PRELIMINARY STUDY ON THE COLLECTIVE EFFECTS IN THE STORAGE RING-BASED COHERENT LIGHT SOURCE*

Y. Wang[1,2], W. Fan[3], Q. Zhang[†4], J. Li[3], Z. Zhao[4]
[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, China
[2]University of Chinese Academy of Sciences, Beijing, China
[3]Zhangjiang Laboratory, Shanghai, China
[4]Shanghai Advanced Research Institute, Shanghai, China

Abstract

The storage ring–based coherent light source (SRCLS) operates under extreme conditions including ultra-low emittance, short bunches, high current, and strong damping. In such conditions, collective effects become critically important. This paper presents a preliminary study of the key collective effects in the SRCLS, including the Touschek effect, intra-beam scattering, resistive-wall impedance, and ion effects. Through numerical simulations and theoretical analysis, the impact of these effects on beam dynamics is evaluated. The results demonstrate that stable operation of the SRCLS can be achieved under the designed parameters.

INTRODUCTION

Synchrotron radiation light sources have undergone four generations of development since the early 1970s. The SRCLS combines the advantages of both diffraction-limited light sources and free-electron lasers, and includes a high-current, short-bunch storage ring [1, 2]. Through the angular dispersion modulation (ADM) scheme, the SRCLS can generate ultra-high-brightness and coherent radiation [3]. The main design parameters are summarized in Table 1.

Table 1: Ring parameters of the SRCLS.

Parameter	**Value**
Beam energy (GeV)	1.4
Circumference (m)	172.8
Horizontal emittance (pm·rad)	800
Vertical emittance (pm·rad)	2.4
Bunch charge (nC)	2.88
Bunch length (mm)	2.72
Energy spread (%)	0.123
Energy loss per turn (MeV)	1.1
RF frequency (MHz)	499.66
Harmonic number	288
Momentum compaction factor	7.67e-4
Damping time (x/y) (ms)	1.46

However, such a light source must operate under extreme conditions: ultra-low vertical emittance, short bunches, high current, and strong damping. These conditions not only inherit the collective-effect constraints of fourth-generation storage rings, but also introduce more severe challenges [4]. High current and short bunches will significantly enhance collective effects, including the Touschek effect, intra-beam scattering (IBS), resistive impedance, and ion effects, thereby threatening beam stability. A detailed study of these collective effects is therefore essential to ensure stable operation.

This paper focuses on the validation operation of the SRCLS and systematically investigates three main types of beam collective effects: the Touschek effect and intra-beam scattering (IBS) under ultra-low vertical emittance and high bunch density; resistive-wall (RW) impedance and transverse coupled-bunch instabilities (TCBI) induced by small-aperture vacuum chambers; and the effects of residual gas ion trapping and fast ions on beam quality. Finally, a summary of the research results is presented at the conclusion.

TOUSCHEK EFFECT AND IBS

The Touschek effect originates from single large-angle Coulomb scattering between electrons inside a bunch, and directly determines the beam lifetime. IBS arises from cumulative multiple small-angle Coulomb scattering. Generally, it manifests as a gradual growth of the beam in its six-dimensional phase space. This leads to simultaneous increases in transverse emittance, bunch length, and energy spread. Consequently, together, these two effects constitute the core physics challenge for maintaining beam quality under ultra-low emittance operation.

Touschek Effect

In this paper, the Piwinski model is adopted to calculate the Touschek lifetime, which is applicable to arbitrary beam energy and transverse momentum distributions [5]. The Touschek lifetime is jointly determined by the local momentum acceptance (defined by the physical and dynamic apertures) and the RF cavity momentum acceptance. The momentum acceptance of the RF cavity can be obtained by Eq. (1) [6],

$$\delta_{\mathrm{RF}} = \sqrt{\frac{2U_0 c}{\pi f_{\mathrm{rf}} E_0 \alpha C}\left(-\cot(\varphi_s) - \varphi_s + \frac{\pi}{2}\right)}, \qquad (1)$$

where U_0 is the energy loss per turn of the storage ring, c is the speed of light, f_{rf} is the radio-frequency frequency, E_0

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† zhangql@sari.ac.cn

is the beam energy, α is the momentum compaction factor, C is the circumference of the storage ring, and φ_s is the synchronous phase.

The local momentum acceptance can be obtained via multi-turn tracking with Elegant. The RF cavity momentum acceptance and local momentum acceptance of SRCLS are shown in Fig. 1. The results indicate that the Touschek lifetime of the storage ring is mainly limited by the local momentum acceptance. Considering the requirement of the

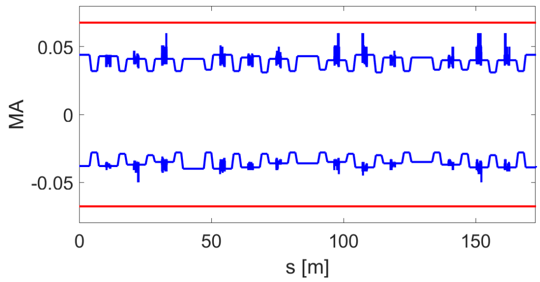

Figure 1: Local momentum acceptance (blue solid line) and the RF cavity momentum acceptance (red solid line) of the SRCLS.

ultra-low vertical emittance for ADM, the calculated Touschek lifetimes with a low coupling factor under 1 A current are shown in Fig. 2. The Touschek lifetime decreases rapidly

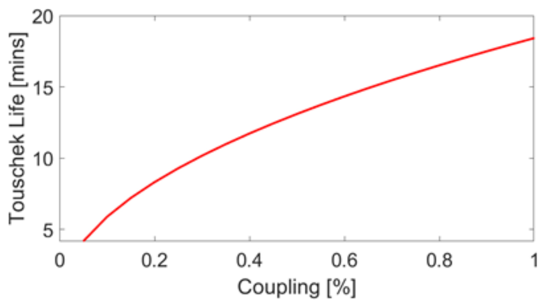

Figure 2: Touschek lifetime versus coupling factor for the SRCLS.

as the coupling factor is reduced in the low coupling factor region. To meet the requirements, the vertical emittance is adjusted by introducing skew quadrupole components in the sextupoles located in the dispersion-free regions at both ends of the straight sections, while keeping the lattice parameters nearly unchanged. With a vertical emittance of approximately 2.4 pm·rad and a coupling factor of 0.30 %, the Touschek lifetime at 1 A current reaches 10.17 minutes, which satisfies the stable operation requirements of the SRCLS.

IBS Effect

The SRCLS operates under ultra-low vertical emittance, high current, and short bunch length. The emittance growth induced by IBS is significantly enhanced, becoming the dominant factor limiting the maintenance of low emittance. Under the constraints of ADM radiation and Touschek lifetime, we have optimized the vertical emittance by adjusting the strength of the skew quadrupole components in the sextupole. The optimization uses the emittance obtained from multi-particle tracking and the results are shown in Fig. 3.

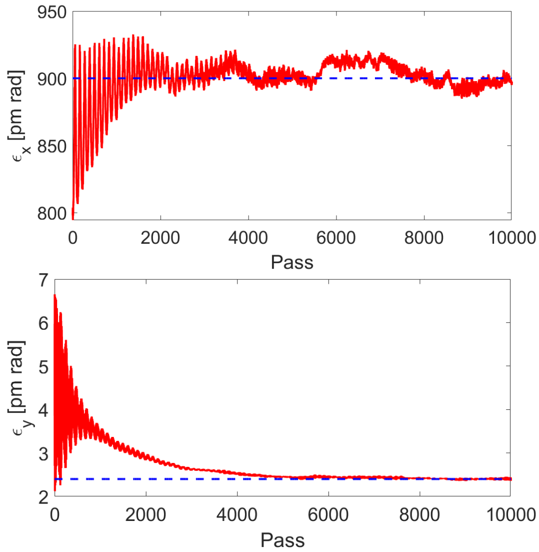

Figure 3: Horizontal and vertical emittances after 10000 turns of tracking.

Using the traditional Elegant tracking code, the results show that after sufficient turn-by-turn iterations with the IBS effect included, the vertical emittance can be stabilized near 2.4 pm·rad, while the horizontal emittance is increased to 900 pm·rad due to IBS. The slight increase in emittance leads to a small rise in the Touschek lifetime to 10.25 minutes.

RW IMPEDANCE

The SRCLS adopts a small-aperture vacuum chamber to suppress CSR and meet magnet aperture requirements, which inevitably introduces a high transverse RW impedance. Therefore, the transverse coupled-bunch instabilities (TCBI) must be evaluated carefully.

In this paper, analytical formulas are used to calculate the transverse impedance for circular and elliptical vacuum chambers [7]. The entire vacuum chamber is divided into straight sections, dipole sections, and wiggler sections for impedance parameter analysis, where straight sections are typically modeled with a circular cross-section, and both dipole sections and wiggler sections with an elliptical cross-section. CuZr alloy is used for the straight sections and dipoles, while oxygen-free copper is employed for the wiggler section at 50 K. Based on the impedance distribution, the transverse growth rates for all coupled modes are computed using the formulas from Ref. [8]. By combining the length, cross-section sizes, and average beta function, the instability growth rates for each section are obtained. The final optimized results are summarized in Table 2.

Calculations show that under the current optimized design, the growth time of transverse coupled instabilities induced by the RW impedance is 7.4 ms in the horizontal plane, which is longer than the synchrotron radiation damping time of

Table 2: Growth rates induced by resistive-wall impedance in the SRCLS.

	Length [m]	**Size** [mm] (x, y)	$\bar{\beta}$ [m] (x, y)	**Growth rate** [s^{-1}] (x, y)
Straight	127.6	25,25	6.01,6.80	120,144
Dipole	22.6	25,11	0.60,14.75	9,432
Wiggler	22.6	75,9.5	1.26,1.13	8,17
Entire	172.8		–	137,594

1.46 ms. This indicates that the stability design requirements are satisfied. However, in the vertical plane, the synchrotron radiation damping time is also 1.46 ms, while the instability growth rate is significantly higher owing to the large beta function and small vacuum chamber aperture in the dipole sections, with a corresponding growth time of only 1.68 ms. This leads to an insufficient vertical damping margin. Therefore, a multi-bunch feedback system is required to provide additional damping to ensure the long-term stable operation of the SRCLS.

ION EFFECTS

The ultra-low vertical emittance and high average current require us to pay close attention to the fast ion effects at high beam intensities, in addition to the conventional ion-trapping effects. In this paper, the ion effects of major residual gases including H_2, N_2, CO, O_2, CO_2 are considered, and the ion-trapping threshold and oscillation frequency are analyzed under the typical vacuum condition of 1.4 nTorr, with the corresponding formulas given by Eq. (2) and Eq. (3), respectively [9, 10].

$$A = \frac{N_b r_p S_b}{2\left(\sigma_x + \sigma_y\right) \min\left(\sigma_x, \sigma_y\right)}, \tag{2}$$

$$f_{x,y} \approx \frac{c}{2\pi}\sqrt{\frac{4 N_b r_p}{3 A_{\text{gas}} S_b \left(\sigma_x + \sigma_y\right) \sigma_{x,y}}}, \tag{3}$$

where A represents the critical mass number of stably trapped ions, A_{gas} is the mass number of the residual gas, r_p the classical radius of the proton, N_b is the number of electrons per bunch, S_b is the distance between adjacent bunches, and $\sigma_{x,y}$ denotes the horizontal or vertical root-mean-square beam size.

The mass numbers and trapping thresholds for different species of residual gas molecules are shown in Fig. 4. Calculation results indicate that H_2 cannot be trapped in the fully filled configuration, while heavier ions can be stably trapped in local regions. In the 200-bunch filling mode, CO_2 exhibits the longest oscillation period in the vertical plane at 21 ns, which is much shorter than the bunch gap cleaning time of 176 ns, indicating that no multi-turn stable trapping of ions occurs and only a single-turn fast ion effect is present.

Following the method described in Ref. [10], 1000 turns of tracking are performed using Elegant, and the total ion

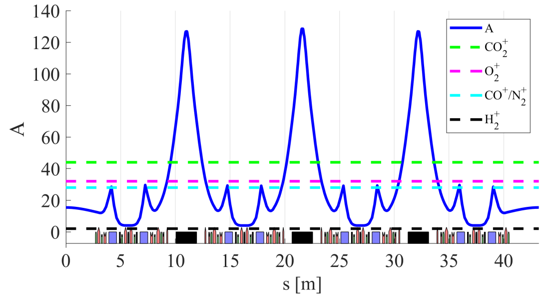

Figure 4: Molecular mass numbers for different residual gas and ion-trapping thresholds in a cell of the SRCLS.

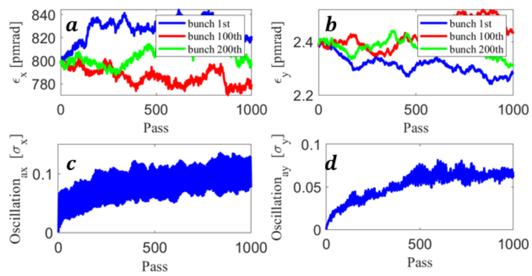

Figure 5: Panels (a) and (b) show the transverse emittance evolution of different electron bunches versus tracking turns. Panels (c) and (d) display the normalized maximum centroid amplitude of the 200 bunches in the transverse plane.

density in the storage ring is finally stabilized at a low level of approximately 1200 ions/m. The simulation results are shown in Fig. 5. Under the present condition, the ion effect has almost no influence on the beam emittance and will only introduce small perturbations to the bunch centroid. The maximum amplitude is about 10 % of the bunch size in the horizontal plane and 6.5 % in the vertical plane. Thus, the ion effect has a limited influence on beam quality.

SUMMARY

In this paper, a preliminary study is carried out on the key collective effects of the SRCLS. For the Touschek effect and IBS, the ultra-low vertical emittance can be stabilized at the design value of 2.4 pm·rad and the beam lifetime maintained at approximately 10 minutes by adjusting the skew quadrupole. For RW impedance, the small-aperture vacuum chamber introduces a high impedance. In the horizontal plane, the instability growth rates are smaller than the damping rates, which basically meets the stability requirement, while additional damping is required for the vertical plane by a multi-bunch feedback system. In terms of ion effects, multi-turn ion trapping will not occur in the 200-bunch filling mode. Besides, fast ion trapping also has no obvious influence on the emittance and will only perturb the bunch centroid slightly. Overall, under the extreme operating conditions, collective effects examined in this paper stay within acceptable limits. These results provide direct support for the physics design and parameter optimization of the SRCLS.

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