DESIGN OF COMPLEX BEND MAGNET FOR TESTING AT NSLS-II STORAGE RING

M. Song*, J. Choi, B. Kosciuk, P. N'gotta, T. Shaftan, S. Sharma, R. Todd, G. Wang,
Brookhaven National Laboratory, Upton, United States
M. Seegitz, National Synchrotron Light Source II, Upton, United States

Abstract

A novel Complex Bend (CB) magnet design has been developed at NSLS-II to support the future storage ring upgrade toward near-diffraction-limited performance. The CB concept replaces conventional dipole electromagnets with compact permanent-magnet combined-function elements, providing both strong focusing and bending within a single curved assembly. The NSLS-II upgrade will implement 120 CBs to achieve a low emittance of 15 pm · rad at 4 GeV, while preserving 8.8 m-long straight sections and reducing the ring magnet power consumption by about 70 %. To further validate the CB approach as a reliable, high-performance solution for next-generation synchrotron light sources, two existing dipoles in the NSLS-II storage ring will be replaced with CBs while maintaining normal operations. The lattice design should preserve the existing tunnel geometry, minimize modifications to power supplies and optics, provide sufficient dynamic and momentum apertures for off-axis injection, and be tolerant to errors. This paper provides an overview of the design considerations for the CB installation.

INTRODUCTION

NSLS-II is one of the third-generation storage ring light sources worldwide. It currently serves 29 state-of-the-art beamlines and covers a broad spectral range from infrared to hard X-rays. The accelerator is a 3 GeV electron storage ring with a beam emittance of 1 nm·rad when three damping wigglers are included. The storage ring consists of 30 cells, each based on a double-bend achromat (DBA) lattice structure [1]. In addition to operating the NSLS-II accelerator and supporting the development of new beamlines, NSLS-II is also exploring an upgrade to achieve higher-brightness photon beams by reducing beam emittance. Instead of following the multi-bend achromat approach [2], we propose an alternative optics solution based on a lattice element called the "Complex Bend (CB)" [3]. To demonstrate the CB concept, a prototype was developed and tested using the NSLS-II linac beamline [4]. The beam energy was scaled from 100 MeV to 200 MeV while maintaining strong focusing. The prototype used a 16-wedge symmetric Halbach permanent magnet design and achieved a gradient of 140 T/m in ultra-compact quadrupoles. In addition, permanent-magnet-based dipole–quadrupole combined-function magnets (PMQs), using either Halbach or hybrid designs, have been developed for the NSLS-II upgrade [5]. To further validate the CB approach as a reliable, high-performance solution for the NSLS-II upgrade, it is necessary to test the resilience of permanent magnets under operational conditions, including temperature and radiation. Recently, a new installation project was initiated to replace two existing dipoles in the NSLS-II storage ring with CBs. This project will provide a functional, long-term demonstration of the CB concept in an operational 3 GeV storage ring and will use beam position monitors (BPMs) in the NSLS-II ring to study beam dynamics with CBs. The CB installation project includes the following goals: (1) Develop and demonstrate the accelerator design of CBs and their integration into the NSLS-II ring lattice; (2) Predict the major impact of mechanical and magnetic constraints on the ring lattice through a beam study, using scrapers and 8-pole magnets to simulate the changes imposed by CBs in the ring; (3) Build and characterize two CBs and verify that they meet the required specifications using mechanical and magnetic measurement benches; (4) Install the CBs in the tunnel and prepare the ring for operation in a single shutdown; (5) Characterize the performance of the CBs and the modified ring lattice. However, there are still constraints on the CB installation: (1) Simplify tunnel installation for dipole and CB swap by keeping the beam entry and exit coordinates unchanged and avoiding modifications to devices on other girders; (2) Meet the minimum required local physical aperture of the CBs of 18 mm; (3) Use a symmetric dipole replacement scheme to maintain overall optics symmetry; (4) Match the local CB optics to the NSLS-II ring lattice while keeping the nearby quadrupole gradients within limits; (5) Achieve a sufficient dynamic aperture (DA) and momentum aperture (MA) for off-axis injection and adequate beam lifetime; (6) Minimize changes in the sextupole power supply by using three pairs of local power supplies for six sextupoles, independent of the shared pentant circuit; (7) Ensure that the lattice is tolerant to magnetic field errors and misalignment.

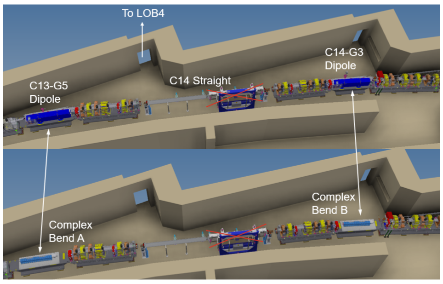

Figure 1: Schematic layout of the dipole replacement with CB magnets in Cells 13 and 14 of the NSLS-II storage ring.

---

[*] msong1@bnl.gov

To meet these goals within the constraints, we selected dipoles in Cells 13 and 14 for local replacement with CBs, as shown in Fig. 1. The main challenges include managing the strong focusing from high-gradient CB elements, controlling the optics distortions, maintaining sufficient DA and MA, and ensuring robustness to field and alignment errors. The remainder of this paper presents our design considerations, including lattice, magnets, vacuum chamber, beam scraper, and 8-pole corrector.

ACCELERATOR DESIGNS

Lattice Development

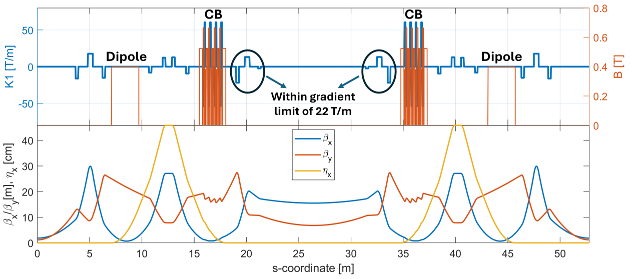

Figure 2: Lattice with CBs and the corresponding Twiss functions in Cells 13 and 14.

The lattice development focuses on integrating the CB magnets into the existing NSLS-II storage ring while preserving overall machine performance. The CB concept consists of an array of PMQs with alternating focusing and defocusing gradients. In designing the CB field layout, several constraints must be considered. The CB replaces a 2.62 m dipole in NSLS-II with a bending angle of 6 degrees, while maintaining the same beam entry and exit coordinates. To achieve this, the CB includes both focusing and defocusing PMQs, as well as pure dipole elements to provide the required bending angle and to match the floor coordinates. In addition, to reach pole-tip fields comparable to those planned for the future upgrade, the focusing and defocusing PMQs are placed close together with a distance similar to the pole distance for the future upgrade. The CB elements introduce strong, high-gradient fields that significantly modify local optics. To compensate for these effects, nearby quadrupoles are re-tuned to match the local optics, while keeping their gradients within the limit of 22 T/m and maintaining global parameters such as tunes and chromaticities within acceptable ranges. Figure 2 shows the developed lattice with CBs and the corresponding Twiss functions in Cells 13 and 14. The CB fields and gradients are higher than those of the existing dipoles and quadrupoles. In addition, the CB replacement breaks the ring symmetry, requiring re-optimization of nonlinear beam dynamics to preserve sufficient DA and MA for off-axis injection and adequate beam lifetime. The harmonic sextupole settings near the CBs are locally adjusted to minimize changes to the existing power supply configuration. Robustness to magnetic field imperfections and alignment errors is also evaluated through sensitivity studies to ensure stable operation under realistic conditions.

Magnets Design

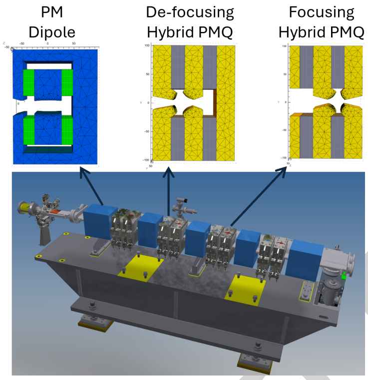

Figure 3: Layout of the CB assembly, including pure dipoles and hybrid PMQs with focusing and defocusing gradients, mounted on a girder.

Figure 3 shows the schematic layout of the CB assembly, including pure dipoles, de-focusing hybrid PMQs, and focusing hybrid PMQs, mounted on a girder, where the magnetic design of the CB PMQs is based on the hybrid type. The CB PMQs are developed to achieve a pole-tip field that is consistent with the performance of the future upgrade. The magnet design is closely related with the vacuum chamber to ensure compatibility with aperture constraints and installation requirements. The field quality of 10 units is expected to be achieved after magnet assembly with field correction possibility with iron shims. The SmCo17 permanent magnet material is selected for its proven radiation resistance, and the pole material is ASI1006 low carbon iron. Through iterative optimization in the design phase, both the required field strength and gradient are achieved while maintaining high field quality. The field and gradient adjustment, as well as temperature compensation, will be implemented to allow fine tuning and mitigate thermal effects on magnet performance. Magnetic cross-talk between closely spaced CB elements is also an important consideration. It arises from interactions between adjacent magnets, leading to deviations in the field, gradients, and higher-order harmonics, which can affect beam optics. These effects will be corrected using shims to restore the integrated field and gradient of each PMQ and to reduce harmonic distortions.

Vacuum Chamber

The CB vacuum chamber design is currently in progress and follows a concept similar to that developed for a prior prototype CB. A preliminary design of the vacuum chamber is shown in Fig. 4. The chamber includes an 18 mm diameter beam pipe to meet beam dynamics requirements at the CB locations. An anti-chamber is incorporated to accommodate non-evaporable getter (NEG) pumping, providing efficient vacuum performance. The design also includes an extraction slot for the synchrotron radiation fan and provisions

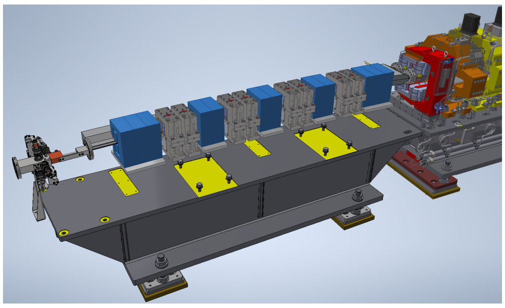

Figure 4: Preliminary design of CB vacuum chamber.

for X-ray beam extraction. Instrumentation and protection elements are integrated into the chamber layout, including two BPM locations, a crotch absorber, and an ion pump. Mechanical considerations are also critical. The chamber includes mounting features for high-stability supports, and its profile allows for ±0.5 mm horizontal motion of the PMQs to support alignment and tuning.

Beam Scraper

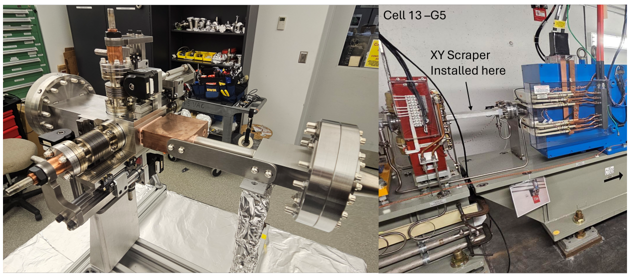

Figure 5: Design of the XY scraper and its installation location in the NSLS-II storage ring.

As part of the CB installation project, a dedicated XY scraper will be designed, constructed, and installed in the early part of the schedule to explore the operational aperture at the planned CB location. A key requirement in the CB magnet design is the bore radius, which sets the upper limit of the magnetic field strength and scales inversely with the square of the radius. The bore radius must be larger than the vacuum chamber radius, with sufficient clearance for mechanical alignment. Although a smaller aperture is desirable to maximize the CB field strength, it must also allow reliable storage ring operation. The proposed XY scraper enables independent control of the horizontal and vertical apertures, allowing us to determine the minimum aperture that without significant loss of beam lifetime or injection efficiency. It will establish a direct link between simulation, beam studies, and experimental validation at the CB location. As shown in Fig. 5, the XY scraper will be installed at Girder 5 in Cell 13. The design includes a transition from the standard chamber aperture (25 mm vertical × 76 mm horizontal) to a reduced circular aperture of 18 mm, consistent with the CB vacuum chamber. It also includes a chamber section to accommodate a 22 mm bore, 8-pole corrector magnet, as well as a support structure for the cantilevered assembly. In addition, the scraper serves as a protective device to reduce radiation exposure to the CB magnets.

8-pole Corrector

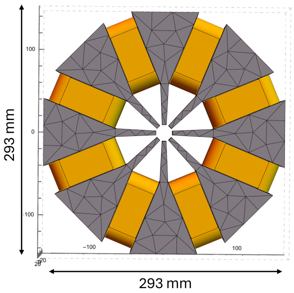

Figure 6: Schematic design of multipole corrector.

Unlike conventional electromagnets, CB magnetic errors cannot be dynamically adjusted during operation. As shown in Fig. 6, a dedicated 8-pole corrector will be designed and installed next to the CB to reproduce CB-like magnetic perturbations before CB installation. Each corrector provides independent control of the normal and skew multipoles from dipole to octupole order (N=1-4) for local correction. This enables beam-based studies of their impact on orbit, optics, injection efficiency, and beam lifetime. The CB alignment and field errors are translated into equivalent 8-pole corrector specifications and the corrector strength is selected to cover the expected error range. This provides a basis for both error sensitivity studies and correction tests. The same corrector can be later used for local error compensation.

CONCLUSION AND OUTLOOK

In this paper, we present the design and integration of CB magnets in the NSLS-II storage ring, including lattice, magnet, and vacuum chamber designs. Dedicated tools, such as an XY scraper and 8-pole correctors, are used to enable beam-based validation of aperture and magnetic error effects. Installation will involve replacing two existing dipole girders with CB girders. The CB girders will be precisely positioned and surveyed. During commissioning, the multipole correctors will be used to test and refine local correction schemes. In operation, the CB magnets will be evaluated under realistic conditions, including long-term exposure to beam losses and radiation. Their impact on injection efficiency, beam lifetime, and overall machine stability will be assessed. These results will provide critical validation of the CB approach and support future large-scale implementation in the NSLS-II upgrade.

ACKNOWLEDGEMENT

This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-SC0012704 and Field Work Proposal No. PS043.

REFERENCES

[1] K. Robinson, “Conceptual design report”, Brookhaven National Laboratory, Upton, NY, USA, Rep., 2006. doi:10.2172/910923

[2] D. Einfeld, J. Schaper, and M. Plesko, “Design of a diffraction limited light source (DIFL)”, in *Proc. PAC’95*, pp. 177–179, 1995. doi:10.1109/PAC.1995.504602

[3] T. Shaftan, V. Smaluk, and G. Wang, “Concept of the complex bend”, Brookhaven National Laboratory, Upton, NY, USA, Rep., 2018.

[4] G. Wang *et al.*, “Commissioning of the complex bend prototype beamline”, in *Proc. NAPAC’25*, pp. 977–980, 2025. doi:10.18429/JACoW-NAPAC2025-THP019

[5] P. N’gotta *et al.*, “Development of combined-function dipole-quadrupole PMQ magnets for NSLS-II upgrade”, in *Proc. NAPAC’25*, pp. 744–747, 2025. doi:10.18429/JACoW-NAPAC2025-WEP027