LIFETIME IMPROVEMENT USING VERTICAL DISPERSION BUMPS IN A STORAGE RING[*]

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Abstract

The beam lifetime is critical for the synchrotron radiation light source storage rings. By increasing the coupling of the storage ring, the beam lifetime can be improved. However, due to the increased coupling, the beam size around the entire ring also increases. A larger beam size degrades the performance of synchrotron radiation from insertion devices in the straight sections. By using skew quadrupoles to excite vertical dispersion bumps in the arc sections, the vertical emittance as well as coupling can be increased. In this way, the coupling can be localized by minimizing it in the straight sections. This improves the beam lifetime while not affecting the synchrotron radiation from the insertion devices. In this paper, simulations of utilizing vertical dispersion bumps to improve beam lifetime for the ZIPS storage ring is presented.

INTRODUCTION

The new generation light source storage rings generally employ MBA lattice structures to realize diffraction-limited emittances [1]. Due to the low emittance of the storage ring, the impact of Tousheck scattering becomes critical, resulting in a degradation of beam lifetime. Appropriately increasing coupling of the storage ring can mitigate Touschek scattering effects. By increasing the coupling of the ring, the Touschek lifetime could be improved. However, the global change of the coupling may result in degrading the light source performance.

To avoid affecting the beam sizes in the straight sections, vertical dispersion bumps can be generated and limited in the arc sections [2]. Meanwhile the optical functions in the straight sections are matched to be unchanged. In this way, the coupling in the arcs is improved, while it is maintained at a low level in the straight sections. Therefore, the synchrotron radiation from insertion devices (IDs) in straight sections is not adversely influenced.

The Zhejiang Industrial Photon Source (ZIPS) is an industrial light source in the design phase. It adopts the five-bend achromat (5BA) lattice structure and the natural emittance reaches 0.64 nm · rad. The storage ring has a circumference of 270 m and maintain the beam energy of 2.7 GeV. It consists of 12 achromats and separated by 4.5 m straight sections for IDs. The optical functions and main parameters are shown in Fig. 1 and Table 1 respectively. In this paper, the simulation of inducing vertical dispersion bumps in arcs by using skew quadrupoles is based on the ZIPS storage ring.

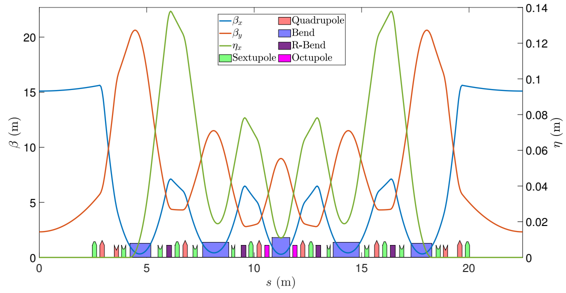

Figure 1: Optical functions of one cell in the ZIPS storage ring.

Table 1: Main Parameters of the ZIPS Storage Ring

Parameters	**ZIPS**
Beam energy (GeV)	2.7
Lattice structure	5BA
Circumference (m)	269.9
Harmonic number	450
RF frequency (MHz)	499.8
Natural emittance (nm · rad)	0.64
No. of straight sections	12
Transverse tunes [H, V]	(25.16, 8.22)
Damping time (ms)	3.89/7.54/7.09

TOUSCHEK LIFETIME AND VERTICAL EMITTANCE

The Touschek lifetime is determined by Touschek scattering in storage ring [6]. Owing to the high density of electron beam bunches, the electrons within the bunches cloud be scattered by other electrons. This scattering is a large-angle Coulomb scattering and lead to the transfer of momentum from transverse to longitudinal plane. If the longitudinal momentum exceeds the longitudinal acceptance of the ring, it results in beam loss. The formula of Touschek lifetime τ is given by [3]

$$\frac{1}{\tau}=\frac{r_\mathrm{e}^2 I_\mathrm{b}}{8\pi e\gamma^3\sigma_s}\oint_C\frac{F([\frac{\delta_\mathrm{acc}(s)}{\gamma\sigma_{x'}(s)}]^2)}{\sigma_x(s)\sigma_{x'}(s)\sigma_y(s)\delta_\mathrm{acc}^2}\mathrm{d}s. \tag{1}$$

Where r_e is the classical electron radius, I_b is bunch current, γ is the Lorentz factor and σ_s denotes the root mean square (rms) bunch length. The σ_x and σ_y are the rms horizontal and vertical beam sizes, δ_acc is the local momentum acceptance, $\sigma_{x'}$ is the horizontal beam divergence. The function $F([\frac{\delta_\mathrm{acc}(s)}{\gamma\sigma_{x'}(s)}])$ is

$$F(x)=\int_0^1(\frac{1}{u}-\frac{1}{2}\ln\frac{1}{u}-1)\cdot\exp(-\frac{x}{u})\mathrm{d}u. \tag{2}$$

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It can be seen from Eq. (1) that the Touschek lifetime τ is scaled by the rms vertical beam size σ_y and the vertical beam size is calculated using

$$\sigma_y = \sqrt{\epsilon_y \cdot \beta_y + (\eta_y \delta)^2}. \tag{3}$$

Where ϵ_y denotes the vertical emittance and it is determined by the residual vertical dispersion function and linear betatron coupling of the storage ring. The vertical emittance ϵ_y is given by [4]

$$\epsilon_y = C_\mathrm{q} \gamma^2 \frac{\langle \mathcal{H}_y / |\rho|^3 \rangle}{\mathcal{J}_y \langle 1/\rho^2 \rangle}, \tag{4}$$

where

$$\mathcal{H}_y = \frac{1}{\beta_y} [\eta_y^2 + (\beta_y \eta_y' + \alpha_y \eta_y)^2], \tag{5}$$

and $C_\mathrm{q} = 3.84 \times 10^{-13}$ m is the quantum constant, $\mathcal{J}_y$ is the damping partition number, β_y and α_y denote the vertical betatron amplitude functions, ρ is bending radius. The η_y and η_y' are vertical dispersion function and its derivative. Thus, by increasing the vertical emittance, the vertical beam size can be enlarged, finally resulting in an improvement of the Touschek lifetime.

METHOD OF INDUCING LOCAL VERTICAL DISPERSION BUMPS

To increase the vertical emittance, vertical dispersion is required. Ideally, the vertical dispersion in a storage ring is designed to be zero and the vertical emittance mainly arises from the linear betatron coupling and residual vertical dispersion, which are caused by magnets alignment errors such as the quadrupoles roll errors. Due to the error and coupling corrections for storage ring, the vertical emittance becomes very small. Through the adjustment of skew quadrupoles strengths, the vertical dispersion as well as betatron coupling can be created, resulting in a increased vertical emittance. The vertical dispersion caused by the skew quadrupole field can be describe by [5]

$$\Delta\eta_{y,k} = -(\Delta a_2 L)_j \eta_{x,j} \cdot \frac{\sqrt{\beta_{y,j}\beta_{y,k}}}{2\sin(\pi\nu_y)} \cos(\pi\nu_y - |\mu_{y,j} - \mu_{y,k}|), \tag{6}$$

where $\beta_{y,j}$ and $\beta_{y,k}$ are the beta amplitude functions at the skew quadrupole j-th position and the induced vertical dispersion k-th position, the $\Delta\eta_{y,k}$ is the induced vertical dispersion. From the Eq. (6), it can be seen that the vertical dispersion appears in both the straight sections and the arcs. The vertical dispersion in straight sections affects the performance of the IDs. Therefore, suitable skew quadrupoles sets and optical functions constraints in straight sections are needed to minimize the vertical dispersion in the straight sections. Moreover, as the emittance is determined by the balance of radiation damping and quantum excitation, it is necessary to introduce vertical dispersion in the bending magnets to improve the vertical emittance. In other words, to create the local vertical dispersion bumps only in arcs.

The magnets layout of one cell in the ZIPS storage ring is illustrated in Fig. 2. To save space, all skew quadrupoles are combined into the sextupoles and octupoles. There are eight families skew quadrupoles can be used to create vertical dispersion. As can be seen from Fig. 1, the horizontal dispersion at the positions of skew quadrupoles SQ1 and SQ2 is zero, thus, it is difficult for them to generate vertical dispersion according to Eq. (6). The skew quadrupoles SQ6, SQ7 and SQ8 are located at the center of arcs, they cannot generate enough vertical dispersion bumps. If combine them with the SQ3, SQ4 and SQ5, the optical functions will be significantly disturbed. Thus, only the skew quadrupoles SQ3, SQ4 and SQ5 are selected to excite the vertical dispersion bumps at the bending magnets positions.

Subsequently, by taking these three sets of skew quadrupoles as variables, vertical dispersion bumps in the dipoles are generated through matching. Some constraints are set in the matching, including the optical functions at the midpoint of the straight sections on both sides, which aims to minimize optics deviations from the originally designed lattice. The matching and calculation of optical functions are based on the Accelerator Toolbox (AT) [7]. Besides, the vertical dispersion at the five bending magnets is include as constraints. Additionally, the vertical dispersion contributions induced by these three skew quadrupoles at the five bending magnets are calculated by using Eq. (6). Using the results, three sets of initial skew quadrupoles strengths are determined, followed by the matching process.

RESULTS

The vertical dispersion bumps generated using three families of skew quadrupoles SQ3, SQ4, SQ5 in the ZIPS storage ring is presented in Fig. 3. The normalized skew quadrupoles strengths of SQ3, SQ4 and SQ5 are listed in Table 2. As can be seen in Fig. 3, the dispersion bumps only appear in the bending magnets. The maximum vertical dispersion is approximately 9 mm and the vertical dispersion in the straight sections is less than 2 mm. With this vertical dispersion, the vertical rms emittance reaches 11.45 pm · rad.

Table 2: Normalized Skew Quadrupole Strengths

Skew quadrupole	**SQ3**	**SQ4**	**SQ5**
Normalized strengths [m^{-2}]	0.091	0.055	-0.104

To study the influence of the skew quadrupole components on the beta functions and horizontal dispersion over the whole ring, the differences from the optical functions between the designed and matched lattices are calculated. The results are shown in Figs. 4 and 5. The maximum perturbations beta functions and horizontal dispersion are less than 1% and 1.5 mm, respectively. The small perturbations do not significantly affect the optical functions of the ZIPS storage ring.

A comparison of the rms beam sizes and emittance between these two lattices are given in Table 3. The devia-

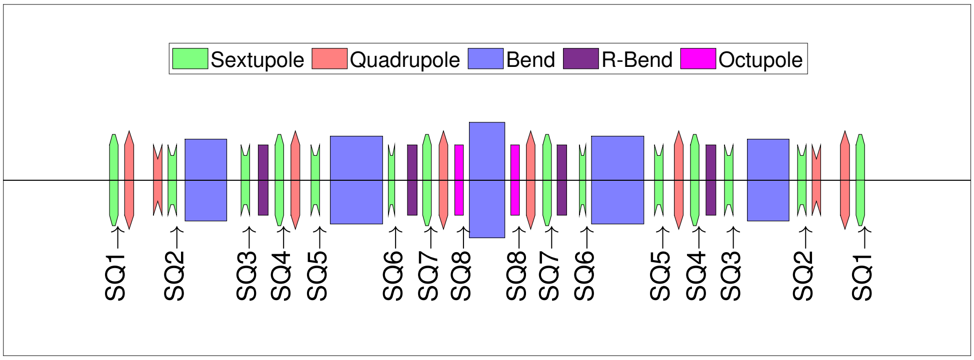

Figure 2: Magnets layout of one cell in the ZIPS storage ring. All skew quadrupoles are integrated to the sextupole families and octupole families. The skew quadrupoles SQ3, SQ4 and SQ5 are used to create the vertical dispersion in arc sections.

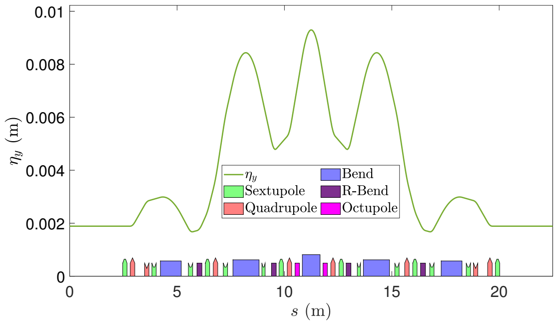

Figure 3: The matched vertical dispersion of one cell in the ZIPS storage ring.

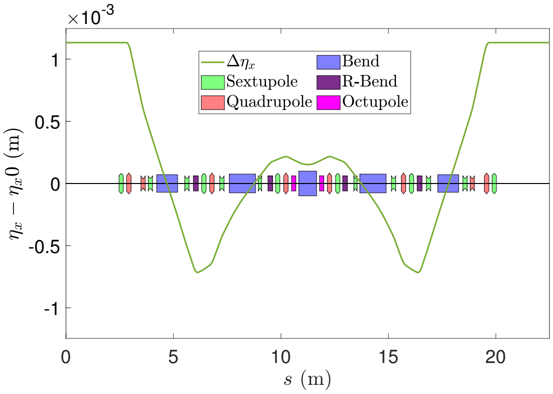

Figure 4: Difference between the horizontal dispersion of the designed and matched lattices.

tion of horizontal rms beam size is very small, therefore, the performance of IDs in the straight sections are not affected adversely. In the ideal lattice of the ZIPS storage ring, the vertical dispersion is designed as zero. Thus, the designed vertical beam sizes in the ideal lattice is zero. The local momentum aperture (LMA) of the ZIPS storage ring is demonstrated in Fig. 6. The particles are tracked for 3000 turns to compute the LMA. The red and blue lines in Fig. 6 represent the 4D LMA and 6D LMA, respectively. According to the 6D LMA and the Piwinski formula, the Touschek lifetime of the matched dispersion lattice is calculated as

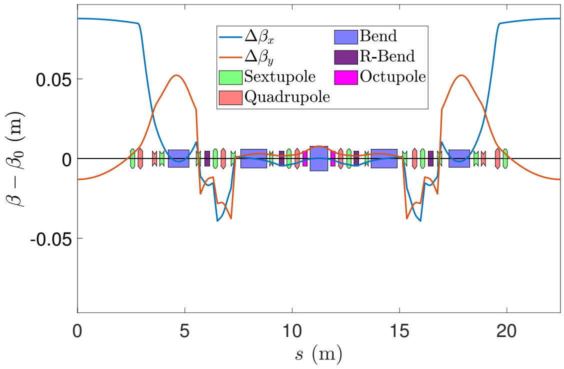

Figure 5: Differences between the transverse beta functions of the designed and matched lattices.

16.05 hours. For the Touschek lifetime calculation, the beam current and number of bunches are set to 400 mA and 450, respectively. In the ideal lattice (without any magnets errors) of the ZIPS storage ring, the transverse coupling is zero and the Touschek lifetime is approximately 0 hour. The Touschek lifetime of the ideal lattice with 2% global transverse coupling is 18.9 hours, which is comparable to that obtained using the vertical dispersion bumps method.

Table 3: Comparison of Projected Emittance and Beam Sizes in the Central Bending Magnets Between These Two Lattices

Parameters	**Designed**	**Matched**
σ_x [μm]	35.64	35.69
σ_y [μm]	0	12.48
Projected ϵ_x [pm · rad]	644.4	643.8

SUMMARY

Vertical dispersion bumps in the arcs are induced by using three families of skew quadrupoles. Moreover, due to the constraints of optical functions in the straight sections, the overall perturbations of the linear optics are restricted at a low level. In this way, the vertical rms emittance of

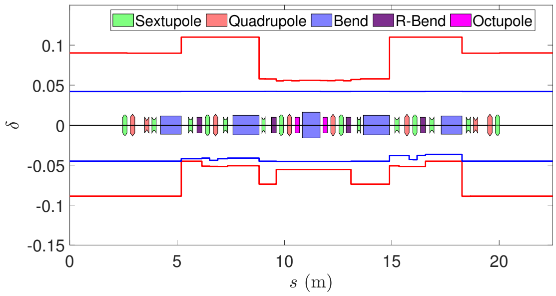

Figure 6: Local momentum aperture of one cell in the ZIPS storage ring.

the whole ring is increased to 11.45 pm · rad, resulting in a Touschek lifetime of approximately 16 hours. Furthermore, the dispersion functions in the straight sections are constrained by matching, ensuring that the performance of the ID radiation is not seriously influenced.

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