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REALIZING LOW-EMITTANCE LATTICE SOLUTIONS WITH COMPLEX BENDS *

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Abstract

A concept of new lattice element called "Complex Bend" is recently proposed at NSLS-II. Replacing the regular dipoles in the Double-Bend Achromat lattice by Complex Bends significantly reduces the beam emittance. The first attempt of lattice design for potential NSLS-II upgrade based on Complex Bend, is described. Compared with the current NSLS-II lattice, the new solution modifies only three of the six girders per cell. The linear optics has been matched keeping unchanged the lattice parameters at the straight sections, where the light-generating insertion devices are located. The Complex Bend gradient is limited by 250 T/m assuming possible use of permanent magnets. The lattice provides 65 pm emittance without damping wigglers, use of which results in further decrease of the emittance.

INTRODUCTION

The brightness of synchrotron light sources is proportional to the photon flux and inversely proportional to the electron beam emittance. Increase of photon flux means higher intensity of the electron beam. This approach is challenging because of many technical problems: high radiation power, vacuum chamber heating, collective instabilities. A straightforward way to increase the brightness is reduction of the electron beam emittance.

The natural beam emittance can be represented in a simple way as

$$\varepsilon_x = F\frac{E^2}{J_x N_B^3}\,, \tag{1}$$

where F is some function of the magnet lattice, E is the electron energy, J_x is the horizontal damping partition, and N_B is the number of bending (dipole) magnets in the ting.

During past 25 years of synchrotron light source evolution, the emittance has been decreased by two orders of magnitude. Increasing number of dipoles is a general trend of the low-emittance ring design. Figure 1 shows the horizontal emittance ε_x of synchrotron light sources as a function of number N_B of bending magnets. This plot includes both the facilities in operation or used to be in operation and new or upgrade projects.

Two possible options for low-emittance NSLS-II upgrade, NSLS-II-TBA and NSLS-II-CB, are also shown in Figure 1. The first option is based on a Triple-Bend Achromat (TBA) with two small anti-bends [1], it provides reduction of the NSLS-II emittance by a factor of five.

The second option we discuss here is based on a novel "Complex Bend" technology proposed at NSLS-II. This upgrade is more challenging, it assumes more significant modification of the NSLS-II hardware but it will reduce the NSLS-II emittance to the level about 50 pm, which is close to the most advanced synchrotron projects.

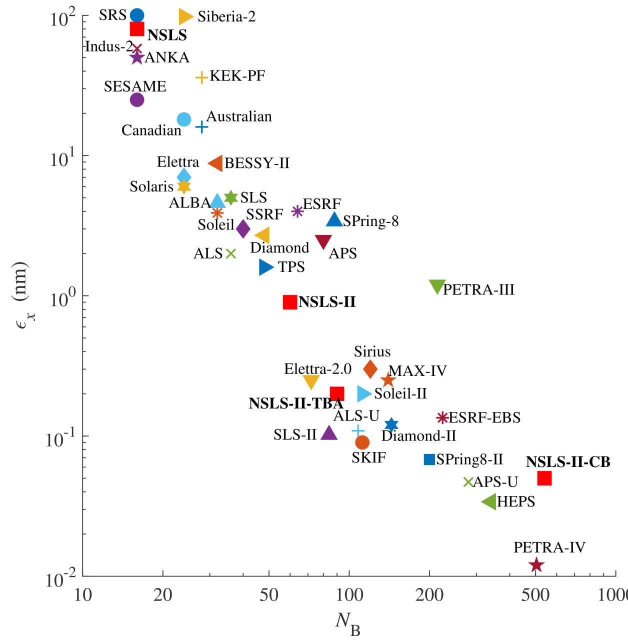

Figure 1: Emittance of synchrotron light sources as a function of number of bending magnets.

COMPLEX BEND

All modern projects of low-emittance synchrotrons follow Multi-Bend Achromat (MBA) approach. MAX-4 (Sweden) has been commissioned in 2016, ESRF-EBS (France) and SIRIUS (Brazil) are in the construction stage and there are many other projects around the world, such as APS-U, ALS-U (both USA), Spring8-II (Japan), HEPS (China), Elettra-2.0 (Italy), Diamond-2 (UK), Soleil-2 (France) and SKIF (Russia).

An alternative way to reach low emittance has been recently proposed at NSLS-II. The idea is to use a lattice element that we call "Complex Bend" instead of regular dipole magnets. The Complex Bend provides a strong alternate focusing distributed along the bending magnet so to maintain the beta function and dispersion oscillating at low values. Increasing the number of dipole magnets and combining them into a single element as poles results in a substantial decrease of the beam emittance.

The first concept of Complex Bend [2] was based on a bending magnet consisting of a number of dipole poles interleaved with strong quadrupoles of the alternative polarity. A cartoon illustrating this concept of Complex Bend is pre-

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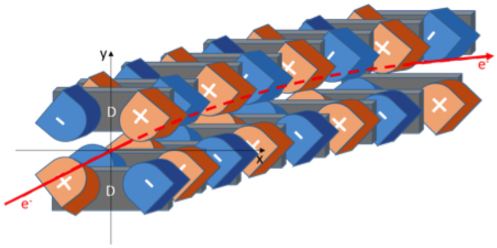
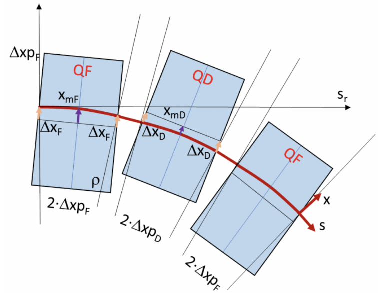
sented in Figure 2a. This option of complex bend requires high magnetic field and gradient, so the design should be based on superconducting magnet technology and thus is far more complex than regular electromagnets.



a) interleaved dipoles and quadrupoles



b) shifted quadrupoles

Figure 2: Complex Bend.

A new optics solution for the Complex Bend is published in [3]. The idea is to remove the dipole poles and realize the beam trajectory bending by shifting the quadrupole poles along the horizontal axis. A sketch illustrating the magnet layout is presented in Figure 2b. This approach provides significant reduction of the field gradient so the Complex Bend can be built using permanent magnet technology, which allows us to reduce complexity and cost of the magnet. A disadvantage of this design is the bending angle dependence on the beam trajectory so we can expect higher sensitivity to the field and alignment errors. This issue can be mitigated by placing the array of permanent-magnet quadrupoles inside a conventional dipole magnet providing the bending field.

In the next sections, we discuss a lattice design for possible low-emittance upgrade of NSLS-II assuming use of the second option of Complex Bend.

LINEAR OPTICS

Unlike a new "green field" project, any upgrade of an existing machine must match many constraints such as the design and location of existing beamlines. For future NSLS-II upgrade, we assume the following constraints:

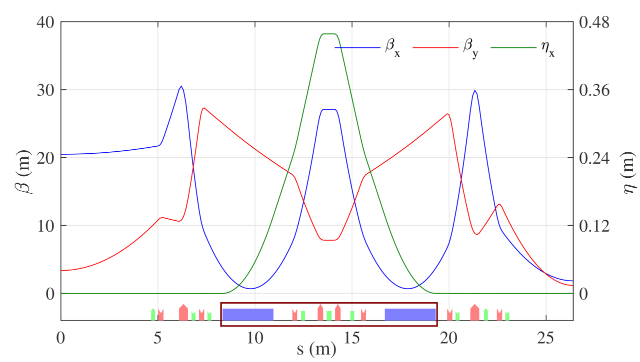
- unchanged layout of the beamlines;
- keeping beta functions in the light-generating devices close to the present values;
- zero dispersion in straight sections;
- minimization of the NSLS-II hardware modifications;
- gradient of Complex Bend quadrupoles lower than 250 T/m (permanent magnets).

A magnet lattice is designed using Matlab Accelerator Toolbox [4]. Table 1 represents a list of accelerator parameters calculated for the Complex Bend lattice in comparison with the present Double-Bend Achromat lattice of NSLS-II. Figure 3 illustrates advantages of Complex Bend in comparison with DBA, the beta functions and dispersion of 1/30 of the NSLS-II storage ring are presented. As one can see, replacement of the conventional dipole magnets in the DBA cell with the Complex Bends provides low values of horizontal beta function and dispersion in the bending magnets and allows us to reduce the emittance by a factor of 30.

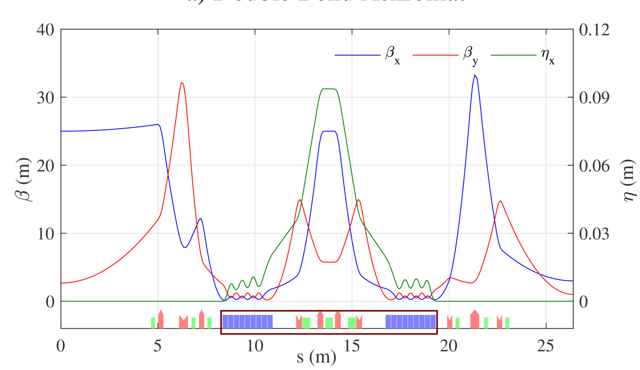
Table 1: Lattice Parameters: NSLS-II vs Complex Bend

	NSLS-II*	NSLS-II CB
Energy	3 GeV	3 GeV
Circumference	792 m	792 m
Horizontal emittance	2.1 nm	0.065 nm
Betatron tunes, h/v	33.22/16.26	76.45/65.10
Natural chromaticity, h/v	−98 / −41	−188 / −168
Momentum compaction	$3.6 \cdot 10^{-4}$	$4.6 \cdot 10^{-5}$
Damping partitions, h/v/l	1 / 1 / 2	2 / 1 / 1
Energy spread	0.0005	0.001
Energy loss per turn	287 keV	648 keV

* "bare" lattice without damping wigglers



a) Double Bend Achromat



b) Complex Bend

Figure 3: Twiss functions of 1/30 of the NSLS-II storage ring.

The high-beta and low-beta sections provide matching the Complex Bends to the straight sections with zero dispersion, in which the light-generating insertion devices are located.

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The middle section is the dispersion amplifier required to create the dispersion bump for correction of natural chromaticity. The horizontal betatron phase advance between the chromatic sextupoles $\Delta\mu_x = 4.98\pi$ is matched to satisfy the condition $\Delta\mu = (2n+1)\pi$ required for compensation of the first-order non-linear perturbation.

The Complex Bend consists of 9 poles. The dipole filed of the middle 5 poles providing the low emittance is 0.213 T for the horizontally focusing poles and 0.638 T for the defocusing poles. The quadrupole gradient is 234 T/m and −201 T/m respectively, so it looks possible to build the Complex Bend using permanent magnets. The dispersion suppressor is realized by 2 poles of the Complex Bend close to the high-beta and low-beta matching sections. The dispersion amplifier is realized by 2 poles of the Complex Bend and four separate quadrupoles in the middle section. The dipole field and gradient of the dispersion suppressor and dispersion amplifier poles are different from the field and gradient of the main Complex Bend poles.

The layout of the straight sections and of the high-beta and low-beta matching sections (outside the red box in Figure 3) is kept the same as the present NSLS-II layout to minimize the hardware modifications and to reduce the cost of upgrade. Quadrupoles in the high-beta section and in the low-beta section need to be enforced by a factor of 1.5-2 compared to the current NSLS-II strength limited by 20 T/m. The quadrupoles of the dispersion amplifier have relatively low gradients, 19 T/m and −34 T/m and can be built using conventional electromagnet technology.

NON-LINEAR BEAM DYNAMICS

To compensate the natural chromaticity, three sextupole magnets are located in the middle section with the dispersion bump. Since the natural chromaticity is big and the maximum dispersion is only 9 cm, the sextupoles must be very strong. To correct the chromaticity to a usual slightly positive value, the sextupole parameters $K_2 = \frac{1}{B\rho}\frac{\partial^2 B_y}{\partial x^2}$ are 205 T/m^3 and −175 T/m^3.

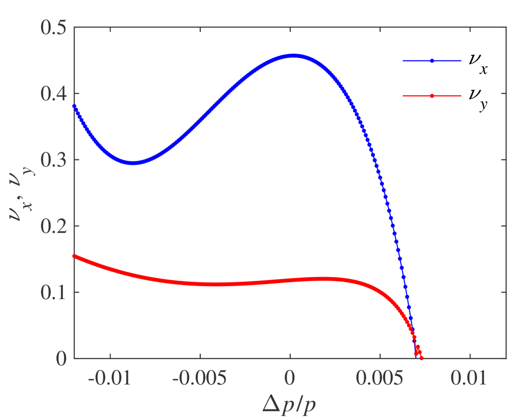

Figure 4: Betatron tune shift with momentum

Figure 4 shows the betatron tune shift with momentum $\delta = \Delta p/p$. As one cam see, the second order chromaticity is large, it results to a small (about 1%) momentum aperture compared to the usual values of several percent for the Double-Bend Achromat lattices.

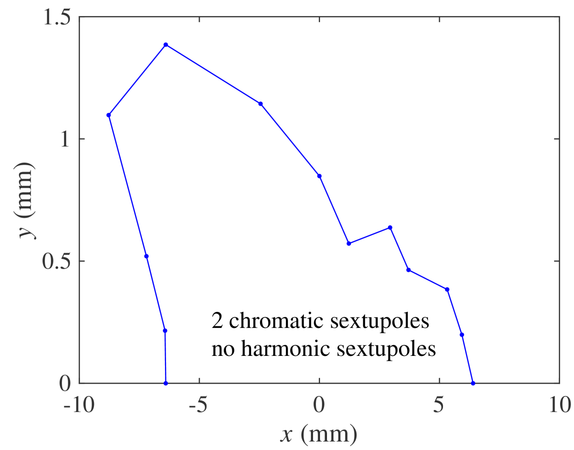

Figure 5: Dynamic aperture with the corrected chromaticity.

Strong chromatic sextupoles limit the dynamic aperture of the Complex Bend lattice as shown in Figure 5. The chromatic sextupoles are set to the above-mentioned values, all the harmonic sextupoles located in the high-beta and low-beta sections are set to zero. The horizontal dynamic aperture is about ±6 mm, so we hope optimization of the harmonic sextupoles can make it big enough for the conventional off-axis injection. The sextupole optimization in order to increase momentum acceptance and dynamic aperture is the next step of the lattice design.

CONCLUSION

A magnet lattice based on Complex Bend is being developed for a potential low-emittance upgrade of NSLS-II. The achieved emittance is 65 pm, which is about 30 times lower than the emittance of the actual DBA lattice. The quadrupole gradient of Complex Bend does not exceed 250 T/m, so it can be built using the permanent magnet technology. The layout of the straight sections and of the high-beta and low-beta matching sections is kept unchanged to minimize the hardware modifications and to reduce the cost of upgrade. Non-linear beam dynamics is the major concern, the sextupole optimization is ongoing.

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