REDUCING HLS-II EMITTANCE BY RADIATION DAMPING PARTITION FACTOR EXCHANGE*

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Abstract

In this paper, we present some preliminary studies on reducing the emittance of the Hefei light source II (HLS-II) storage ring by redistributing the synchrotron damping partition factor using a Robinson wiggler. The studies demonstrate that it is possible to reduce the emittance by 50% using a 2-meter long wiggler on a rematched lattice. This encouraging result suggests a feasible option to significantly improve the machine performance at a relative low cost.

INTRODUCTION

For a storage ring based light source, the beam emittance is one of the key parameters to ultimately determine the performance – the achievable brightness. The horizontal emittance of an electron storage ring is determined by the equilibrium between the quantum excitation due to emission of photons and damping of the betatron oscillation by RF acceleration field, which is used to compensate the energy loss due to synchrotron radiation. The vertical emittance comes from the transverse coupling, which can be controlled by skew quadrupoles. Minimizing the horizontal emittance always holds the highest priority in the storage ring lattice design.

The Hefei light source (HLS) was a 2nd generation synchrotron light source operating with an electron energy of 800 MeV. It have provided vacuum ultra-violet (VUV) and soft X-ray radiations for various experiments in last two decades. The light source is being upgraded to increase its brightness using a low emittance ($\sim$35 nm·rad) storage ring lattice, and named HLS-II. A four-fold double-bend achromatic (DBA) lattice is adopted to replace the previous triple-bend achromatic (TBA) structure. It has four 4-meter and four 2-meter long straight sections. Apart from the two straight sections used for the injection and RF system, it can host up to six insertion devices.

To further increase the brightness using an even lower emittance lattice needs significant modification to the current configuration of the storage ring, which is difficult due to various limitations. However, the transverse emittance can be reduced by exchanging the synchrotron damping partition factor between horizontal and longitudinal planes using a Robinson wiggler. Robinson wiggler was first introduced by K. W. Robinson to redistribute the synchrotron damping between horizontal and longitudinal planes in 1958 [1]. A Robinson wiggler is comprised of an array of dipole magnets with alternating fields and gradients. The first Robinson wiggler was installed and tested on the Cambridge Electron Accelerator (CEA) in 1966 [2, 3, 4]. The horizontal emittance reduction using a Robinson wiggler was first successfully observed on the PS storage ring at CERN [5]. SOLEIL is considering to implement a Robinson wiggler to further reduce its emittance [6]. In principle, the horizontal emittance can be reduced 50% 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 reports some preliminary studies on reducing the emittance of the Hefei light source II (HLS-II) storage ring by redistribution the synchrotron damping partition factor using a Robinson wiggler.

REDUCING THE HLS-II HORIZONTAL EMITTANCE USING A ROBINSON WIGGLER

Emittance Exchange between Horizontal and Longitudinal Planes

The volume of an electron beam in phase space is determined by the transverse emittance and energy spread of the beam. For a storage ring, the balanced horizontal emittance and energy spread are given by

$$\epsilon_0 = C_q\gamma_e^2\frac{\oint\frac{\mathscr{H}(s)}{|\rho_x|^3}dx}{J_x\oint\frac{1}{\rho_x^2}ds}, \tag{1}$$

and

$$\delta = \frac{\sigma_E}{E} = \left[\frac{C_q\gamma_e^2}{J_e\left\langle\frac{1}{\rho^2}\right\rangle}\left\langle\frac{1}{|\rho|^3}\right\rangle\right]^{1/2}, \tag{2}$$

respectively, where $C_q = 3.83\times10^{-13}$ m is constant, $\gamma_e = \frac{E}{m_0c^2}$ is the Lorentz factor of electrons, 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

$$\mathscr{H}(s) = \gamma_x\eta_x^2 + 2\alpha_x\eta_x\eta_x' + \beta_x\eta_x'^2, \tag{3}$$

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

$$J_x = 1 - D,$$

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$$\begin{aligned} J_y &= 1, \\ J_e &= 2 + D, \end{aligned} \quad (4)$$

where

$$D = \frac{\oint \frac{\eta_x}{\rho_x^3} \mathrm{d}s}{\oint \frac{\mathrm{d}s}{\rho_x^2}} + \frac{\frac{2}{(B\rho)_0^2} \oint \eta_x B_y \frac{\mathrm{d}B_y}{\mathrm{d}x} \mathrm{d}s}{\oint \frac{\mathrm{d}s}{\rho_x^2}} = D_0 + D_{\mathrm{w}}, \quad (5)$$

$(B\rho)_0$ is the magnetic rigidity of the dipoles, D_0 and D_{w} are the normal dipole and Robinson wiggler contributions to the D integral, respectively. Hence, the synchrotron damping partition factor can be shifted from longitudinal plane (energy spread) to horizontal plane using a Robinson wiggler, which would result in the horizontal emittance reduction.

Lattice Rematching for the HLS-II

Equation 5 indicates that to make Robinson wiggler contribute to the damping partition factor $J_{x,e}$, η_x should not be zero at the location where the wiggler is installed. However, the design lattice of HLS-II storage ring has an achromatic structure, i.e. the η_x function in straight sections is zero. So we redesign one of the four cells to raise the η_x function to about 0.2 meters in the straight section for installing a Robinson wiggler, see Fig. 1. The linear optics in the rest of ring is kept unchanged.

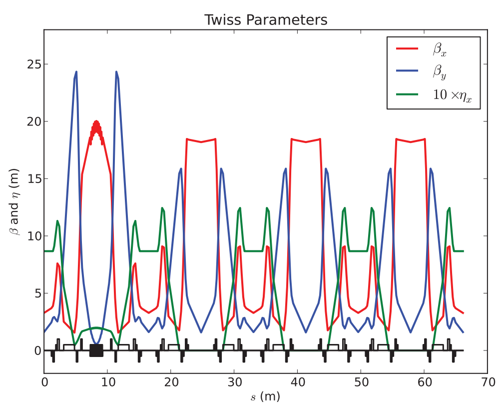

Figure 1: The rematched lattice of HLS-II storage ring.

Emittance Exchange

The Robinson wiggler induced change of the horizontal damping partition factor, ΔJ_x, can be calculated using B, $\mathrm{d}B/\mathrm{d}x$ and other parameters of the wiggler based upon Eq. (4) and Eq. (5). Figure 2 illustrates a contour of ΔJ_x as a function of B and $\mathrm{d}B/\mathrm{d}x$ of a Robinson wiggler. The black line in Fig. 2 represents different combinations of B and $\mathrm{d}B/\mathrm{d}x$ to achieve $D = -1$ or $\Delta J_x \approx 1$, i.e. $J_x = 2$. The wiggler parameters indicated by a solid red circle in Fig. 2 are chosen in our proof-of-principle studies, and listed in Table 1, which are not difficult to realize in a real device. In order to learn the impact of a Robinson wiggler on the beam dynamics, a simple wiggler model

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

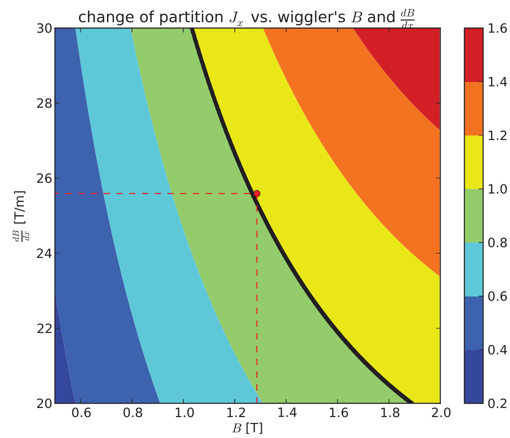

Figure 2: Contour of ΔJ_x changes with wiggler's field B and gradient $\frac{\mathrm{d}B}{\mathrm{d}x}$ based on Eq. (4) and Eq. (5). The black line represents combinations of wiggler's field and gradient to achieve $D = -1$, i.e. $J_x = 2$. The red circle represents the Robinson wiggler's parameters we choose for our proof-of-principle study.

comprised of an array of dipoles with alternating field polarity and gradient is adopted in our studies. Making more precise model for Robinson wiggler is an important topic and needs further investigation. The focusing strengths of the neighboring quadrupoles are adjusted to match the linear optics to make the Robinson wiggler "transparent" to the rest of the storage ring. The matched optics functions are shown in Fig. 1. Some main parameters of the HLS-II storage ring with/without the Robinson wiggler are listed in Table 2 for comparison. As expected, the horizontal 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 length, which only results in small shifts for both betatron tunes and chromaticities.

It is known that the brightness of a storage ring based light source is mainly determined by the transverse beam size. The comparison of beam sizes under conditions with and without Robinson wiggler along the HLS-II storage ring is illustrated in Fig 3. The beam size decreases significantly (40%) in the non-dispersive straight sections, decreases slightly in the dipoles, and increases less than 10% in the dispersive straight sections. Therefore it is worth-

Table 2: Proposed Robinson wiggler parameters

Parameter	No Robinson wiggle	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
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

while to build such equipment to enhance HLS-II's global performance.

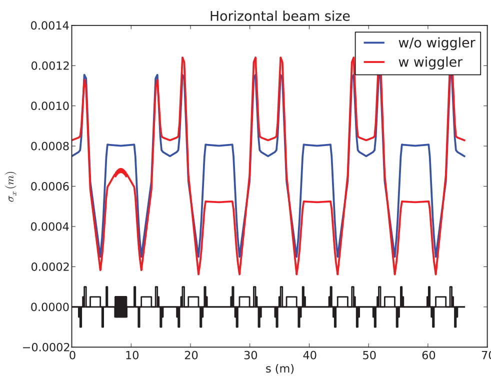

Figure 3: Horizontal beam sizes w/o Robinson wiggler. Comparing with the beam size of the bare lattice (shown in blue), a Robinson wiggler can decrease beam size significantly (up to 40%) in the non-dispersion straights, decreases slightly in the dipoles, and increases less than 10% in the dispersive straights as shown in red.

IMPACT OF THE ROBINSON WIGGLER ON NONLINEAR DYNAMICS

The nonlinear dynamics of the HLS-II storage ring with a Robinson wiggler is also preliminarily studied by particle tracking with the Tracy code [7]. The first and primary task is to have a sufficient dynamic aperture to ensure injection efficiency and long Touschek lifetime. Studies show a quite large dynamic aperture in the HLS-II storage ring, as shown in Fig. 4.

SUMMARY

We present proof-of-principle studies on using a 2-meter long Robinson wiggler to further reduce the emittance of the HLS-II storage ring more than 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.

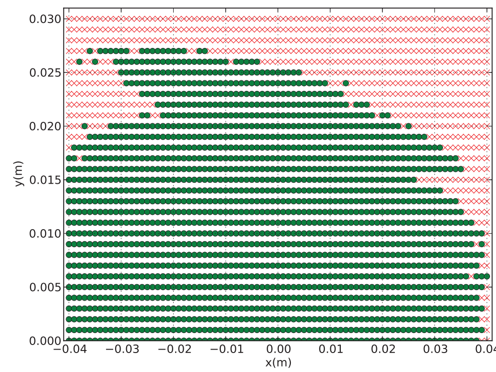

Figure 4: The dynamic aperture of the HLS-II storage ring with a perfect Robinson wiggler. The tracking starts from the center of the straight section. The green circles and red crosses represent the initial conditions of particles. With these initial conditions, the green circles mean the particles survive after 1024 turns, and the red crosses indicate the particles are lost before that.

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