A PRELIMINARY STUDY OF FULL-COUPLING OPERATION FOR THE HALF STORAGE RING

P. Yang, X. Liu*, G. Liu, Y. Huang, Z. Bai
National Synchrotron Radiation Laboratory, USTC, Hefei, China

Abstract

To mitigate the intra-beam scattering effects and improve Touschek lifetime, a full-coupling operation based on the linear difference resonance is preliminarily studied for the Hefei Advanced Light Facility (HALF). The dependence of coupling ratio on skew quadrupole strength and the distance to the difference resonance is analyzed. With a coupling ratio of 90 %, particle tracking simulations confirm that the expected equilibrium emittances are achieved. However, beam loss occurs during the off-axis injection due to the excitation of the vertical motion. Amplitude-dependent tune shifts are tailored by reducing the octupole strengths to shift the injected beam away from the coupling resonance, which suppresses the beam loss effectively. This study demonstrates the feasibility of high-coupling operation in HALF and highlights the importance of optimizing nonlinear detuning for good injection efficiency.

INTRODUCTION

The Hefei Advanced Light Facility (HALF) is a greenfield fourth-generation synchrotron radiation light source proposed by NSRL [1]. It operates at 2.2 GeV with a 480 m circumference comprising 20 hybrid six-bend achromat lattice cells, yielding a natural emittance of 86 pm rad. The relatively low beam energy and ultra-low emittance result in strong intra-beam scattering (IBS) effects in the storage ring, significantly increasing the equilibrium emittance and limiting the Touschek lifetime. To suppress the IBS effects and further improve the beam lifetime, a full-coupling operation (or round beam operation) mode can be adopted, in which the horizontal and vertical beam emittances are made comparable. Simulations for HALF show that, if the transverse coupling ratio is increased from 10 % to 100 %, the horizontal equilibrium emittance with the IBS effect considered can be reduced from 190 pm rad to 88 pm rad, and the Touschek lifetime increases by approximately a factor of two.

Operating the machine on the linear difference resonance with finite coupling is a straightforward way to generate round beams, which has been studied in many storage rings including APS, NSLS-II, ALBA, HEPS, Korea-4GSR, PETRA IV and SLS 2.0 [2–8]. In this scheme, the transverse tunes are adjusted to approach the difference resonance, and then weak skew quadrupoles are used to excite the resonance, thereby causing the exchange between horizontal and vertical motions. Detailed theories on the weak betatron coupling can be found in Ref. [9]. Since strong skew quadrupoles are not needed, the operation remains near a typical decoupled regime, allowing horizontal and vertical optics to be handled independently. In addition, distortions to the closed orbits, linear optics and nonlinear dynamics performance are relatively small. However, for HALF, which adopts an off-axis injection scheme, beam loss at devices with small vertical apertures (the vertical collimator and in-vacuum undulator, etc.) may occur during the injection, due to the excitation of the vertical motion.

In this paper, the full-coupling operation scheme based on the linear difference resonance is preliminarily studied for the HALF Storage. The key factors affecting the coupling ratio are first studied and then the realization of high-coupling beam is verified based on particle tracking. Finally, the issues of beam loss during the beam injection are briefly discussed.

FACTORS AFFECTING THE COUPLING RATIO

Based on the perturbation theory and ignoring the vertical dispersion, the coupling ratio of transverse equilibrium emittance at the coupling resonance can be expressed as

$$\kappa = \frac{\varepsilon_y}{\varepsilon_x} = \frac{|C|^2}{\frac{4}{1+J_x}\Delta^2 + |C|^2}, \qquad (1)$$

where J_x is the horizontal damping partition number and $\Delta = \nu_x - \nu_y$ is the difference of the fractional parts of unperturbed betatron tunes. C is the coupling driving term, defined as

$$C = \frac{1}{2\pi} \oint \mathrm{d}s \sqrt{\beta_x \beta_y} K_{sq}(s) e^{i[\phi_x(s) - \phi_y(s) - \frac{2\pi s}{L}\Delta]}, \qquad (2)$$

where L is the circumference, K_{sq} the skew quadrupole strength, $\beta_{x,y}$ and $\phi_{x,y}$ the unperturbed beta functions and phases at skew quadrupoles, respectively. From the equation, we see that the coupling ratio is mainly decided by the distance from resonance Δ and the coupling coefficient C, with the later one depending on the layout and the strengths of skew quadrupoles. While for Δ, in a real machine, it cannot be made exactly zero due to the tune spread inside the bunch, power supply noise and so on. APS operation shows that $\Delta \leq 0.005$ is easily reachable [2].

To avoid generating undesired vertical dispersion, 40 skew quadrupoles located in the dispersion-free regions of HALF are used to excite the linear coupling resonance. These quadrupoles currently share the same strength but different polarities to maximize $|C|$ with the smallest possible strength. The dependence of the coupling ratio on skew quadrupole strength is then studied. With Δ tuned to be 0.005, the variations of $|C|$ and κ with skew quadrupole strengths are

---

* liuxy@ustc.edu.cn

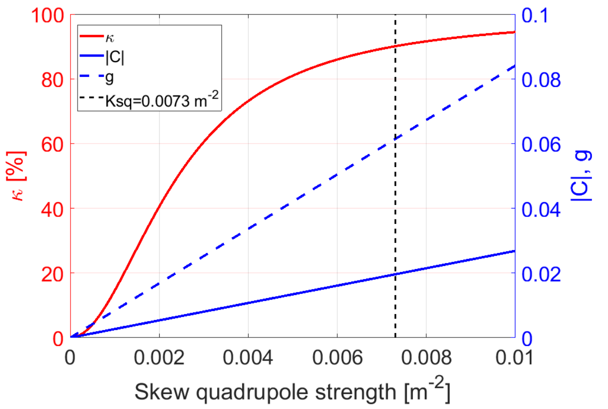

Figure 1: Variations of κ, $|C|$ and g factor with skew quadrupole strength at Δ=0.005.

scanned, as shown in Fig. 1. The results show that $|C|$ is proportional to K_{sq} but the increase of the coupling ratio is subject to diminishing marginal returns. One way to evaluate the x-y coupling strength is to use the g factor, which represents the ratio of the RMS value of the orbit in the non-kicked plane to that in the kicked plane [2]. Larger g means stronger transverse coupling and g<0.1 can be treated as the weak coupling regime. The variation of g factor with skew quadrupole strengths is shown in Fig. 1, which also exhibits a proportional relationship. It indicates that realizing a large coupling ratio, for example, >95 % or even near 100 %, needs much stronger skew quadrupoles, consequently causing large distortions to beam dynamics. So a coupling ratio of 70 %~90 % may be more appropriate considering both the aim of high coupling and relatively small distortions. For HALF, K_{sq} needs to be 0.0073 m^{-2} (corresponding to $|C|$=0.0197 and g=0.061) to obtain a coupling ratio of 90 % at Δ=0.005.

Another factor affecting the coupling ratio is Δ. We then scanned the variation of κ with Δ at different skew quadrupole strengths, as shown in Fig. 2. The results show that larger $|C|$ provides a wider tolerance range of Δ for achieving a high coupling. In addition, the stability of κ will also be better with larger $|C|$. For example, consider to achieve the same coupling ratio of 80 % under different values of $|C|$. When $|C|$=0.005, Δ=0.0019 is required; when $|C|$=0.02, Δ=0.0077 is required. If there is a tune perturbation of ±0.001, the coupling ratio of the former will vary between 63.7 % and 94.8 %, while coupling ratio varies in the range of 75.7 %~84.0 % for the latter, which is clearly more stable.

VERIFICATION OF THE HIGH COUPLING RATIO BASED ON PARTICLE TRACKING

Ignoring the IBS effect, the equilibrium emittance is determined by the quantum excitation and radiation damping in the storage ring, given by the expression of

$$\varepsilon_x = J_x\varepsilon_0/(J_x+\kappa), \quad \varepsilon_y = \kappa J_x\varepsilon_0/(J_x+\kappa), \tag{3}$$

where ε_0 is the natural emittance. For the HALF baseline lattice with J_x=1.36, ε_x and ε_y are expected to be 51.8 pm rad and 46.6 pm rad, respectively, when the IBS effect is ignored and κ=90 %. Multi-particle tracking was performed to verify the realized high coupling ratio, using the injected beam with the main parameters listed in Table 1. In the tracking, the bunch has 1000 particles, and the physical apertures are set to be large enough values to avoid beam loss in the vertical plane. Figure 3 shows the evolution of ε_x and ε_y during the tracking. Due to the long damping times of HALF (bare lattice), it takes about 1.5×10^5 turns to reach the equilibrium emittance, about 52 pm rad and 46 pm rad in the horizontal and vertical planes, respectively, which accord well with the calculation results from Eq. 3.

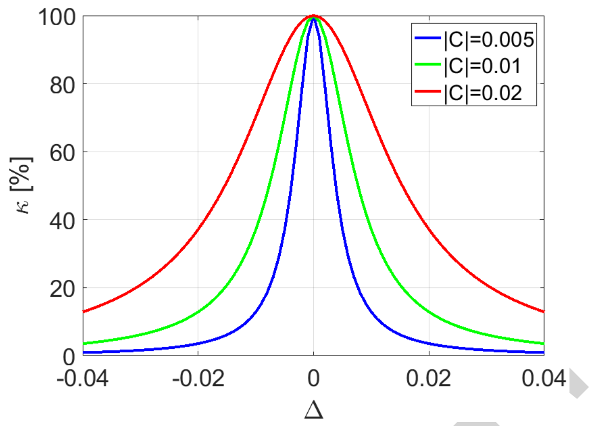

Figure 2: Variations of κ with Δ at different skew quadrupole strengths.

Table 1: Main Parameters of the Injected Beam

ε_x	ε_y	RMS bunch length	Energy spread
12 nm	12 nm	1 mm	1×10^{-3}

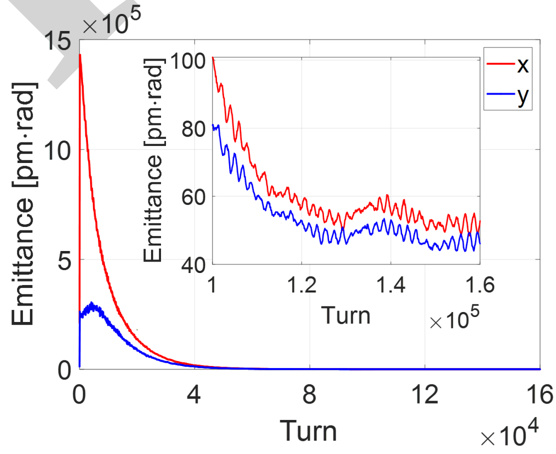

Figure 3: Evolution of ε_x and ε_y during the tracking. The lattice is tuned to have a coupling ratio of 90 %. The inset shows a zoom of the last 60,000 turns.

BEAM LOSS ISSUE DURING THE BEAM INJECTION

The previous particle tracking was performed without including the real physical apertures, so no particle was lost.

However, with practical physical apertures considered, the injected beam with a large horizontal amplitude may be lost at the vertical plane due to the energy exchange between horizontal and vertical planes. For HALF, the location of minimum vertical acceptance is the vertical collimator (nominal gap of ±3.5 mm). With $|C|$=0.0197 and the coupling ratio tuned to be 90 %, Fig. 4 shows the survival ratios of the injected beam at different turns. The beam loss occurs rapidly since the energy exchange period is only about 49 turns, which can be calculated from $T = 1/\sqrt{\Delta^2 + |C|^2}$. For the baseline lattice with nominal octupole strengths, about 51 % of the beam is lost within one interchange period, and the remaining 49 % is lost gradually over 12,000 turns.

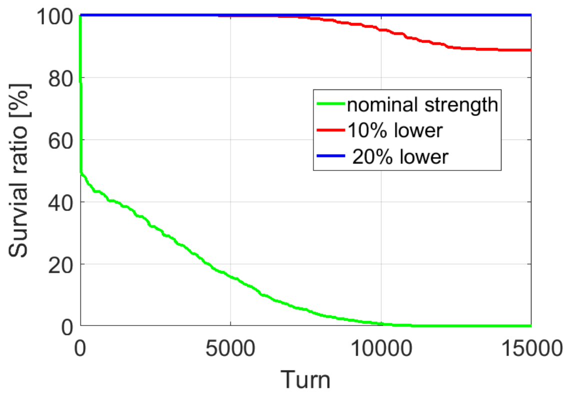

Figure 4: Survival ratios of the injected beam at different turns for the lattice cases with different octupole strengths.

Strong nonlinear detuning can be utilized to reduce beam loss by shifting the injected beam away from the coupling resonance [10]. By directly adjusting the octupole strengths in HALF storage ring, the amplitude-dependent tune shifts (ADTS) are tailored to increase the Δ of the particles with large horizontal amplitudes, as shown in Fig. 5. For a particle with a horizontal amplitude of 6 mm, the Δ is increased from 0.044 to 0.076 with the octupole strengths lowered by 10 %, and increased to 0.11 when lowered by 20 %, thereby significantly suppressing energy exchange between the two planes for the injected beam.

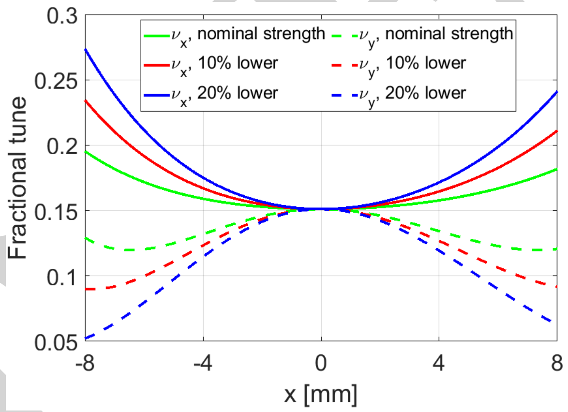

Figure 5: Horizontal ADTS for the lattice cases with different octupole strengths.

Figure 6 shows the vertical oscillations tracked at the position of the vertical collimator at different octupole strengths. Note that in the tracking, the physical apertures are ignored to avoid beam loss. The results clearly show that the vertical motion excited by coupling weakens as octupole strengths are reduced, and the vertical amplitude no longer exceeds the aperture of the vertical collimator if the octupole strengths are reduced by 20 %. This is confirmed by tracking with realistic physical apertures, as shown in Fig. 4. Here, the octupole strengths were simply reduced to demonstrate the effectiveness of tailoring the ADTS for suppressing beam loss. In practice, octupole strengths will also affect the dynamic aperture and momentum aperture, and they should be optimized considering ADTS, dynamic aperture and momentum aperture simultaneously.

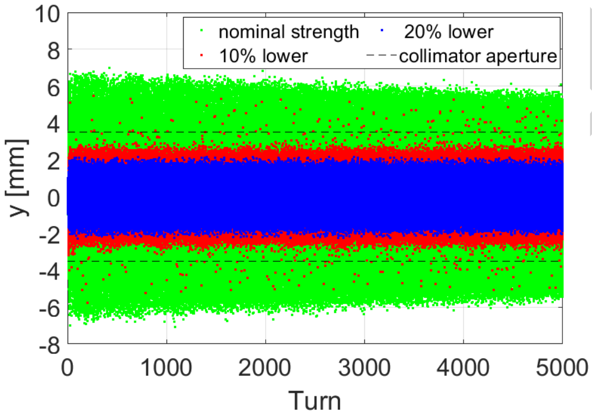

Figure 6: Vertical oscillations tracked at the position of the vertical collimator for the lattice cases with different octupole strengths.

CONCLUSION

In this paper, the full-coupling operation based on the linear difference resonance is preliminarily studied for the HALF storage ring. The analysis shows that increasing the coupling ratio by enhancing the skew quadrupole strength (or $|C|$) exhibits diminishing marginal returns. However, a larger $|C|$ may provide a more stable coupling ratio with disturbances considered. Particle tracking simulations confirm that a high coupling ratio can be achieved, consistent with theoretical expectations. However, for HALF adopting an off-axis injection scheme, beam loss may occur due to the excitation of the vertical motion. To address this issue, ADTS are tailored by simply adjusting octupole strengths to suppress transverse coupling for the injected beam. Future work will focus on the simultaneous optimization of ADTS, dynamic aperture and momentum aperture to ensure both a high injection efficiency and a long lifetime.

ACKNOWLEDGEMENTS

This work was supported by the Fundamental Research Funds for the Central Universities (No. WK2310250135, No. WK2310000107).

REFERENCES

[1] Z. Bai, G. Feng, T. He, *et al*, “Progress on the storage ring physics design of Hefei Advanced Light Facility (HALF)”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1075-1078. doi:10.18429/JACoW-IPAC2023-MOPM038

[2] A. Xiao, L. Emery, V. Sajaev, and B. X. Yang, “Experience with round beam operation at the Advanced Photon Source”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 562-564. doi:10.18429/JACoW-IPAC2015-MOPMA013

[3] Y. Hidaka, W. X. Cheng, Y. Li, T. V. Shaftan, and G. M. Wang, “Round beam studies at NSLS-II”, in *Proc. IPAC’18*, Vancouver, Canada, Apr.-May 2018, pp. 1529-1532. doi:10.18429/JACoW-IPAC2018-TUPMK018

[4] M. Carlà, G. Benedetti, U. Iriso, *et al.*, “Methods for full coupling operation in a synchrotron light source”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 28, p. 082803, Aug. 2025. doi:10.1103/rhfy-8jsp

[5] C. C. Du, J. Q. Wang, D. H. Ji, *et al.*, “Studies of round beam at HEPS storage ring by driving linear difference coupling resonance”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 976, p. 164264, Oct. 2020. doi:10.1016/j.nima.2020.164264

[6] J. Lee, S. Ahn, J. Ko, *et al.*, “Concurrent operation of round beam and flat beam in a low-emittance storage ring”, *Nuclear Engineering and Technology*, vol. 55, pp. 3866-3873, Oct. 2023. doi:10.1016/j.net.2023.07.002

[7] E. C. Cortés García and I. Agapov, “Dynamics of off-axis injection near the coupling resonance at PETRA IV”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1148-1151. doi:10.18429/JACoW-IPAC2023-MOPM072

[8] J. Kallestrup, “Feasibility of round beams in SLS 2.0”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1027-1030. doi:10.18429/JACoW-IPAC2023-MOPM021

[9] P. J. Bryant, “A simple theory for weak betatron coupling”, 1994.

[10] P. Kuske. “Round beam related challenges in storage ring light sources”, in *Proc. FLS2018*, Shanghai, China, May 2018.