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STUDY OF THE INTRA-BEAM SCATTERING EFFECTS IN THE HALS STORAGE RING

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Abstract

The Hefei Advanced Light Source (HALS) is designed to be a dedicated 4^{th} generation diffraction limited light source. In 2018, the baseline lattice of the HALS storage ring has been proposed, with an ultra-low natural emittance of about 25 pm-rad. The intra-beam scattering effects on the beam emittance growth in the HALS storage ring have been studied with this baseline lattice. Due to the limited synchrotron radiation in this storage ring, damping wigglers are required to reduce the damping time and reduce the emittance. In this paper, we will present the simulation results of the IBS effects, estimate the effectiveness of damping wiggler and calibrate the corresponding linear optics perturbation due to the insertion device, and finally, the estimated Touschek lifetime will be shown.

INTRODUCTION

With the development of particle accelerator science and technology, the committee of accelerator physicists is pursuing synchrotron light sources for higher brightness, better coherence and stability. The door to the diffraction limited storage ring (DLSR), the next generation light source, has been opened since the commission and operation of MAX-IV [1]. Many advanced light sources are under design or constructions to achieve an ultra-low emittance of a few hundred or a few tens of pm-rad, some light sources are planning and proposing upgrade projects to further reduce beam emittance [2–4].

Table 1: Main Parameters of HALS Storage Ring

Parameter	Value
Energy E_0	2400 MeV
Circumferences C_0	672 m
Natural Emittance (bare) ϵ_n	24.7 pm
Number of cells	30
Harmonic number h	1120
Damping time $\tau_x/\tau_y/\tau_s$	37.7/58.8/40.9 ms
Synchrotron radiation U_0	182 keV
Revolution frequency f_0	0.446 MHz
Natural bunch length σ_z	2.35 mm

Hefei Advance Light Source (HALS) is a project proposed by the National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China (USTC), which is designed to be a dedicated 4^{th} generation DLSR. As shown in Table 1, the HALS storage ring (SR) is to be operated at the energy of 2400 MeV with an ultra-low natural bare emittance of ϵ_n=24.7 pm-rad [5]. To achieve the ultra-low emittance, the strengths of dipoles employed in this lattice are not too strong, which reduces both the quantum excitation and the radiation damping. However, the limited synchrotron radiation leads to a relatively large damping time, thus the beam emittance is expected to be sensitive to the beam intensity, i.e. the effect of intra-beam scattering (IBS) is expected to be significant.

In this paper, we will show the preliminary simulation result of emittance growth due to the IBS effects in the HALS-SR, a few methods are proposed to minimize this effect. Then we will discuss the effect of damping wiggler (DW) in reducing the beam emittance, as well as the related correction of linear optics perturbation introduced by an insertion device. The Touschek lifetime is also estimated.

THE IBS EFFECTS

Intra-beam scattering is the process that the particles in a beam elastically scatter off each other, leading to the growth of the beam size. In the electron accelerators, IBS is counteracted by radiation damping, resulting in an equilibrium beam emittance with relaxation time, typically on the order of milliseconds. This equilibrium beam emittance is calculated using the Bjorken and Mtingwa's formula in the ELEGANT [6].

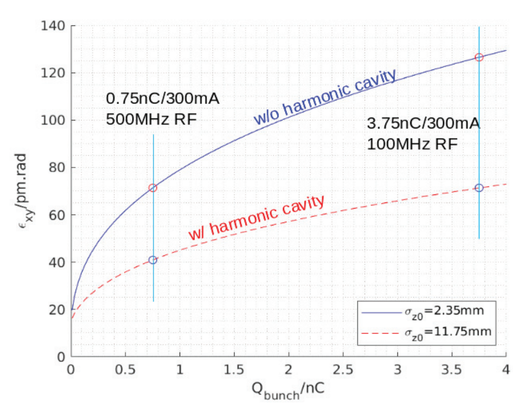

Figure 1: Emittance change with bunch charge. Full coupling is assumed, 80% of the buckets are equally filled.

As shown in Fig. 1, the equilibrium beam emittance growth with bunch population is calculated with different bunch length, so that to compare the effectiveness of harmonic cavity which lengthens the bunch. The bunch length is assumed to be lengthened by a factor of 5 in the harmonic cavity. In this simulation, full coupling is assumed in trans-

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verse directions, and only 80% of all the buckets are equally filled. Setting the beam current to be 300 mA in operation, the bunch charge would be 0.75 nC if the RF frequency is 500 MHz, and 3.75nC if the RF frequency is 100 MHz. It can be observed from Fig. 1 that:

- The beam emittance is sensitive to the particle population in a bunch, even with a small bunch charge, the emittance substantially grows up.
- With the bunch lengthened by the harmonic cavity, the emittance growth is significantly retarded;
- The IBS effect can be reduced by employing RF with higher frequencies. This is because there are more buckets with RF of higher frequency, therefore, to achieve the same beam current in a storage ring, the bunch charge is smaller in the case of RF with higher frequency (e.g. 500 MHz) than that of lower frequency (e.g. 100 MHz).

To reduce the IBS effect in the HALS-SR, the harmonic cavity is to be used. 500 MHz RF cavity is also preferred to reduce the IBS effect, but this demands for significant improvement of the pulsed power supply for injection. The severeness of the IBS effect in the HALS-SR is highly related to the limited synchrotron radiation, e.g. long damping time. Hence, the insertion devices can be used to increase the damping and reduce the beam emittance.

DAMPING WIGGLER

The effects of an insertion device on the emittance is estimated using the formula presented by H.Wiedemann [7]:

$$\frac{\epsilon_{x,w}}{\epsilon_{x,0}} = \frac{1 + \frac{8C_q}{30\pi J_x} N_p \frac{\beta_x}{\epsilon_{x,0}\rho_w} \gamma^2 \frac{\rho_0}{\rho_w} \Theta_w^3}{1 + \frac{1}{2} N_p \frac{\rho_0}{\rho_w} \Theta_w} \qquad (1)$$

where $\Theta = \lambda_p/(2\pi\rho_w)$, λ_p is the periodic length of the wiggler field, ρ_w is the bending radius of the peak magnetic field in the wiggler, N_p is the number of periods. β_x is the average value of horizontal beta-function over the wiggler, J_x is the horizontal partial number. $\epsilon_{x,w}$ and $\epsilon_{x,0}$ are the emittance with and without wiggler respectively. By implementing the parameters of HALS-SR lattice, the rate of emittance reduction is obtained, as shown in Fig. 2 and Fig. 3. In this calculation, we assumed that there are 3 straight sections, a total length of 12 m, for DW installation.

It should be noticed that this is a rough estimation, because the parameters used here are averaged or assumed unchanged, which is not true. For example, the β_x in the DW is different in each point, it might be changed after the installation of IDs (due to the related optical perturbation), and the partial number J_x also changes.

It is obvious that wigglers with a higher peak magnetic field and smaller periodicity are preferred for better emittance reduction, but this is of great challenge in technology. It is also observed that the K-value of IDs for damping is

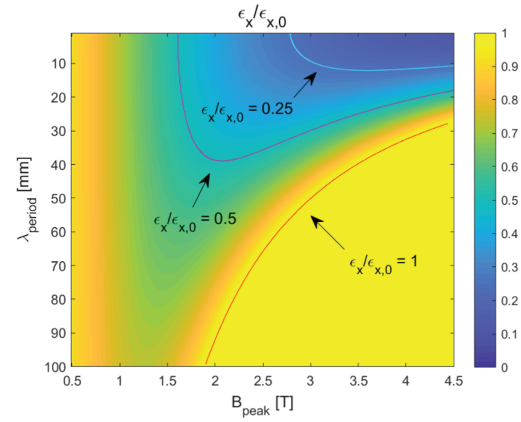

Figure 2: Illustration of estimated emittance reduction with different wiggler settings.

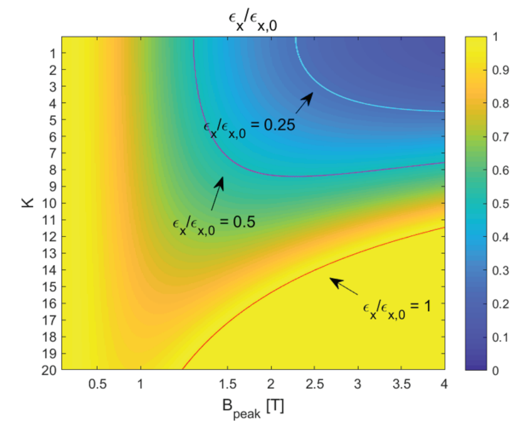

Figure 3: Illustration of estimated emittance reduction with different wiggler settings, in coordinates with K and B_{peak} .

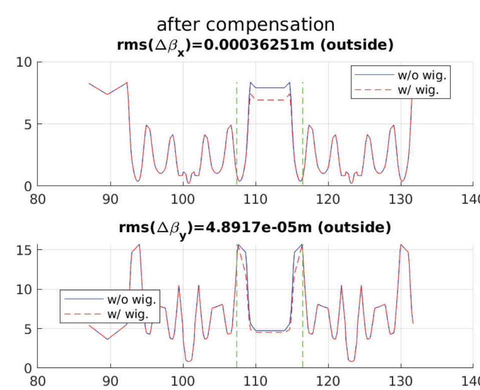

Figure 4: Calibrated linear optics vs the designed lattice in the cell installed DW. The blue lines: designed lattice, the red dash-lines: linear optics with DW and calibration.

relatively small, this is likely due to the ultra-low natural emittance of the DLSR.

The vertical linear optics is expected to be perturbed by the DW, hence the lattice compensation is needed. Since the source of the perturbation is well known, a local com-

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pensation scheme is preferred. In the simulation, a wiggler (B_{peak} = 2.1 T, λ = 31 mm, L_{tot}=4 m) is installed in a straight section. Then the calibration is performed by minimizing the deviation of $\beta_{x,y}$, $\alpha_{x,y}$ in the entry and exit point of the "local area", and also to minimize the tune shift. Therefore, a minimal of 6 correctors (quadrupoles) are needed, 3 approximate quadrupoles in up-stream and downstream side of this SS are employed. The compensated beta-functions are compared with unperturbed ones in Fig. 4, and the changes of parameters are shown in Table 2.

Table 2: Parameter Change Before and After the Calibration

Parameter	Before	After	Initial
ΔK_{Q1} [Tm]	0	-0.2081	5.52
ΔK_{Q2} [T/m]	0	1.04831	-5.09
ΔK_{Q3} [T/m]	0	-0.8115	-5.42
$rms(\Delta\beta_x)$ [m]	4e-14	3.6e-4	–
$rms(\Delta\beta_y)$ [m]	1.51	4.9e-4	–
$\Delta\nu_x$	0	4.2e-3	71.296
$\Delta\nu_y$	0	1.9e-4	23.296

β_x in the straight section is observed that to be slightly decreased after compensation, this is beneficial to reducing the beam emittance with wiggler according to the aforementioned formula. It is also noticed that the strengths of the third quadrupoles are increased, thus we shall expect sufficient redundancy for these quadrupoles in design.

TOUSCHEK LIFETIME

In the ELEGANT, the Touschek lifetime is computed using A. Piwinski's formula which includes beam envelope variation [8]. As shown in Fig. 5, the momentum aperture of a cell is obtained by tracking particles with different momentum deviations at each point of the cell. Then the Touschek lifetime is computed using the Twiss parameters and the momentum aperture. It shows that the Touschek lifetime is estimated to be 28.8 hours with an un-lengthen bunch (σ_z =2.35 mm). This result is close to the Touschek lifetime calculated using a uniform momentum aperture of 5.5% which is expected to be dominated by the momentum acceptance of the RF cavity, see Fig. 6.

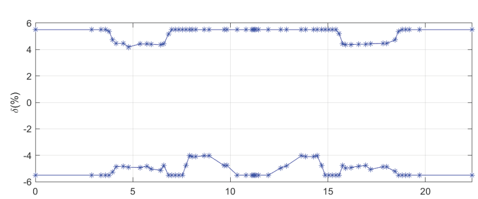

Figure 5: Momentum aperture in a cell of HALS-SR.

Based on this result, if the disturbance of the beam current needs to be controlled within 1%, the injection needs to be activated every 17 minutes. Here we assumed that the Touschek lifetime dominates the beam lifetime, elastic lifetime and inelastic lifetime are not considered yet. Further study will focus on the interaction of the electron beam with residual gas and ions is needed.

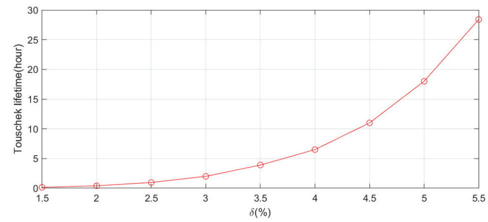

Figure 6: Touschek lifetime calculated using uniform momentum aperture.

DISCUSSIONS

The preliminary study of the IBS effect in the HALS-SR is present in this paper, it suggests that to reduce the IBS effect: the bunch shall be lengthened with high order harmonic cavity; the bunch charge shall be reduced using RF cavity with higher frequency, but it brings challenges to the pulsed PS for injection; DWs are needed to increase the synchrotron damping and to reduce the beam emittance. The Touschek lifetime is reasonably good, this benefits from the large momentum aperture in the lattice design. Further work will focus on the study of the beam lifetime due to other mechanisms, and beam instabilities.

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