PARAMETER OPTIMIZATION OF A NOVEL EMITTANCE COMPENSATION SCHEME FOR THE HALF STORAGE RING*

Xiaoyu Liu, Zhenghe Bai†, Gangwen Liu, Zhouyu Zhao
National Synchrotron Radiation Laboratory, USTC, Hefei, China

Abstract

The Hefei Advanced Light Facility (HALF) is a diffraction-limited storage ring light source, and the random adjustments in insertion device gaps can result in significant beam emittance variations. In prior work, we introduced a novel emittance compensation scheme based on the quantum excitation effect, utilizing a short variable-gap wiggler and a fixed dispersion. This paper investigates the influence of wiggler parameters on the compensation performance and beam dynamics. With the installation space requirements, the optimal parameters for the compensation wiggler within the HALF storage ring are determined.

INTRODUCTION

Diffraction-limited storage rings (DLSRs) employ multi-bend achromat (MBA) lattices to achieve ultra-low emittances. The average dipole field is reduced compared to third-generation light source storage rings, which makes the the radiation energy from bending magnets has a significant reduction and becomes comparable to that from insertion devices (IDs). As a result, independent adjustment of ID gaps by users will induce random emittance variations. HALF storage ring is a DLSR utilizing a hybrid-MBA lattice, with 20 long dispersion-free straight sections and 20 short dispersive straight sections [1, 2]. The Phase-I IDs of HALF include 10 user undulators and 2 damping wigglers (DWs) [3], the emittance variation induced by independent adjustment of user ID gaps reaches ±7.5%, which need to be compensated.

Several methods have been developed to compensate for ID-induced emittance variations in DLSRs [4–7]. These approaches include active compensation using variable-gap wigglers in dispersion-free straight sections to leverage radiation damping, passive compensation via dispersion leakage into ID straight sections to minimize effective emittance variations, and the use of variable dispersion bumps within fixed-gap wigglers. Recently, a novel emittance compensation scheme based on the quantum excitation effect has been proposed for the HALF storage ring, in which a short variable-gap wiggler is installed in a dispersive straight section and the two DWs are fixed at their minimum gaps [8]. This scheme offers multiple advantages compared to the original radiation-damping-based scheme, such as shorter damping times, smaller energy spread variations, two additional wiggler beamlines and weaker attraction force between compensation wiggler poles.

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† baizhe@ustc.edu.cn

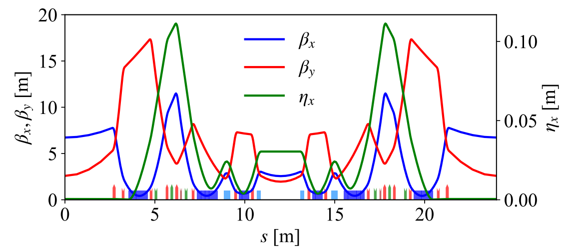

Figure 1: Linear optics of the HALF H6BA lattice.

To optimize the compensation wiggler parameters in the quantum-excitation-based scheme, this paper presents an investigation of their interrelations for emittance compensation and their influence on beam dynamics. This paper is organized as follows: Section II introduces the novel emittance compensation scheme and its advantages for the HALF storage ring. Section III investigates the dependence of the wiggler field on the effective length and period length. Section IV examines the linear and nonlinear beam dynamic effect associated with compensation wiggler parameters. Section V addresses the installation space requirements. Section VI presents the conclusions.

NOVEL EMITTANCE COMPENSATION SCHEME

The HALF H6BA lattice, as shown in Fig. 1, comprises 20 cells that each feature a 5.3 m dispersion-free straight section and a 2.2 m dispersive straight section. The latter has a dispersion of 31 mm. To compensate for emittance variations, the original emittance compensation scheme for HALF is to adjust the gaps of two DWs located in long dispersion-free straight sections, which is the widely used method in other DLSRs. This method works primarily based on the radiation damping effect. The emittance will decrease to the target value when the magnetic fields of two DWs increase. Recently, a novel quantum-excitation-based emittance compensation scheme was proposed for the HALF storage ring. In this scheme, a variable-gap wiggler will be installed in the 20th short straight section of the HALF storage ring, which is currently vacant and unavailable for user beamlines, with two DWs operating at their minimum gaps. The scheme exploits the relatively large dispersion in the short straight sections to compensate for the emittance decrease induced by IDs. As the wiggler field increases, the quantum excitation effect is enhanced through the synchrotron radiation integral I_5, which raises the emittance back to the target

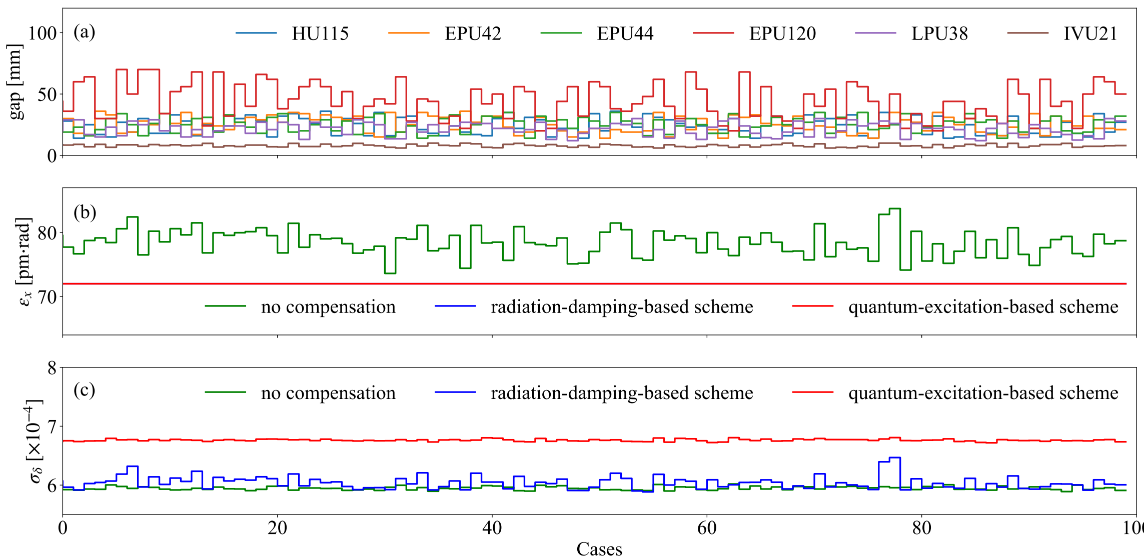

Figure 2: Comparison of radiation-damping-based and quantum-excitation-based emittance compensation schemes. (a) Random adjustment of the ID gaps; (b) Emittance variations before and after the compensation using the two schemes; (c) Energy spread variations before and after the compensation using the two schemes.

value. Since the two DWs operate at their mininum gaps to reduce the emittance, the compensated emittance could be the same as the radiation-damping-based scheme.

To compare the performance of the two emittance compensation schemes, a emittance compensation simulation has been conducted for the zero current case. The random adjustment of user ID gaps is shown in panel (a) of Fig. 2, and the emittance and energy spread variations are shown in panel (b) and (c), respectively. The compensated emittance is 72 pm·rad for both schemes, however, the energy spread variations during emittance compensation are significantly different. In the radiation-damping-based scheme, the user ID gap reduction induces a smaller emittance and energy spread, to compensate for emittance variation, the compensation wiggler field needs to be decreased, and the emittance and energy spread will further decrease, which induces relatively large energy spread variation during emittance compensation. While in the quantum-excitation-based scheme, to compensate for emittance variation, the compensation wiggler field needs to be increased, so the energy spread variation induced by user IDs will be reduced. For 1000 random samplings of the user ID gaps, the standard deviation of the energy spread variation before compensation is 0.324×10^{-5}. After compensation, this value rises to 1.130×10^{-5} for the radiation-damping-based scheme, whereas it is reduced to 0.196×10^{-5} for the quantum-excitation-based scheme. Additionally, with fixed gaps of two DWs, the damping time is reduced, which is benefit to suppress beam instabilities. The two DWs can also serve as two additional experimental beamlines, and thereby increasing the overall user beamline capacity of the HALF storage ring.

EFFECT OF WIGGLER PARAMETERS

In the quantum-excitation-based emittance compensation scheme, the wiggler length and period length are key parameters determine the required maximum effective magnetic field. To obtain a reasonable maximum wiggler field, parameter scans are performed as a function of effective length and period length.

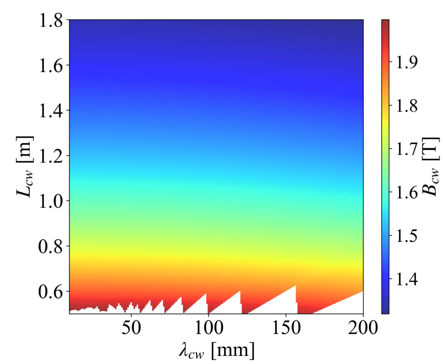

Figure 3: Parameter scans of the wiggler field as a function of effective length and period length.

As shown in Fig. 3, in the quantum-excitation-based scheme, to compensate the emittance to 72 pm·rad, the required wiggler field B_{cw} decreases as the wiggler length and period length increase. The required wiggler field is more sensitive to the wiggler length than to the period length. To minimize the required wiggler field while maintaining a safety margin, both the effective length and the period length of the wiggler should be chosen as large as possible.

IMPACT ON BEAM DYNAMICS

While the quantum-excitation-based scheme is more effective in emittance compensation, the wiggler in dispersive straight section can also introduces detrimental effects on beam dynamics, including linear optical distortions and dynamic aperture degradation. To ensure stable operation, these effects must be characterized and mitigated.

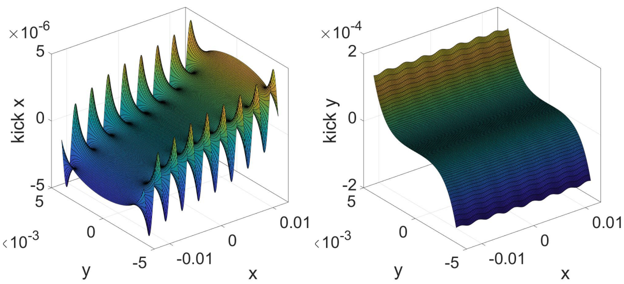

Figure 4: Kickmap for wiggler length of 1.5 m and period length of 125 mm.

When the wiggler length is 1.5 m and the period length is 125 mm, after preliminary design and optimization, the maximum magnetic field reaches 1.82 T. The effect of the wiggler on the beam can be represented by the kickmap shown in the Fig. 4. Using the AT code [9], the linear optical distortion and dynamic aperture degradation induced by the wiggler are calculated and presented in Fig. 5 and 6. The β-beating caused by the compensation wiggler is less than $\pm 0.05\%$, which is negligible and requires no linear optics compensation. The degradation in dynamic aperture after adding the wiggler is also acceptable.

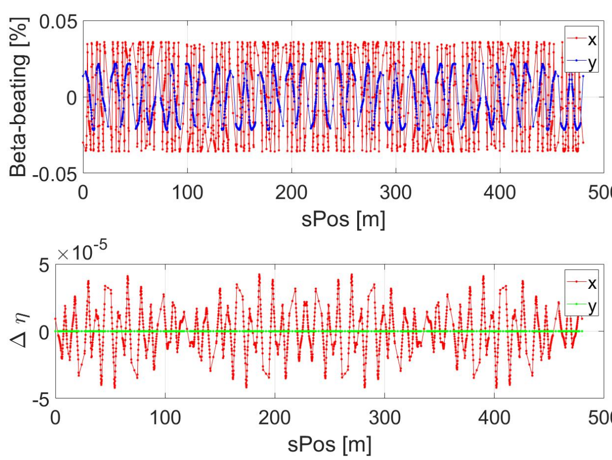

Figure 5: Linear optics distortion for wiggler length of 1.5 m and period length of 125 mm.

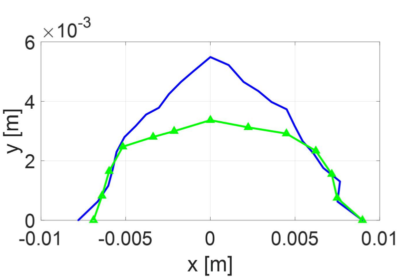

Figure 6: Dynamic aperture without (blue) and with (green) the compensation wiggler.

When the wiggler length is 1.5 m and the period length is 150 mm, after preliminary design and optimization, the maximum magnetic field reaches 1.88 T. The linear optical distortion is serious. After linear optics compensation, the β-beating and dispersion distortion are shown in Fig 7. The

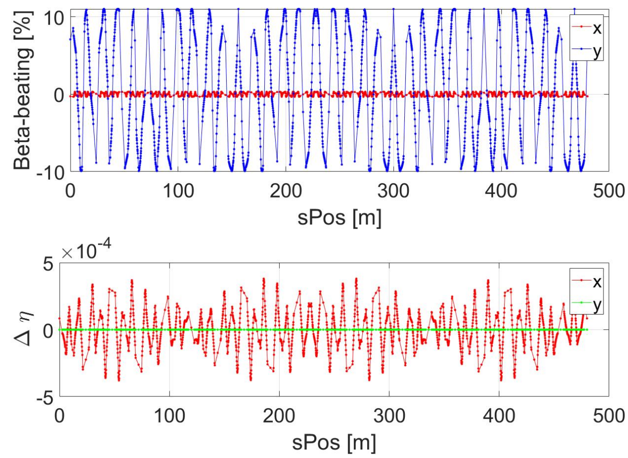

Figure 7: Linear optics distortion after optics compensation for wiggler length of 1.5 m and period length of 150 mm.

maximum β-beating is approximately 10% and the maximum dispersion distortion is 1.4 mm, requiring an adjustment in quadrupole strength of 3%, which is relatively large. As shown in Fig. 3, the difference in required magnetic field for emittance compensation between the 125 mm and 150 mm period lengths is minimal. Although optimizing the magnetic field distribution of the 150 mm period wiggler could further reduce its linear optical perturbations, the 125 mm period length is the better choice when considering both emittance compensation and beam dynamics.

INSTALLATION SPACE REQUIREMENTS

The maximum wiggler length is determined by the available installation space. The total length of the vacuum pipe between the BPM flanges is 1844 mm, and the distance between the centers of the two corrector magnets (each 110 mm long) is 1680 mm. After allocating space for the vacuum pipe supports and the photon mask, as well as reserving the necessary clearance between the correctors and the wiggler, the remaining available length for the wiggler is 1460 mm. Subtracting the end structures and magic fingers, the maximum effective length of the wiggler is 1200 mm. To minimize the required wiggler field, the wiggler period length should be 120 mm and the effective length 1.2 m.

CONCLUSION

The novel quantum-excitation-based emittance compensation scheme for HALF storage ring offers multiple advantages. To reduce the required wiggler field, both the wiggler length and period length should be as large as possible. However, to mitigate their impact on beam dynamics, the period length should not exceed 125 mm. Subject to this upper limit and the strict installation space constraints, the optimal wiggler effective length and period length are chosen as 1.2 m and 120 mm, respectively.

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