STUDY OF RADIATION DAMPING ENHANCED STORAGE RING LATTICE

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Abstract

The reduction of beam emittance from third-generation to fourth-generation storage ring light sources is based on suppression of quantum excitation, while radiation damping becomes weaker. This leads to severe intra-beam scattering effect in fourth-generation light sources. To suppress this effect, this paper proposes a radiation damping enhanced lattice concept, which is numerically studied.

INTRODUCTION

The natural emittance of a storage ring is determined by the balance between quantum excitation and radiation damping. Suppressing quantum excitation or enhancing radiation damping can lower the emittance. Fourth-generation storage ring light sources commonly employ multi-bend achromat (MBA) lattices, where the dispersion function in bends is significantly reduced, thereby effectively suppressing quantum excitation [1]. However, the increased number of bends leads to a weaker average dipole field, which reduces the radiation energy loss. Consequently, the radiation damping becomes weaker and the damping time becomes longer. Table 1 lists the changes in natural damping time for several light sources before and after their upgrades to the fourth generation. The damping time becomes longer after the upgrade. Therefore, in the lattice design of diffraction-limited storage rings (DLSRs), the ultra-low emittance is achieved mainly by suppressing quantum excitation, while the radiation damping is generally not enhanced but rather significantly weakened, resulting in a longer damping time.

Table 1: Natural Damping Time Becomes Longer After Upgrading Third-Generation Storage Ring Light Sources to Fourth-Generation Ones

	Energy	τ_y	τ_y **before upgrade**
ESRF-EBS	6 GeV	13.0 ms	7.0 ms
Diamond-II	3.5 GeV	18.1 ms	7.2 ms
SOLEIL II	2.75 GeV	14.0 ms	3.3 ms
SLS 2.0	2.7 GeV	7.6 ms	6.1 ms
Elettra 2.0	2.4 GeV	9.2 ms	7.8 ms
ALS-U	2 GeV	14.4 ms	9.1 ms

Note: For ease of comparison, the natural damping times in the table are uniformly taken in the vertical direction, as the damping partition number in this direction is always 1. Meanwhile, for light sources with beam energy changes before and after the upgrade, the damping times before upgrade are converted to correspond to the upgraded energy.

In DLSRs, especially medium- and low-energy rings, the ultra-low natural emittance and weak radiation damping can cause severe intrabeam scattering (IBS), leading to an increase in the actual equilibrium emittance. In the Hefei Advanced Light Facility (HALF) storage ring, the emittance growth induced by IBS is very severe [2]. Raising the storage ring energy to enhance radiation damping can effectively suppress this emittance growth [3, 4], which is also why HALF employs electromagnets to retain the capability for energy increase. Furthermore, as the radiation from bends weakens, the contribution of radiation from insertion devices (IDs) relatively increases, and the emittance fluctuation caused by adjusting the ID gaps becomes more pronounced. which requires compensation wigglers or other means to suppress the emittance variation [5,6]. In addition, the weak radiation damping is also unfavorable for suppressing beam instabilities.

If quantum excitation is suppressed while radiation damping is not weakened but even enhanced in lattice design, the aforementioned problems will be better resolved. This paper proposes a novel wiggler-bend element for the design of radiation damping enhanced lattices.

PRINCIPLE OF RADIATION DAMPING ENHANCED LATTICE

A common solution for enhancing the radiation damping is to place damping wigglers in the dispersion-free straight sections. Damping wigglers can reduce the emittance while significantly enhancing radiation damping. The emittance reduction due to a damping wiggler with N_p periods in a dispersion-free section is [7]:

$$\frac{\epsilon_{xw}}{\epsilon_{x0}} = \frac{1 + \frac{8C_q}{30\pi J_x} N_p \frac{\beta_x}{\epsilon_{x0}\rho_w} \gamma^2 \frac{\rho_0}{\rho_w} \Theta_w^3}{1 + \frac{1}{2} N_p \frac{\rho_0}{\rho_w} \Theta_w}, \tag{1}$$

where ϵ_{x0} is the natural emittance without wiggler and ϵ_{xw} is the emittance with wiggler, Θ_w, ρ_w are wiggler parameters, J_x is the horizontal dampling partition number, C_q is the quantum radiation constant. Therefore, it would be more effective to place the wiggler at low-β_x positions. However, the β_x at straight sections is usually not very small. Taking the HALF storage ring as an example, the straight-section β_x is close to 7 m. We notice that β_x is usually small in bending magnets, and therefore a damping wiggler can be combined with a bending magnet to form wiggler-bends that can effectively enhance radiation damping and reduce emittance.

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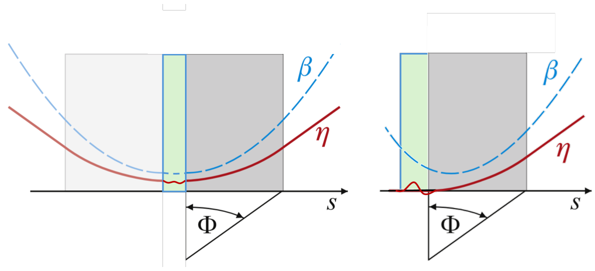

Figure 1: Symmetric wiggler-bend (left) and achromat wiggler-bend (right). The green blocks represent short wigglers with one or several periods.

The achromat bending magnet (ABM) has an adjacent achromatic section with very small β_x. At the midpoint of a symmetric bending magnet (SBM), both β_x and the dispersion function are very small. If reverse bends (RBs) are employed, the dispersion function at the SBM midpoint can be further reduced to nearly zero. It is more effective to install damping wigglers in these low-β_x sections than in the long straight sections. These two types of bending magnets can be combined with the wiggler to form symmetric wiggler-bend (SWB) and achromat wiggler-bend (AWB), as sketched in Fig. 1.

A DBA LATTICE EXAMPLE

In this section, we use the achromat wiggler-bend to design a double-bend-achromat (DBA) lattice example. To demonstrate the effectiveness of wiggler-bend,we compare a conventional DBA lattice with a wiggler-bend DBA lattice and optimize both lattice designs using a genetic algorithm. The two lattices have the same beam energy of 2.0 GeV and the same number of periods, 20. The cell length of the conventional DBA is 14 m, while that of the wiggler-bend DBA is 14.8 m, which provides extra space for two one-period wigglers in the dispersion-free sections adjacent to the ABMs.

During the optimization, the cell length, the length of the long straight section, and the magnet lengths were kept fixed, while the quadrupole strengths and drift lengths were taken as the optimization variables. For the conventional DBA, the radiation damping is fixed because the bends remain unchanged, and the optimization objective is to minimize the emittance. For the wiggler-bend DBA, two additional variables of wiggler angles are introduced, together with a maximum field constraint of 1.5 T, and the optimization objectives are to minimize the vertical damping time τ_y and to reduce the emittance. In addition, the betatron tunes of the two lattices are kept the same for a better comparison.

Figure 2 shows the optimization results of the wiggler-bend DBA, with the minimum-emittance solution of the conventional DBA indicated by a red star. As can be seen, the wiggler-bend achieves lower emittance and much shorter damping time. We select an optimized solution from the Pareto front, and compare it in more detail with the minimum-emittance solution of the conventional DBA. Figure 3 shows the linear optics of the two lattices, and Table 2 lists their main storage ring parameters.

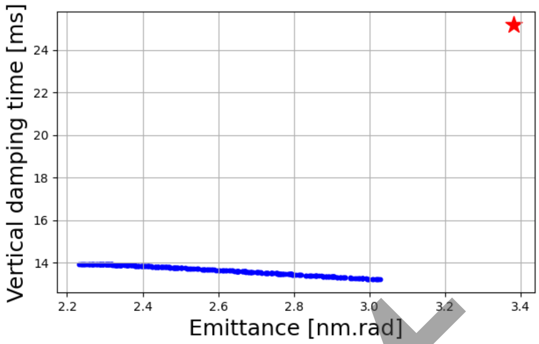

Figure 2: Optimization result of the two lattices in the ε-τ_y space. Blue dots shows the Pareto front for the wiggler-bend DBA lattice and the red star marks the conventional DBA lattice.

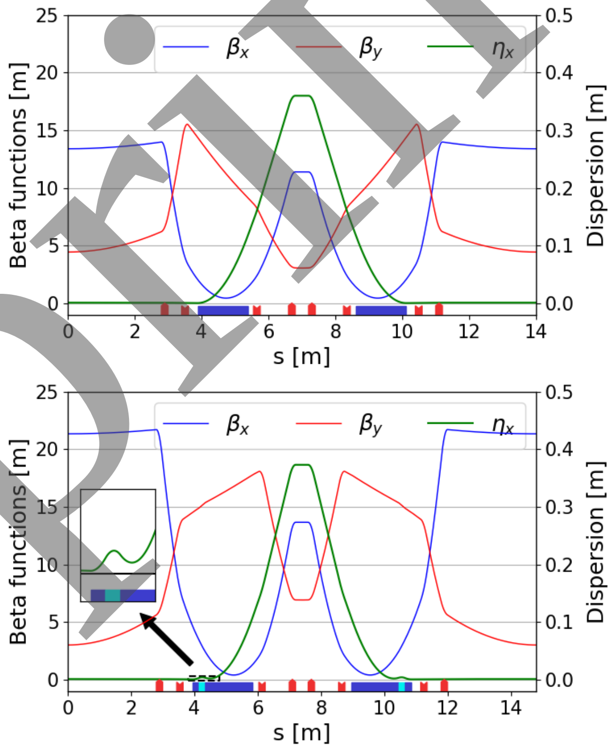

Figure 3: Linear optical functions and magnet layout of the conventional DBA (top) and wiggler-bend DBA (bottom). The blue blocks at the bottom of the plots indicate bending magnets, the red blocks represent quadrupoles, and the cyan blocks represent reverse bends.

DISCUSSION OF APPLICATION TO MBA LATTICE

In the previous section, we used the DBA lattice as an example to demonstrate that the wiggler-bend can effectively enhance radiation damping and reduce emittance. The DBA was chosen because of its structural simplicity. However, as mentioned in the Introduction, radiation damping is weak-

Table 2: Main Parameters of Two DBA Lattices

	conventional DBA	**wiggler-bend DBA**
ε_0 [nm]	3.38	2.24
U_0 [keV]	148	283
Tunes (H/V)	18.3 / 7.2	18.3 / 7.2
τ_y [ms]	25.21	13.95
α_c	8.81×10^{-4}	7.74×10^{-4}
σ_δ	5.55×10^{-4}	6.41×10^{-4}

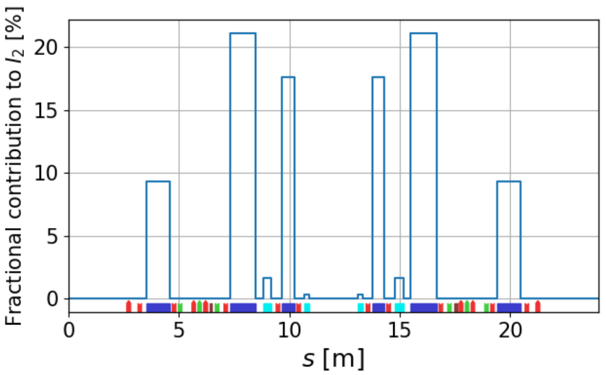

Figure 4: Fractional contribution to the second synchrotron radiation integral I_2 for each element in the HALF storage ring lattice.

ened in the MBA lattices employed in DLSRs, which makes the wiggler-bend more suitable for such lattices.

An MBA lattice can be viewed as a DBA lattice with additional unit cells inserted in between. For example, inserting TME-like (TME: theoretical minimum emittance) unit cells results in a conventional MBA lattice with distributed chromatic correction, while inserting unit cells with a $-I$ transformation yields a hybrid MBA lattice. Therefore, the application of the wiggler-bend can be extended to MBA lattices. Taking the H6BA lattice of the HALF storage ring as an example, Fig. 4 shows the fractional contribution of each element to the second synchrotron radiation integral I_2. It can be seen that the ABMs on both sides contribute the least to I_2 among the main bending magnets. Replacing these ABMs with AWBs can significantly enhance the radiation damping of the storage ring. In the case of conventional MBA lattices, the SBMs in the TME-like unit cells can be replaced with SWBs. In addition, longitudinal gradient bends (LGBs) and RBs can be adopted. On the one hand, they can reduce the dispersion in the bending magnets to nearly zero, thereby providing more suitable linear optics for the SWBs. On the other hand, for LGBs, the non-uniformity of the dipole field can increase the radiation energy loss compared to a uniform dipole field; for RBs, the radiation energy loss can be significantly increased by enlarging the total absolute bending angle of the entire ring.

CONCLUSION

A damping wiggler is more effective at reducing emittance when placed at locations with low β_x. In this paper, we integrate a wiggler with a bending magnet to propose a novel wiggler-bend element for lattice design. This element exploits the low-β_x dispersion-free sections inside or adjacent to the bending magnet to simultaneously enhance radiation damping and reduce emittance. The effectiveness of the wiggler-bend is demonstrated using a DBA lattice as an example. This method can be further extended to MBA lattices, offering a promising route toward achieving ultra-low emittance with strong radiation damping in DLSRs.

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