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COMPLEX BEND PROTOTYPE BEAMLINE DESIGN AND COMMISSIONING*

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Abstract

Modern synchrotron light sources are competing intensively to increase X-ray brightness and, eventually, approach the diffraction limit, which sets the final goal of lattice emittance. Recently, we proposed a new optics solution aimed at reaching low emittance, using a lattice element "Complex Bend". The Complex Bend is a sequence of dipole poles interleaved with strong alternate focusing so as to maintain the beta-function and dispersion oscillating at low values. By integrating this element at low emittance lattice, the designed emittance is around 20 pm-rad. To prove the feasibility of this new design, we have planned the key element prototype test, in the beam line with 168 MeV beam energy. We designed and fabricated the prototype complex bend, with gradient at 140 T/m. It is installed and commissioned at NSLS-II linac beamline. In this paper, we report the test beamline design and beam commissioning progress.

INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV, third generation light source at Brookhaven National Laboratory with emittance at 1 nm-rad in horizontal plane and 8 pm-rad, high brightness. It's been in operation since 2015, and steadily increase current and beamlines sources while maintain high operation reliability. Currently, there are 29 beamlines in routine operation at 400 mA beam current, while reached 500 mA in beam study.

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 limit emittance, using a novel concept, 'complex bend' element [1, 2, 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. Comprising the ring lattice of Complex Bends instead of regular dipoles will minimize the Ḥ-function and reduce horizontal emittance while localizing bending to a small fraction of the storage ring circumference, thus will provide more space for Insertion Devices.

In the complex bend lattice design, one challenge is the high gradient focusing quadrupoles, 150 T/m, in a compact space. To prove the the feasibility of the full-scale CB for 3 GeV machine, we designed a prototype of CB by scaling beam energy down to 100-200 MeV while maintain 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 lists the bend magnet parameters for NSLS-II, upgrade lattice with complex bend and scaled prototype CB.

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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 reach high gradient focusing quadrupoles, we choose the standard 16-wedge symmetric Halbach design with permanent magnet [4]. As shown in figure 1, the overall dimensions of 46.7 mm (L) * 43.75 mm (W) * 40 mm (H). The quads aperture is 12.7 mm with vacuum aperture at 8 mm.

Figure 1: Prototype CB from RadiaBeam.

We built 9 poles in total and 8 of them are used for 4 cells CB prototype beamline test. In figure 2, it showed

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magnetic measurement results. The integrated field is 6.45 ~ 6.50 T for a 7.05 T specification. The measured gradient is 137 ~ 139 T/m for a 149.6 T/m specification. However, the field variation among 9 quads is small, <1% difference and average gradient is 139.1 +/- 0.6 T/m. So even the gradient is lower than specification, the impact on optics is small.

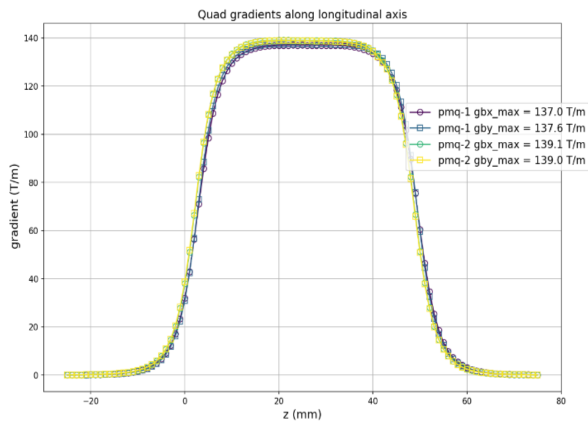

Figure 2: Measurement of CB field gradient.

In figure 3, it shows the stable optics at 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 a few mm. Scaling beam energy up will increase beta function, but still have stabilized periodic optical solution.

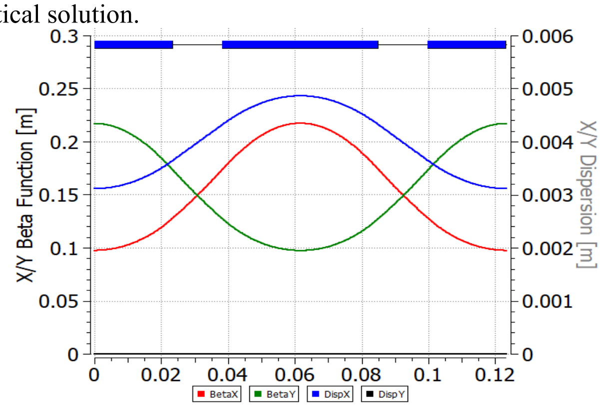

Figure 3: Stable optics for one cell CB at 100 MeV.

CB prototype test beamline design

To verify the strong focusing and bending property of CB with match period optical solution, we designed a beamline with new elements to replace one of the diagnostic beamline [5] at the end of NSLS-II linac, as shown in Figure 4. The switching dipole is to control beam between normal operation beamline and complex bend prototype test beamline. In CB beamline, it includes 6 quadrupoles to adjust and match optics from different beam energy from linac and different optical CB solution. There are four correctors to control beam trajectory passing though CB. The diagnostics includes three flags to measure beam profile and optics. There is a high-resolution flag to characterize beam focusing property after CB and can resolve a few µm. Besides that, we also install two slits before CB to trim beam profile as needed. The slits aperture can vary in a large range, to 9 mm in both planes. In each complex bend pole, there is a Translation Stage for fine tune and alignment of complex bend.

NSLS-II linac [6] has the flexibility to vary beam energy from 100 MeV to 200 MeV. At 200 MeV, beam energy spread is about 0.5% and geometric emittance at 70 nm-rad. The bunch charge can vary upto 15 nC with bunch structure from single bunch mode to 100s bunches.

At different charge, different beam energy, beam optics from linac changes. At different beam energy, the periodic solution of CB also changes. Figure 5 shows one example with matched optics between linac and CB along beamline.

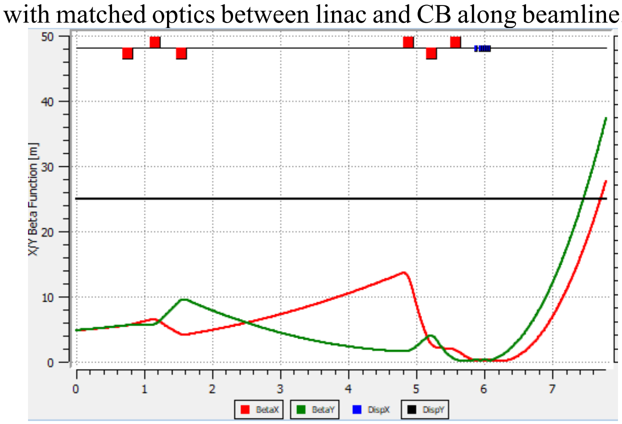

Figure 5: Test Beamline optics.

This beamline commissioning includes two phases. In phase I, CB functions as strong periodic focusing quadrupoles with beam passing through CB center. In phase II, CB functions as both bending and focusing element by offset CB poles. The designed offset of CB poles is about 1 mm to generate bending angle, 1.2 degree C for one period of CB. In each phase, we vary and install different number of periods of CB to prove the field quality variation impact.

Beamline commissioning progress

The beamline installation was finished in Jan. 2023 with one period of CB. Beam commissioning started thereafter. The CB beam commissioning is limited to beam study period while prioritize NSLS-II operation related studies.

To match beam optics to complex bend, we used two ways, offline model-based optimization by characterizing beam twiss parameters and online optimizer using Robust Conjugate Direction Search (RCDS), which was developed at SPEAR3, SLAC using Matlab [7].

We optimized linac with small energy spread at nominal beam energy, 168 MeV. We measured beam energy and energy spread at dispersion beamline. At upstream of CB beamline, we use quads scan method to measure Twiss parameters. The energy spread is 0.55% with beam emittance (X/Y) at 57 nm-rad/ 70 nm-rad.

With measured Twiss parameters and beam energy, we can retrieve the related values at beginning of complex bend beamline using quads unit conversion. Beam energy defines the periodic optics solution of complex bend. Based on both sides' optics, we used Elegant to match optics with two triplets/six quads. Lastly, we applied the optimized

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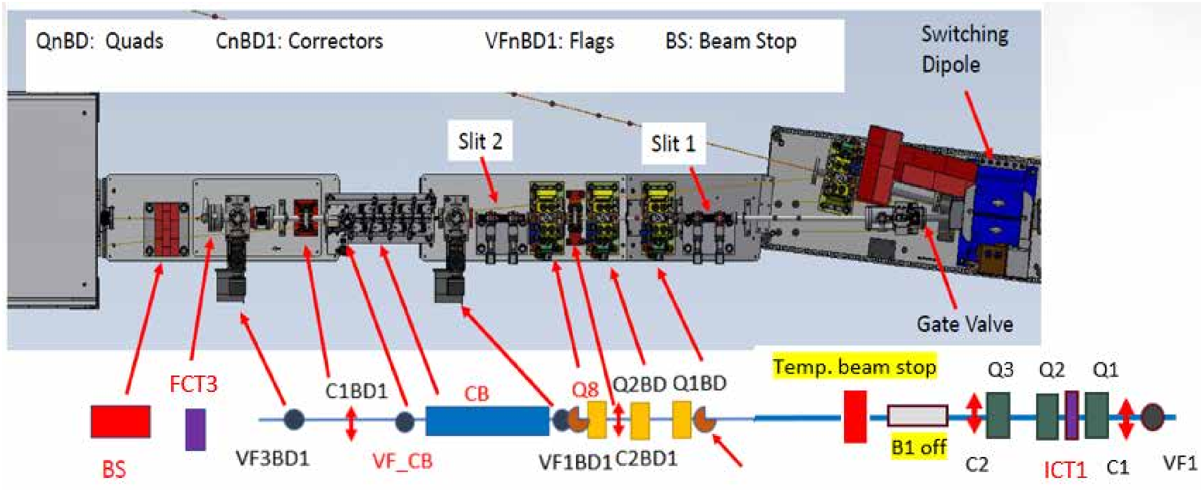

Figure 4: Layout of complex bend prototype test beamline.

quads strength to live machine. This method relies on magnet unit conversion. As a result, the beam size is close to predicted value but need further tune. Overall, we reached beam size at 76/100 µm (X/Y) after CB, while the ideal beam size is 67/134 µm.

Based on offline model working point, we applied RCDs to further optimize beam profile and reached 72 um/91um (X/Y) after CB, as shown in figure 6.

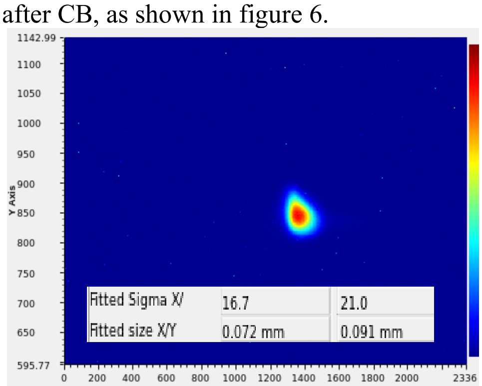

Figure 6: Optimized beam size after complex bend.

We also studied complex bend offset impact on beam position and nonlinear focusing effect by moving the complex bend poles. As shown in Figure 7, by moving one pole 1.5 mm, we can see beam in the downstream shift about 2.5 mm from bending effect. Besides that, the CB pole movement in x plane is coupled with y plane. The beam profile does not show obvious change.

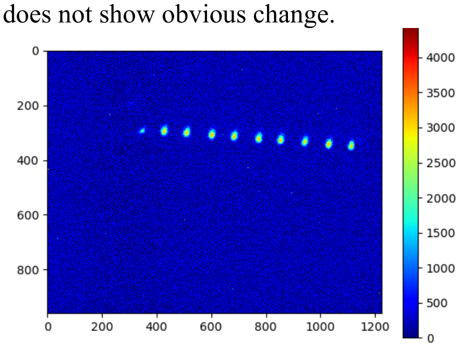
Figure 7: Complex bend offset impact on beam.

CONCLUSION

To verify the ideal of complex bend for low emittance lattice, we designed prototype complex bend and the test beamline. The initial beam commissioning result showed good agreement with model. Further studies will be conducted with more period of CB and at different beam energy to study the strong focusing effect and bending effect.

ACKNOWLEDGMENT

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REFERENCES

[1] G. Wang *et al.*, “Complex bend: Strong-focusing magnet for low-emittance synchrotrons,” *Physical Review Accelerators and Beams*, vol. 21, no. 10, 2018. doi:10.1103/physrevaccelbeams.21.100703

[2] G. Wang *et al.*, “Complex bend. II. A new optics solution,” *Physical Review Accelerators and Beams*, vol. 22, no. 11, 2019. doi:10.1103/physrevaccelbeams.22.110703

[3] G. M. Wang *et al.*, “Reaching Low Emittance in Synchrotron Light Sources by Using Complex Bends”, in *Proc. NA-PAC'19*, Lansing, MI, USA, Sep. 2019, pp. 352-355. doi:10.18429/JACoW-NAPAC2019-TUZBB2

[4] S. K. Sharma, “Development of Advanced Magnets for Modern and Future Synchrotron Light Sources”, presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper THIYSP1, unpublished.

[5] G. M. Wang *et al.*, “Preparation for NSLS II Linac to Booster Transport Line Commissioning”, in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper MOPPR094, pp. 1002-1004.

[6] R. P. Fliller *et al.*, “Results of NSLS-II Linac Commissioning”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPWA083, pp. 2301-2303.

[[7] X. Huang, J. Corbett, J. Safranek, and J. Wu, “An algorithm for online optimization of accelerators”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 726, pp. 77–83, Oct. 2013. doi:10.1016/j.nima.2013.05.046