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COMPLEX BEND PROTOTYPE COMMISSIONING RESULT*

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Abstract

For the NSLS-II upgrade, a novel Complex Bend (CB) optics solution has been proposed to achieve near-diffraction-limited emittance. A key challenge in this design is the requirement for high-gradient quadrupoles (150 T/m) in a compact space. To demonstrate feasibility, a CB prototype was developed and tested using the NSLS-II linac beamline, scaling the beam energy to 100–200 MeV while maintaining strong focusing. The prototype utilized a 16-wedge symmetric Halbach permanent magnet design, achieving a gradient of 140 T/m within ultra-compact quadrupoles. The CB beamline was installed and commissioned in two phases, first as a strong periodic focusing element and later as a combined bending and focusing system. The beam commissioning results showed good agreement with theoretical models, confirming that the Complex Bend functions effectively as both a strong focusing and bending element by offsetting CB poles. This validates the strong focusing design of the Complex Bend for future synchrotron light source upgrades.

INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV, third-generation light source at Brookhaven National Laboratory with an emittance at 1 nm-rad in the horizontal plane and 8 pm-rad vertically, providing high brightness. It has been in operation since 2015 and has steadily increased both the beam current and the number of beamlines while maintaining high operational reliability. Currently, there are 29 beamlines in routine operation at a beam current of 500 mA.

To further increase photon brightness and coherence, low emittance is highly desired to enhance experiments' imaging resolution, coherence, scan time, etc. For NSLS-II future upgrade, we explored one optics solution to approach diffraction-limited emittance, using a novel concept, 'complex bend' element [1-3]. Complex Bend (CB) is a sequence of dipole poles with strong alternate focusing to maintain the beta-function and dispersion oscillation at low values. Using Complex Bends instead of regular dipoles in the ring lattice will minimize the $\mathcal{H}$-function and reduce horizontal emittance, while localizing bending to a small portion of the storage ring circumference, thereby freeing more space for insertion devices.

In the complex bend lattice design, a major challenge is achieving the high-gradient focusing quadrupoles of 150 T/m within a compact space. To prove the the feasibility of the full-scale CB for a 3 GeV machine, we designed a prototype of CB by scaling beam energy down to 100-200 MeV while preserving high-gradient focusing for experiments using NSLS-II linac beam. We scaled the Complex Bend parameters from 3 GeV down to 100 MeV, which corresponds to a reduction in magnetic rigidity (BR) by a factor of $C_E = 0.033$. We also reduced the quadrupole pole length by a factor of $C_L = 6$ while keeping the values of bend angle and $\sqrt{K_1}L_Q$ the same as for the 3 GeV CB cell. The drift between the poles is reduced by a factor of 2, considering the space limitations. The CB prototype pole is 46 mm long and consists of four cells, with the field gradient at 150 T/m. The dipole component is realized by offsetting quads in ~mm. Table 1 compares the bend magnet parameters for NSLS-II lattice, upgraded CB lattice scaled prototype.

Table 1: Bending Magnets Parameters

	NSLS-II Dipole	**3 GeV CB**	**100-200 MeV Prototype**
Length (m)	2.6	3.1	0.50
Cell Length (cm)	-	62	12.3
Bending Angle per Cell (°)	6	1.2	1.2
Gradient (T/m)	0	250/-250	150/-150
β_{Xmax} / β_{Xmin} (m)	3.7/0.7	0.94/0.22	0.22/0.09
η_{max} / η_{min} (mm)	137/0	4.41/8.52	0.5/0.3

PROTOTYPE OF COMPLEX BEND

To achieve the required high gradient, we adopted a standard 16-wedge symmetric Halbach permanent magnet quadrupole (PMQ) design [4]. As shown in Fig. 1, the overall dimensions of each pole is 46.7 mm (L) × 43.75 mm (W) × 40 mm (H), with a 12.7 mm quad aperture and 8 mm vacuum aperture.

We built a total of nine poles, eight of which were used for the 4-cell CB prototype beamline test. Figure 2 shows the magnetic measurement results. The integrated field ranges from 6.45 to 6.50 T, compared to the specification of 7.05 T. The measured gradient ranges from 137 to 139 T/m, against the specified 149.6 T/m. However, the field variation among the 9 quads is small, <1% difference, with an average gradient of 139.1 +/- 0.6 T/m. Therefore,

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although the gradient is lower than specified, the impact on the optics is small.

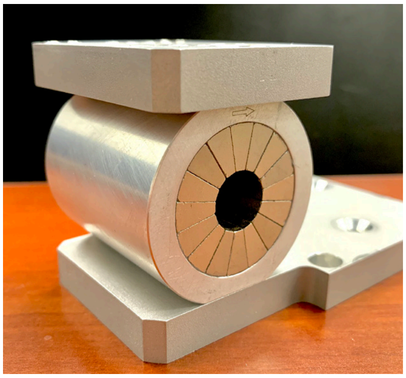

Figure 1: Prototype CB mounted on translation stage.

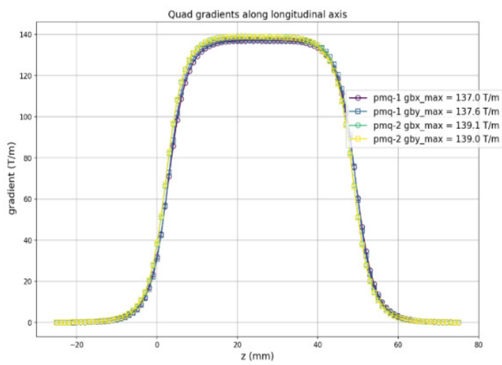

Figure 2: Measurement of CB field gradient.

Figure 3 shows one period of stable optics for a 100 MeV beam with 140-T/m strong focusing quads. The drift space between poles is 1.5 cm. The minimum beta function is ~0.1 m with dispersion on the order of a few mm. Scaling up beam energy will increase the beta function, but still yield a stable, periodic optical solution.

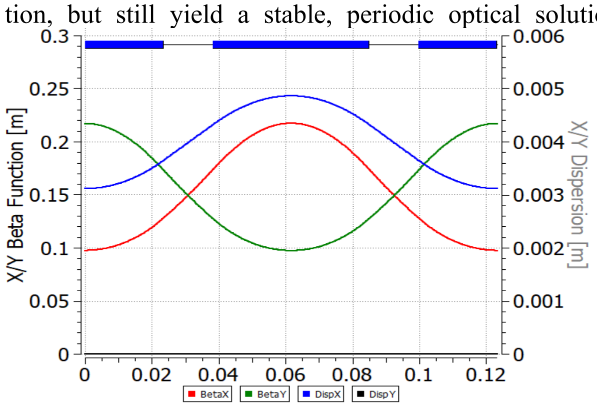

Figure 3: Stable optics for one cell CB at 100 MeV.

CB PROTOTYPE TEST BEAMLINE DESIGN

To verify the strong focusing and bending properties of the CB with a matched periodic optical solution, we designed a beamline with new elements to replace one of the diagnostic beamline [5] at the end of the NSLS-II linac, as shown in Fig. 4. The switching dipole is used to control the beam between the normal operation beamline and the complex bend (CB) prototype test beamline. The CB test beamline includes six quadrupoles to adjust and match the optics for different beam energies from the linac and various CB optical solutions. There are four correctors to control the beam trajectory passing through the CB and multiple diagnostics (three flags, two slits, and a high-resolution flag capable of resolving a few microns). Each CB pole is mounted on a translation stage for fine tuning and alignment of the complex bend.

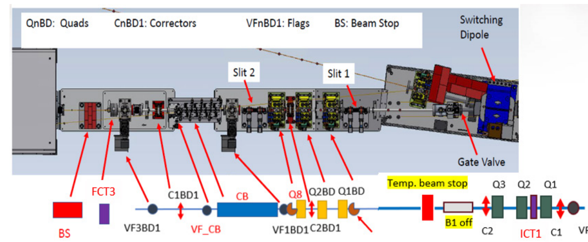

Figure 4: Layout of complex bend prototype test beamline.

The NSLS-II linac [6] has the flexibility to vary the beam energy from 100 to 200 MeV. At 200 MeV, the beam energy spread is about 0.5%, and the geometric emittance is roughly 70 nm-rad. The bunch charge can vary up to 15 nC, with bunch structures ranging from single-bunch mode to 100 s bunches. The optics vary with both energy and charge. Figure 5 shows one example of matched optics between the linac and the CB along beamline.

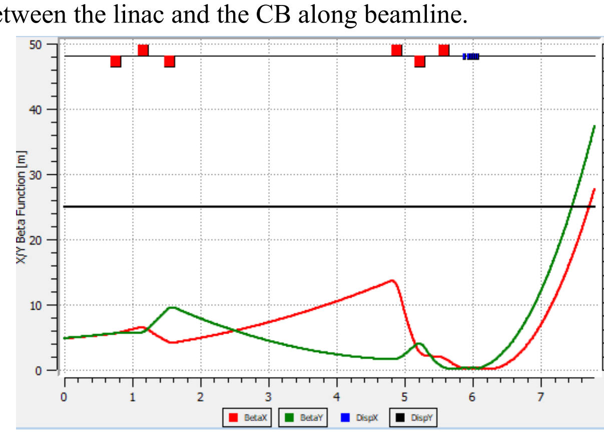

Figure 5: Test beamline optics.

The beamline commissioning was carried out in two phases. In Phase I, the CB served purely as a strong periodic focusing system, with the beam passing through the center of each quadrupole. In Phase II, the CB functioned as a combined bending and focusing element by offsetting the CB poles. Each pole was intentionally shifted by approximately 1 mm from the quadrupole center, generating a bending angle of 0.8 degrees per CB period (as shown in Fig. 6). The resulting beam trajectory, illustrated in Fig. 7, showed a cumulative bend of 3.2 degrees, with the quadrupole center in the final period displaced by about 13 mm from the straight-line path. The offset quads posed a significant challenge for the 8-mm vacuum chamber, compared to the 12.7-mm aperture of the quadrupoles. To address this, a flexible vacuum chamber was implemented, capable of adapting to the curved beam path and returning

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to its original shape without distorting the vacuum chamber or compromising vacuum performance.

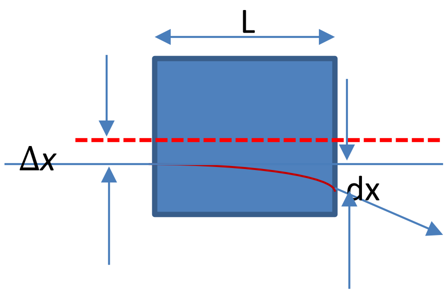

Figure 6: Phase II to shift quad center as a bending magnet.

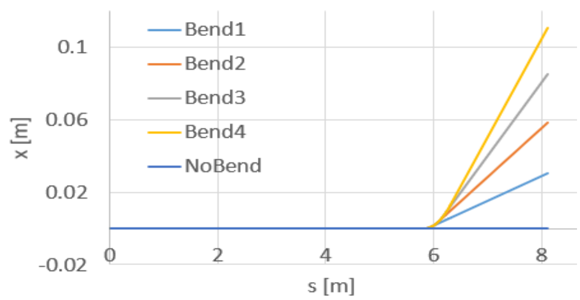

Figure 7: Phase II, beam bend with 1 to 4 periods CB.

BEAMLINE COMMISSIONING RESULTS

Commissioning began in Jan. 2023 with a CB period, conducted during beam study time to minimize the impact on NSLS-II operations. Figure 8 shows the CB installation in the linac tunnel.

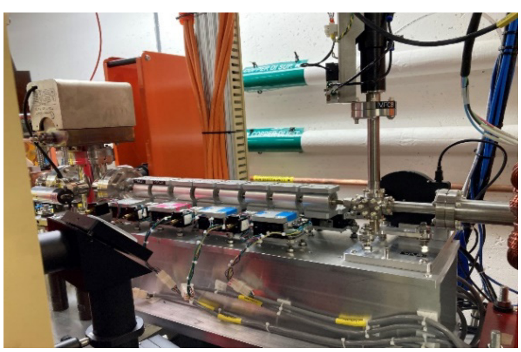

Figure 8: CB installation in tunnel.

Phase I focused on matching the CB optics as a strong-focusing quadrupole. Beam matching was achieved through both offline (Twiss characterization) and online optimization using RCDS [7] and Badger [8]. At 168 MeV, the beam energy spread was 0.55% with emittances of 57/70 nm-rad (X/Y). Twiss parameters were measured via quad scans upstream of the CB. Matching optics with Elegant and applying the nominal quadrupole settings to the live machine yielded beam sizes of 76/100 µm (X/Y), close to the theoretical values of 67/134 µm. Further tuning with RCDS and Badger improved the beam sizes to 72/91 µm (Fig. 9) [9].

During Phase II commissioning, the CB poles were installed with a predefined offset center to study the complex bend's impact as a combined bending and strong-focusing magnet. As expected, the beam trajectory followed the designed path very well. At the end of the beamline, the beam was deflected by 11 cm on the diagnostic flag, confirming a 3.2-degree bend angle resulting from the CB quadrupole offset effect.

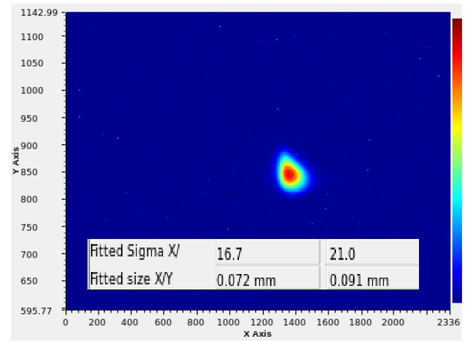

Figure 9: Optimized beam size after complex bend.

Each CB pole is mounted on a motorized stage, allowing precise adjustment of the quadrupole offset. We studied the impact of these offset kicks on beam position and nonlinear focusing effects by purposely shifting individual poles. As shown in Fig. 10, offsetting a single pole by 1.5 mm resulted in a downstream beam displacement of approximately 2.5 mm, confirming the expected bending behavior. The beam profile remained largely unchanged. The bending angle exhibited a strong linear correlation with the PMQ offset, consistent with theoretical predictions within 15%. These results validate that the CB offset introduces a significant bending effect while preserving its strong focusing function.

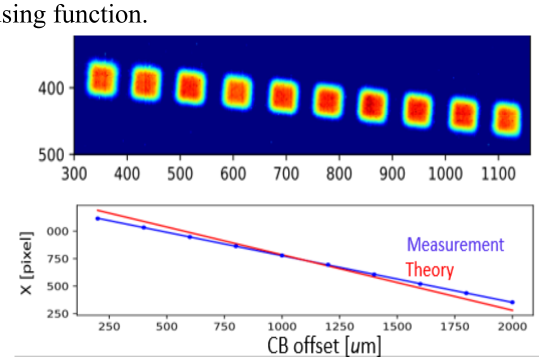

Figure 10: Complex bend offset impact on beam.

CONCLUSION

We designed and commissioned a prototype complex bend magnet and beamline to validate a novel low-emittance optics solution. The beam commissioning results demonstrated good agreement with theoretical models, confirming the feasibility of the complex bend for future synchrotron light source upgrades.

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