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INTRA-BEAM SCATTERING AND TOUSCHEK SCATTERING OPTIMIZATIONS FOR THE UPGRADED SSRF *

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Abstract

In this study, we present the design of a candidate lattice for the Shanghai Synchrotron Radiation Facility Upgrade (SSRF-U) storage ring, targeting the soft X-ray diffraction limit. Due to its ultra-low emittance, intra-beam and Touschek scattering are significant and require attention. We conducted simulations to examine the emittance growth and beam lifetime of different machine configurations in the SSRF-U storage ring. Equilibrium beam emittance variations due to beam coupling and bunch lengthening were identified through simulations. Additionally, Touschek scattering and beam lifetime were calculated.

INTRODUCTION

To enhance the brightness and improve the light source quality for advanced scientific studies [1-2], the Shanghai Synchrotron Radiation Facility (SSRF) has an upgrade plan, referred to as SSRF-U. This upgrade targets achieving the diffraction limit in the soft X-ray region, necessitating an emittance below 80 pm·rad. A suite of simulations using the Accelerator Toolbox (AT) was carried out to mitigate the impact of intra-beam scattering (IBS) and Touschek scattering within the SSRF-U storage ring [3]. Initially, the impact of IBS on emittance, bunch length, and energy spread was analyzed by varying the beam coupling coefficient (defined by $\kappa = \varepsilon_y/\varepsilon_x$) across different RF frequencies. This analysis was extended by examining changes in bunch length under various conditions. Subsequently, the influence of IBS on emittance with respect to energy at different currents was explored [4]. The investigation focused on Touschek scattering and beam lifetimes as influenced by beam coupling.

LATTICE DESIGN OF THE SSRF-U STORAGE RING

The SSRF-U storage ring, designed to operate at a beam energy of 3.0 GeV, achieves a natural emittance of 53.2 pm·rad, meeting the soft X-ray diffraction limit. Leveraging the existing tunnel infrastructure, the SSRF-U lattice includes twenty 7BA cells distributed over four superperiods, creating a total circumference of 432 meters [5]. The beam optics and lattice configuration for one superperiod are depicted in Fig.1. Main parameters of the SSRF-U are summarized in Table 1.

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In the SSRF-U storage ring, both the momentum acceptance (MA) and dynamic aperture (DA) were determined through tracking. MA along the SSRF-U storage ring was greater than ±1.5%. The influence of this MA on the Touschek lifetime is examined in Section III. At the injection point, the MA reaches over ±2%, ensuring efficient capture of all injected electrons despite their energy spread.

Table 1: Principal Parameters of the SSRF-U

Parameter	Value	Units
Lattice	20 × 7BA	
Beam energy	3.0	GeV
Circumference	432	m
Current	500	mA
Tune (H, V)	51.17, 16.22	
Bunch number	360	
Number of particles per bunch	1.25e9	
Bunch charge	2.0	nC
Natural bunch length	2.60	mm
RF frequency	499.654	MHz
RF voltage	2000	kV
Harmonic number	720	
Natural chromaticity (H, V)	-98.63, -68.11	
Damping time (H, V, E)	5.98, 13.57, 18.53	ms
Corrected chromaticity (H, V)	2.0, 1.0	
Energy loss per turn	637.128	keV
Natural energy spread	1.351	10-3

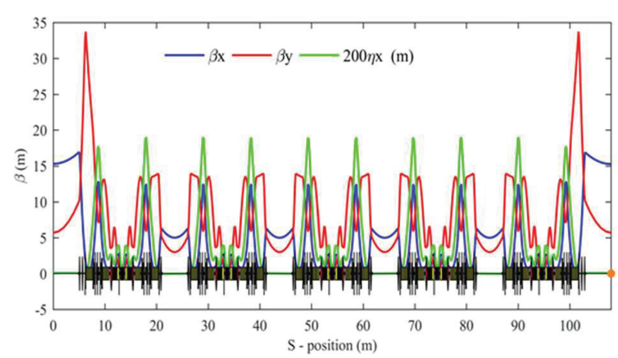

Figure 1: Depicts the beam optics and lattice layout for a single super-period of the SSRF-U.

EQUILIBRIUM BEAM PARAMETERS WITH IBS EFFECT

IBS involves multiple small-angle Coulomb scattering events among electrons within a bunch resulting in electron diffusion across the six-dimensional phase space. This phenomenon is quantitatively described by the Bjorken–Mtingwa model, which allows for precise calculation of the

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IBS rate, expressed as follows [6]:

$$\frac{1}{T_i}=4\pi A(\log)\left\langle\int_0^\infty d\lambda\frac{\lambda^{1/2}}{\left[\det(L+\lambda I)\right]^{1/2}}\times\left\{TrL^iTr\left(\frac{1}{L+\lambda I}\right)-3Tr\left[L^i\left(\frac{1}{L+\lambda I}\right)\right]\right\}\right\rangle \quad (1)$$

$$A=\frac{r_0^2cN}{64\pi^2\beta^3\gamma^4\varepsilon_h\varepsilon_v\sigma_s\sigma_p} \quad (2)$$

The IbsEmittance code, which implements the Bjorken–Mtingwa model, was used to evaluate the impact of IBS. The equilibrium beam parameters influenced by IBS were calculated, and the values are summarized in Table 2.

Conventionally, third-generation light sources maintain beam coupling at 1% or lower. However, simulations show that at a current of 500 mA with 1% coupling, both horizontal and vertical emittances increase threefold, a rise that is unsustainable for the SSRF-U storage ring's operation. Illustrations in Fig. 2 demonstrate that by setting the beam coupling to 10% or higher, the adverse effects of IBS are significantly reduced. Consequently, adjusting the beam coupling to 10% not only reduces the equilibrium horizontal emittance to 95.54 pm·rad but also lowers the energy spread to 0.165%.

To accommodate different user requirements and ensure stable beam operation, two filling patterns have been devised for SSRF-U: a high average brightness mode and a mode for high charge in a single bunch. Comparative analyses reveal that operating frequencies of 500 MHz and 100 MHz are optimal for the high-brightness and high-bunch charge modes, respectively. Additionally, the high-brightness mode at 500 MHz significantly outperforms the 100 MHz setting in user demand and efficiency for the SSRF-U storage ring. The employment of a 500 MHz RF frequency is deemed superior, optimizing bucket occupancy and weaken IBS impacts. Prospects for further decreasing rise and fall times could lead to filling four of the five available RF buckets in the high-brightness mode at this frequency, allowing for 480 bunches and further diminishing IBS effects.

Furthermore, using third harmonic cavities to lengthen the electron bunch length is an effective strategy to diminish IBS impacts, the technique widely adopted in synchrotron radiation sources [7]. Theoretically, with a single third-harmonic cavity, the maximum bunch-lengthening factor at SSRF-U could reach nine, but practically, a limit of five or less is used. This setting increases the SSRF-U bunch length to 13.0 mm, effectively reducing emittance growth from 80% to approximately 20%, and similarly decreasing.

TOUSCHEK LIFETIME

Touschek scattering involves large-angle Coulomb scattering within a bunch that transfers momentum from transverse to longitudinal directions. This increase in longitudinal momentum can exceed the limits of the momentum aperture or RF bucket, leading to particle loss. The formula for calculating Touschek lifetime, derived by Piwinski, is shown below [8]:

$$1/\tau\_Touschek=\left\langle\frac{r_0^2cN_b}{8\pi\gamma^2\sigma_s}F(\delta\_m,B_1,B_2)\frac{1}{\sqrt{\sigma_x^2\sigma_y^2-\sigma_\delta^4D_x^2D_y^2}\beta\delta_m}\right\rangle \quad (3)$$

In the context of the SSRF-U storage ring, r_0 denotes the classical electron radius, c represents the speed of light, N_b refers to the number of particles per bunch, γ is the Lorentz factor, σ_s indicates the bunch length, δ_m signifies the momentum acceptance, σ_x and σ_y are the transverse beam sizes, and function F is influenced by the Twiss parameters and momentum acceptance. According to Equation (3), the average Touschek scattering lifetime is dependent on the Twiss parameters, electron density, energy acceptance, and beam size. The momentum acceptance along the SSRF-U was greater than ±1.5%.

Using the IbsEmittance software, integrated within AT, the equilibrium emittance, bunch length, and energy spread were quantified. These parameters, along with the Touschek lifetime tool, facilitated the estimation of Touschek lifetimes under the high-brightness filling pattern characterized by 500 MHz frequency, 360 buckets, and 500 mA current. Initial evaluations revealed a Touschek lifetime of merely 0.69 hours at 10% coupling and σ_s of 3.3 mm.

To increase the Touschek lifetime, strategies such as increasing beam coupling and lengthening the bunch were used. Variations in Touschek lifetimes and scattering rates for different bunch lengths and couplings in the high-brightness mode were analyzed using AT. The outcomes are depicted in Fig. 3 (a), showing the Touschek lifetimes, and in Fig. 3 (b), illustrating the distribution of Touschek scattering rates along the ring.

Data from Fig. 3 (a) demonstrate that a fivefold increase in bunch length in the high-brightness mode with a 10% coupling, enhances the Touschek lifetime to 2.5 hours. Additionally, Fig. 3 (b) indicates that the Touschek scattering rate in the bending sections is elevated compared to other sections of the SSRF-U. Significantly, lengthening the bunch reduces the Touschek scattering rates in these critical sections. Achieving full coupling locally in the curved sections could further increasing the beam lifetime.

Table 2: Equilibrium Beam Parameters for the SSRF-U

Parameter	κ=1%	κ=1%	κ=10%	κ=10%	Units
Beam current	0	500	0	500	mA
Emitx	52.81	149.48	48.46	95.54	pm·rad
Emity	0.5281	1.489	4.846	9.554	pm·rad
Energy spread	1.35	1.86	1.35	1.65	10^{-3}
Bunch length	2.60	3.57	2.60	3.18	mm

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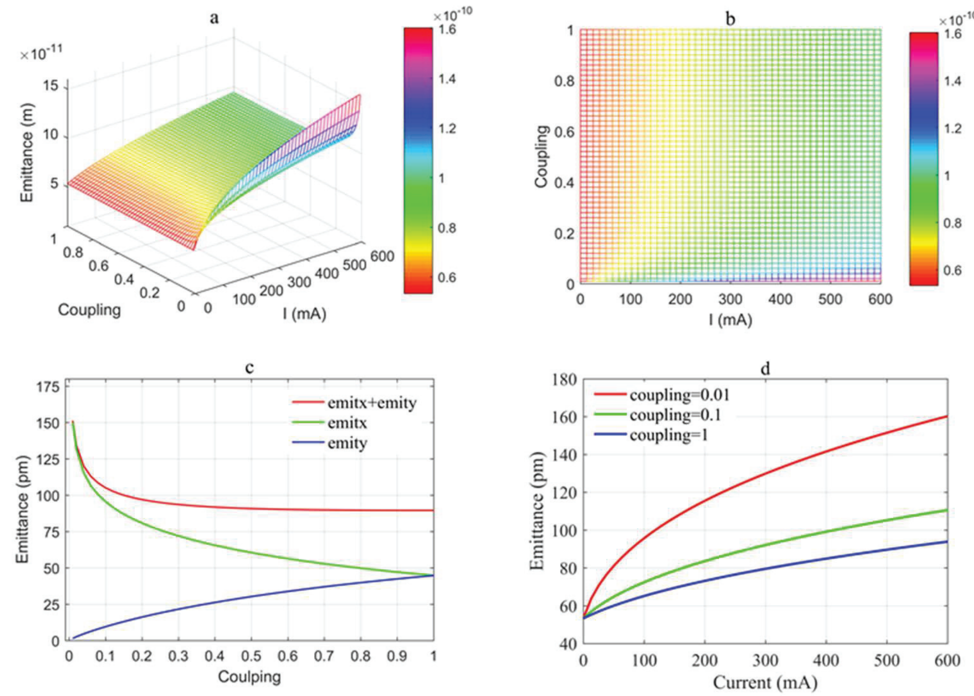

Figure 2: Displays the relationship between estimated equilibrium transverse emittances, coupling, and beam current for the SSRF-U, detailing variations by coupling at 500 mA (c) and by beam current across different couplings (d).

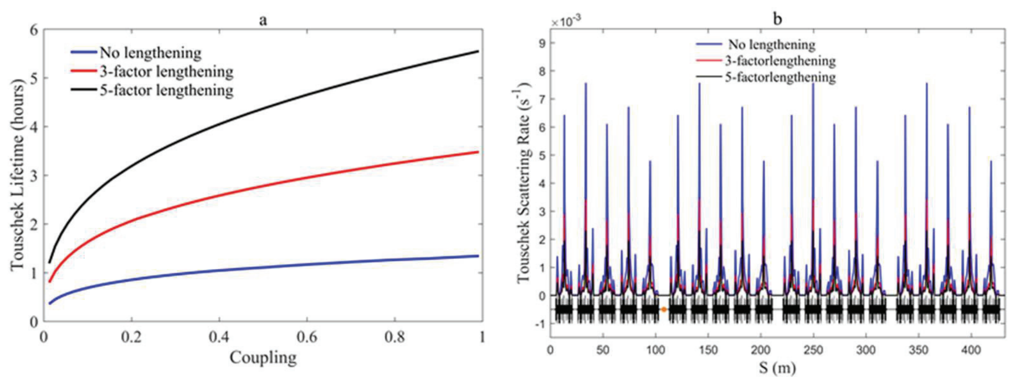

Figure 3: Illustrates Touschek lifetimes across various bunch lengths as a function of coupling at the SSRF-U (panel a), and Touschek scattering rates along the ring for different bunch lengths at the SSRF-U (panel b).

CONCLUSION

The lattice of the SSRF-U storage ring, comprising twenty 7BA cells, achieves a natural emittance of 53.2 pm·rad. Simulation studies confirm that the high-brightness mode, with a 500 MHz RF frequency, 500 mA current, and 360 bunches, is well-suited to the specifications of the SSRF-U storage ring, satisfying high brightness requirements. Furthermore, it is recommended to extend the bunch length fivefold using a third-harmonic cavity and to adjust the coupling to 10%. Operating at these settings, with an energy of 3.0 GeV, the SSRF-U can maintain a total beam lifetime exceeding 2.0 hours and achieve the targeted beam emittance for the soft X-ray diffraction limit. This improved lattice configuration not only reduces beam emittance but also significantly enhances brightness for scientific experiments compared to the original SSRF.

REFERENCES

[1] H. J. Xu, Z. T. Zhao, "Current status and progresses of SSRF project", *Nucl. Sci. Tech.*, vol. 19, no. 1, pp. 1-6, 2008. doi:10.1016/S1001-8042(08)60013-5

[2] L Yin, R. Tai, D. Wang, Z. Zhao, "Progress and future of shanghai synchrotron radiation facility", *Jour. Vac. Soc.*, vol. 59, no. 8, pp. 198-204, 2016. doi:10.3131/jvsj2.59.198

[3] A. Terebilo, "Accelerator toolbox for MATLAB", SLAC National Accelerator Lab., Menlo Park, CA, USA, SLAC-PUB-8732, 2001. doi:10.2172/784910

[4] S. K. Tian, J.-Q. Wang, G. Xu, Y. Jiao, "Intra-beam scattering studies for low emittance at BAPS". *Chin. Phys. C*, vol. 39, no. 6, p. 067001, 2015. doi:10.1088/1674-1137/39/6/067001

[5] X.-Z. Liu, S.-Q. Tian, X. Wu, *et al.*, "Intra-beam scattering and beam lifetime in a candidate lattice of the soft X-ray diffraction-limited storage ring for the upgraded SSRF", *Nucl.*

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Sci. Tech., vol. 32, no. 8, pp. 1-10, 2021. doi:10.1007/s41365-021-00913-y

[6] K. Kubo, K. Oide, “Intrabeam scattering in electron storage rings”, *Phys. Rev. Spec. Top. Accel Beams*, vol. 4, no. 12, p. 124401, 2001. doi:10.1103/PhysRevSTAB.4.124401

[7] X.-Y. Pu, H.-T. Hou, Y. Wang, *et al.*, “Frequency sensitivity of the passive third harmonic superconducting cavity for SSRF”, *Nucl. Sci. Tech.*, vol. 31, no. 3, p. 31, 2020. doi:10.1007/s41365-020-0732-x

[8] A. Piwinski, “The Touschek effect in strong focusing storage rings”, DESY, Hamburg, Germany, Rep. DESY-98-179, Mar. 1999. arxiv:physics/9903034