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STUDY OF NONLINEAR BEAM DYNAMICS OF AN ASYMMETRIC NSLS-II LATTICE

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Abstract

NSLS-II is planning an upgrade to an ultra-low emittance storage ring using a novel lattice concept, the complex bend, composed of combined-function magnets. To evaluate technical challenges and study beam dynamics with complex bend, two bending magnets of existing NSLS-II bare lattice are proposed to be replaced with complex bends, introducing lattice asymmetry. To study the impact of asymmetry on NSLS-II bare lattice, an asymmetric lattice is developed by adjusting quadrupole triplets in the Cell 8 long straight section. This paper presents the modified linear optics, optimization of nonlinear dynamics, and a comparison with the nominal bare lattice. The optimized asymmetric bare lattice is also experimentally measured in the machine, and dynamic aperture measurements are reported.

INTRODUCTION AND MOTIVATION

In recent decades, storage ring light sources have developed rapidly toward achieving lower emittance, allowing for the generation of higher-brightness photon beams. One of the upgrade methods adopted in new-generation storage rings is the use of the complex bend, a novel magnet design first proposed for the NSLS-II upgrade [1]. The complex bend has experienced several stages of development: it started as a series of short dipole magnets interleaved with strong quadrupoles [2], then evolved to a layout where quadrupoles are transversely shifted to create dipole fields [3], and finally reached the current design using permanent magnets with combined magnetic fields, either of the Halbach type or Hybrid type [4, 5]. Using this latest version of the complex bend, low-emittance storage ring designs have been developed for the NSLS-II upgrade at beam energies of 3 GeV [6] and 4 GeV [7].

To assess the potential limitations and technical challenges introduced by the complex bend lattice, we propose a near-term plan to replace the two bending magnets in a single NSLS-II lattice supercell with complex bends. This modification will allow us to study the beam dynamics involving complex bends during regular machine operation. However, the change breaks the symmetry of the current NSLS-II lattice. To minimize this impact on normal operations, it is essential to maintain high injection efficiency and a long beam lifetime in the resulting asymmetric lattice. In this study, an asymmetric NSLS-II lattice was created by adjusting only the quadrupole triplets within the Cell 8 long straight section. This paper presents both simulation and experimental results on the nonlinear beam dynamics of the modified lattice. The results indicate that performance degradation caused by the lattice change can be improved through further optimization. These studies pave the way for the future upgrade of NSLS-II to a complex bend-based lattice.

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ASYMMETRIC NSLS-II LATTICE

The NSLS-II storage ring lattice consists of 30 cells, each configured with a double-bend achromat (DBA) lattice structure [8]. The NSLS-II lattice is designed with 15 superperiods, where each superperiod contains one long and one short straight section. In the development of an asymmetric NSLS-II lattice, beta functions were modified within the Cell 8 long straight section by adjusting the strengths of the quadrupole triplets located in that region. The quadrupole strengths before and after the change are presented in Table 1. As a result of this change, the lattice tunes deviated from those of the operational NSLS-II lattice. To restore the desired fractional tunes to $(\nu_x, \nu_y) = (0.22, 0.26)$, slight adjustments were made to the quadrupole triplets in the long straight sections of other cells. Figure 1 shows layout of the developed asymmetric NSLS-II lattice, where the black dashed box indicates the region where the beta functions were modified as a result of changes in the strengths of the quadrupole triplets.

Table 1: Strengths of Quadrupole Triplets Within the Cell 8 Long Straight Section Before and After the Lattice Modification

Quadrupole	K1 [m^{-2}] (before)	K1 [m^{-2}] (after)
QH1G6C07B/ QH1G2C08A	-0.641957315	-1.123111246
QH2G6C07B/ QH2G2C08A	1.436730571	1.632228331
QH3G6C07B/ QH3G2C08A	-1.753550425	-1.721123947

NONLINEAR LATTICE OPTIMIZATION

Due to the modification of the linear optics in the developed asymmetric NSLS-II lattice, the performance of nonlinear beam dynamics has degraded, as illustrated in Fig. 2. Consequently, it is necessary to optimize the asymmetric bare lattice to improve the nonlinear beam dynamics performance, specifically by achieving sufficiently large dynamic aperture (DA) and momentum aperture (MA).

In the DA and MA optimization process, the harmonic sextupoles SH1, SH3, and SH4 located in the long straight section of Cell 8 are optimized independently. The strength of each harmonic sextupole is constrained within the current operational threshold of 40 T/m^2. Optimization is carried

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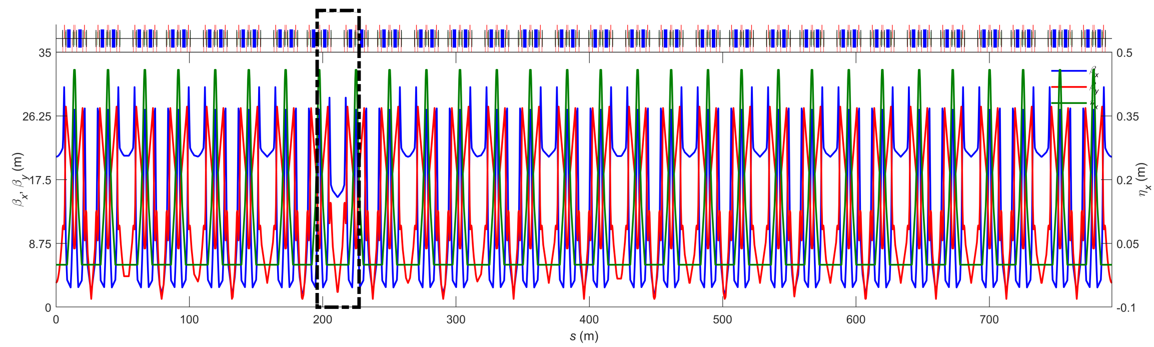

Figure 1: Layout of the asymmetric NSLS-II lattice. The black dashed box highlights the region where the beta functions were modified as a result of changes in the strengths of the quadrupole triplets.

Table 2: Strengths of Harmonic Sextupoles Before and After the Nonlinear Lattice Optimization

Sextupoles	K2 [m^{-3}] (before)	K2 [m^{-3}] (after)
SH1G6C07B/ SH1G2C08A	19.8329121	29.72281
SH3G6C07B/ SH3G2C08A	-5.855108411	-1.505269
SH4G6C07B/ SH4G2C08A	-15.820900707	-28.47633
rest SH1	19.8329121	21.49651
rest SH3	-5.855108411	-5.020804
rest SH4	-15.820900707	-12.24733
SL1	-13.271606055	-19.547
SL2	35.677921453	35.50194
SL3	-29.460860606	-29.72747

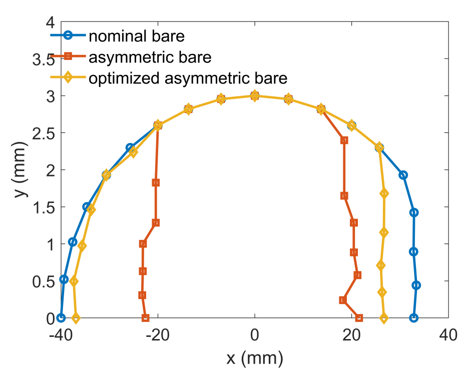

Figure 2: Comparison of the dynamic aperture for the bare lattice, the unoptimized asymmetric lattice, and the optimized asymmetric lattice.

out by simultaneously improving both DA and MA. The dynamic aperture and momentum aperture are evaluated by calculating, respectively, the maximum stable area in the transverse x-y plane and the maximum momentum deviation at the injection point.

Following optimization, a solution is selected based on its overall performance in terms of both DA and MA. The harmonic sextupole strengths before and after optimization are summarized in Table 2. After implementing the optimized

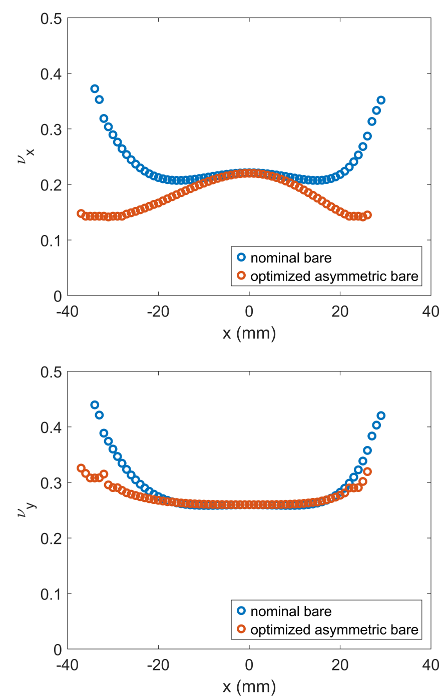

Figure 3: Comparison of tune shift with amplitude for the nominal bare lattice and the optimized asymmetric bare lattice.

sextupole settings, the dynamic aperture of the asymmetric bare lattice is successfully improved, as shown in Fig. 2.

To further assess the performance of the optimized asymmetric lattice, tune shifts with respect to amplitude and momentum are analyzed and compared to those of the bare lattice, as shown in Fig. 3 and Fig. 4, respectively.

EXPERIMENTAL MEASUREMENTS

To demonstrate the effectiveness of the optimized asymmetric NSLS-II lattice found in simulation, experimental tests were conducted on the real machine. The harmonic sextupoles were ramped to the optimized strengths listed in Table 2, and the dynamic aperture was measured by scanning the kicker voltage in both the horizontal and vertical planes. Figure 5 presents a comparison of the experimental dynamic aperture measurements for the nominal bare lattice and the

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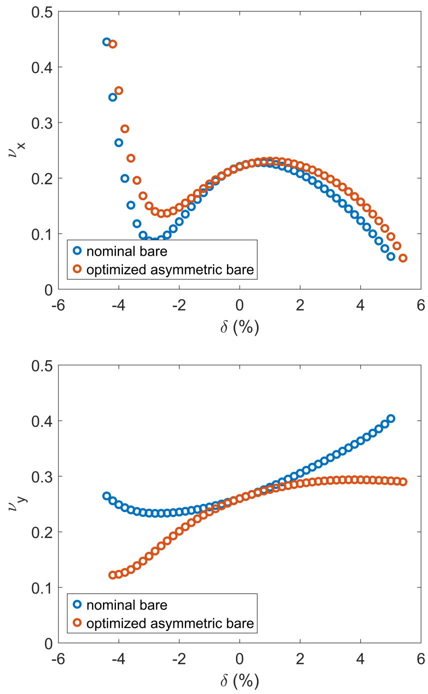

Figure 4: Comparison of tune shift with momentum for the nominal bare lattice and the optimized asymmetric bare lattice.

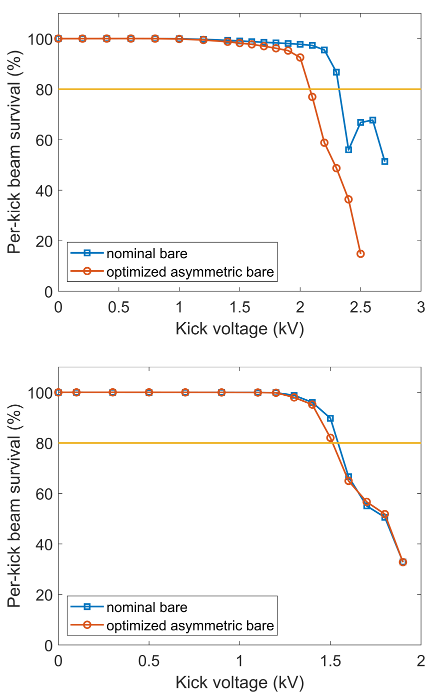

Figure 5: Comparison of experimental dynamic aperture measurements in the horizontal (top) and vertical (bottom) planes for the nominal bare lattice and the optimized asymmetric bare lattice. The yellow line indicates the minimum required injection efficiency.

optimized asymmetric lattice. The results indicate that the horizontal dynamic aperture is slightly reduced, while the vertical dynamic aperture is well preserved.

CONCLUSION

In this work, an asymmetric NSLS-II bare lattice was developed to study the effects of asymmetry on nonlinear beam dynamics. The introduction of asymmetry led to reduced performance in nonlinear beam dynamics. To improve this, the lattice was optimized to increase both the dynamic aperture and momentum aperture. The performance of the optimized asymmetric lattice was compared with the bare lattice and demonstrated through experimental measurements.

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