ESTIMATES OF COLLECTIVE EFFECTS IN THE HALS STORAGE RING HAVING THE FIRST VERSION LATTICE

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Abstract

The Hefei Advanced Light Source (HALS) is a diffraction-limited storage ring with a beam energy of 2.0 GeV. Recently the first version lattice has been designed for the HALS storage ring, and the natural emittance is about 18 pm·rad. In this paper, we study the collective effects in this storage ring, including calculations of intra-beam scattering effect and Touschek lifetime, and estimates of the thresholds of some single-bunch and multi-bunch instabilities.

INTRODUCTION

The Hefei Advanced Light Source (HALS) is a 2 GeV diffraction-limited storage ring in the design stage. The first version lattice of the HALS has been studied using a new lattice concept of multi-bend achromatic (MBA), locally symmetric MBA, which can promise large dynamic aperture and momentum acceptance. At present, a locally symmetric 6BA lattice is considered as the nominal HALS lattice of the first version, the natural emittance of which is 18.4 pm·rad [1].

Table 1: The Main Parameters of the HALS

Parameter	Value	Units
Energy	2.0	GeV
Circumference	648	m
Average current	300	mA
Bunch charge	3.77	nC
Harmonic number	216	
Number of bunches	172	
Bunch length	12	mm
Natural emittance	18.4	pm·rad
Transverse coupling factor	0.05	
Synchrotron tune	4.23	10^{-4}
Momentum acceptance	0.06	
Momentum compaction factor	3.42	10^{-5}
Natural energy spread	0.45	10^{-3}

Coulomb scatterings of electrons and instabilities driven by impedance in a synchrotron storage ring can affect the quality of the electron beam and thus the brightness of the machine. The intra-beam scattering (IBS) effect will increase the transverse and longitudinal emittances of the beam, the Touschek effect will limit the lifetime of the beam, and the instabilities driven by impedance will limit the current of the beam. These collective effects will be more serious in a diffraction-limited storage ring like HALS.

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In this paper, we will estimate these collective effects in the HALS storage ring having the first version lattice.

The main parameters of the HALS are listed in Table 1. To estimate the values of some parameters in this table, the radiation from insertion devices is also included. In this paper, the coupling factor is assumed at 0.05, and the bucket filling at 80% for the following calculations. In addition, the bunch length is estimated at 12 mm when considering the bunch lengthening cavity.

INTRA-BEAM SCATTERING AND TOUSCHEK LIFETIME

Coulomb scatterings in the beam bunch of electron storage ring are usually divided into two parts when evaluating the influence. IBS describes the small multiple Coulomb scattering which can lead to an increase in the six dimensional emittance. Touschek scattering describes the large single Coulomb scattering which can lead to a particle loss. Now we use the program ELEGANT [2] to calculate the steady-state beam parameters under IBS effect and the Touschek lifetime for the HALS.

Intra-Beam Scattering

The IBS algorithm in ELEGANT is based on Bjorken and Mtingwa's formula and the calculated steady-state bunch parameters for HALS are shown in Table 2. We can see that the two transverse emittances at the nominal current are about 8 times as larger as they at zero current. The bunch length and energy spread are about 3 times as larger as they at zero current. The impact of the IBS effect on transverse direction is more serious than it on longitudinal direction in HALS.

Table 2: Steady-state Bunch Parameters at the Zero and Nominal Currents

Parameter	Zero current	Nominal current	Units
Beam current	0	300	mA
Horizontal emittance	17.53	142.78	pm·rad
Vertical emittance	0.88	7.14	pm·rad
Bunch length	12	37.62	mm
Energy spread	0.45	1.41	10^{-3}

We calculated the total steady-state emittance with the IBS effect as a function of single bunch charge, which is shown in Fig. 1. We can see that the IBS effect is very serious and the emittance changes very fast with bunch charge, especially from 0 nC to 1 nC. Fig. 1 also shows two other cases with the coupling factors of 0.01 and 1. We can see that the total steady-state emittance at the coupling factor of 0.01 is about two times larger than that at the coupling factor of 1.

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For further study, we calculated the total steady-state IBS emittance and the natural emittance as a function of running energy, which are shown in Fig. 2. We can see that the IBS effect is more serious at low energies and the minimum IBS emittance is obtained at the energy of about 3.5 GeV. The IBS effect is quite serious in HALS and damping wigglers are needed to reduce the emittance.

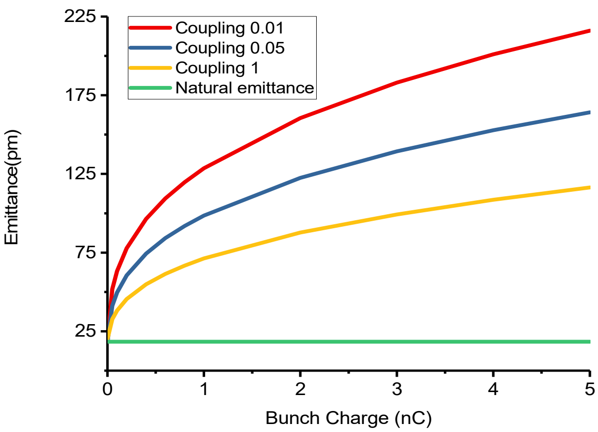

Figure 1: Total steady-state emittance vs single bunch charge.

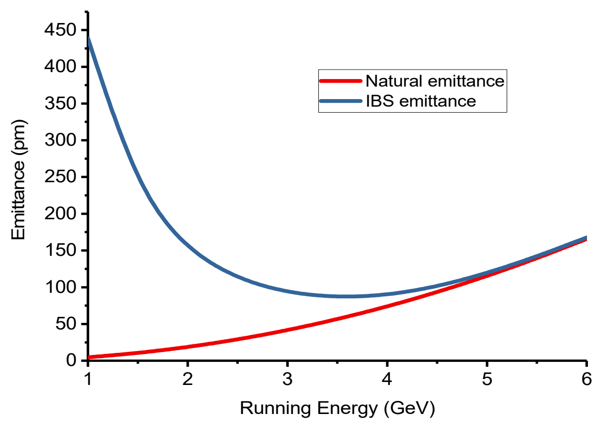

Figure 2: IBS emittance and natural emittance vs running energy.

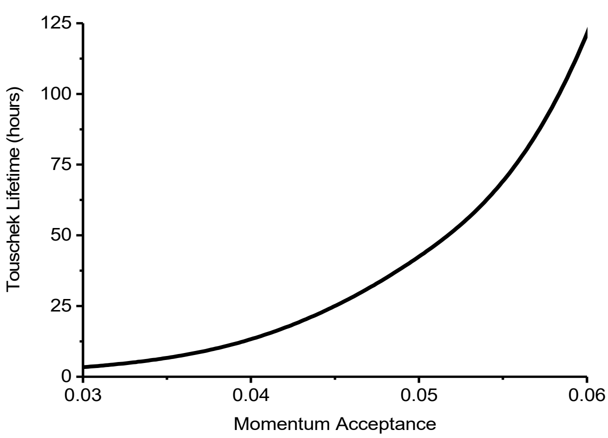

Figure 3: Touschek lifetime vs momentum acceptance.

Touschek Lifetime

Touschek lifetime is dependent on the momentum acceptance (MA) of a storage ring. Since the concept of locally symmetric MBA is used in HALS [1], the MA is decided by longitudinal MA (about ±6％). Then we obtain the Touschek lifetime in HALS: more than 100 hours, which is far enough for running a light source.

There may be some difference between the actual MA and the theoretical MA. To see the dependence of Touschek lifetime on MA, we calculated the Touschek lifetime as a function of MA, which is shown in Fig. 3. We can see that when MA is larger than 0.04, the Touschek lifetime is no longer a problem.

INSTABILITIES DRIVEN BY IMPEDANCE

Since HALS is in the early design stage and detailed physical parameters of the components are not determined yet, here we just briefly estimate some instabilities driven by impedance.

Longitudinal Microwave Instability

We use Boussard's criterion to estimate the threshold of longitudinal effective impedance under the condition of a beam current of 300 mA. The equation calculating the threshold of longitudinal microwave instability is [3, 4]:

$$I_{th} = \frac{\sqrt{2\pi}\eta(\frac{E}{e})\sigma_{e0}^2\sigma_{l0}}{R\left|\frac{Z}{n}\right|_{eff}}, \quad (1)$$

where η is the slipping factor, E is the beam energy, σ_{e0} and σ_{l0} are the natural rms energy spread and bunch length respectively, R is the average radius of the ring, $\left|Z/n\right|_{eff}$ is the longitudinal effective broadband impedance. For a single bunch current of 1.7 mA, the threshold of longitudinal effective broadband impedance is 0.073 Ω, which is a high requirement for the impedance optimization. Since Boussard`s criterion is not accurate enough, multi-particle tracking with realistic impedance will be done as the design goes on.

Microwave Instability Due To CSR

Since the components are not determined, we calculated the microwave instability only due to shielded CSR to estimate the threshold. The beam is assumed moving in a circle (y=0) between two parallel plates at locations y=±h in the calculation model. An approximation to estimate the threshold of shielded CSR is given by [5]:

$$S^{th} = 0.5 + 0.12\Pi \quad (2)$$

$$S^{th} = \frac{eN_b\rho^{1/3}}{2\pi\nu_s\gamma\sigma_\delta\sigma_z^{4/3}} \quad (3)$$

$$\Pi = \frac{\sigma_z\rho^{1/2}}{h^{3/2}} \quad (4)$$

where S^{th} is the strength parameter, Π is the shielding parameter, N_b is the number of electrons per bunch, ν_s is the synchrotron tune and ρ is the bending radius. This approximation fits well except when Π is near 0.7. We let

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the half height of vacuum chamber h=12.5 mm and the bending radius ρ=16.399 m in the calculation. With the assumption, we obtain that the shielding parameter Π=109 and the threshold of single bunch current I_{th}=26 mA which is high above the design current.

Potential Well Distortion

When the beam current is below the threshold of microwave instability, the bunch is lengthened by the potential well distortion (PWD), which can be calculated with the following equation [6]:

$$\left(\frac{\sigma_l}{\sigma_{l0}}\right)^3-\left(\frac{\sigma_l}{\sigma_{l0}}\right)-I_b\frac{e\alpha_p \operatorname{Im}\left|Z/n\right|_{eff}}{\sqrt{2\pi}\nu_s^2 E}\left(\frac{R}{\sigma_{l0}}\right)^3=0 \quad (5)$$

where α_p is the slipping factor, σ_l and σ_{l0} are the lengthened rms bunch length and original rms bunch length respectively, I_b is the average beam current. If the longitudinal effective impedance is below 0.1 Ω, the bunch lengthening caused by the PWD is within 6%.

Transverse Mode Coupling Instability

The transverse mode coupling instability (TMCI) is also called the transverse microwave instability. An approximate relation determining the threshold of this instability at zero chromaticity is given by [7, 8]:

$$I_{th}=0.7\frac{4\pi c(\frac{E}{e})\nu_s}{C}\frac{1}{\sum_i\beta_{y,i}\kappa_{y,i}} \quad (6)$$

$$\kappa_{y,i}=0.723\frac{l_i c}{\pi^{3/2}b^3}\sqrt{\frac{Z_0}{\sigma_z\sigma_c}} \quad (7)$$

where C is the circumference of the ring, κ is the kick factor of the pipe, σ_c is the conductivity of the beam pipe, b is the radius of the pipe, l is the length of the pipe, $Z_0 = 377\,\Omega$. As in the PEP-X, we assume that in the HALS the pipes are all made of Al ($\sigma_c = 3.5\times 10^7\ \Omega^{-1}m^{-1}$) and the radius of the pipes is 12.5 mm. With the assumption, the bunch current threshold of TMCI without insertion device is 2.9 mA, which is above the nominal current.

Longitudinal Coupling Bunch Instability

We only consider the contribution of the higher order modes of the RF system to the impedance when calculating the longitudinal and transverse coupling bunch instabilities, since wakefields from other sources will be damped to zero. The equation for calculating the threshold of longitudinal coupling bunch instability inspired by narrow-band impedance is [9]:

$$R_{th}^{\parallel}\omega_{HOM}=\frac{4\pi\nu_s(\frac{E_0}{e})}{\tau_s I\eta} \quad (8)$$

where τ_s is the longitudinal radiation damping time, ω_{HOM} and $R_{th}^{\parallel}$ are frequency and shunt impedances of a higher order mode of the RF cavities, η is the slipping factor. With a beam current of 300 mA, the threshold of $R_{th}^{\parallel}\omega_{HOM}$ is $1.84\times10^{13}\ \Omega\, s^{-1}$ for RF cavities in HALS.

Transverse Coupling Bunch Instability

A similar equation for calculating the threshold of transverse coupling bunch instability inspired by narrow-band impedance is [9]:

$$R_{th}^{\perp}=\frac{4\pi(\frac{E_0}{e})}{\tau_\perp\omega_0 I\beta_\perp} \quad (9)$$

where $\tau_\perp$ is the transverse radiation damping time, $\beta_\perp$ is the average beta function and ω_0 is the revolution frequency. From the equation, we obtain that the threshold of impedance is 69.07 kΩ for RF cavities in HALS.

CONCLUSION

We have studied the collective effects in the HALS storage ring for its first version lattice. In HALS, the IBS effect is extremely strong at the design current of 300 mA and running energy of 2 GeV. Damping wigglers will be used in the future work to reduce the emittance. The locally symmetric lattice design for the HALS makes the momentum acceptance quite large and leads to a large enough Touschek lifetime. Since the components of the HALS storage ring are not determined, we have just briefly estimated the impedance driven instabilities. According to our estimates, the requirement for the impedance optimization is very high. More work on the IBS and the impedance driven instabilities will be done for the HALS as the design goes on.

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