A possible approach to reduce the emittance of HLS-Ⅱ storage ring using a Robinson wiggler *

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Abstract: In this paper, we present some preliminary studies on using a Robinson wiggler to reduce the horizontal beam emittance in the Hefei Light Source Ⅱ (HLS-Ⅱ) storage ring. A proof-of-principle lattice demonstrates that it is possible to reduce its emittance by 50% with a 2-meter long wiggler. This encouraging result suggests a feasible option to significantly improve the machine performance at a relatively low cost.

Key words: storage ring, emittance, Robinson wiggler

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1 Introduction

For a storage ring based light source, its horizontal beam emittance is one of the key parameters to ultimately determine its performance–the achievable brightness. A light source brightness is defined as the number of photons emitted per second, per photon energy bandwidth, per solid angle, and per unit source size. Brightness is important because it determines how efficiently an intense flux of photons can be refocused to a small spot and a small divergence. The brightness of the dipole radiation scales with the beam current in the storage ring, and the brightness of the undulator radiation increases with both the beam current and total number of the undulator field periods. The beam current and, in case of undulator radiation, the number of the undulator periods, contribute linearly to the total flux of the emitted photon beam. The brightness is also inversely proportional to the horizontal and vertical emittances, the product of the beam size and divergence, of the electron/positron beam in the storage ring. Raising the beam current is ultimately limited by the beam-driven, collective instabilities. Thus, to maximize the brightness, the horizontal and vertical emittances must be made as small as possible. In order to maximize the brightness, all modern third generation light sources have optimized their lattices, without any exception, to minimize their emittances while maintaining a large dynamic aperture for an efficient injection and a long beam lifetime [1–9].

The horizontal emittance of an electron storage ring is determined by the equilibrium between the quantum excitation due to the emission of photons and the damping of the betatron oscillation by the RF acceleration field, which is used to compensate the energy loss due to the synchrotron radiation. The vertical emittance comes from the transverse coupling, which can be easily controlled by skew quadrupoles. Therefore, minimizing the horizontal emittance always holds the highest priority in the storage ring lattice design. The “emittance” in this paper only refers to the horizontal emittance unless otherwise specified.

Beam emittance can be reduced in several ways. One of the most common strategies is to increase the number of dipoles to reduce the quantum excitation effect, like the MAX-IV’s design [3]. This scheme dramatically increases the cost of constructing the storage ring, and also the difficulties of the nonlinear dynamics optimization. Another method is to install some damping wigglers in non-dispersive straight sections. The energy loss due to the radiation in damping wigglers enhances the damping effect. Meanwhile the wigglers only have negligible contribution to the quantum excitation. Damping wigglers can be installed in straight sections like other insertion devices. This method was adopted by some major facilities in the last decade around the world, such as PETRAIII [1] (in operation), PEP-X [9] (in design) and NSLS-Ⅱ [2] (under construction). However, this solution requires sufficient straight sections to accommodate

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damping wigglers. For those middle- and small-size storage rings, losing precious straight sections to achieve a lower emittance is not favorable. An alternative and also less expensive option for such storage rings is to install a special type of magnet, a Robinson wiggler, in a dispersive section.

The Robinson wiggler was first introduced by K. W. Robinson to redistribute the synchrotron damping between horizontal and longitudinal planes in 1958 [10]. It is composed of some magnetic units with an alternating field and gradient. The first Robinson wiggler was installed and tested on the Cambridge Electron Accelerator (CEA) in 1966 [11–13]. The horizontal emittance reduction using a Robinson wiggler was first successfully observed on the PS ring at CERN [14]. SOLEIL is considering implementing a Robinson wiggler to further reduce its emittance [15]. In principle, horizontal emittance can be reduced nearly 50% by using only one Robinson wiggler instead of numerous damping wigglers. Thus the Robinson wiggler can be applied for both compact and large storage rings.

This paper first revisits the basic principles of using a Robinson wiggler to reduce the horizontal beam emittance in Section 2. A proof-of-principle study on a possible approach to reduce the emittance of the upgraded Hefei light source (HLS), the HLS-II, is reported in Section 3. Section 4 foresees some possible challenges on both accelerator physics and technology, followed by a brief conclusion in Section 5.

2 Revisit of the principles of the beam emittance and Robinson wiggler

In this section, we will revisit the theorem of the beam emittance and the principle of damping redistribution using a Robinson wiggler.

2.1 The beam emittance of a storage ring

The equilibrium between the quantum excitation and radiation damping determines the beam emittance of an electron/positron storage ring with plane symmetry, and is given by [16, 17]

$$\epsilon_0 = C_{\mathrm{q}}\gamma_{\mathrm{e}}^2 \frac{\oint \frac{\mathscr{H}(s)}{|\rho_x|^3}\mathrm{d}s}{J_x \oint \frac{1}{\rho_x^2}\mathrm{d}s}, \tag{1}$$

where $C_{\mathrm{q}}=3.83\times10^{-13}$ m and $\gamma_{\mathrm{e}}=\frac{E}{m_0c^2}$ are constants, m_0 is the rest mass of electron, c is the speed of light, ρ_x is the dipole bending radius in the horizontal plane, $\mathscr{H}(s)$ function is given by

$$\mathscr{H}(s)=\gamma_x\eta_x^2+2\alpha_x\eta_x\eta_x'+\beta_x\eta_x'^2, \tag{2}$$

where α_x, β_x and γ_x are horizontal twiss parameters, η_x function describes the dispersive properties of the storage ring, and J_x is called horizontal radiation damping partition factor. Horizontal, vertical and energy damping partition factors are given by,

$$J_x = 1-D,\ J_y=1,\ J_{\mathrm{e}}=2+D, \tag{3}$$

where

$$D=\frac{\oint\frac{\eta_x}{\rho_x}\left[\frac{1}{\rho_x^2}+2K_x\right]\mathrm{d}s}{\oint\frac{\mathrm{d}s}{\rho_x^2}}, \tag{4}$$

$K_x=\frac{1}{(B\rho)_0}\frac{\mathrm{d}B_y}{\mathrm{d}x}$ is the strength of the quadrupole component inside dipoles, $(B\rho)_0$ is the magnetic rigidity of the dipoles. The radiation damping factors have to fulfill the Robinson theorem [10]

$$J_x+J_y+J_e=4. \tag{5}$$

Both $\mathscr{H}$ and $J_{x/\mathrm{e}}$ depend on the storage ring lattice configuration. Eq. (3) indicates if there is no transverse gradient ($K_x=0$) inside the dipoles, the second term in D is zero, which is the common situation in the second and third generation light sources. In order to assure a stable motion of particles in a storage ring, all three damping partition factors must be positive to balance the quantum excitation.

2.2 Methods used to reduce the beam emittance

As we mentioned before, there are several options to optimize beam emittance. Eq. (1) indicates that there are at least three ways to reduce beam emittance. First, one can optimize the $\mathscr{H}$ function inside dipoles to reduce the numerator. This scheme can be realized by employing small bending angle dipoles [16], and strong quadrupoles and sextupoles. However, it turns out to be limited by the project budget and strong nonlinear beam effects [18, 19]. The second way is to increase the denominator by enlarging the integral $\oint\frac{1}{\rho_x^2}\mathrm{d}s$, which is usually realized by introducing damping wigglers at non-dispersive straights. Since damping wigglers have very little impact on the $\mathscr{H}$ function due to the negligible η function at the hosting straights, they have only a tiny contribution to the quantum excitation, but significant contribution to the radiation damping. Therefore the beam emittance can be reduced by 50%–75% depending on the wiggler properties. This approach has been proved by the successful operation of PETRA III[1, 20] at DESY since 2009, and adopted by NSLS-II at Brookhaven National Lab [2] and PEP-X at SLAC National Lab [9]. The main side effect of using damping wigglers is that some precious straights are occupied, which greatly constrains the space availability for user insertion devices. Obviously, the option of using damping wigglers is not suitable for compact storage rings, like the HLS-II storage ring. The third option is to increase the horizontal damping partition factor J_x by reducing the integral D. This can be fulfilled by employing a set of dipole magnets with transverse gradient, the Robinson wiggler. The principle of using the Robinson wiggler to reduce the beam emittance is described in Section 2.3.

2.3 Reducing the beam emittance using a Robinson wiggler

For most existing dedicated light sources, J_x is very close to 1. If one can increase J_x to 2, beam horizontal emittance can be reduced by 50%. In order to keep sufficient damping in the longitudinal direction, the maximum J_x should not be much greater than 2 according to the Robinson theorem [10]. As indicated in Eq. (3) and (4), J_x can be increased by a Robinson wiggler, which is composed of a dipole array with integrated quadrupole components. A period of a Robinson wiggler is illustrated in Fig. 1.

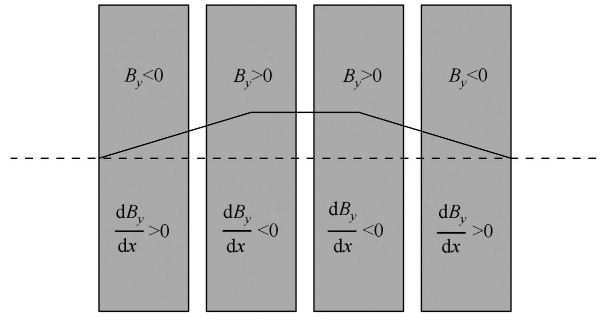

Fig. 1. Schematic diagram for one period of a Robinson wiggler.

Eq. (4) indicates that D depends on dispersion function $\eta_x(s)$ and the strength of quadrupole component $K(s)$ in the dipole array. Therefore, in order to make a contribution to D, a magnetic element introducing nonzero $B_y\times\frac{\mathrm{d}B_y}{\mathrm{d}x}$ must be installed in a dispersive section with $\eta_x\neq0$. For convenience sake, we rewrite Eq.(4) as

$$D=\frac{\oint\frac{\eta_x}{\rho_x^3}\mathrm{d}s}{\oint\frac{\mathrm{d}s}{\rho_x^2}}+\frac{\frac{2}{(B\rho)_0^2}\oint\eta_x B_y\frac{\mathrm{d}B_y}{\mathrm{d}x}\mathrm{d}s}{\oint\frac{\mathrm{d}s}{\rho_x^2}}. \tag{6}$$

The Robinson wiggler only makes a very small contribution to the first term in the right hand of Eq. (6). The second term is the main contribution to D. Assuming η_x is constant all through the wiggler, we can further simplify the Robinson wiggler's contribution to D as

$$D_\mathrm{w}\approx\frac{\frac{2}{(B\rho)_0^2}L_\mathrm{w}\eta_x B_y\frac{\mathrm{d}B_y}{\mathrm{d}x}}{\frac{2\pi}{\rho_\mathrm{d}}+\frac{L_\mathrm{w}}{\rho_\mathrm{w}^2}}, \tag{7}$$

where ρ_d and ρ_w are the storage ring's dipole and the wiggler bending radii respectively, L_w is wiggler length. The contributions of a Robinson wiggler to a ring's damping partition factors are

$$\Delta J_x = -D_\mathrm{w},\ \Delta J_\mathrm{e}=D_\mathrm{w}. \tag{8}$$

Like an ordinary insertion device, the first and second field integrals of a Robinson wiggler field are zeros, thus it can be accommodated into a straight section without disturbing designed beam orbit. The impact on the linear focusing needs to be taken into account during lattice design.

Eq. (8) indicates that the synchrotron radiation damping effect is redistributed between the horizontal and longitudinal directions. After the redistribution, the radiation damping in the longitudinal plane becomes weaker, which means that it takes a longer period of time for energy oscillation to damp. If the rising time of the energy oscillation, due to some excitation, is shorter than radiation damping time, the beam becomes unstable longitudinally. In order to keep longitudinal motion stable, longitudinal partition factor J_e should not be too close to zero. An active feedback system can increase longitudinal damping rate if necessary. Another impact due to weaker longitudinal damping is the increase of beam energy spread and bunch length. The equilibrium energy spread of a bunched beam is given by

$$\frac{\sigma_E}{E}=\left[\frac{C_\mathrm{q}\gamma_\mathrm{e}^2}{J_\mathrm{e}\left\langle\frac{1}{\rho^2}\right\rangle}\left\langle\frac{1}{|\rho|^3}\right\rangle\right]^{1/2}. \tag{9}$$

When J_e is reduced by 50%, both beam energy spread and bunch length will increase approximately by a factor of $\sqrt{2}$, which leads to a decrease on beam longitudinal line density. This decrease has little impact on most user experiments, because it does not change their light source integrated brightness. On the other hand, due to Landau damping [21], an increase on beam energy spread can suppress collective instabilities, which actually is a positive side effect of the Robinson wiggler.

In the next section, we will give a preliminary calculation result of reducing the HLS-Ⅱ emittance by introducing a Robinson wiggler.

3 Proof-of-principle studies on reducing the beam emittance for the HLS-Ⅱ

3.1 The HLS-Ⅱ storage ring lattice

The HLS was a 2^{nd} generation synchrotron light source operating with an energy of 800 MeV. It provided vacuum ultra-violet (VUV) and soft X-ray radiations for various experiments during the last two decades. The light source is named HLS-Ⅱ after it was upgraded recently to increase its brightness using a low emittance lattice. The new lattice provides more straight sections for insertion devices. A four-fold double-bend achromatic (DBA) lattice, as shown in Fig. 2, has been adopted to replace the previous triple-bend achromatic (TBA) structure. It has four 4-meter and four 2-meter long straight sections. Therefore, apart from the two straight sections used for injection and RF system separately, it can host up to six insertion devices. According to the current design [22], there is one spare 4-meter long zero-dispersion straight section available for a Robinson wiggler. In order to make the Robinson wiggler contribute to J_x, we redesign this spare cell to raise the η_x function at the location of its straights to about 0.2 meters (see Fig. 3). The linear optics in the rest of the ring are kept unchanged.

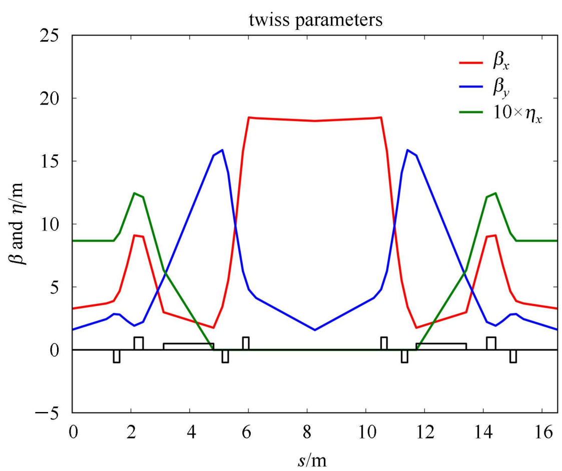

Fig. 2. (color online) HLS-Ⅱ ring achromat optics (one cell as $\frac{1}{4}$ ring).

3.2 Reducing the HLS-Ⅱ emittance using a Robinson wiggler

A 2-meter long Robinson wiggler is proposed to be installed in the modified straight section with $\eta_x\approx0.2$ m. The change of the damping partition factor, ΔJ_x, can be calculated with B, $\mathrm{d}B/\mathrm{d}x$ and other parameters of the wiggler based on Eq. (7) and Eq. (8). For a proof-of-principle study, we choose the wiggler parameters as listed in Table 1, which are not difficult to realize in a real device.

Fig. 4 illustrates a contour of ΔJ_x as a function of B and $\mathrm{d}B/\mathrm{d}x$ of the Robinson wiggler. The black line in the figure represents different combinations of B and $\mathrm{d}B/\mathrm{d}x$ to achieve $D=-1$ or $\Delta J_x\approx1$, i.e. $J_x=2$. In our studies, we choose B and $\mathrm{d}B/\mathrm{d}x$ of the wiggler indicated by a solid red circle in the figure.

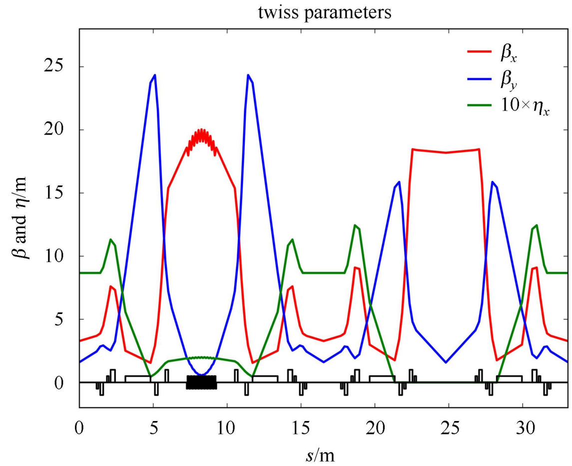

Fig. 3. (color online) Rematched ring optics (2 cells) with a Robinson wiggler. The left half is the modified cell holding the wiggler; and the right half is a standard cell.

Table 1. Proposed Robinson wiggler parameters.

parameters	values
device length/m	2
period length/m	0.2
number of period	10
bending radius/m	2.0747
center field/T	1.2862
gradient/(T/m)	25.5910

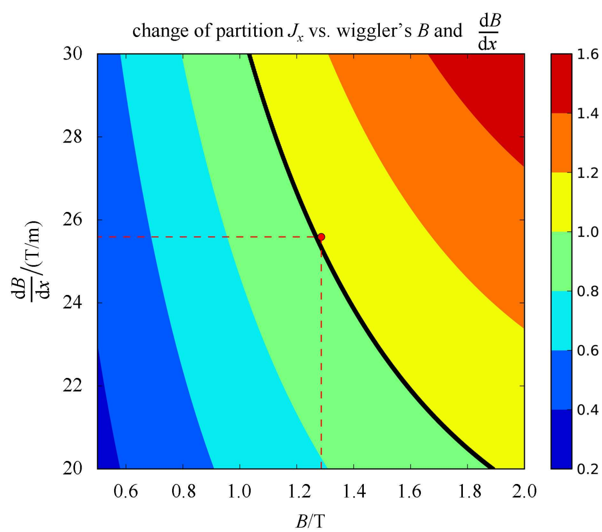

Fig. 4. (color online) Contour of ΔJ_x changes with wiggler's field B and gradient $\frac{\mathrm{d}B}{\mathrm{d}x}$ based on Eq. (7). The black line is combinations of wiggler's field and gradient to achieve $D=-1$, i.e. $J_x=2$. The red circle represents the Robinson wiggler's parameters we choose for our proof-of-principle study.

Table 2. The main parameters of the HLS-Ⅱ storage ring with/without a Robinson wiggler.

parameter	no Robinson wiggler	with Robinson wiggler
beam energy/MeV	800	800
emittance ϵ_x/(nm.rad)	35.32	14.91
damping partition factor J_x	1.055	2.110[1)]
damping time $\tau_x/\tau_y/\tau_e$/ms	19.99/21.08/10.84	8.61/18.17/20.46
betatron Tune ν_x/ν_y	4.414/3.346	4.393/3.419
Natural chromaticity ξ_x/ξ_y	−10.98/−5.90	−10.69/−6.98
natural relative energy spread	4.72×10^{-4}	7.01×10^{-4}
radiation lost per turn/keV	16.74	19.42

1) J_x is actually changed by 1.055, which slightly deviates from the estimation of Eq. (7). This is because the dispersion η_x is not constant all along the Robinson wiggler (see Fig. 3).

In order to learn the impact of a Robinson wiggler on the beam dynamics, a simple wiggler model comprised of an array of dipoles with alternating polarity and gradient is adopted in our studies. Making a more precise model for the Robinson wiggler is an important topic and needs further investigation. In order to make the Robinson wiggler "transparent" to the rest of the storage ring, the focusing strengths of its neighboring quadrupoles are adjusted to match the linear optics. The matched optics functions are shown in Fig. 3. Some main parameters of the HLS-Ⅱ storage ring with/without the Robinson wiggler are listed in Table 2 for comparison. As expected, the emittance is reduced more than 50%, from 35.32 nm·rad to 14.91 nm·rad. Although the Robinson wiggler has transverse gradient, its integrated focusing effect over one period is zero because of the alternating gradients within a short period of length, which results in small shifts for both betatron tunes and chromaticities.

The nonlinear dynamics of the storage ring with the Robinson wiggler is also preliminarily studied by particle tracking with the Tracy code [23]. The first and primary task is to have a sufficient dynamic aperture to ensure off-axis injection efficiency and long Touschek lifetime. Some initial studies promise a quite large dynamic aperture, as shown in Fig. 5.

3.3 Discussion

After shifting one unit of damping partition factor from the longitudinal plane to the horizontal plane, beam energy spread and bunch length are increased by a factor of $\sqrt{2}$. Since most synchrotron radiation users only care about the integrated brightness of photon beam, this effect has negligible impact on their experiments if their radiation points are located at non-dispersive sections. If the radiation point is located at a dispersive section, its effective brightness depends on the actual beam size which is given by

$$\sigma_x=\sqrt{\beta_x\epsilon_x+(\eta_x\delta)^2}, \tag{10}$$

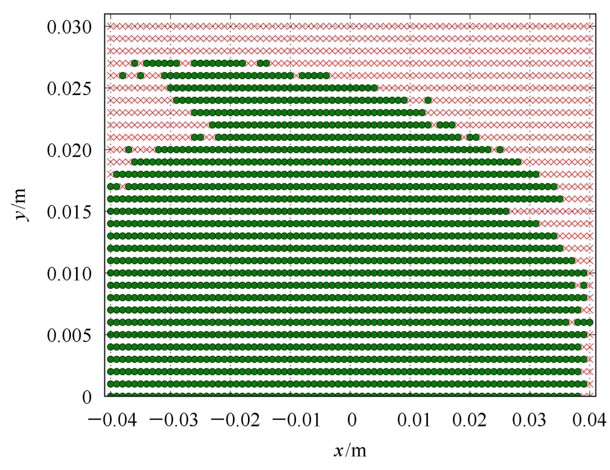

Fig. 5. (color online) The dynamic aperture of the HLS-Ⅱ storage ring with a perfect Robinson wiggler. The tracking starts from the center of the straight section. The green circles and red crosses represent the initial conditions of particles. With these initial conditions, the green circles mean the particles survive after 1024 turns, and the red crosses indicate the particles are lost before that.

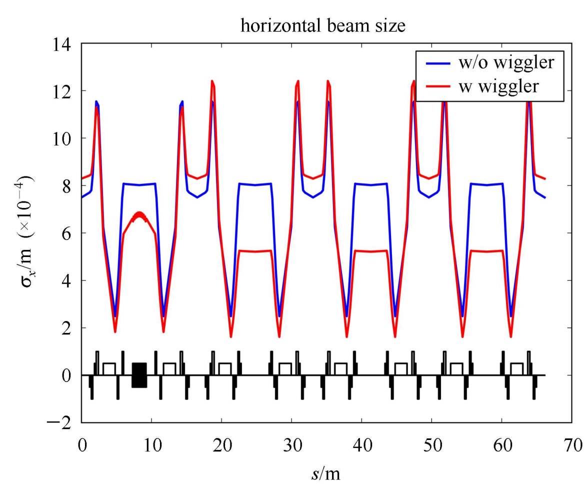

Fig. 6. (color online) Horizontal beam sizes with/without Robinson wiggler. Comparing with the beam size of the bare lattice (shown in blue), a Robinson wiggler can decrease beam size significantly (up to 40%) in the non-dispersion straights, decreases slightly in the dipoles, and increases less than 10% in the dispersive straights as shown in red.

where $\delta = \frac{\sigma_E}{E}$ is the rms relative energy spread. This means insertion device's brightness is determined by not only ring's emittance, but also the dispersion function where the source point is located and the rms beam energy spread. The comparison of beam sizes with/without Robinson wiggler along the HLS-II ring is illustrated in Fig. 6. The beam size decreases significantly (40%) in the non-dispersion straights, decreases slightly in the dipoles, and increases less than 10% in the dispersive straights. Therefore it is worthwhile to build such equipment to enhance HLS-II global performance.

4 Challenges in accelerator physics and technology

Although the preliminary study on applying the Robinson wiggler gives positive and promising results, we can still foresee some challenges both in accelerator physics and technology.

4.1 Optimization of the storage ring lattice

In order to accommodate the Robinson wiggler, we match the linear lattice of one cell by adjusting the focusing strength of quadrupoles in this cell. Another possible solution involving the focusing effect of the wiggler is being considered. Optimization of the lattice with multiple constraints can be a potential challenge for accelerator physics. Another important accelerator physics issue is the modeling of a real Robinson wiggler. The actual field will be s-dependent and have considerable high order components. The model with hard edge dipole array we are using needs improvement for further nonlinear dynamics studies. The third challenge is to reduce the η function in short straight sections to lower the beam size enlarging effect due to energy spread increase.

4.2 Magnetic field quality control

The Robinson wiggler is assembled with magnetic units with an alternating dipole field and gradient along the longitudinal direction. Therefore, the magnetic field interference between adjacent poles needs to be solved to satisfy the strict requirement of the field quality. Some advanced magnet manufacturing and field measuring technologies are required, and might be challenging.

4.3 Orbit control

In order to achieve a proper damping rate, the electron beam has to be precisely controlled to pass through the wiggler along a specific orbit. Therefore, achieving a precise control of beam motion is another challenging issue for beam control and manipulation.

4.4 Stabilization of the longitudinal motion

As mentioned in the previous section, after redistributing the damping partition factors, how to stabilize the longitudinal beam motion becomes a challenging issue. Instabilities caused by collective effects need to be studied, and an active feedback system is needed to suppress these instabilities.

5 Conclusion

We present a proof-of-principle study of using a 2-meter long Robinson wiggler to further reduce the emittance of the HLS-II storage ring by 50%. The calculation result shows a very promising and encouraging prospect to further improve the HLS-II performance at a relatively low cost without significant modifications to its global configuration. Although there exist some potential challenges, further studies are worthwhile because the significant potential improvement on the storage ring performance can be achieved at a low cost.

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