A NUMERICAL STUDY ON INJECTION EFFICIENCY IMPROVEMENT AT SuperKEKB ELECTRON RING

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Abstract

SuperKEKB is an asymmetric lepton collider with 7-GeV electron and 4-GeV positron beams. In Run 2024, the vertical beta function β_y^* at the collision point was set to approximately 1 mm. The measured results confirmed that reducing β_y^* led to narrower dynamic apertures in the horizontal and vertical directions and decreased the beam injection efficiency into the ring. This study describes a potential mitigation scheme of aperture sharing injection to improve the electron injection efficiency and achieve higher beam luminosity.

INTRODUCTION

The SuperKEKB collider comprises a high-energy electron ring (HER) and a low-energy positron ring (LER). The peak luminosity of SuperKEKB [1] was recorded at over $5.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ in Run 2024. To further increase the luminosity, it is crucial to improve: 1) beam injection performance [2, 3], 2) beam backgrounds on Belle2 detectors from stored and injected beams, 3) Sudden Beam Loss [4], and 4) specific beam luminosity. These technical challenges are primarily due to SuperKEKB being the first collider to employ low-beta optics with a vertical beta function, β_y^*, of ≤ 1 mm at the interaction point (IP). This study discusses several issues related to beam injection performance based on our operational experience. Additionally, we propose a potential mitigation scheme to improve the HER beam injection efficiency.

BEAM INJECTION OVERVIEW

Dynamic Apertures

The shrinkage of both the horizontal and vertical dynamic apertures, as illustrated in Fig. 1, is one of the unfavorable effects of the low-beta optics scheme. The data were measured using Turn-by-Turn Beam Position Monitors (TbT-BPM) and dipole kickers in the operational collimator setting. The transverse dynamic apertures shrank rapidly as β_y^* decreased. Lower β_y^* optics require a larger $\beta_{x/y}$ at the superconducting quadrupole magnets near the IP because the lower β_x^* is correspondingly reduced. Hence, the HER injection efficiency drops were observed as β_y^* decreased, although this varied with the HER collimator setting.

Injection Efficiencies in Collision

Injection efficiencies are affected by beam collisions at the IP owing to the beam-beam kick. Figure 2 depicts an overview of the HER and LER injections at peak luminosity.

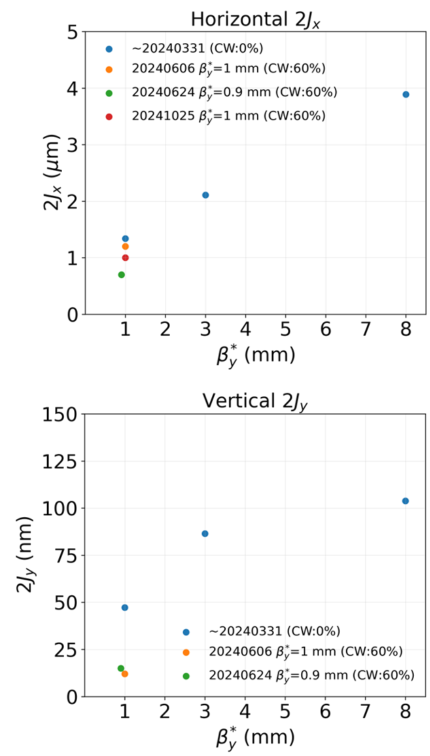

Figure 1: Measured horizontal (top) and vertical (bottom) dynamic apertures of HER with different β_y^* values and crab waist (CW) conditions.

Single-bunch and double-bunch injections were performed for HER and LER, respectively. The HER injection efficiency decreased when the HER storage current exceeded approximately 1 A, whereas the LER injection efficiency decreased when the LER storage current increased [Fig. 2(d)]. Furthermore, the beam lifetimes [Fig. 2(f)] decreased as the stored bunch currents [Fig. 2(e)] increased, in addition to an increase in the ring vacuum pressures (not shown in the figure), owing to the Touschek effect and residual gas scattering. Consequently, the injection power and beam loss rates were balanced at peak luminosity [Fig. 2(g)] in both rings. However, the HER and LER injection performances for high-luminosity operations require further improvement. Stable double-bunch injection is useful for the HER; however, issues like aging degradation of the photocathode gun and frequent HER beam aborts caused by the injected beams must be addressed. The newly designed photocathode gun is planned to be installed in the summer of 2025.

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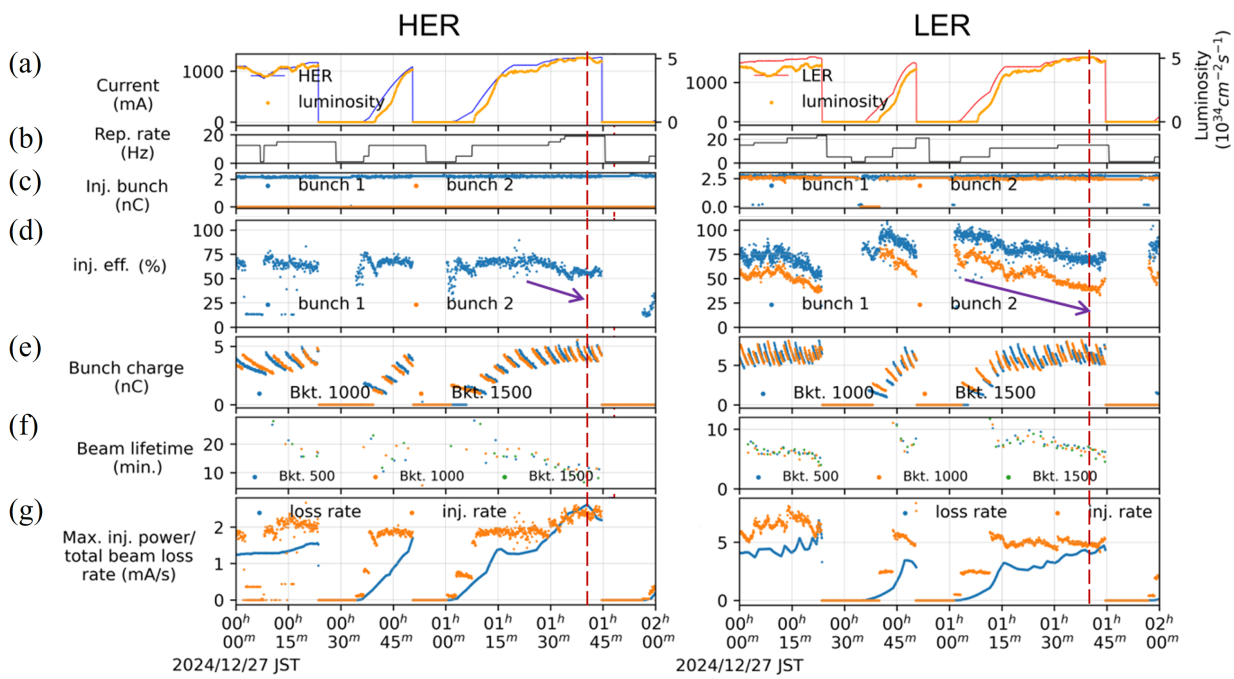

Figure 2: Injection overview of HER (left) and LER (right): (a) storage currents and luminosity, (b) injection frequencies, (c) bunch charges at the injector ends, (d) injection efficiencies, (e) bunch charges and (f) beam lifetimes at some buckets, and (g) injection powers and beam losses. The dashed red lines correspond to the peak luminosity.

SEVERAL INJECTION SCHEMES

As mentioned previously, low-beta optics reduce the transverse dynamic aperture. We explored the possibility of an Aperture Sharing (AS) Injection scheme [5] for SuperKEKB. This approach differs from those using multipole kicker magnets [6, 7] developed by several light source facilities.

A schematic comparison of conventional betatron injection and AS schemes is illustrated in Fig. 3. In the betatron injection, the horizontal oscillation of the stored beam is nominally zero, whereas the injected beam has a large amplitude at the 0th turn after injection. Each particle of the injected beam is lost when its horizontal action ($2J_x$, the Courant-Snyder invariant) exceeds the horizontal dynamic aperture of the ring.

By contrast, in the AS scheme, the stored and injected beams exhibits nearly the same oscillation amplitude after the injection. This scheme requires two new fast pulsed kickers (~100 ns) in the ring and a sophisticated bunch-by-bunch (B-by-B) orbit feedback (FB) system. The FB system must be configured to turn off for the injected buckets and turn on for all the others until the next injection. The present B-by-B FB system, which is active for all buckets, rapidly reduces the barycenter oscillation of both the stored and injected beams. This implies that the injected beam centroid oscillation was not damped at high storage currents owing to the low ratio of the injected bunch charge to the stored bunch charge. In addition, even when the injected and stored beams have the same amplitude at the zeroth turn, the amplitude of the injected beam rapidly increases during the first 100 turns because the conventional B-by-B feedback system works properly. Therefore, it is essential to develop a new TbT-FB system. The new pulsed kickers placed after the main injection kickers are key devices for nullifying the intermediate trajectory between the horizontal orbits of the injected and stored beams. Notably, the non-injected

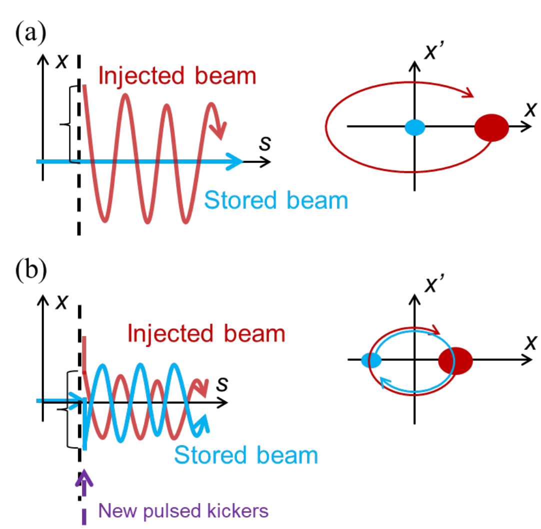

Figure 3: Schematic comparison of the two injection schemes: (a) conventional betatron and (b) aperture sharing (AS) injections. The stored (blue) and injected (red) beams around the injection are illustrated.

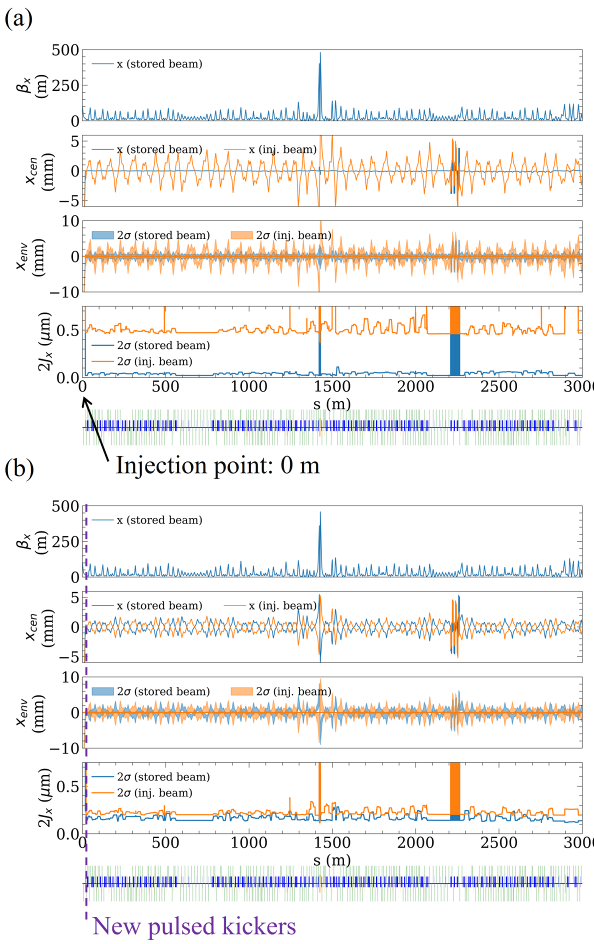

Figure 4: Comparison of (a) present betatron injection and (b) AS injection schemes, with stored (blue) and injected (orange) beams after the injection. The graph shows, from top to bottom, the horizontal beta function of HER optics, beam orbits, 2σ beam envelopes, and actions $2J_x$.

adjacent bunches are affected by fast kickers but are rapidly damped by the TbT-FB system.

To evaluate the AS scheme, simulations were performed with the particle tracking code SAD using HER optics with $\beta_y^* = 1$ mm. The horizontal emittances of the injected and stored beams were 10.9 nm and 4.45 nm at the injection point, respectively. The collimators were completely open. Fig. 4 shows a comparison of $2J_x$ for the injected and stored beams in each scheme at the zeroth turn after the injection.

Table 1: Comparison of the horizontal actions $2J_x$ (μm) in the betatron and AS injection schemes.

Injection scheme	Stored beam	Injected beam	Stored and injected beams
Betatron	0.022	0.47	0.47
AS	0.14	0.20	0.20

In the conventional betatron injection, the $2J_x$ of the injected beam (2σ) is higher than that of the stored beam, whereas, in the AS injection, it becomes less than half of $2J_x$ of the conventional betatron injection. The detailed values are listed in Table 1. These simulation results demonstrated the advantages of AS injection over betatron injection.

A technical feasibility study on fast kickers, sophisticated TbT feedback systems, beam instabilities, and emittance degradation of non-injected adjacent bunches will be conducted in the future.

SUMMARY

Since SuperKEKB operation has demonstrated that low-beta optics with $\beta_y^* \leq 1$ mm significantly reduce the transverse dynamic apertures and lower the beam injection efficiencies, particularly at high storage currents. An AS injection scheme was proposed to mitigate this issue.

ACKNOWLEDGEMENTS

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