STATUS OF SuperKEKB INJECTION

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Abstract

Injection efficiency of the electron and positron beams is of great importance to achieve high luminosity in the SuperKEKB collider. The injection efficiencies for both rings are crucial for high luminosity, but have been still insufficient. It has become clear that there are many reasons for the bad injection not only in the injector complex, but in the collider rings. As for the injected beam, unexpected huge emittance growths, or blowups, appear in both beam transport (BT) lines. Energy jitter and drifts cause the beam fluctuation and poor injection efficiency. After injected into the ring, the injection efficiency seriously decreases at high bunch current. In this paper, we will describe several measurements and particle-tracking simulations on these phenomena, and present several possible solutions toward the next operation, at the end of 2025, and for the future.

INTRODUCTION

As for the LER, the achieved charge/pulse q^b_{inj} has not reach the required value, q^a_{inj} yet. Even the achieved value of q^b_{inj} for the HER looks higher than the required, the injection efficiency ϵ_{inj} for the luminosity 1×10^{35}/cm^{2}s can be degraded due to higher stored/bunch currents, tighter collimation, stronger beam-beam, and collective effects. At $\beta^*_y = 0.8$ mm, the injection situation is expected to worsen even further.

Table 1: Beam Parameters for a Luminosity of 1×10^{35}/cm^{2}s

Parameters	LER	HER	LER	HER
bunches/ring	2345+1		2345+1	
Luminosity [/cm^{2}s]	1×10^{35}		$1{\times}10^{35}$	
I_{total} [A]	2.08	1.48	2.78	1.65
β^*_y [mm]	0.8	0.8	1	1
σ_z [mm]	6.49	6.35	7.26	6.51
τ_{beam} [min.]	3.4	14.8	4.7	16.9
$\epsilon^a_{\mathrm{inj}}$ [%]	68	17	66	16
$Q \times n^a_{\mathrm{bi}}$ [nC]	3×2	2×2	3×2	2×2
q^a_{inj} [nC/pulse]	4.1	0.68	4.0	0.64
q^b_{inj} [nC/pulse]			2.6	0.69

The SuperKEKB B-factory [1] is a double-ring collider consisting of the HER (7 GeV electrons) and the LER (4 GeV positrons), aiming at a very high luminosity of 6.5×10^{35}/cm^{2}s with low emittance beams based on the "nano beam" scheme [2]. Small emittances of the injection beams are required to achieve the high luminosity. The last SuperKEKB operation named 2024c, from Oct. 9 through Dec. 27, recorded the highest luminosity of 0.51×10^{35}/cm^{2}s. The next milestone is 1×10^{35} /cm^{2}s by Jan. 2027. The beam parameters for this luminosity are summarized in Table 1 [3, 4], where the superscript * denotes the values at the interaction point. The superscripts a and b denote the requirement for injection for 25 Hz, $q^a_{\mathrm{inj}} \equiv \epsilon^a_{\mathrm{inj}} Q n^a_{\mathrm{bi}}$ and parameters at the maximum luminosity achieved in 2024c, respectively. The beam life time in the collision is expressed by τ_{beam}. The injection efficiency $\epsilon^a_{\mathrm{inj}}$ is defined in [3].

LAYOUT OF THE INJECTOR COMPLEX

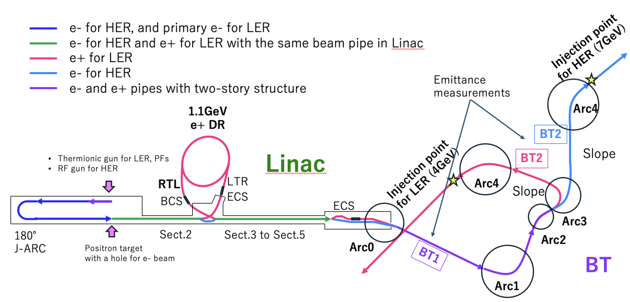

Figure 1: Layout of the injector complex for SuperKEKB. Emittances are mainly measured at locations "BT1" and "BT2" for both e$^-$ and e$^+$ beams. A set of four wire scanners is used in BT1, and a OTR screen monitor with two quadrupoles are used by so-called "Q-scan" method in BT2.

The injector complex for SuperKEKB consists of a Linac [5, 6], and a positron damping ring (DR) [1], as shown in Fig. 1. The Linac provides alternatively, pulse by pulse, beams with different species, charges, and energies in the pulse-by-pulse basis with maximum frequency of 50 Hz to five rings. There are two 500 m-long beam transport (BT) lines for electrons and positrons between the Linac and the collider rings. In the first half of the BT, e$^-$ and e$^+$ lines are vertically stacked. Each line has five arcs with large bending angles, and the sum of the absolute values of the bending angles is 260°/374° for electron/positron lines, respectively. The maximum bending angle of the dipoles is about 5.8°/12°, with curvature radius of about 20 m/10 m, which requires strong magnetic fields, which a cost of possible multipole components. As a result, the R_{56} component of transfer matrix reaches -5.8/-6.1 m (e$^+$/e$^-$), which makes a large longitudinal mismatch of the injected beam to the ring. High magnetic field also generates intense synchrotron radiation, especially in the e$^-$ BT.

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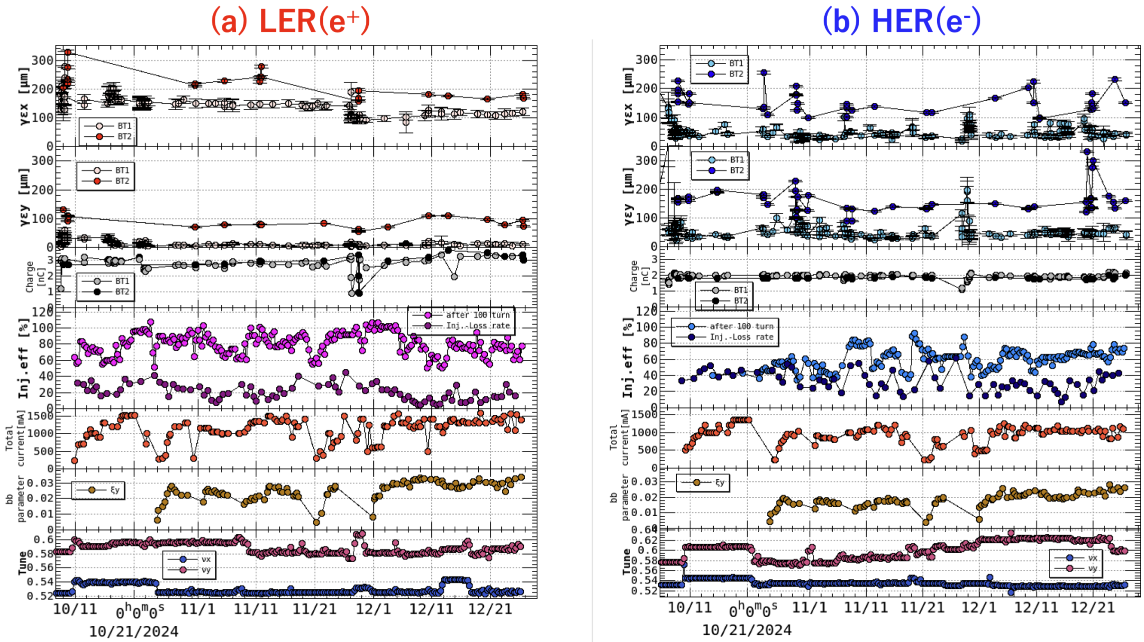

Figure 2: The trend graphs of measured parameters in 2024c are shown in (a) and (b) for LER and HER, respectively. The measured values are shown, from top to bottom, the horizontal emittances measured at BT1 and BT2, the same of vertical emittance, bunch charge of the injection beam, injection efficiencies after 100 turns and $\Delta Q_{ring}/\Delta Q_{inj}$, total current, beam-beam parameters, and tunes.

All magnets and power supplies in the BT are mostly reused from the KEKB/TRISTAN era, although some have been modified. It has recently become clear that one of the causes of the emittance growth in the e^+ BT is the large multipole components introduced in the dipole of Arc2-3 when the magnet pole was modified as the energy increased from 3.5 GeV for KEKB to 4 GeV for SuperKEKB. Vertical asymmetric structure introduced in the modification also contributed the vertical emittance growth. This will be discussed in Sec. Plan of injection improvements below.

INJECTION ISSUES

The injection status in 2024c is shown in Fig. 2. The injection efficiency depends on only the emittances but also the charge of the injection beam, the bunch current of the stored beam, the beam-beam effect. There exist additional effects such as an error of “QCS cancel coil” for the HER as well as the stability of injected beam. In this section, we will discuss each of these phenomena.

Emittance Blowup

The emittance blowups in the BT lines are summarized in Table 2. The measurements are performed in the period from Nov. 7/29 (e^-/e^+) to Dec. 27, 2024. The measured emittances at BT1 are almost within the requirements of the rings in both horizontal and vertical planes. However in BT2, large emittances have been observed at all times. The horizontal emittance blowup in e^- BT of about 75 μm can be explained by the incoherent synchrotron radiation (ISR) of about 55 μm, and the coherent synchrotron radiation (CSR) of about 20 μm for 2 nC/bunch. However, the vertical blowup is still a mystery.

Table 2: Emittance Blowup in the BT Lines and Required Value for SuperKEKB

		BT1	→	**BT2**	Req.
e^-	$\gamma\varepsilon_x$ [μm]	39.2±9.6		143±38	40
	$\gamma\varepsilon_y$ [μm]	42.5±7.7		136±22	40
e^+	$\gamma\varepsilon_x$ [μm]	110±10		174±11	100
	$\gamma\varepsilon_y$ [μm]	10.5±4.0		81.0±20	15

As shown in Fig. 3, when a vertical local bump is created a particular location of Arc1/Arc3 (e^+/e^-) of the BT lines, an unexpected horizontal kick is observed in the local bump region. One of the possible causes of the emittance blowup is unexpected magnetic fields (e.g., skew components or higher-order magnetic field components) in these arcs. A solution for the e^+ BT is discussed in a later section.

The horizontal action ×2, $2J_x$, of the injected beam is shown in Fig. 4. The actions of the injected beams in the rings are summarized in Table 3. The apertures in the ring shown in Table 3 are the measured value [7]. For both rings, the vertical emittances of the injected beam are much larger than the measured acceptance of the ring. Emittance blowups along the BT lines together with the narrow acceptance in the ring, especially in the vertical direction, is the most serious problem that must be solved. In addition, the measured vertical acceptance of the HER seems much

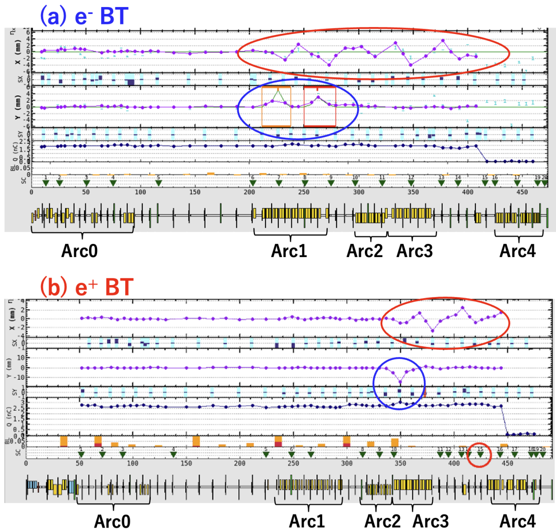

Figure 3: The vertical local bump (blue circle) makes an abnormal horizontal orbit (red circle) in (a) e^- BT and (b) e^+ BT lines. The name of each arc is also shown.

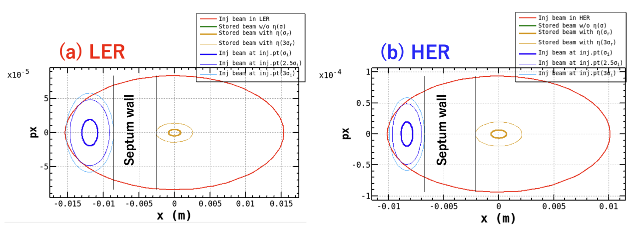

Figure 4: The horizontal phase space in (a) LER, and (b) HER. The red ellipse shows $2J_x$ of the injected beam. The blue and pale blue ellipses show 1σ and 2.5σ of the injected beam. The yellow and pale yellow ellipses show 1σ and 3σ of the stored beam.

smaller than the simulated value without the impedance effects. [7]

Table 3: The Action of the Injected Beam and the Measured Acceptance of the Ring

	Action	Injected beam		Ring acc.
HER	$2J_x$ [μm]	0.95	~	0.90
	$2J_y$ [μm]	0.060 ($6\varepsilon_y$)	>	0.04
	$\delta_{\max}$ [%]	±0.31 (95% Incl.)	<	0.56
LER	$2J_x$ [μm]	1.29	~	1.4
	$2J_y$ [μm]	0.062 ($6\varepsilon_y$)	>	0.025
	$\delta_{\max}$ [%]	±0.32 (99% Incl.)	<	1.03

Bunch Current

Figure 5 shows the betatron oscillation of the injected beam and survived charge after injection. The transverse damping times are 5800/4600 turns for the HER/LER, respectively. Even if the injection efficiency is low due to large horizontal injection oscillation, as shown in Fig. 5(a2) and (b2), the oscillation can be suppressed by the BxB FB

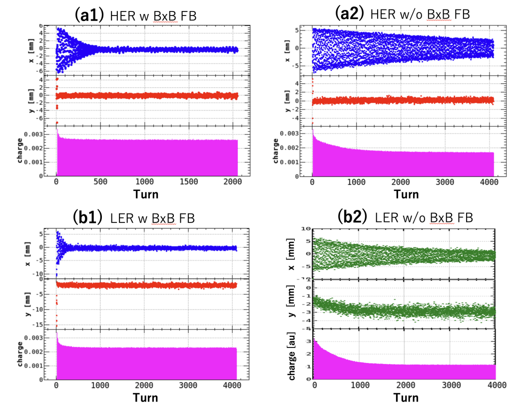

Figure 5: Measured betatron oscillation of injection beam with the turn by turn BPM (TbT-BPM). The three plots in each graph show, from top to bottom, measured horizontal and vertical oscillations and charge, of the injected beam after 4000 turns (2000 turns only for (a1)) of the injection. (a1) and (a2) show those with and without bunch-by-bunch feedback (BxB FB) in the HER. (b1) and (b2) show the same plots as (a1) and (a2) in the LER.

and injection can be improved, as shown in Fig. 5 (a1) and (b1). However, at the high current, the center of mass of charge in the bucket gets close to the stored bunch, the injection oscillation is less suppressed by BxB FB. The effect of BxB FB gets weaker at the high stored current, e.g., the stored/injected bunch charges are 5.4/2.0 nC for the HER, and 7.0/3.0 nC for the LER, respectively

Charge of the Injected Beam

One of the reasons for the low injection efficiency is the narrow vertical aperture of the ring [7], physically and dynamically. For both rings, the measured vertical apertures are less than half of those obtained from the tracking simulations without machine errors and collective effects. This is likely due to the impedances, which have been missing in the simulation, of the narrow vertical collimator setup in the rings. The collimators reach minimum full width about 4.7/2.0 mm (HER/LER), which induces short-range wake field by the injection beam passing close to the collimator.

The $2J_y$ with the narrowest collimator is about $8/12\varepsilon_y$ (LER/HER) of the injected beam shown in the Table 3, which is especially narrow in the LER.

Beam-beam Effect

As shown in Fig. 6, the beam-beam effect also decreases the injection efficiency, especially for the LER rather than the HER. In the LER, immediately after the HER beam was aborted, the injection efficiency obtained 5 seconds after injection rose from 60% to 80%, even though the stored current in the LER did not change. This indicates that the injection efficiency had decreased due to the effects of collisions. The reason why there is little change in the injection efficiency obtained after 100 turns is because the beam-beam effect affects the injection efficiency only after ~ 300 turns [8]. On the other hand, in the HER, despite the sudden abort of the LER, there was no significant change in the injection efficiency obtained 5 seconds after the injection.

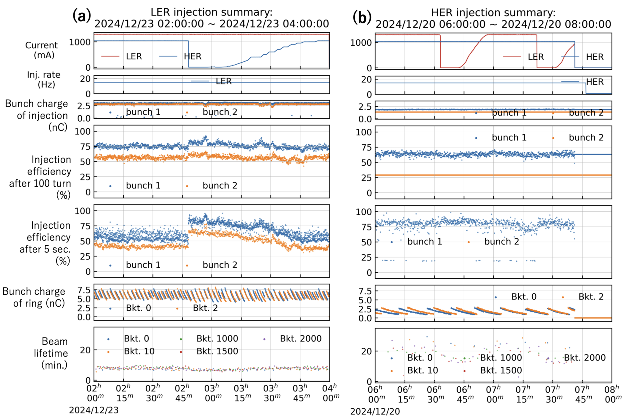

Figure 6: Trend graphs of injection parameters around the time the luminosity record was achieved. (a) and (b) show the LER and HER, respectively. Starting from the top of the graph, plots are; stored current, injection rate, bunch charge of injected beam, injection efficiency obtained after 100 turns, that after 5 seconds, stored bunch charge, and beam lifetime.

QCS Cancel Coil Error

In the final focus quadrupoles, QCS, there have been assembly "errors" in the cancel coil in the HER to compensate the leakage fields from the final focus quadrupole in the LER. [7]. Its effect on the injection is not negligible. This error reduces the horizontal dynamic aperture of the nearly on-momentum injected beam. It is expected that the dynamic aperture can be recovered by using skew sextupole correctors in the HER QCS.

Stability of the Injection Beam

To maintain good injection efficiency, the stability of the injection beam is important. Unlike the positron beam for the LER, which is extracted from the DR, the electron beam for the HER inherits all fluctuations caused by the RF gun through the Linac. The crucial locations for electrons are the RF Gun, J-ARC, and the hole region around the positron target. For example, if the orbit fluctuates in the Linac due to temperature fluctuation, the wakefield effect increases the emittance resulting in a poor injection. To examine this issue, the injection into SuperKEKB had to be suspended, and corrected using screen monitors and wire scanners in the BT line. In addition, since the Linac pulse by pulse supplies beams to the photon factories (PFs) and SuperKEKB, the orbit feedback must maintain the orbits in sectors 3 to 5 of the Linac by the pulse steering magnets. Currently there are not enough pulse magnets at near places, operators had to correct the orbit more globally with careful tactics. However, in 2024, by introducing a non-destructive synchrotron radiation monitor (SRM) in the e^- BT line, a real-time detection of the increase of transverse beam sizes has become available. Then it has made possible to examine and tune the beam without an intervention of the injection. In future operation, we will try to replace these procedures in the BT lines including injection with automatic tuning.

PLAN OF INJECTION IMPROVEMENTS

Emittance of the Positron Beam

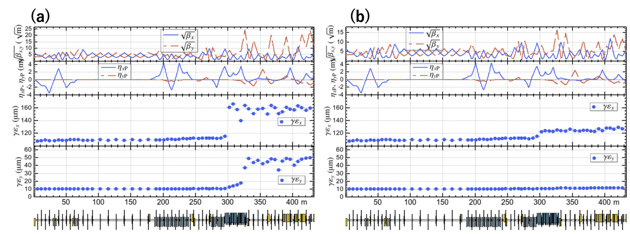

Figure 7: The results of the tracking simulation of the e^+ BT line. From top to bottom, the graph shows the β function, the dispersion function, the horizontal normalized emittance, and the vertical emittance, along the BT line. (a) Simulation by using the magnetic field calculation of the eleven dipoles in the Arc3, with the current magnet. (b) Same as (a) but with the newly designed magnetic poles.

Table 4: Simulation of the Emittance Improvement in e^+ BT

e^+	(measured)	**present**	→	**reformed**
$\gamma\varepsilon_x$ [μm]	174±11	160		125
$\gamma\varepsilon_y$ [μm]	81±20	47		12

The dipoles installed in Arc2-3 of the e^+ BT lines have multipole magnetic fields that caused the emittance blowup. Using the calculated multipole magnetic fields of these dipoles, a tracking simulation [9] through the BT line has been has explained the blowup of the horizontal emittance as shown in Fig. 7(a). This also explains about 60% of the increase of the vertical emittance, but some residuals remain. If we modify the pole of the dipoles [10, 11], the blowup could be mitigated as whown in Fig. 7(b). These results are summarized in Table 4. More than 2/3 of those dipoles will be reformed during the summer 2025.

Stability of Klystrons

The klystron power supplies used to set the voltage in an analog form until Oct. 2024, but it has been changed to digital transmission in order to stabilize the power supply voltage. Thanks to this, the 1σ of the RF phase jitter was reduced from approximately 0.035° to 0.01°, and the 1σ of the e^- beam energy jitter has reduced from 0.029% to 0.018%.

An update to the air conditioning temperature control in the klystron gallery will be implemented.

A new synchronization system based on laser pulse light signals instead of electronic radio frequency signals was developed. Then the RF signal generated by the RF gun's laser source is not affected by temperature fluctuations or klystron interference. The laser signal has the capacity to cover the entire Linac.

e⁻ Energy Compression System (ECS)

A new ECS is planned to be installed in the e⁻ BT line. This requires the beam orbit deviation near the accelerating structure to be reduced in order to prevent emittance blowup due to wakefield effects. The BPM readout system will be replaced with one with an accuracy under 10 μm, as that in the Linac, from the current accuracy of about 100 μm.

Automatic Tuning with Machine Learning

Various automated tuning techniques using machine learning have significantly improved the injector performance [12]. Regarding the positron yield, by optimizing the pulsed electromagnet and DC electromagnet upstream of the target (Bayesilian optimization + downhill simplex method), the positron charge at the Linac terminal was increased from 3 nC to 4.2 nC, which is the recorded value.

Since tunings of the orbit were previously performed by an operator, now they can be quickly optimized through automatic tuning. For example, to suppress the emittance blowup of the electron beam in the Linac caused by the wake field, the pulsed dipole corrector upstream of the hole in the positron target optimized to reduce the beam size looking at the SRM in the BT line. In addition, optimization of the injection orbits can be quickly optimized through automatic tuning.

The Second Bunch Orbit Tuning

Fast kicker magnets that kick only the second bunch have been introduced to the Linac and DR extraction lines. This allows us to correct the orbital difference between the two bunches, caused by the difference in beam energy in the Linac, the long range wake, and the difference in kick angle between the bunches of the DR extraction kicker. In addition, since the orbits of the first and second bunches usually overlap, it is not possible to measure the emittance separately on the OTR, however, by intentionally kicking only the second bunch vertically during OTR measurement, it is now possible to measure both bunches separately on the OTR.

Future Plan of the New BT Line

The horizontal emittance growth in e⁻ BT is mainly caused by ISR and CSR [13]. To solve ISR at least, there is no other way than to make the present BT line (A) shown in Fig. 8(a) straighter. A new BT line (B) was considered [3]. Furthermore, we considered ECS1 and ECS2 as new ECS installation locations. As a result, as shown in Fig. 8(b), ECS2 has a smaller longitudinal $2J_z$ for both beam lines, (A) and (B). In addition, as shown in Fig. 8(c), it was found that the horizontal emittance blowup due to ISR is reduced in (B) line. However unfortunately, construction is currently underway in ECS1, and if the BT line is changed to (B) in the future, ECS1 will have to be moved to ECS2.

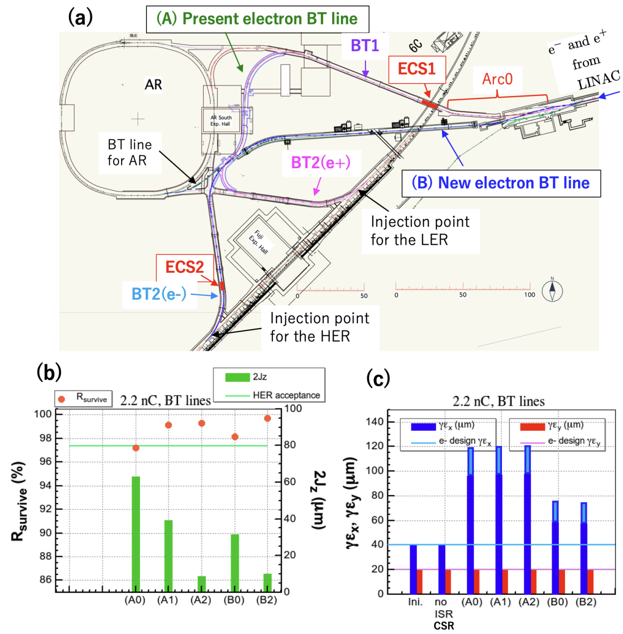

Figure 8: (a) Layouts of the present electron BT line for the SuperKEKB (A), and a proposal of the new straight BT line (B). (b) shows the injection efficiency including the beam loss in the BT line and $2J_z$ of the particles for each case. Green straight bars show the acceptance of the HER, $5\sigma_z$. (c) shows the horizontal, vertical emittances, and the horizontal straight lines show their design values. The blue bars show the horizontal emittance including the ISR effect, and the pale blue bars show the additional emittance growth due to the CSR.

CONCLUSION

The current injection performance for both rings are insufficient for the luminosity of 1×10^{35} /cm^{2}s. Everything is entangled with; the beam emittances (6D), stability, bunch charge, stored bunch current, total current, collimator setting, beam-beam interactions, dynamic aperture, affect the injection performance. The considerations to improve the injection performance are; the rebuilding the dipole magnets in Arc3 of the e⁺ BT line to mitigate the emittance growth, and the construction the e⁻ BT line to the straight path (future plan). The source of the vertical emittance blowup still remains to be solved. Automatic tunings of the emittance and injection efficiency with machine learning are scheduled to start in the next operation. Improvement of stability in the Linac is to be done before next run.

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