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# A CROSS-CELL INTERLEAVED NONLINEAR LATTICE FOR POTENTIAL NSLS-II UPGRADE

Yongjun Li*, An He, Timur Shaftan, Victor Smaluk, Bernard Kosciuk
Brookhaven National Laboratory, Upton, New York 11973, USA
Zhenghe Bai†, Lin Wang
National Synchrotron Radiation Laboratory, USTC, Hefei 230029, China

*Abstract*

An interleaved sextupole scheme using a cross-cell betatron phase cancellation technique is adopted as a candidate for a future upgrade to the NSLS-II lattice. The upgraded lattice will use as many NSLS-II installed magnets as possible, including 30 dipoles, which will create a triple bend achromat configuration. A 300 pm·rad horizontal beam emittance has already been achieved with the current configuration. The emittance can be further reduced to around 200 pm·rad with damping wigglers. Some new design concepts used in modern 4th-generation light sources, such as adopting longitudinal gradient bends and reverse bends, are incorporated into the design as well. The betatron phase-advance between sextupoles is designed to have a cross-cell interleaving cancellation pattern in the transverse planes. The dynamic aperture is sufficient to allow the conventional off-axis top-off injection. At the same time, a large energy acceptance looks promising and would ensure a sufficiently long beam lifetime.

## INTRODUCTION

NSLS-II is a middle energy 3rd generation light source operated by Brookhaven National Laboratory. Its main ring is composed of 30 double bend achromat (DBA) cells and $3 \times 7$ m damping wigglers, which deliver an electron beam with the horizontal emittance around 0.9 nm·rad. A future upgrade plan is currently under consideration. An option for a relatively cost-effective upgrade is presented in this paper.

The main goals and constraints of this upgrade option are:

- Without influence of insertion devices, the horizontal emittance of the storage ring needs to reach 300 pm·rad. It can be further reduced to 200 pm·rad with the contribution of existing damping wigglers.
- The layout of the existing beam-lines and the ratchet walls must be kept unchanged. Therefore, the straight sections for undulators and their matching sections (3 out of 6 girders per cell) will remain unchanged.
- Existing magnets need to be reused as much as possible to maintain cost-effectiveness. Their focusing strength ranges and the corresponding power supplies in the new design must therefore match the current specifications.
- The nonlinear lattice design needs to provide a 10 mm dynamic aperture at the injection straight for conventional off-axis top-off injection. Simultaneously, a ±3% energy acceptance is required for decent beam lifetime (⩾1 hour).
- The beam envelope function $\beta$ at certain undulator straight sections should be optimized to achieve high brightness performance.

## LAYOUT OF MAGNETS AND LINEAR OPTICS

To achieve the design goals under the given constraints as mentioned in the previous section, a triple bend achromat (TBA) magnetic lattice combined with two embedded reverse bends, has been designed and proposed. The lattice layout and the linear optics are illustrated in Fig. 1. The whole ring is composed of 30 TBAs with alternating high-low $\beta$ straight sections, placed with mirror symmetry throughout the ring. The optics design adopts a similar concept proposed for the HALS 6-bend-achromat [1]. The horizontal and vertical phase advances crossing two adjacent cells are chosen as $(3\pi, \pi)$ to cancel nonlinear dynamics effects. All existing undulator beam-line layouts and the corresponding shielded ratchet walls are compatible with this new layout as shown in Fig. 2. The main parameters for the upgrade proposal to NSLS-II and its lattice are listed in Table. 1. The design emittance is reduced from 2.1 nm·rad to 0.3 nm·rad.

For each TBA cell, the middle bend can be taken from the existing 2.62 m long 6° bend pool. In total, there are 60 such bends and half of them can be reused. The existing dipole beam-lines can utilize the X-ray from those bends, but some adjustments might be needed. In order to reduce the emittance, the other two main bends would need a longitudinal gradient, which is borrowed from the 4th generation diffraction limited ring design concept [2–9]. At the current stage, these bends are modelled as a dipole array with a hard-edge step function profile as illustrated in Fig. 3. A realistic transfer map for the detailed beam dynamics studies will be extracted from its 3-dimensional field map once the magnet prototype model is ready. Besides three main bends, two reverse bends integrated with a transverse gradient are used for two purposes: (1) allocating the damping partition rate in three planes to stretch bunched beam in the longitudinal direction and squeeze it in the transverse planes; (2) controlling the horizontal dispersion to suppress the quantum excitation rate. The horizontal damping partition number

* yli@bnl.gov
† baizhe@ustc.edu.cn

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increase to 1.8 in this design. The longitudinal damping rate reduces significantly compared to the existing NSLS-II ring. A longitudinal feedback system to suppress longitudinal beam instability might be necessary for this design.

All quadrupole gradients are controlled within the same range, i.e. [-22, 22] T/m, as the existing ring. Therefore the existing quadrupoles and power supplies can be reused. In high $\beta$ straight sections, a quadrupole doublet, instead of the existing triplet is used for optics matching. The extra quadrupole knob "QH1" can be used for compensating damping wiggler in the future if needed. The gradients of most of sextupoles increase by a factor of 2 to reach 800 T/m$^2$. Therefore, it may be necessary to manufacture these sextupoles and their power supplies. An alternative nonlinear dynamics optimization using some extra octupoles to reduce the harmonic sextupoles gradients is under consideration.

The new design is more compact than its current layout after squeezing more magnets into the same physical space, making the gaps between magnets tighter. Therefore, the interference between neighboring magnets would need to be investigated. Soft-edge magnet models might be applied if necessary. Another concern of the tighter layout is that sufficient correcting magnets and beam diagnostics instruments might need to be reallocated or redesigned to fit into the ring.

The radiation fan's pattern and X-ray beam extraction will significantly affect the magnet yokes shape, as well as the vacuum chamber profile. Multiple iterations between the optics design and the hardware design is expected.

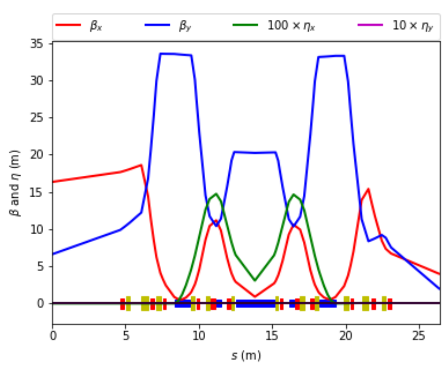


Figure 1: Linear optics and magnetic lattice layout for one TBA cell. A supercell is composed of two such symmetrical cells. This layout provides the same number of alternating high- and low-$\beta$ straights as the existing NSLS-II ring.

## NONLINEAR BEAM DYNAMICS

The requirement of the on-momentum dynamic aperture is to accommodate the existing off-axis top-off injection mode. This means that the horizontal inboard aperture needs to be greater than 8-10 mm at the long straight center. The betatron phase advance between the two dispersion bumps within one cell can not satisfy the cancellation condition as the hybrid multi-bend achromat lattice. Therefore, an interleaved, and cross-cell phase cancellation sextupole scheme was adopted, as illustrated in Fig. 4. The betatron phase on both the horizontal and vertical planes is optimized to cancel out the first order nonlinearity between three families of chromatic sextupoles. The higher order nonlinearity is optimized with 6 harmonic sextupole families, which are located at sections matched to the straight sections. These harmonic sextupoles are seated in the exact same positions as in the existing ring,

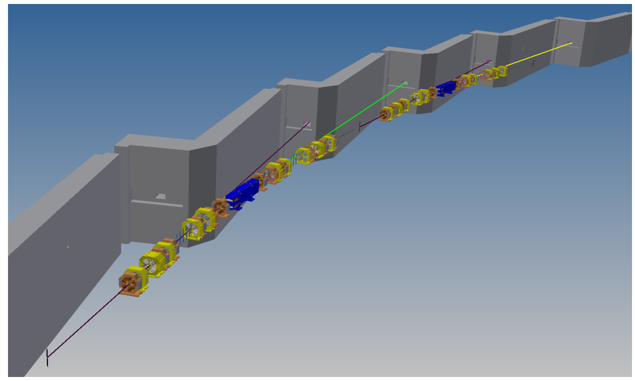

Figure 2: Fitting the existing beam-line layouts and the ratchet wall extraction ports with the new TBA lattice. Two longitudinal gradient bends and two reverse bends are not shown in this plot.

Table 1: Comparison of Main Parameters

| **Parameters** | **NSLS-II-U** | **NSLS-II** |
|---|---|---|
| Emit. (x nm·rad) | 0.3 | 2.1 |
| Chrom. (x/y) | -81/-66 | -101/-40 |
| Tune (x/y) | 42.24/13.28 | 33.22/16.26 |
| Moment. comp. $\alpha_c$ | $1.0\times10^{-4}$ | $3.6\times10^{-4}$ |
| Damp. part. (x/y/s) | 1.8/1.0/1.2 | 1.0/1.0/2.0 |
| Damp. time (x/y/s ms) | 19/35/29 | 55/55/28 |
| Rad. loss (keV/turn) | 457 | 287 |
| Energy spread | $8.2\times10^{-4}$ | $5.1\times10^{-4}$ |
| H. $\beta_{x,y}$ str. (m) | 16.3/6.6 | 20.5/3.4 |
| L. $\beta_{x,y}$ str. (m) | 4.0/2.0 | 1.8/1.2 |

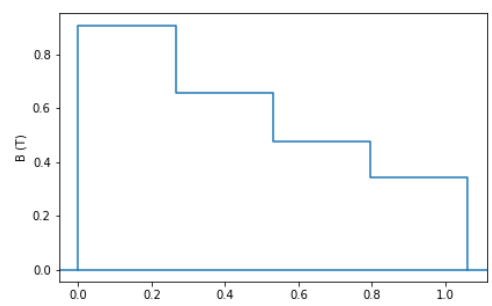


Figure 3: Profile of the vertical magnetic field strength along the upstream longitudinal coordinates for the gradient dipole. The magnet is simply modelled as a hard-edge dipole array. The downstream one is symmetrically mirrored to it.

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but with stronger excitations. This optimization was accomplished with the multi-objective genetic algorithm enhanced by machine learning techniques(MOGA) [10]. Multiple sextupole schemes were discovered which would satisfy the dynamic aperture requirements and have different footprint patterns in the tune space. Their robustness was compared to the engineering tolerance to determine the practicality of their implementation. The on-momentum dynamic aperture for one of the candidates obtained with the particle tracking simulation code "ELEGANT" [11] is shown in Fig. 5.

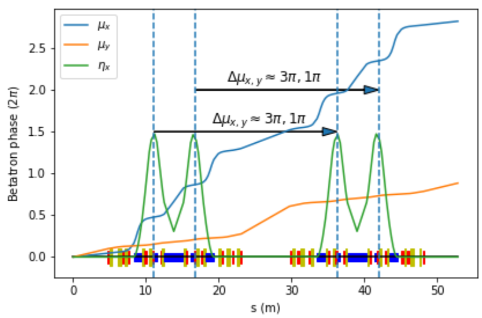


Figure 4: Interleaved betatron phase pattern within a supercell. Four dispersion bumps, inside of which the chromatic sextupoles are located, have a cross-cell interleaved phase cancellation scheme for both the horizontal and vertical planes.

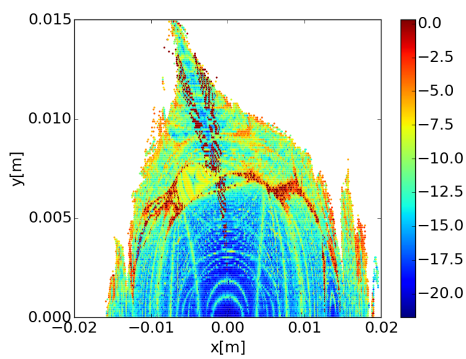


Figure 5: On-momentum dynamic aperture observed at the high $\beta$ straight section. The color represents the tune diffusion rate in turn-by-turn tracking.

For most of the nonlinear optics solutions obtained using MOGA, their energy acceptance are larger than the required beam lifetime. For the selected candidate, its energy acceptance at the horizontal plane is shown in Fig. 6. The nonlinear lattice can allow particles up to ±5% off-energy to survive. This cross-cell interleaved sextupole scheme also allows for on-axis longitudinal top-off injection mode in which a large energy acceptance is needed.

Thus far, chromatic sextupoles are grouped into 3 families within a cell. A preliminary study indicates that, by grouping them into six families, dynamic aperture and energy

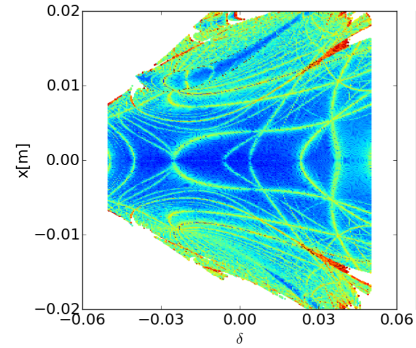


Figure 6: Energy acceptance at the horizontal plane.

acceptance could be further improved. Further investigation is ongoing.

## SUMMARY

A preliminary lattice scheme is presented as a potential candidate for a future upgrade of the NSLS-II. Even though there are many constraints to fitting the new lattice into the existing tunnel, while preserving beamline compatibility, a TBA lattice seems promising. The new design incorporates ideas used in designing 4$^{th}$ generation diffraction-limited light sources, such as using longitudinal gradient and reverse bends. Some preliminary tracking studies on an error-free model are positive. Sources of error including engineering imperfections on magnets and their supporting girders, implementation and integration of insertion devices , and simulating orbit/optics correction are currently being investigated.

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