ID effects on beam dynamics in the SSRF-U storage ring

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Abstract

This paper introduces the proposed Insertion Device (ID) scheme for the Shanghai Synchrotron Radiation Facility Upgrade (SSRF-U). Based on this scheme, the influences of the ID radiation on the Intra-Beam Scattering (IBS) emittance and energy spread were evaluated. Optical distortion caused by the IDs was comprehensively examined and compensated using both local and global corrections. Subsequently, a Frequency Map Analysis (FMA) method was used to identify potentially dangerous resonance lines. In addition, the dynamic aperture, energy acceptance, and Touschek lifetime were calculated after considering high-order magnetic field errors to ensure that the ID effect did not affect the operation of the storage ring.

Full Text

Preamble

ID Effects on Beam Dynamics in the SSRF-U Storage Ring

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Abstract

This paper introduces the proposed Insertion Device (ID) scheme for the Shanghai Synchrotron Radiation Facility Upgrade (SSRF-U). Based on this scheme, the influences of ID radiation on Intra-Beam Scattering (IBS) emittance and energy spread were evaluated. Optical distortion caused by the IDs was comprehensively examined and compensated using both local and global corrections. Subsequently, a Frequency Map Analysis (FMA) method was used to identify potentially dangerous resonance lines. The dynamic aperture, energy acceptance, and Touschek lifetime were calculated after considering high-order magnetic field errors to ensure that ID effects did not compromise storage ring operation.

Keywords: SSRF-U; Insertion devices; Emittance; Beam dynamics

1 Introduction

The Shanghai Synchrotron Radiation Facility has devised an upgrade plan (SSRF-U) that aims to achieve the soft X-ray diffraction limit. The SSRF-U plans to install numerous insertion devices to provide superior light sources for additional beamline users. Compared to third-generation light sources, these IDs feature smaller magnetic gaps and higher magnetic fields, exerting greater influence on beam dynamics.

The ID effect on beam dynamics manifests primarily in three aspects: radiation, closed orbits, and optics. First, owing to high magnetic fields, ID radiation losses are equivalent to or exceed those in bending magnets, resulting in significant reduction in the equilibrium emittance and energy spread. Furthermore, beamline users may induce non-negligible fluctuations in beam parameters such as emittance and energy spread through independent adjustments of the ID field, potentially affecting photon brightness or distribution stability. These fluctuations may impact sensitive beamline techniques such as microfocus beamlines, scanning transmission X-ray microscopy, and other experimental methods. Second, ID mounting and magnetic field integral errors can lead to closed-orbit distortion (COD), necessitating feedforward compensation using trim coils on both sides of the ID. Even in an ideal planar horizontal wiggler, the fringe field focusing of each pole can induce vertical focusing and distort the vertical beta function. This optical distortion breaks lattice periodicity, excites previously insignificant resonance lines, generates new higher-order resonance lines, and degrades the dynamic aperture and momentum acceptance, decreasing injection efficiency and beam lifetime. Therefore, it is essential to examine ID effects on beam dynamics in the SSRF-U.

Several methods have been proposed to compensate for ID effects. To address ID effects on emittance, effective approaches include installing a fixed-gap wiggler in a variable dispersion bump, adjusting the variable-gap wiggler based on a feedback system with real-time monitoring, and optimizing dispersion in straight sections. To investigate the necessity of emittance compensation in the SSRF-

U, we conducted a detailed analysis of ID radiation effects. These findings demonstrate that the Intra-beam Scattering (IBS) effect significantly dilutes emittance fluctuations, thereby making emittance compensation unnecessary.

A feedforward system based on response-matrix measurements can effectively compensate for closed-orbit distortions, optical distortions, tune shifts, and coupling distortions. Shimming with permanent magnet shims or active shim wires is also an effective way to decrease field integrals and phase errors in APPLE-II-type IDs. In addition, global compensation for closed orbits and optics can be achieved using the Linear Optics from Closed Orbits (LOCO) method. Beta beating is widely used to quantify ID effects on optics.

Analysis of IDs in the SSRF-U reveals that elliptically polarized undulators (EPUs) and superconducting wigglers (SCW) require local compensation, whereas other IDs exert minor influence and only require global compensation.

In this study, the kick map method was used to evaluate ID effects on closed orbits and optics. Kick map tables were generated by the symplectic integrator method in the ELEGANT software and then imported into the AT software for particle tracking. ID radiation and dispersion were not included in the kick map model. When these elements need to be calculated, effective approaches include either slicing the ideal planar ID into a combination of bending magnets or manually incorporating radiation into the calculation formula.

This study focused on ID effects on the SSRF-U storage ring. Section 2 briefly introduces basic information about the lattice and ID schemes. Section 3 examines variations in emittance and energy spread caused by ID radiation effects, considers the IBS effect, and discusses the necessity for emittance compensation in the SSRF-U. Section 4 evaluates optical distortion and tune shift using local and global compensation methods to restore optics. Section 5 presents Frequency Map Analysis (FMA) results of ID effects on oscillation detuning and dynamic apertures, comparing the lattice with all IDs to that with all IDs and high-order magnet errors. Energy acceptance and Touschek lifetimes were also examined after considering ID effects and magnet errors. Finally, Section 6 concludes the paper.

2 Descriptions of the SSRF-U

The SSRF-U storage ring lattice consists of 20 7BA cells with a circumference of 432 m. This section presents the basics of the SSRF-U and briefly describes the ID scheme.

The main parameters of the bare lattice are summarized in and the beam optics within a super period are shown in [Figure 1: see original paper]. Four straight sections with a length of 10.1 m were set up separately, two of which were used for the beam injection and high-frequency systems; only the other two sections were available for ID installation. The length of the standard straight section was 5.1 m, which was suitable for the current ID configuration of the SSRF. Each short straight section can accommodate two IDs with a length of approximately 2 m or one ID with a length of approximately 4 m. The maximum value of the dispersion function, approximately 0.095 m, occurred in the optical hump section, whereas the dispersion in the straight sections was negligible.

An additional quadrupole was added on both sides of the long straight section to amplify the beta function at the injection point, thereby appropriately increasing the dynamic aperture in the x-direction while correspondingly decreasing it in the x'-direction. Consequently, ID perturbation in the long straight sections was much higher than that in the short straight sections. Moreover, the 2.1 Tesla super bending magnet and 1.1 T dipoles in the arc section can also provide X-rays for beamline users. The total radiation loss per turn, calculated only for the dipoles and anti-bends, is 637.128 keV. However, this radiation loss almost doubled when the IDs were included. The natural beam emittance of 53.2 pm • rad reached the diffraction limit for soft X-rays. Nevertheless, the low emittance implies that the beam emittance affected by IBS will increase rapidly.

An insertion device scheme comprising 18 IDs was proposed to satisfy the requirements of different users. The ID parameters, including In-Vacuum Undulators (IVU), Cryogenic Permanent Magnetic Undulators (CPMU), Wiggler, Elliptically Polarized Undulator (EPU) and Superconducting Wiggler (SCW), are listed in . The short straight sections can only accommodate a 4 m ID and there are two additional quadrupole correctors on either side of the long straight sections. In the ensuing research, we assume that 2 EPUs are installed in the middle of the long straight sections, whereas the other IDs are installed in the middle of the short straight sections.

The dual-canted-ID strategy enables the installation of additional IDs by placing two IDs in the same straight section and providing beamlines for different users. In this scheme, although 18 IDs already occupy all the straight sections, summarizes the main parameters of insertion devices at SSRF-U.

3 Radiation Effects of the IDs

The ID radiation effect significantly increases the energy loss per turn, leading to higher radiation damping and lower natural emittance. The natural emittance and energy spread can be calculated using the synchrotron radiation integrals expressed in Eq. (1) and Eq. (2), assuming that the ID optics effect is not considered. The contribution of IDs to the emittance and energy spread can be described by their synchrotron radiation integrals when the ID is assumed to be a periodic magnet system. The complete expressions are given in Eqs. (4). The ID radiation damping effect is included in the equation and the quantum excitation effect caused by the dispersion contributed by the ID itself is included in the equation, although they are not explicitly shown.

To date, the natural emittance and energy spread have been calculated using synchrotron radiation integration with the given ID and ring parameters. In this approach, the contribution of optical distortion is ignored and we assume that both EPUs are in a horizontal linear polarization model and that the effective magnetic fields of all IDs are negligible at their maximum magnetic gaps. The ID parameters listed in were sequentially incorporated into the synchrotron radiation integrals, and the calculated results are shown in [Figure 2: see original paper]. The results demonstrate the variation in the emittance and energy spread from the bare lattice (left) to the lattice with all IDs (right), while the ID gap is sequentially closed. Due to these variations, the horizontal emittance decreased from 53.2 to 43.6 pm • rad, along with a reduction in energy spread from 0.00134 to 0.00115. This decrease was due to the gradual increase in the radiation loss from the bare lattice (637 keV) to almost double (1185 keV) when all IDs were included. In addition, a sharp increase owing to the high-field SCW in both the emittance and energy spread can be observed at the rightmost point of [Figure 2: see original paper]. This phenomenon was due to the high quantum excitation associated with the large dispersion contributed by the SCW. When the contribution of the SCW was excluded, each general ID decreased the emittance by approximately 1.3% and the energy spread by 1.1%.

In future low-emittance storage rings, in which the electron density will be extremely high, there will be a high rate of small-angle Coulomb scattering. This implies that the IBS effect may significantly impact new-generation light sources. A common strategy for mitigating the IBS effect is bunch lengthening using high-order harmonic cavities. Simultaneously, it is also an effective way to reduce electron density by increasing transverse coupling. In the subsequent study, after accounting for the ID radiation effect and disregarding the optical distortion, the Bjorken–Mtingwa model was used to calculate the equilibrium IBS emittance and energy spread as a function of coupling, including no bunch-lengthening, 3-factor, 5-factor and 7-factor bunch lengthening. [Figure 3: see original paper] depicts the results for both the bare lattice and the lattice with all IDs, under fixed beam parameters of I = 500 mA, filling 500 bunches, and an RF frequency of 500 MHz. The dashed line represents the bare lattice, and the solid line corresponds to the lattice with all IDs. The area between the dashed and solid lines indicates the potential variation range induced by the IDs.

Compared with the result without the IBS effect shown in [Figure 2: see original paper], the IBS equilibrium emittance increased by approximately 56% (without IDs) and 20% (with all IDs) in the case of 100% beam coupling and 5-factor bunch lengthening, as depicted in [Figure 3: see original paper]. Simultaneously, the energy spread increased marginally. When comparing the results between the scenarios with no ID and with all IDs, after considering the IBS effect, the increase in transverse damping led to an emittance reduction of approximately 9 pm • rad for 100% beam coupling in 3-factor, 5-factor and 7-factor bunch lengthening. The equilibrium IBS energy spread exhibited a substantial drop of approximately 25%. This phenomenon is caused by ID radiation, which is particularly significant in storage rings where ID-induced radiation prevails over bending-magnet radiation. In the SSRF-U, each ID decreased the emittance by 0.9% (with IBS), which was much less than the result without the IBS effect of 1.3%. This indicates that the IBS effect significantly diluted the emittance variation in the SSRF-U storage ring.

If the coupling is greater than 0.2, further increasing coupling has little influence on weakening the IBS effect. It can be observed that the effects of higher bunch lengthening and coupling gradually worsened. Additionally, it is worth noting that the dispersion contributed by the ID itself was ignored in the kickmap model used in the above simulation results. Therefore, in actual operation, the emittance will be marginally higher than the results shown in [Figure 3: see original paper].

Upon analyzing the operational data from the current SSRF, we found that the variation in brightness was primarily attributed to EPUs. Consequently, we focused on the IBS emittance and energy spread resulting from the EPUs (in the case of 5-factor lengthening and 20% beam coupling) and incorporated these factors into the SPECTRA software to evaluate brightness variations in different beamlines. presents the brilliance ranges of CPMU18, IVU20, and EPU58 for different harmonic numbers (1, 3, 5, 7, and 9), and the 2.1 T Super-B at different photon energies. The results indicate that the brilliance variation for each ID is approximately 0.5% (contributed by the EPUs), which does not affect beamline users during actual operation. Therefore, emittance variations do not cause significant instability in photon brightness or distribution, which eliminates the need for emittance compensation in the SSRF-U storage ring.

4 Restoration of the Beam Optics Distorted by the IDs

In this section, we focus on the ID effect on linear optics, which can be characterized by the Root Mean Square (RMS) beta-beating. The EPUs and SCW, which caused significant optical distortion, were corrected locally, whereas the other IDs were corrected globally using the LOCO method. Initially, we analyzed the optical distortion induced by ideal periodic-field insertion devices. The simulation results of the RMS beta beating of planar undulators and EPUs in the helical polarization operation model are shown in [Figure 4: see original paper] as a function of magnetic field intensity. The solid line represents the RMS beta beating in the horizontal plane, and the dashed line indicates that in the vertical plane. As shown in the graph, the EPUs contribute approximately 6% to horizontal beta-beating, which is significantly higher than the 2% contributed to vertical beta-beating. The SCW had a 9% impact, exceeding that of the other planar undulators, which ranged from 1.5 to 3%. This substantial beta beating highlights the necessity of establishing a local feedforward compensation system to mitigate the impact of the EPUs and SCW on linear optics.

Furthermore, we examined the impact of ID errors. The ID field integral and integral multipole errors were considered, as listed in . The IDs were modeled using kickmap slices owing to the periodicity of the ID magnetic field. Additional kick angles at the entrance and exit of the IDs were added to the ideal kick map table to simulate field integral error, whereas the integral multipole errors were incorporated into each kick map slice. Subsequently, we used correctors located throughout the ring and the trim coils on both sides of the ID for orbit correction. In this section, we study only the Closed Orbit Distortion (COD) contributed by the IDs and consider a beam position monitor (BPM) measurement error of 0.2 µm. More complex error analysis was not the subject of this study; if needed, a first-turn simulation could be an effective method for further research. A comparison of the COD before and after correction is shown in [Figure 5: see original paper]. Even when the ID field integral errors reach their maximum values, the maximum kick angle for the feed-forward coil is less than 1 µrad.

4.1 Local Correction

As shown in [Figure 4: see original paper], the EPUs and SCW have a significant influence on optics, which may substantially reduce the dynamic aperture, momentum acceptance, and Touschek lifetime. To mitigate ID effects on beam dynamics, local compensation was built for these two EPUs and the SCW. By adjusting the quadrupoles nearest to the EPUs and SCW, this method facilitates restoration of the optics and tunes the shift. The biggest advantage of this method is that the ID remains transparent to other areas after correction, even when beamline users adjust the ID magnet gap. In actual operation, the feed-forward table can be generated based on the measured response matrix of the corrector coils or nearest quadrupoles to restore closed-orbit distortion and optical distortion.

The compensation parameters for the quadrupoles were calculated using optical and tune-shift matching methods. Twelve quadrupoles were located on both sides of the arc sections that could be adjusted to compensate for the two EPUs installed in the long straight sections. Additionally, 10 quadrupoles were available to compensate for the SCW installed in the short straight section.

summarizes the results of the local correction for the EPUs and SCW, including the RMS beta-beating, RMS dispersion deviation, and tune-shift, both before and after correction. As shown in the results, the remaining optical distortion for the EPUs was less than 0.4% in both the horizontal and vertical planes, and the tune shift was negligible. However, for the high-field SCW48, the optical distortion persisted at 0.67% in the horizontal plane and 1.32% in the vertical plane, even after local optics correction. It should be noted that local correction has a greater influence on dispersion, particularly in the horizontal plane. After local correction for EPUs and SCW, there was still an RMS beta-beating of 0.78% in the horizontal plane and 3.77% in the vertical plane, primarily attributable to the other IDs. Consequently, a global correction method is used in the following section to further reduce optical distortion.

4.2 Global Correction by the LOCO Method

The LOCO method is a widely used technique for compensating global optics in particle accelerators. Based on the existing local compensation results, the LOCO method was used to correct the global optics and tune shifts by iteratively adjusting quadrupole strengths. There are 240 Beam Position Monitors (BPMs) and 208 quadrupole correctors on the ring that can be used for LOCO compensation and global tune-shift correction.

[Figure 6: see original paper] shows a comparison of beta-beating along the ring with all IDs before and after LOCO correction in both the horizontal and vertical planes. provides metrics describing the effect of LOCO correction, including RMS beta-beating and RMS dispersion deviation; the tune shift after LOCO correction can be neglected. As shown in [Figure 6: see original paper], there is still minor optical distortion near the IDs, especially near the high-field SCW. The residuals are mostly concentrated between the ends of the ID and the nearest quadrupole correctors. In addition to the horizontal distortion contributed by the EPUs, part of the horizontal distortion is produced when the quadrupole correctors are adjusted to compensate for the more substantial vertical distortion. As shown in , the residual RMS beta beating is 0.77% in the horizontal plane and 2.39% in the vertical plane, which cannot be further reduced without additional correctors. Simultaneously, the RMS dispersion deviation after LOCO correction is reduced to 0.05%. These factors can significantly affect the dynamic aperture and momentum acceptance of the storage ring, which will be discussed in the following section.

5.1 Oscillation Detuning and Dynamic Apertures

In this section, we study beam dynamics in the SSRF-U storage ring with all IDs after LOCO correction. First, we discuss the dynamic aperture and nonlinear resonance caused by the IDs using FMA. Furthermore, to analyze whether IDs affect stable operation of the storage ring, the dynamic aperture, momentum acceptance, and beam lifetime were calculated after adding high-order magnetic field errors.

[Figure 7: see original paper] presents a comparison of tune shifts between the bare lattice and the lattice with all IDs after LOCO correction, along with deviation in oscillation amplitude. It can be seen that the tune shift is effectively adjusted by LOCO correction. When the particle oscillation frequency approaches or crosses resonance lines at horizontal oscillation amplitudes of -1, 1, -2, and 1.7 mm, this suggests that it is worth examining whether small quadrupole field errors in the storage ring can result in loss of particles with larger amplitudes.

The nonlinear features of the SSRF-U storage ring detailed in this section were obtained from simulation tracking of 2000 turns using the AT software. In addition to the FMA method, which uses four-dimensional particle tracking, the other simulations used six-dimensional particle tracking, encompassing both radiation loss and RF cavity.

Frequency Map Analysis (FMA) is a powerful tool used in accelerator physics to assess the stability of particle motion and characterize the dynamic aperture and oscillation frequency around a closed orbit. Introduced in the early 1990s, FMA has been used extensively to analyze resonance structures within dynamic storage ring apertures. This tool helps us take measures to mitigate the presence of detrimental nonlinear resonances, which can affect injection efficiency, beam lifetime, and overall operational performance. FMA establishes a one-to-one mapping from action to angular frequency using tracking data to accurately calculate the frequency and its diffusion rate. The diffusion velocity is then used to illustrate the stability of the corresponding particle motion. FMA is effective for near-integrable systems with toroidal motions and helps avoid the occurrence of wide resonance, strong resonance, and resonance intersections by selecting appropriate tune and chromaticity. For simulation tracking to yield accurate results with FMA, radiation losses and energy compensation from the cavity must be removed.

The diffusion rate in tune space is defined by Eq. (5), where the transverse tunes are labeled on the color scale. Areas of instability are characterized by high diffusion rates with bright colors, and are usually related to the intersection of nearby resonance lines.

[Figure 8: see original paper] presents the frequency map graph of the SSRF-U storage ring, encompassing both the bare lattice and the lattice with all IDs after LOCO correction. The color in the figure represents the difference between particle oscillation frequencies calculated using tracking data from the first and last 1000 turns. The horizontal and vertical tunes were 51.17 and 16.22, respectively. Only a single third-order structural resonance was present in this region.

In the bare lattice ([Figure 8: see original paper]a,b), several “islands” are separated by resonance lines, especially the half-integer resonance and the structure resonance. The half-integer resonance 2Qy=33 creates ‘islands’ in regions with vertical amplitudes greater than 2 mm. The frequencies of particles with horizontal amplitudes of -2 and 1.7 mm lie on the third-order unstructured resonance line 3Qx=154. Ideally, particle motion is only slightly affected by this resonance. Within the dynamic aperture, no dangerous resonances exist except for some apparent resonance nodes. The third-order structure resonance Qx+2Qy=4$×$21 has a significant effect on the dynamic aperture, separating the region at vertical amplitudes of approximately 1.5 mm. Although dynamic aperture with radiation loss tracking does not identify particle loss caused by this resonance, it is highly sensitive to magnetic field errors, which makes the resonance dangerous. In fact, particles are lost soon after entering the region owing to oscillation.

[Figure 8: see original paper]c,d clearly shows that optical distortion caused by the IDs disrupts the periodicity of the storage ring, significantly amplifies the third-order structure resonance line Qx+2Qy=4$×$21, and excites numerous additional higher-order resonance lines. As illustrated in the frequency space of [Figure 8: see original paper]d, the most dangerous resonance line restricts the dynamic aperture. This implies that if optics distortion in the horizontal plane further increases, particles in the zone with x less than -2 mm will be entirely lost. More detailed simulation results in the SSRF-U have demonstrated that the threshold value of horizontal RMS beta beating is approximately between 1 and 1.3%. If it exceeds 1%, particles in the destabilized region will be entirely lost; if it surpasses 1.3%, the resonance line will be significantly excited, rendering the vicinity unstable. SWAPOUT injection is currently under preliminary consideration, and as long as the effects of the IDs on the optics are properly compensated, these effects should not significantly affect SSRF-U injection.

In the ensuing research, 50 high-order magnetic field error seeds were added to the dipoles, quadrupoles, and sextupoles, including normal and skew errors, as listed in . Normal and skew errors were assigned the same amplitude. Based on measurement data from the SSRF, the maximum amplitude of intrinsic errors in the magnets was assumed to be one value, while non-intrinsic errors were presumed to have a different maximum amplitude.

After adding multipole errors, we first compared optical distortion caused by ID effects and multipole errors. The maximum RMS beta-beating contributed by multipole errors was less than 0.015% in both the horizontal and vertical planes. In addition, the ID integral multipole errors were of the same order of magnitude. Therefore, compared with optical distortion caused by the IDs, the errors contributed a small proportion.

[Figure 9: see original paper] illustrates the dynamic aperture at the center of the long straight section under different conditions, including the bare lattice and all IDs with 50 high-order magnetic field error seeds after LOCO correction, at energy deviations ΔP/P of 0, 1.5, and -1.5%. The solid lines represent the median numbers of calculated data points. The figure shows that the dynamic aperture (ΔP/P=0) reduced by less than 10% after adding all IDs when considering high-order magnetic field errors. The dynamic aperture with a 1.5% energy deviation decreased slightly. Consequently, ID effects and high-order magnetic errors will not significantly affect beam injection.

5.2 Energy Acceptance and Touschek Lifetime

The energy acceptance of a storage ring is determined by its nonlinear dynamics as well as limitations imposed by RF voltage and dynamic aperture size. This parameter refers to the maximum energy deviation at which a particle remains stable while circulating within the ring. Energy acceptance, which is also affected by the dispersion function, tends to be smaller in areas where dispersion is greater. [Figure 10: see original paper] shows the fractional tune shift with deviation of oscillation energy at the center of the long straight section. Particles with an energy deviation of -2.2% have already exceeded the half-integer resonance. Because the errors considered were not very large, particles were not lost when crossing the half-integer resonance.

[Figure 11: see original paper] shows the energy acceptance distribution of the storage ring for both the bare lattice and all IDs after considering magnetic errors. The figure was obtained by tracking each position according to the arrangement of magnetic elements. The vacuum chamber was assumed to have a circular cross-section with a radius of 10 mm, which represents the maximum amplitude of particles during tracking.

In the bare lattice, the energy acceptance in the long straight section exceeded \$±\$2.5% and the minimum value was approximately \$±\$1.5% in the arc section, effectively capturing the injected beam with energy dispersion. This energy acceptance ensures substantial beam lifetime in the storage ring. However, after considering the IDs and multipole errors, [Figure 11: see original paper] shows a notable reduction in the arc sections, particularly on the negative side. In high-dispersion areas, where optical distortions were most sensitive, the minimum value decreased from 1.5 to 1%. This reduction in energy acceptance is inevitable because of the existence of multipole errors and residual optics distortion after LOCO correction.

The primary factor influencing beam lifetime is the Touschek lifetime, which results from electron Touschek scattering. Unlike multiple small-angle scatterings (intrabeam scattering) within a bunch, Touschek scattering constitutes a large-angle scattering process that transfers transverse momentum of a particle to the longitudinal direction. If the energy deviation of a particle exceeds the acceptable energy, the particle is lost, thereby considerably reducing beam lifetime. In this section, we discuss the Touschek lifetime with IDs after LOCO correction in the SSRF-U storage ring. The Touschek lifetime was calculated using Eq. (6), as derived by Piwinski.

In this equation, represents the classical electron radius, is the speed of light in vacuum, is the number of particles in each bunch, is the Lorentz factor, is the bunch length, is the momentum acceptance, correspond to the transverse beam sizes, and is a function of the Twiss parameter and momentum acceptance.

Eq. (6) shows that the average Touschek lifetime is determined by the Twiss parameter, electron density, energy acceptance, and beam size. The Touschek lifetime is strongly dependent on electron density and energy acceptance. However, both electron density and beam size are influenced by the IBS effect, whereas the Twiss parameter is associated with optics. To calculate the Touschek lifetime, we used the IBS results from Section 3, optics results after LOCO correction (with errors) from Section 5.1, and momentum acceptance results from Section 5.2.

These results were substituted into Eq. (6) to calculate the Touschek lifetime. Similar to the IBS effect analysis, we considered bunch-lengthening factors of 1, 3, 5, and 7, under a beam current of 500 mA, filling 500 bunches, and an RF frequency of 500 MHz. The Touschek lifetime as a function of beam coupling with all IDs and multipole errors is shown in [Figure 12: see original paper], where the solid lines represent the median number and the error bars represent the standard deviation.

The Touschek lifetime of the bare lattice is discussed in Ref. [3]. In the case of 5-factor bunch lengthening, the Touschek lifetime was approximately 3.1 hours. However, after adding IDs and multipole errors, the Touschek lifetime significantly decreased to lower values, as shown in [Figure 12: see original paper]. Two factors contributed to this substantial reduction in Touschek lifetime. First, the radiation damping contributed by the IDs reduces the IBS equilibrium emittance and energy spread, leading to decreased bunch size and increased charge density. This triggered a considerable increase in the Touschek scattering rate, which primarily accounts for the deterioration in beam lifetime. Second, multipole errors and residual optics distortions inevitably reduce the momentum acceptance. Increasing bunch lengthening continues to be an effective method for enhancing Touschek lifetime. Additionally, if coupling can be increased, the Touschek lifetime can be further improved.

6 Conclusions

In this study, we present an overview of the SSRF-U storage ring and propose an ID scheme based on user requirements. The effects of ID radiation and optics on beam dynamics were calculated by incorporating the IBS effect. The results indicated that the average impact of each ID on emittance was less than 1%. The RMS beta beating contributed by the EPUs and SCW exceeded 5%, necessitating separate local compensation. Local and global compensation were used to restore global optics and tunes. After LOCO correction, the RMS beta beating was reduced to 0.77% in the horizontal plane and 2.39% in the vertical plane. Subsequently, the dynamic aperture and nonlinear resonance were analyzed using the FMA method. The most dangerous resonance line was identified, which could restrict the horizontal oscillation amplitude to less than 2 mm if horizontal optical distortion continued to increase.

High-order magnetic field errors were also factored into the calculation, and the resulting dynamic aperture satisfied the requirements for transverse on-axis beam injection. The average energy acceptance can still ensure beam lifetime during high-current operation.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Li-Yuan Tan, Shun-Qiang Tian and Xin-Zhong Liu. The first draft of the manuscript was written by Li-Yuan Tan and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement

The data that support the findings of this study are openly available in Science Data Bank at https://doi.org/10.57760/sciencedb.j00186.00088 and https://cstr.cn/31253.11.sciencedb.j00186.00088.

Note: Figure translations are in progress. See original paper for figures.