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Novel Magnet Lattice for the High-brightness Upgrade of NSLS-II

Victor Smaluk, Timur Shaftan, Minghao Song, Yongjun Li, Yoshiteru Hidaka, Aamna Khan, Gabriele Bassi, Dean Hidas, Guimei Wang, Xi Yang, Sushil Sharma, Patrick N'Gotta, Bernard Kosciuk, Jinhyuk Choi, James Rose, Toshiya Tanabe and Robert Todd

NSLS-II, Brookhaven National Laboratory, Upton, NY, USA

E-mail: smaluk@bnl.gov

Abstract. The main trend in the decades-long evolution of synchrotron light sources is continuously increasing photon beam brightness demanded by the user community. Since reducing the electron beam emittance is a straightforward way to increase the brightness, new and upgraded synchrotron light sources are now based on the multi-bend achromat approach providing much lower emittance than synchrotrons of previous generations. For the high-brightness upgrade of NSLS-II, we designed a low-emittance lattice based on the novel concept of complex bends. Key advantages of this lattice are the use of permanent magnets reducing power consumption and compact magnet design providing longer straight sections for light-generating insertion devices. For this lattice, we estimated the lowest possible emittance at the operational beam intensity taking into account collective effects of beam dynamics.

1 Introduction

For synchrotron light sources, the brightness of photon beams is one of the main figures of merit. High brightness is crucial for advanced research of light source users with enhanced spatial and time resolution, and high data measurement and processing rate. Since the brightness is proportional to the electron beam intensity and inversely proportional to the beam emittance, it can be increased either by higher intensity of the electron beam or by lower emittance. Increasing the electron beam intensity is technically challenging; this approach is limited by the required high RF power, beam-induced heating of the accelerator and beamline components, and collective instabilities of the electron beam. No synchrotrons are operating with the beam current exceeding 500 mA. Reducing the emittance of the electron beam is a straightforward way to achieve higher brightness.

A general trend in the synchrotron lattice design is increasing the number of bending dipole magnets because the emittance is inversely proportional to the cube of their number. The recent transition from Double- and Triple-Bend Achromat (DBA and TBA) lattices of the 3rd generation light sources to Multi-Bend Achromats (MBA) resulted in a number of 4th generation synchrotron projects. Four new MBA-based light sources have been recently commissioned: MAX-IV (Sweden, 2016) [1], ESRF-EBS (France, 2020) [2], SIRIUS (Brazil, 2020) [3], and APS-U (USA, 2024) [4]. HEPS (China) [5] is in its commissioning stage now and many other projects of new and upgraded facilities are being developed worldwide. The beam emittance was continuously being reduced in a few decades, as shown in Figure 1.

However, the lattice design is quite challenging because strong focusing of the electron beam by high-gradient quadrupole magnets is essential to achieve low emittance. This, in turn, results in high natural chromaticity, which is compensated by sextupole magnets located in dispersive sections. Strong sextupole

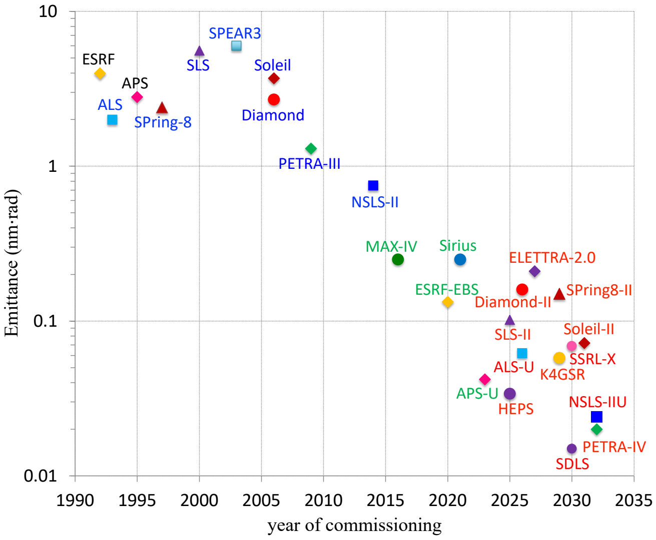

Figure 1: Evolution of the electron beam emittance in synchrotron light sources.

magnets introduce essential nonlinearity to the beam dynamics, leading to a reduction in the dynamic aperture (DA). Whereas the DA of 10s of millimeters is typical for DBA and TBA lattices, the DA of single millimeters is usual for the MBA lattices. A modern approach to designing low-emittance rings assumes strict conditions imposed on the betatron amplitude and phase functions at the sextupoles to minimize nonlinear driving terms. Since there is no general formula, the nonlinear lattice optimization is based on numerical simulations using advanced computer codes. The momentum acceptance in the MBA lattices is also quite low, resulting in a shorter beam lifetime dominated by the Touschek effect. While the DBA and TBA lattices typically provide a Touschek lifetime of the order of 10 hours, it is approximately 10 times lower for most of the new MBA-based machines. The small dynamic aperture and short lifetime pose challenges for the injection systems since frequent injection of intense bunches is required to maintain the stored beam intensity stable, with a deviation lower than 1% required for user experiments.

2 New approach: Complex Bend

At NSLS-II, we proposed a new approach of low-emittance lattice design alternative to MBA [6]. We designed a new lattice element we call “Complex Bend” replacing regular dipole magnets. The complex bend magnet consists of multiple combined-function poles providing both strong focusing and bending in a single device. Replacing regular dipole magnets with complex bends in a synchrotron lattice brings several benefits:

- Since the emittance scales inversely as the cube of the number of dipoles, complex bend enables lattice designs featuring record-low beam emittance, of the order of 20 pm for an 800-m long 3 GeV ring.
- The compact design of complex bends provides substantial extra space for insertion devices and other components, as compared to the MBA lattices.
- The dipole magnetic field is localized within the complex bends, simplifying the design of the vacuum chambers together with pumping and cooling systems.
- For a medium-energy light source, the required quadrupole gradient is lower than 150 T/m, which can be achieved using permanent magnet technology thus advancing the concept of a “green” accelerator facility by reducing the number of magnet power supplies and the overall power consumption.
- The synchrotron radiation pattern and associated heat load are localized to a smaller fraction of the ring circumference, which should reduce the number of synchrotron radiation absorbers.

In the past few years, our development of complex bend magnets evolved from the first concept to the beam-based testing of a low-energy prototype and building full-scale magnets to be installed in NSLS-II for beam tests. For example, just a replacement of dipole magnets with complex bends in the

NSLS-II DBA lattice keeping the layout of matching quadrupole triplets and straight sections unchanged, results in the emittance reduction by a factor of 30 [7]. A complex bend lattice assuming replacement of all the storage ring magnets provides a 24 pm emittance, large dynamic aperture, and good beam lifetime [8]. Various options of complex bend design are being analyzed including bending by a wide-gap long dipole magnet and strong focusing by short quadrupoles installed in the dipole's gap or a combined dipole-quadrupole permanent magnet with multipole poles.

3 Lattice for the NSLS-II Upgrade

Unlike a new "green-field" project, low-emittance upgrade options of the existing NSLS-II facility are restricted by many constraints:

- Fitting to the existing tunnel and X-ray ports;
- Sufficiently long straight sections for light-generation insertion devices (wigglers and undulators);
- Optimal beta functions in straight sections for high brightness;
- Reasonable energy spread and bunch length;
- Dynamic aperture sufficient for off-axis injection;
- Large enough momentum aperture for beam lifetime;
- Sufficient space for vacuum and beam diagnostics components.

We applied a detailed methodology of lattice design [9] assuming binning space for the complex bend achromat (CBA) lattice, consequent optimization of the central complex bend and dispersion bump, the outer complex bends, and the design of straight sections. As a result, we designed a lattice providing an extremely low emittance of about 23 pm at the energy of 3 GeV. As well as the present NSLS-II, the upgraded ring consists of 15 super periods, most of which are regular cells with low beta functions in the straight sections to maximize the brightness. We also designed two special cells: one with a higher horizontal beta function in the long straight section for the off-axis injection and the other with double-minimum beta functions to accommodate tandem undulators. For accurate analysis of beam dynamics, especially with magnet misalignments and field errors, we are implementing 3D field maps in the simulations.

Table 1: Lattice parameters: CBA vs DBA

	NSLS-II DBA	NSLS-IIU CBA
Energy (GeV)	3	3
Circumference (m)	791.958	791.768
Emittance (pm·rad)	2086	23.5
Betatron tunes, hor/ver	33.22/16.27	84.22/28.27
Natural chromaticity, hor/ver	-98 / -40	-132 / -125
Momentum compaction	$3.6 \cdot 10^{-4}$	$0.78 \cdot 10^{-4}$
Radiation damping partitions, hor/ver/long	1 / 1 / 2	2.24 / 1 / 0.76
Radiation damping time (ms), hor/ver/long	55 / 55 / 28	36 / 81 / 106
Energy spread	$5.1 \cdot 10^{-4}$	$7.3 \cdot 10^{-4}$
Energy loss per turn (keV)	286	196
RF frequency (MHz)	499.681	499.801
RF voltage (MV)	3.6	3.6
Synchrotron tune	0.0087	0.0044
Bunch length (mm)	2.7	1.6
Length of straight sections (m), long/short	9.3/6.6	8.4/6.1
Beta functions in long straight center (m), hor/ver	20.1/3.4	2.0/3.0
Beta functions in short straight center (m), hor/ver	1.8/1.1	1.9/2.0

Table 1 represents a list of main accelerator parameters calculated for the CBA lattice in comparison with the DBA lattice of present NSLS-II (both without wigglers/undulators). In Figure 2, the upper graph shows lattice functions and schematic magnet layout of half of the regular cell, and the lower graph shows dipole magnetic fields and quadrupole gradients. Note, the gradient does not exceed 130 T/m, this allows us to use permanent magnets significantly reducing power consumption in operations.

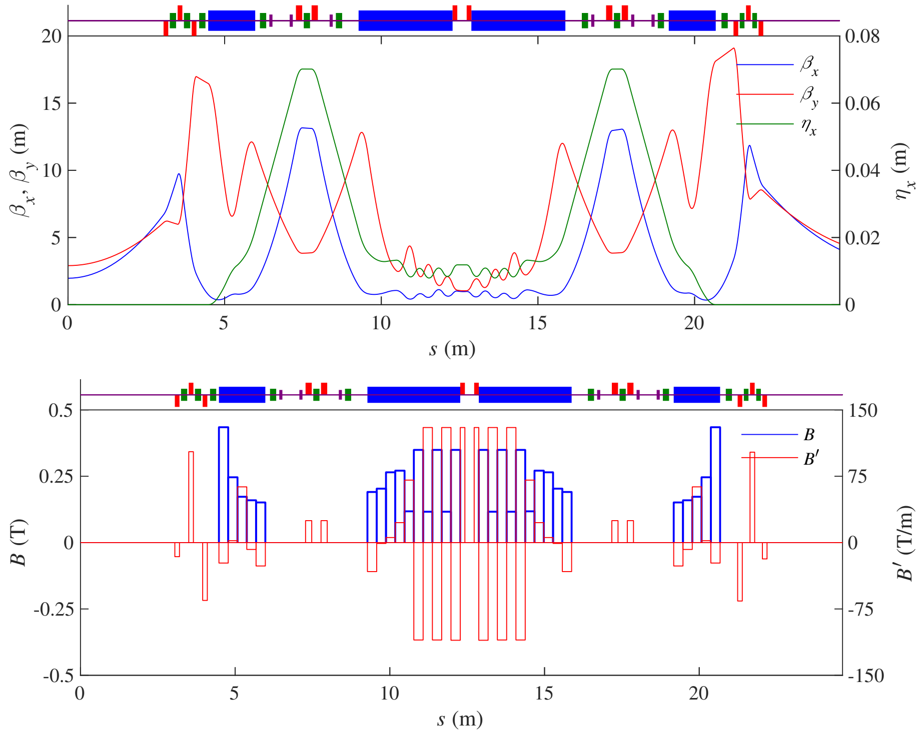

Figure 2: Lattice functions (upper graph); magnetic fields and gradients (lower graph).

Radiation generated by the electron beam in wigglers and undulators results in additional beam energy loss, and this effect is dominant for the NSLS-IIU lattice. To estimate the effects of the light-generating insertion devices (IDs) on the beam parameters in the upgraded machine, we included models of all IDs now installed in NSLS-II [10] except the superconducting wiggler, and a few new devices from the approved NEXT-III project. With a full set of IDs, the total radiation energy loss per turn is about 1 MeV compared to 0.2 MeV caused by bending magnets only. Figure 3 shows the cumulative effect of the IDs on emittance and energy spread, the damping wigglers (ID08, ID18, ID28) have the most effect on the emittance reduction.

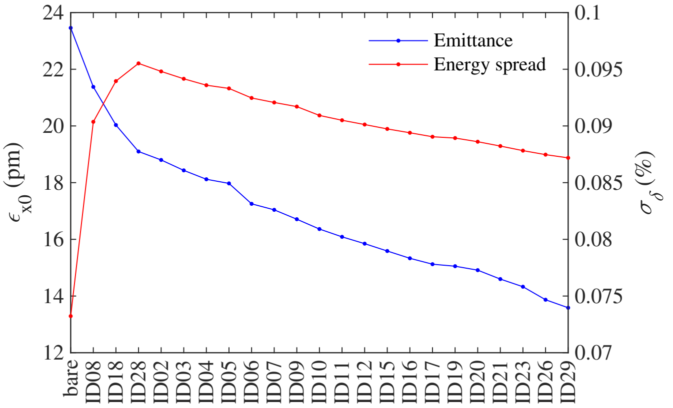

Figure 3: Effect of IDs on the beam emittance and energy spread.

4 Scaling Emittance with Energy and Intensity

The major practical limit of the beam energy and intensity is large synchrotron radiation power requiring complex and expensive RF systems. Since the radiation energy loss is proportional to the energy in the 4th power, this is the primary reason why higher-energy synchrotrons operate with lower beam intensity: typical beam current is 400-500 mA in the 2-3 GeV rings (ALS, NSLS-II, SOLEIL) and 100-200 mA in the 6-8 GeV rings (ESRF, APS, SPring8). Another important factor that could limit the beam intensity is the beam-induced heating of vacuum chambers, which is directly proportional to the longitudinal impedance (mainly the resistive-wall one) and to the square of the beam current. Strong focusing magnets and high-brightness insertion devices require low-aperture vacuum chambers. Since the longitudinal impedance is inversely proportional to the vacuum chamber size, the smaller chamber apertures lead to higher beam-induced power.

A common feature of modern low-emittance rings is the small size of electron beams in all three dimensions because a small momentum compaction results in a short bunch length and a low emittance determines small transverse sizes. As a result, the particle density within the bunch is considerably high, amplifying the collective effects of beam dynamics. Intra-beam scattering (IBS) is one of the most adverse effects that can impact beam quality and impose limitations on the ultimate performance of synchrotrons, especially low- and medium-energy machines. IBS is a small-angle scattering that does not cause particle loss but results in a substantial intensity-dependent increase in emittance, energy spread, and bunch length. The theory of IBS has been well-developed for quite some time and has been implemented into particle tracking codes. We employed the high-energy approximation of the IBS theory [11] to examine the combined effect of IBS and the bunch lengthening resulting from the longitudinal impedance and higher-harmonic cavities.

We calculated the emittance as a function of the beam current and energy for the CBA lattice, considering both IBS and impedance effects. The bunch lengthening caused by the beam interaction with the longitudinal impedance was computed using the modified Zotter equation [12] assuming a typical value of the normalized longitudinal impedance equal to 0.5 Ω. The effect of higher-harmonic cavities was simply modeled by multiplying the zero-intensity bunch length by a moderate factor of 3. In this calculation, we assumed betatron coupling of 0.8. Figure 4 shows the horizontal emittance affected by all these collective effects. The red line represents empirical scaling of the operational beam current with energy.

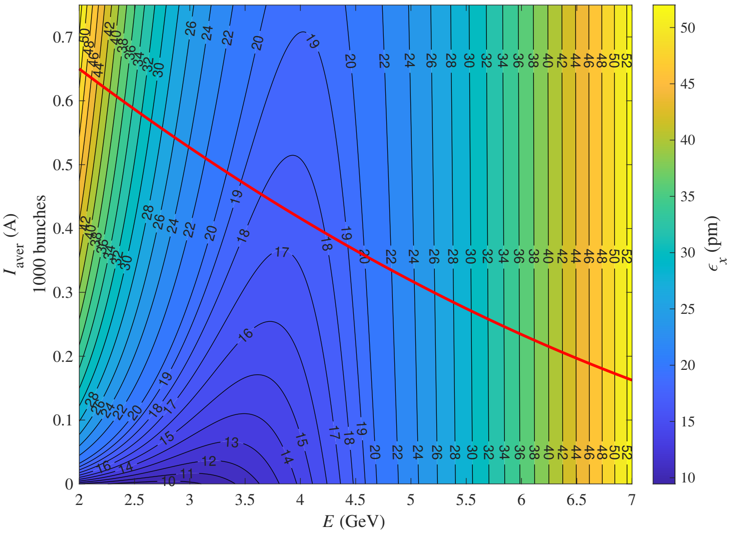

Figure 4: Combined effect of IBS, impedance, and higher-harmonic cavities on the beam emittance.

We found that the emittance at the operational beam intensity reaches a minimum in the energy range of 3.5-4 GeV. This is due to the strong emittance blow-up caused by IBS at lower energies, while the quadratic proportionality to the energy leads to an increase in emittance at higher energies. So we now consider an increase of the NSLS-IIU energy up to 4 GeV to achieve the minimum emittance and ultimate brightness at the operational beam intensity.

5 Summary

The ultimate brightness of light sources is essential for cutting-edge science. Reducing the electron beam emittance is the main trend to increase the brightness resulting in the transition of synchrotron lattice design from DBA/TBA to MBA. We propose Complex Bend Magnet, a new approach opening the possibility of designing lattices with record-low electron beam emittance. The complex bend development at NSLS-II evolved from the first concept to the beam-based testing of a low-energy prototype and the building of a full-scale prototype. Lattice design for the high-brightness upgrade of NSLS-II is ongoing, the most updated Complex Bend Achromat Lattice provides a 23 pm emittance at 3 GeV and insertion devices reduce it to 14 pm. Collective effects of beam dynamics, especially intra-beam scattering, are the main limiting factor of emittance and brightness at operational beam Intensity. The NSLS-II upgrade team received recommendations from the U.S. DOE Basic Energy Sciences Advisory Committee to study engineering challenges for the new accelerator concept, and then proceed to Critical Decision 0 (CD-0), Approve Mission Need.

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