320	0.1	0.318

SOFT BEND AND THREE-POLE WIGGLER

The critical energy of the x-rays for ρ_o =25m dipole is 2.4 keV, yielding bright sources for the soft x-ray and VUV beamlines. However, there is a significant demand for the hard x-ray "bending magnet-like" sources to utilize the large available beamline resources of existing NSLS x-ray ring which cannot handle the DW power or brightness of the IDs. In order to satisfy this need Three-Pole Wigglers (TPWs) will be installed at the upstream end of the second dipole of selected cells. The TPW (permanent magnet) will have a central pole with 30 mm gap that will produce the magnetic field >1 T over the length of ~3 cm for hard x-ray beamlines. This central pole is sandwiched between two moderate field poles so that the field integral through the TPW will become zero. The TPW installed in the NSLS-II lattice will produce an x-ray flux (or power) equivalent to the dipole radiation from NSLS x-ray ring and the existing beamlines can be transferred without significant upgrade. However, the brightness of these beamlines will increase more the 100 times, providing a new life to a major financial resource. However, the installation of TPW in non-achromatic section of the lattice will contribute to the quantum excitation of the ring, resulting in an increase of $\varepsilon_{x,tot}$. Estimate made for installation of 15-TPW is an increase of $\varepsilon_{x,tot}$ by ~ 0.2 nmrad, or about 10% of the achievable emittance. This increase is tolerable considering the enhancement to the research program.

LATTICE EFFECTS OF DW

The impact of DWs to the lattice will be similar to that 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 the beta function modulation is <8% [12]. These effects can be sufficiently corrected using the quadrupole triplets.

While the nonlinear impact of the DWs is significant, it is only ~30% of the tune shift expected for the short-period (λ_W =19 mm) undulators, that are planned. The DA is adequately maintained for both DW and undulators by correcting for the linear tune and beta beating with the three ID quads, including the effects of engineering tolerances [12].

There was concern that this large reduction of emittance would cause extremely 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 only slightly increased, as was pointed out in Ref. [10].

CONCLUSIONS

The lattice design for NSLS-II has taken a novel approach toward achieving the ultra-low emittance goal of (<1nm), 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. The authors wish to express their gratitude to the important contributions of the entire NSLS-II accelerator design team for the development of the accelerator system design [13], and with special thanks to Weiming Guo for contributions to the present lattice design and manuscript editing.

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