DEVELOPMENT OF NON-DESTRUCTIVE EMITTANCE TUNING SYSTEM UTILIZING SYNCHROTRON RADIATION MONITORS

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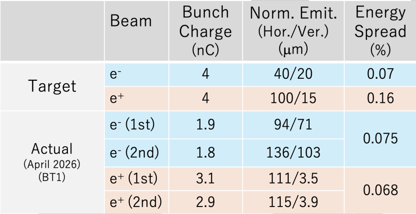
Abstract

In SuperKEKB, the emittance of the injected beam is an essential parameter that significantly affects the injection rate. In the LINAC, the beam tail can be kicked depending on the orbit through the accelerating structures, which leads to a degradation of the emittance. Fortunately, these effects can be minimized by appropriately optimizing the beam oribt. On the other hand, the KEKB LINAC uses pulse steering to supply beams to four different rings. However, the number of pulse steering is limited in the upstream part of the LINAC, and orbit drift in the upstream part often leads to emittance drift, deteriorating injection rate. To address this issue, we have developed a non-destructive emittance tuning system utilizing Synchrotron Radiation Monitors.

INTRODUCTION

SuperKEKB is e-/e+ collider for high energy particle physics in KEK. Recent operation is as described in the following report [1, 2]. Required beam parameters for injection beam are shown in Fig. 1. These emittance values are slightly large since that is included during troubles and studies. Double bunches are delivered at 96 ns intervals in the LINAC. The current bunch charge is lower than the target especially for HER. This reason is that low emittance transport is not successful at high bunch charge, and the impact of the emittance growth to the background of Belle II detector also cannot be ignored. We have to convey this high quality beam to the main ring without emittance degradation as far as possible. Otherwise, the injection rate would be worse and the luminosity would not be able to reach the target value.



	Beam	Bunch Charge (nC)	Norm. Emit. (Hor./Ver.) (μm)	Energy Spread (%)
Target	e^-	4	40/20	0.07
	e^+	4	100/15	0.16
Actual (April 2026) (BT1)	e^- (1st)	1.9	94/71	0.075
	e^- (2nd)	1.8	136/103	
	e^+ (1st)	3.1	111/3.5	0.068
	e^+ (2nd)	2.9	115/3.9	

Figure 1: Required and averaged measured beam parameters at BT1 in April 2026 for SuperKEKB injector LINAC. The energy spread value is the value of 1σ when the total width is assumed to be 3σ.

A layout of the LINAC and the beam transport line (BT) is shown in Fig. 2. The LINAC is composed of Sector A, B, J-ARC, C, and 1-5. The LINAC has two kinds of electron gun; a thermionic gun to obtain high-current beam used for positron production and a photocathode RF gun for low emittance electron beam. The large emittance of the positron beam emittance for LER is reduced by a damping ring (DR), which is placed beside the end of Sector 2. The beam is extracted from the end of Sector 2 to the LTR line at 1.1 GeV and injected to the DR. After two cycles of the LINAC pulse, the damped beam is, through the RTL line, resumed to the start of Sector 3 in the LINAC. Positron beam is accelerated up to 4 GeV and transported through the positron BT line and finally reaches the low energy ring (LER). Low emittance electron beam is accelerated up to 7 GeV and transported through the electron BT line and finally reaches the high energy ring (HER). We mainly discuss injection beam for HER in this report.

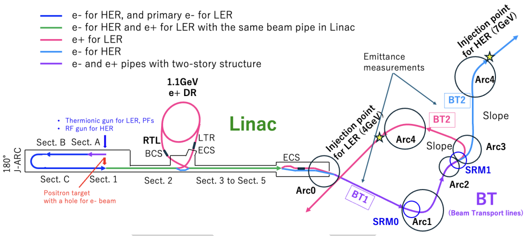


Figure 2: A layout of SuperKEKB injector LINAC and the beam transport line.

EMITTANCE FLUCTUATION

Emittance fluctuation has been observed in the LINAC. One of the reason is orbit fluctuation. In the LINAC, the beam tail is kicked depending on the orbit through the accelerating structures, which leads to a degradation of the emittance. The emittance growth in the LINAC cause a reduction of injection efficiency. Since beam lifetime of SuperKEKB ring is much shorter than KEKB, injection efficiency affects total beam current of the ring. Therefore, emittance fluctuation sometimes causes reduction of the SuperKEKB performance, luminosity. Main orbit fluctuations are correlated with temperature fluctuations in the upstream of the LINAC. Despite ongoing mitigation efforts, the impact remains significant.

The LINAC performs continuous injection into four different rings, HER, LER, PF, and PF-AR. The orbit for each ring is controlled by pulsed steering magnet. Unfortunately, the number of the pulsed steering magnet is limited at the LINAC upstream, Sector A, B, J-ARC, and C. We cannot fix the orbit at the region completely.

As an example, orbit drifts of two nearby BPMs was found at the entrance of J-ARC. The orbital difference shifted by about 0.1 mm to 0.2 mm over a few days. To verify the effect of this orbital difference on emittance, we reproduced this orbital difference by changing the upstream steering magnet during LINAC's standalone operation and performed emittance measurements. As a result, it was confirmed that

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the 0.1 mm orbital difference causes emittance growth of approximately 70 μm, which is non-negligible value.

As an interesting example, we present a phenomenon in which the beam has double peak transversely even on a straight section where dispersion normally does not occur, due to a wake field generated by the orbit. As the beam charge increases, the beam loading caused by the wake field also increases. Figure 3 shows that when the beam charge is approximately 2 nC or greater, the energy spread minimization results in a double peaked energy distribution by superimposing the RF curvature and wake field [3, 4]. If the beam has double peak energy distribution in the dispersive section, double peak beams appear on the screen as usual. On the other hand, Fig. 3 shows not only that a double peak is observed, but also that there is a z-δ dependence in which energy peaks appear at the head and tail of the beam. Meanwhile, the beam is kicked by transverse wake field, which makes x-z dependency. The dependencies on both z-δ and x-z eventually lead to the emergence of a dependency on x-δ. In other words, even in straight section where dispersion is normally absent, beams with double peak transversely appear via the energy distribution of the double peak. Figure 4 compares tracking simulations that take the wake field into account using SAD [5] as a simulation code with actual measurements and successfully reproduces the measurement.

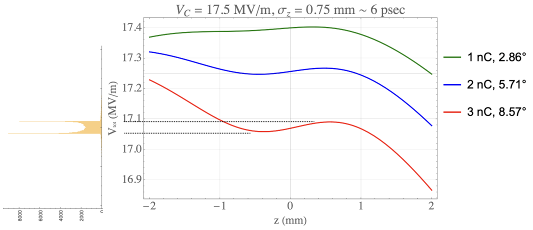

Figure 3: Acceleration curvature including longitudinal wake field (right) and energy distribution (left).

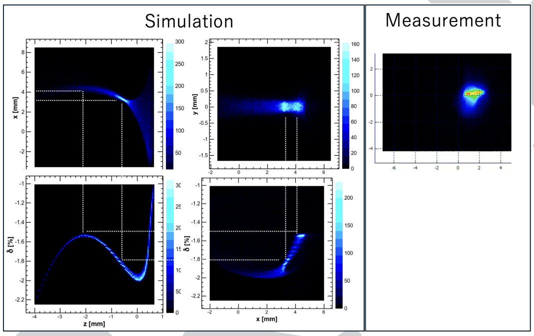

Figure 4: Comparison of simulation and actual measurement of beam profile at Sector A.

The beam profile improvement by orbit correction is shown in Fig. 5. The double peak beam phenomenon disappeared by only the orbit tuning, and the emittance was also significantly improved. In principle, this double peak beam issue can be mitigated using the energy spread tuning by changing the RF phase; however, this does not provide a fundamental solution. Since RF phases are key parameters for minimizing the energy spread, unless there is a specific reason not to, this issue should be corrected by the orbit.

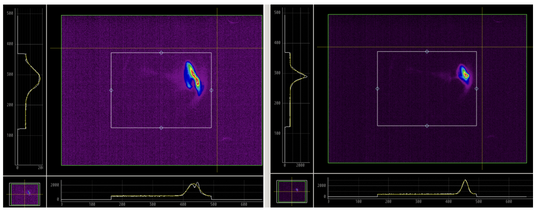

Figure 5: Beam profile at LINAC end before (left) and after (right) the orbit tuning was performed.

EMITTANCE AUTO TUNING SYSTEM

Two Synchrotron Radiation Monitors (SRMs) system were installed at BT electron line [6] with different phases at SRM0 and SRM1 in Fig. 2. The beam tail, kicked by the wake field in the accelerating structure, generally has different transverse position and transverse momentum from the beam head. As a result, emittance growth occurs for the whole beam. Conversely, if we can find a steering magnet parameters set which minimize the beam sizes at the SRMs, this is equivalent to minimizing the difference in position and momentum between the beam head and tail, and thus minimizing the emittance. We established a system that automatically searches for the smallest beam size at BT SRMs, which can perform non-destructive measurement, using several pulsed steerings in LINAC upstream as search parameters. This system is called as Emittance Auto Tuning system (EAT), and it can select Downhill Simplex or Bayesian as its optimization method. We didn't notice much difference between the two methods about convergence value and convergence rate. Recently, the downhill simplex method is selected for stable injection. The objective function is as follows:

$$\frac{\Sigma_i \sigma_{x,i}^2/\beta_{x,i} + \mathrm{w}\ \Sigma_i \sigma_{y,i}^2/\beta_{y,i}}{Q_{\text{Linac end}}^2/Q_{\text{RF gun}}^2}, \qquad (1)$$

where σ is beam size, β is β function, $i = 0, 1$ corresponded to SRM0 and SRM1, Q is bunch charge, and w is weight. Since vertical emittance is more important for injection efficiency than horizontal emittance, w=2 is set currently. This system continuously tuning during injection to SuperKEKB. It needs to be carefully explored since it may cause beam abort due to increased background of Belle II. Therefore, this system is designed to work in conjunction with the orbital feedback systems in Linac and BT to avoid unintentionally disturbing the orbit.

As an example, emittance before and after tuning by EAT is shown as Table 1. Emittance was measured by wire scanner (WS) system at BT1(LINAC end), which is destructive measurement. In the case of double bunch operation, the beam sizes measured by SRMs are the superposition of two distributions. EAT optimize to minimize the beam sizes of this superposition. Since this optimization is equivalent to minimizing emittance of the superposition, it aligns with the objective of improving injection performance. Not only

1st bunch but also 2nd bunch emittance were successfully improved by EAT in this case.

Table 1: Emittance Measurement Results Before and After Running EAT

	Bunch	$\gamma\beta\epsilon_x$ [μm]	$\gamma\beta\epsilon_y$ [μm]
Before	1st	81 ± 16	37 ± 10
	2nd	116 ± 18	54 ± 13
After	1st	44 ±12	21 ± 4
	2nd	66 ± 6	49 ± 6

Injection improvement by RF phase (all) and EAT is shown as Fig. 6. By recent study, we found that all RF phase tuning as a unit in the LINAC affects injection efficiency. This RF phase (all) tuning is equivalent to changing the laser's phase for RF gun. In the figure, KL down was happened 3 times, and there are periods of time when the currents decreased. At the time, the injection efficiency increases. Thus we should ignore at the time for fair evaluation of injection performance. Both RF phase and EAT contributed injection efficiency and background reduction of Belle II significantly. Since the RF phase tuning alters the orbit, the EAT must be run after the RF phase has been tuned. Figure 7 shows the trend of objective function value (left top, purple) and the pulsed steering current (right) when the EAT was running. As time progresses, the objective function value decreased, and in correlation with this, the injection efficiency improved as shown in Fig. 6.

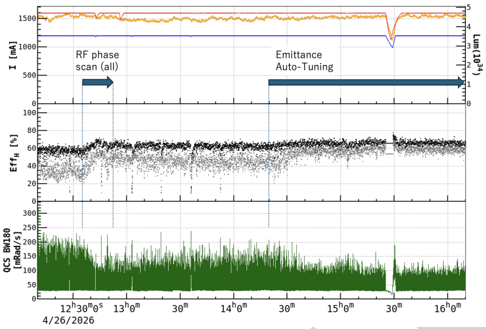

Figure 6: Injection improvement by LINAC tuning. From top to bottom, this figure shows current (LER: red, HER: blue, luminosity:yellow), injection efficiency (1st bunch: black, 2nd bunch: gray), and one of the Belle II backgrounds.

This optimization is basically performed every few hours, which depends on the beam repetition rate, except during study or trouble. As shown in Fig. 8, EAT operations began in late January 2026. Where there is no value for the 2nd bunch, it indicates that only the 1st bunch was operating. This figure displays all emittance measurements, including those taken during the trouble and study phases. In the case of only the 1st bunch operation, i.e., during the period when the 2nd bunch plot is not available, the vertical emittance, which affect injection performance significantly, is large and unstable before EAT operation. After the EAT operation, the vertical emittance often stabilizes and improve below 50 μm. On the other hand, in the case of double bunch operation, the emittance had not improved as much as expected. Possible causes include orbital drift between the first and second orbits and RF phase drift. Since the current EAT system only alters the orbit, the improvement is limited to the part of the emittance that was degraded by the orbit. Since we are optimizing the emittance by superimposing the 1st and 2nd bunches, we believe this contributes more to the injection efficiency than the measured emittance values suggest; however, as a fundamental solution, we are considering implementations of RF phase (all) and fast kickers.

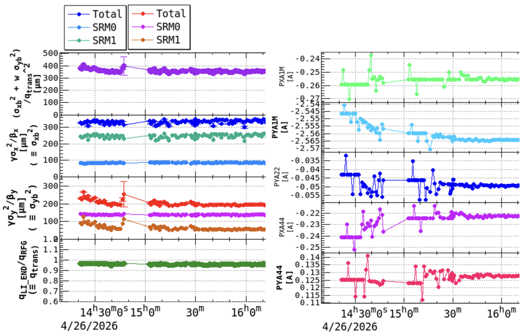

Figure 7: Trend graph of several parameters related to objective function (left) and currents of pulsed steering magnets using as search parameters in EAT (right).

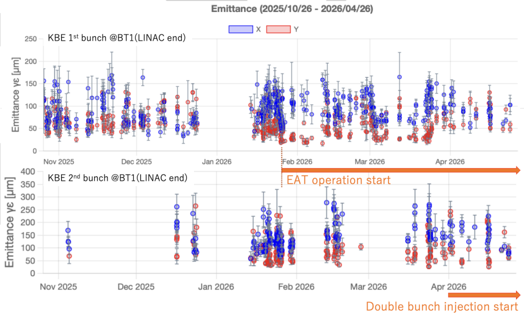

Figure 8: Emittance history at BT1. The upper and lower diagrams represent the emittance of the 1st bunch and 2nd bunch, respectively.

SUMMARY

In SuperKEKB injector LINAC, beam emittance is one of the important parameters that affects injection efficiency to the SuperKEKB. The emittance is fluctuating due to beam orbit variation in the LINAC. To mitigate this fluctuation, we developed non-destructive emittance tuning system utilizing synchrotron radiation monitors. This system improved emittance, increased stability, injection efficiency to the SuperKEKB, and background of Belle II. However, the stability of the injection is still insufficient. We plan to develop this system to achieve higher injection efficiency and stability by tuning the RF phase (all), which has been shown to have a significant impact on injection performance, and by adding a Fast kicker parameters that can selectively kick only the second bunch.

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